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# 16.4.3.2 ICES reference points for stocks in categories 3 and 4

## Introduction

This document offers a description of the reference points used by ICES for stocks in categories 3 and 4, including the purpose of the reference values and the basis for their calculation (see ICES, 2012 for a full description of the ICES stock categories). Guidance for developing the key outputs required for the advice sheets on the basis of this reference point analysis is also given.

For stocks with analytical assessments (category 1 and 2 stocks), MSY reference points are used in the advice rule applied by ICES to give advice consistent with the objective of achieving MSY. For stocks in categories 3 and 4 ICES currently uses MSY proxy reference points as part of a Precautionary Approach to provide advice on the status of the stock and exploitation. The $F_{MSY}$ proxy corresponds to the exploitation rate that will provide maximum long-term yield. The MSY $B_{trigger}$ proxy corresponds to the stock size that triggers a cautious response; *i.e.* advice on a reduced fishing mortality relative to the $F_{MSY}$ proxy to allow the stock to rebuild.

**Background**

The guidance for estimation of proxy MSY reference points for category 3 and 4 stocks was developed at two workshops in 2015: WKLIFE V and WKProxy. ICES convened these workshops to develop and apply MSY reference point for selected category 3 and 4 stocks in Western Waters (ICES subareas 5–10). The objective of this work was to have reference point proxies that fall within the ICES MSY and precautionary frameworks. In 2017 ICES continued to build upon these methods in an effort to have these MSY reference points for all category 3 and 4 stocks each time an assessment is conducted and updated advice provided; this includes updating previously calculated MSY reference points where appropriate. In 2017 an ICES review group reviewed all the proxy reference points used for advice in 2017. The recommendations of this review group have been incorporated into these guidelines.

**$B_{MSY}$ and MSY $B_{trigger}$**

The ICES approach to the provision of scientific advice does not use a $B_{MSY}$ estimate but instead, an MSY $B_{trigger}$ (ICES, 2015a). $B_{MSY}$ is a notional value around which stock size fluctuates when fishing at $F_{MSY}$. $B_{MSY}$ strongly depends on the interactions between the fish stock and the environment it lives in, including biological interactions between different species. Historical stock size trends may not be informative about $B_{MSY}$; e.g. when F has exceeded $F_{MSY}$ for many years or when current ecosystem conditions and spatial stock structure are, or could be, substantially different from those in the past.

MSY $B_{trigger}$ is considered the lower bound of stock size fluctuation around $B_{MSY}$. It is a reference point that triggers a cautious response, in the form of reduced fishing mortality, to allow the stock to rebuild. Determination of MSY $B_{trigger}$ in principle requires contemporary data with fishing at $F_{MSY}$ to identify the normal range of fluctuations in biomass when stocks are fished at this fishing mortality rate.

SPiCT, one of the methods applied by ICES for category 3 and 4 stocks, is based on a biomass dynamics model (*i.e.* a surplus production model). These models internally estimate $F_{MSY}$ and $B_{MSY}$ as part of the model fitting. In line with the ICES approach, and for the reasons stated above, the $B_{MSY}$ parameter estimated by these models is not considered as a reference point. For stocks for which these models have been applied, ICES set MSY $B_{trigger}$ at $B_{MSY}$ / 2, in parallel with what has been the usual ICES practice when surplus production models are used for category 1 and 2 stocks (see, for example, the advice sheets in 2017 of megrim in divisions 4.a and 6.a, black anglerfish in divisions 8.c and 9.a, and Greenland halibut in subareas 5, 6, 12 and 14).

Defining MSY $B_{trigger}$ as ½$B_{MSY}$ is consistent with other management systems. For example, U.S. fishery management defines the minimum stock size threshold as <½$B_{MSY}$, and fishing mortality needs to be reduced to less than $F_{MSY}$ when the stock is less than the threshold (NOAA, 2009).

## Methods for estimating MSY reference points for category 3 and 4 stocks

There are four methods approved by ICES for calculation of MSY reference points for category 3 and 4 stocks. These are:

- Length based indicators (LBI)
- Mean length Z (MLZ)
- Length based spawner per recruit (LBSPR)
- Surplus Production model in Continuous Time (SPiCT)

The methods considered have clearly specified data requirements and needs, and the strengths and weaknesses of each approach are identified. It is important to identify the data sources and assumptions that are pertinent for each stock to be assessed and to select the most appropriate methods which best use the available information. This clearly requires applying the knowledge of stock experts, including knowledge about the fisheries catching the stock.

The adopted method, or methods, will depend on data quality, preliminary model diagnostics, and participants' understanding of exploitation history and perceptions of stock development by the relevant ICES stock co-ordinator(s). All methods should be considered if the data allows (though not necessarily used), the required data and life-history inputs detailed, and the strengths and weaknesses of each method summarized. General agreement between different models strengthens inference while disagreements among methods can highlight problems with data or model assumptions.

Length data are relatively inexpensive and straightforward to obtain and usually form one of the datasets from which catch numbers-at-age are derived. Size–frequency data are the primary data collected under the DCF (ICES, 2014). Size-based methods were explored and validated further through simulation testing (ICES, 2015, 2016).

The following provides basic step-through guidance for experts in selecting an appropriate method.

1. Given that little may be known about stock-specific growth profiles and the historic exploitation of these stocks, it is advisable to begin the exploration of reference points with the length-based indicators/screening method. These indicators can be applied systematically to all stocks, and they produce an overall perception of stock status that can be used to guide experts on the choices for parameters (initial values/ranges) used in other methods.
2. If the available length data have adequate sampling information (possibly, but not necessarily, together with effort data) then the mean length-based mortality estimator (Z) should be investigated (see Section 1.4). If the diagnostics are acceptable then use this method as the basis for further analyses; if unacceptable then consider methods based solely on length data; *i.e.* length-based indicators. However, the LB-SPR requires the assumption of equilibrium, which the length-based mortality estimators do not.
3. If previous ICES advice used a catch/landings and biomass/abundance series, apply SPiCT using these data series. This method provides model diagnostics, as well as biomass and fishing mortality reference points. If the diagnostics are acceptable, then SPiCT should be used as the basis for further analyses; if unacceptable then consider analyses based on length data only.
4. In the ICES 3.3 DLS method a target is defined ("F-proxy") based on exploitation history and changes in biomass indicator. In WKPROXY (2016) it was stated that for aru.27.5a15 the 3.3 method and the Fproxy target was appropriate. In WKLIVE VII (2017) the Fproxy method was tested through simulations for management advice and found to perform reasonably well assuming that the Fproxy target was set appropriately. When the biomass index is increasing or stable over a representative period of time, then the reference Fmsy-proxy can be calculated as the average of a time-series of total catch divided by survey biomass.

When problems and uncertainties seem to contradict the use of a method, the consequence of the problems should be explored by sensitivity analysis or simulation. Data-limited methods often have less demanding data requirements than data-rich methods, and may be robust to problems with data quality or model assumptions. For example, if there is high uncertainty in natural mortality rate or growth parameters, a sensitivity analysis can explore whether or not overall conclusions about stock status change over a suite of plausible values of these parameters.

## Length Based Indicators (LBI screening methods)

A set of length-based indicators are used for screening catch/landings – length composition and to classify the stocks according to conservation/sustainability, yield optimization and MSY considerations. These indicators require data on the stock catch/landings–length composition and life-history parameters and can be applied systematically to all category 3 and 4 stocks. The overall perception of stock status from this method can be used to guide experts on the choices for parameters (initial values and/or ranges) used in other methods (e.g. SPiCT), such as picking a starting value of biomass relative to carrying capacity.

### Information required

**Table 1** Explanation of information required for ICES LBI screening methods.

| Parameter | Abbreviation | Notes |
|---|---|---|
| Length at maturity | $L_{MAT}$ | |
| von Bertalanffy growth parameters | $L_{inf}$ | By sex, if dimorphic growth.<br>Can be obtained from fishbase.org if data of a suitable quality are not available to estimate this for the stock in question. |
| Catch at length by year | | by sex in case of crustaceans |
| Length-weight relationship parameters for landings and discards | a, b | or mean weights-at-length per year |

### Method description

Length-based indicators describe length frequencies of landings and discards. Length-based indicators can be calculated by sex (e.g. *Nephrops*) and by year from length–frequency distributions. They are compared to appropriate reference points related to conservation, optimal yield and length distribution relative to expectations under MSY assumptions. When calculated by sex it is most precautionary to treat the whole species as if it were being exploited like the sex that is being fished the hardest.

Table 2 presents the selected indicators, reference points, indicator ratios and their expected values. These are grouped in terms of: i) conservation/sustainability; ii) optimal yield; and iii) MSY considerations.

**Table 2** Selected indicators for LBI screening plots. Indicator ratios in bold used for stock status assessment with traffic light system.

| Indicator | Calculation | Reference point | Indicator ratio | Expected value | Property |
|---|---|---|---|---|---|
| $L_{max5\%}$ | Mean length of largest 5% | $L_{inf}$ | $L_{max5\%}$ / $L_{inf}$ | > 0.8 | Conservation (large individuals) |
| $L_{95\%}$ | 95th percentile | | $L_{95\%}$ / $L_{inf}$ | | |
| $P_{mega}$ | Proportion of individuals above $L_{opt}$ + 10%. ($L_{opt}$ is estimated from $L_{inf}$). | 0.3 – 0.4 | Pmega | > 0.3 | |
| $L_{25\%}$ | 25th percentile of length distribution | $L_{mat}$ | $L_{25\%}$ / $L_{mat}$ | > 1 | Conservation (immatures) |
| $L_c$ | Length at 50% of modal abundance* | $L_{mat}$ | $L_c/L_{mat}$ | > 1 | |
| $L_{mean}$ | Mean length of individuals > $L_c$ | $L_{opt} = {}^2/_3\, L_{inf}$ | $L_{mean}/L_{opt}$ | ≈ 1 | Optimal yield |
| $L_{max_y}$ | Length class with maximum biomass in catch | Lopt = ${}^2/_3\, L_{inf}$ | $L_{maxy}$ / $L_{opt}$ | ≈ 1 | |
| $L_{mean}$ | Mean length of individuals > $L_c$ | $L_{F=M} = (0.75L_c + 0.25L_{inf})$ | $L_{mean}$ / $L_{F=M}$ | ≥ 1 | MSY |

*Note this definition is different from the $L_c$ used for the Mean-length Z estimator.

**Assumptions**

1. Equilibrium conditions are assumed (total mortality and recruitment have been constant for a period as long as the lifetime of the time-series).
2. Selectivity follows a logistic curve (*i.e.* is flat-topped, not dome-shaped).
3. A length-based proxy for MSY is $L_{F=M}$ = $0.75L_c+0.25L_{inf}$ (where $L_c$ is the length at first capture) and the length of optimal yield is $L_{opt}$ = $2/3L_{inf}$. The method assumes that input parameters are known, but life-history parameters $L_{MAT}$, $L_{inf}$ are often uncertain for category 3 – 4 stocks.

The equations for $L_{opt}$ and $L_{F=M}$ can both be expressed assuming M/K = 1.5, as such:

$$L_{opt} = {}^{2}/_{3}\, L_{\infty} \tag{1}$$

$$L_{F=M} = 0.75L_c + 0.25L_{\infty} \tag{2}$$

They can also be expressed in a more generalized form to allow for any value of M/K (see appendix A in Jardim *et al.,* 2015):

$$L_{opt} = L_{\infty} \frac{3}{3+{}^{M}/_{K}} \tag{3}$$

$$L_{F=\gamma M, K=\theta M} = \frac{\theta L_{\infty} + L_c(\gamma+1)}{\theta+\gamma+1} \tag{4}$$

For consistency, the same M/K ratio should be used for the calculations of $L_{opt}$ and $L_{F=M}$. A Shiny app is available for the calculation of $L_{opt}$ and $L_{F=M}$ (https://github.com/ices-tools-dev/LBIndicator_shiny).

The selection of the value for M/K can be complex. Then *et al*. (In Press) refer to a website that list the M and K values for 200 species (http://www.vims.edu/research/departments/fisheries/programs/mort_db/index.php). From this, it is possible to create a histogram of M/K values for all species, or for a relevant subspecies of species, and use this as guidance for an appropriate vlaue of M/K for the species of interest.

A lower and upper bound for the parameter $L_{\infty}$ should be used, and the LBIs recalculated using the two extreme values. This is an important exercise to check if the results are sensitive to the value placed on $L_{\infty}$. If $L_{\infty}$ is being underestimated, the resulting LBIs may give the impression that a stock is in a better state than it actually is; conversely if $L_{\infty}$ is being overestimated, the stock may appear in a worse state than it actually is. The same applies to estimates of $L_{mat}$.

$L_{max}$ should not be used as an estimate of $L_{\infty}$. $L_{\infty}$ should generally be greater than $L_{max}$: $L_{max}$ (heavily exploited) < $L_{inf}$ < $L_{max}$(lightly exploited). From (2) above, using $L_{max}$ from historical records reflecting light exploitation would give rise to a conservative assessment (making the stock look worse than it is).

Where data allows, LBI should be computed for every year, not just the most recent three years. This gives a better impression of the variability in the indicators. The trends in the indicators can also be informative, especially when they are compared to trends in effort and/or survey data. Results over time should be evaluated for evidence of departure from equilibrium conditions, *i.e.* look for possible changes in recruitment and mortality over time.

The assumption of constant (or modest, random variability in) recruitment causes some difficulties in practice. It should be understood that strong year classes reduce the mean length, suggesting high mortality when the situation is actually good (strong recruitment) and vice versa. What is critical is to determine whether an extreme (large or small) year class is distorting the mean length in the terminal year and thus distorting the perception of stock status in the most recent years. The best way to assess if there is a problem if to examine the series of annual length frequency distributions to look for evidence of modes migrating from left to right over time.

LBI can also be used when catches are a mixture of stocks. If two stocks have the same recruitment, growth, and mortality parameters (including the same selectivity patterns), then the length distributions should be the same and the LBI should reflect the situation for the stock of interest. However, if the length frequency distribution for the stock of interest is thought to be comprised of P% migrants from an adjacent stock with a different length-frequency distribution (reflecting a different length-history and exploitation pattern), then the hypothesised P% of the catch - with the alternate length-frequency distribution - can be subtracted in order to perform a sensitivity analysis. Thus, when a mixture of stocks is suspected, sensitivity analyses can be used to study the effect of stock mixing by subtracting a hypothetical distribution of contaminating lengths.

Example: For inshore west Greenland cod it can be seen that most of the indicators have low variability (lines are rather smooth) and that there are some light trends. Because it takes time for equilibrium to become established when there is a change in mortality the indicators reflect "ancient history" to some degree, that is, they tend to represent an average of the previous and the current conditions. Therefore, changes in indicators tend to under-estimate the changes in the stock.

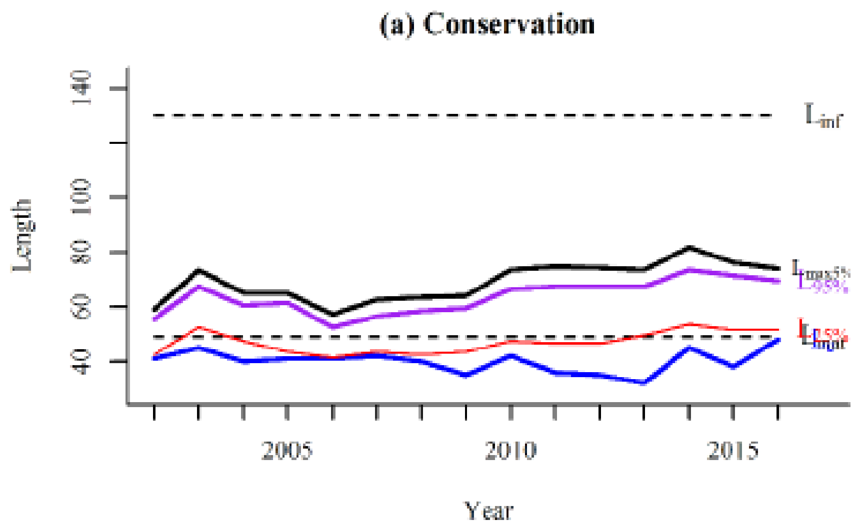


**Figure 1** Cod in NAFO Subarea 1, inshore. Conservation indicator time series.

## Outputs expected

Plots of time-series length distributions, indicators, indicators ratios, and the traffic light table to inform stock status in recent years. The traffic light table shows a green tick for stocks that are being exploited in line with MSY considerations and a red cross for those that are not.

## Caveats

- Selectivity determines catches
- Catch indicators may not directly reflect stock status

Example: catchability of mature females of *Nephrops* is lower because they spend more time in burrows, and the lower catchability may lead to an underrepresentation in the catches and the impression of overexploitation. The LBI relies on assumptions on life-history parameters, $L_{MAT}$ and $L_{inf}$.

**Software**

The R-script *LBIndicators.R* and the output table *stock_sex_IndicatorRatios_table.csv* is available on https://github.com/ices-tools-dev/ICES_MSY.

**Reporting**

- Results are sensitive to assumed values of $L_{inf}$ and $L_{mat}$ and some stocks may derive $L_{inf}$ from FishBase or from dedicated sampling efforts. The source of $L_{inf}$ and $L_{mat}$ should be identified and acknowledged, where appropriate.
- The general assumption of $M/K = 1.5$ should be clarified, and the realism of this assumption should be considered whenever applied; e.g. estimates of *k* associated with the assumed values of $L_{inf}$ should be reported, along with typical approximations of M to test the realism of assuming $M/K = 1.5$.
- Histograms of length frequencies are needed to visually inspect the implicit assumption of a unimodal distribution that reflects near-equilibrium conditions. LBI is based on relative size frequencies so absolute scales are not needed. Histograms should be scaled so that each annual length distribution can be seen.
- Time-series of indicators are informative for qualifying the most recent period for status determination.
- The traffic light table is an effective way to communicate results from multiple indicators and whilst the grey shading for uncertain indicators is appropriate, this may need explanation in table descriptions.

## Mean length-based mortality estimators (MLZ)

The mean length of animals that are fully vulnerable to the sampling gear can be used to estimate total mortality from basic growth parameters and a known length at first capture. This Beverton-Holt length-based mortality estimator is widely used in data-limited fish stock assessment, however, the method requires equilibrium conditions because the mean length of a population will change only gradually after a change in mortality. The Gedamke-Hoenig length-based estimator of total mortality rate was developed from the Beverton-Holt estimator to allow for non-equilibrium conditions. Gedamke and Hoenig (2006) derived the transitional behaviour of the population mean length following a change in instantaneous total mortality (Z) and then generalized the derivation to include length changes due to multiple changes in total mortality. Using a time-series of mean length observations, the Gedamke-Hoenig Mean Length Z estimator yields period-specific estimates of total mortality rates and the corresponding year(s) of change in total mortality rates (Gedamke and Hoenig, 2006).

Then *et al.* (2015) developed a new formulation of the Gedamke-Hoenig estimator that utilizes additional information from a time-series of fishing effort to estimate the catchability coefficient *q* and the natural mortality rate *M* and thus year-specific total and fishing mortality rates. It is assumed that catchability coefficient and natural mortality rate are constant across all fishable ages and years in the available time-series. Although estimates of catchability and natural mortality rate are highly negatively correlated, Then *et al.* (2015) expect more accurate estimates of total mortality rate than of *q* and *M*. The assumptions of constant *q* and *M* may be rather tenuous, especially in stocks that have been exploited for some time, but the primary utility of length-based estimators is in the realm of data-limited fisheries where our ability to estimate time-varying *q* and *M* is highly limited. It is also possible to fix the values of *M* and estimate just *q*. The estimates of F will depend directly on the value of *M* but the estimates of *Z* are generally stable over a wide range of *M*.

### Information required

The mean length Z-estimator of Gedamke and Hoenig (2006) requires a time-series of length measurements and von Bertalanffy growth parameters $L_\infty$ and *k* for the stock. Information on annual fishing effort is not a requirement.

The mean length with effort estimator of Then *et al.* (In Press), an expansion of Gedamke and Hoenig's method, additionally requires a time-series of fishing effort. The effort time-series can be derived as the ratio of the catch and a CPUE series; in this case the estimated catchability coefficient will be for the fleet or survey providing the CPUE series and the year-specific total mortality rate will be computed as M + q * (total catch)/(corresponding CPUE).

For the per-recruit analysis, natural mortality and weight-at-age are required for both the yield per recruit (YPR) and spawner per recruit (SPR) analyses, and maturity information is needed for SPR. The value for the natural mortality rate (M) is obtained either externally or estimated using the Then *et al.* (In Press) method.

**Table 3** Explanation of information required for ICES length-based Z reference point methods.

| Parameter | Abbreviation | Notes |
|---|---|---|
| Time-series of length measurements | | Gedamke and Hoenig (2006) |
| von Bertalanffy growth parameters for the stock | $L_{inf}$, k | Gedamke and Hoenig (2006) |
| Time-series of fishing effort | | Then *et al.* (In Press)<br>Can be derived as the ratio of the catch and a CPUE series |
| Natural mortality | M | For the yield per recruit (YPR) and spawner per recruit (SPR) analyses obtained either externally or estimated using the Then *et al.* (In Press) method |
| Weight at age | $W_a$ | SPR |
| Maturity | $L_{MAT}$ | SPR |
| Fishing effort prior to the first year of the mean length data | | Specification required for the model* |

| Parameter | Abbreviation | Notes |
|---|---|---|
| Length of full selection | $L_c$ | The length at which 100% of individuals are vulnerable to capture was determined by using the peak of the length frequency distribution after combining across all years, but may be altered if a bimodal distribution was found.<br>Note that this definition of $L_c$ is separate and entirely different from the $L_c$ used in the screening methods, which is defined as the length at which 50% of individuals are vulnerable to capture. |

* It is necessary to describe the effort leading to the first observations in the time-series, e.g. effort before = 0 or effort before = effort at start of the time-series.

**Method description**

From a time-series of mean length data, total mortality rates are estimated in blocks of time as well as the years in which the mortality changed. The model uses a likelihood approach to obtain parameters that maximize goodness-of-fit to the mean length data. With an external estimate of the natural mortality rate (M), the fishing mortality rate (F) in the most recent time block of the time-series can be derived.

A method to extend the non-equilibrium mean length estimator to incorporate a time-series of fishing effort is described in Then *et al.* (In Press). In this method, the total mortality rate in each year is parameterized as the sum of the annual fishing mortality and time and age-invariant natural mortality rate. Assuming that fishing mortality is proportional to fishing effort by the catchability coefficient, the model estimates the catchability coefficient and the natural mortality rate, again with the goodness-of-fit to the mean length data. The use of fishing effort allows for annual estimates of fishing and total mortality. The model requires a specification of the fishing effort prior to the first year of the mean length data. A natural mortality rate obtained from external sources can be fixed in the model if desired.

If effort information is desired for use with mean length data, it can be obtained by two methods. First, it can be enumerated directly. Second, an alternative is to take the total catch and divide by the catch rate in one métier or in one survey. Thus, effective error (E) = total catch/ CPUE from reference series. Catch/(catch/effort) = Effort where Effort refers to the effective amount of effort that would be needed to account for the observed total Catch if everyone fished used the same gear and methods deployed in the selected métier or survey. The estimated catchability would then pertain to the selected métier or survey but the product catchability x effective Effort gives the instantaneous fishing mortality rate F experienced by the stock. Thus, F in year t is $F_t = q * E_t = q * Catch_t / CPUE_t$.

For both models, the terminal (most recent) fishing mortality rate can be compared with reference points obtained from a length-based per-recruit analysis. Expert groups should decide whether yield-per-recruit or spawning potential ratio is preferable and define the appropriate reference point (e.g. F / M = 1).

*Method of operation*

1. The length of full selectivity ($L_c$) is obtained from the data. Typically, the $L_c$ is selected to be the peak (mode) of the length–frequency histogram of data combined for all years in the time-series. Note this is a different definition of the $L_c$ than for the length-based indicators.
2. The annual mean lengths of animals of lengths larger than $L_c$ are calculated.
3. The annual length-frequency histograms should also be examined to explore trends in the mode of the histogram over time, which would coincide with changing selectivity or possibly the progression of a strong or weak year class through the time-series of length distributions. Histograms of length-frequencies should be prepared by year and displayed in columns.
    a. For the mean length-only estimator, the number of time blocks is initially specified by the user. The model is fitted multiple times with increasing complexity (more time blocks) until the increase in goodness-of-fit is no

longer statistically significant with increasing complexity as judged by an information theoretic criterion such as AIC. Residual analysis of mean length data is also used to diagnose goodness-of-fit. A sensitivity analysis should be performed in which several values of $L_c$ are chosen as a trend in estimates with increasing $L_c$ might indicate failure of the assumption of a knife-edged (flat-topped) selectivity curve.

b. For the mean length with effort estimator, natural mortality can either be estimated or fixed in the model. Hence, a diagnostic for this model is whether the predicted value of M is consistent with what is known about natural mortality from life-history considerations.

**Assumptions**

See Gedamke and Hoenig (2006) and Then *et al.* (In Press) for further information on the assumptions.

**Table 4** Assumptions for Gedamke and Hoenig (2006) mean-length Z method and Then's (2014) expansion of the method.

| Assumptions for Mean Length Z | Gedamke and Hoenig (2006) and Then et al. (In Press) |
|---|---|
| Recruitment (R) | Constant over time or variation over time are small and without trend |
| Growth | Deterministic, following a von Bertalanffy growth equation<br>Time-invariant |
| Selectivity | Knife-edge above the length of full selectivity ($L_c$)<br>Time invariant |
| Length of full selectivity | $L_c$ (taken from the data); 100% of individuals are vulnerable to capture |
| Fishing effort[1] | Known without effort and proportional to fishing mortality |

As in the length-based indicators, the assumption of constant (or modest, random variability in) recruitment causes some difficulties in practice. It should be understood that strong year classes reduce the mean length, suggesting high mortality when the situation is actually good (strong recruitment) and vice versa. What is critical is to determine whether an extreme (large or small) year class is distorting the mean length in the terminal year and thus distorting the perception of stock status in the most recent years. The best way to assess if there is a problem if to examine the series of annual length frequency distributions to look for evidence of modes migrating from left to right over time.

The mean length-only estimator assumes continuous recruitment; however, the estimator is derived to accommodate annual recruitment by replacing the integrals in Equation A.2.1 of Gedamke and Hoenig (2006) with summations. The mean length with effort estimator can accommodate both types of recruitment numerically: the annual recruitment modelled with an annual time-step and continuous recruitment with a monthly time-step. The difference between continuous and annual (pulsed) recruitment is only important if total mortality is extremely high.

An assumption of the GH method that can examined through a diagnostic procedure is that of knife-edge selectivity. The GH estimates can be computed repeatedly, each time using a different value of $L_c$. If selectivity is flat-topped, there should be no trend in a plot of estimated mortality versus value of $L_c$except that, as you discard more and more data by increasing the value of $L_c$the results will become less precise (more variability on the right). Declining selectivity at increasing lengths is interpreted in the model as increased mortality (the large animals are not there, hence they are being fished out). As one increases the value of $L_c$, one discards more and more data so the influence of the larger sizes becomes greater in the mortality estimates. The opposite can also happen if selectivity increases from the smallest animals to the mid-sized animals.
This diagnostic procedure examines whether the low numbers of large fish is due to high mortality or selectivity.

When there is uncertainty about the growth parameters, one can look at proportional changes in total mortality rate, Z. The proportional change in Z from one time period to the next depends on the value of Linfinity but not on the value of K. Thus,

[1] This assumption is only pertinent to Then *et al.* (In Press).

one can examine the proportional change in Z for several candidate values of Linfinity to see how much the mortality rates change. In the equilibrium solutions for two levels of mortality (the original Beverton-Holt equation):

$$\text{Proportional change in } Z = (Z_2 - Z_1)/Z_1$$

which is

$$\text{Proportional change in } Z = \frac{\frac{K(L_\infty - \bar{L}_2)}{\bar{L}_2 - L_c} - \frac{K(L_\infty - \bar{L}_1)}{\bar{L}_1 - L_c}}{\frac{K(L_\infty - \bar{L}_1)}{\bar{L}_1 - L_c}}$$

from which K cancels out of the equation. Hence, the percent change in Z can be determined without knowing the value of K. It is necessary to know the value of $L_{inf}$ precisely enough to be able to narrow down the possibilities for proportional change in Z.

**Outputs expected**

The Gedamke-Hoenig (2006) method estimates the number of change points, the years of change, and the total mortality rate in each time block. The method of Then *et al*. (In Press) gives estimates of *q* and *M* as well as derived, year-specific fishing and total mortality rates. Both methods use maximum likelihood estimation and provide asymptotic variances and covariances of the parameter estimates.

**Caveats**

- When working with *Nephrops*, all mean length Z methods applied by ICES have been discretized and used modifiers for annual production.
- Mean length in a population is determined by the mortality history and the recruitment history experienced by the population. Without further information, the effects of changing recruitment and mortality are confounded.
- The $L_c$ is often assumed to be larger than the true size of full selection to ensure that all fish are fully recruited and meet the assumption of flat-topped selectivity. In this case, to the extent that some animals below the size of $L_c$ are harvested, the recruitment to size $L_c$ will depend on the fishing effort; if fishing effort (or selectivity) changes over time this will induce changes in the recruitment to size $L_c$.
- Mean-length Z does not work well for short-lived animals.

Example: in the Chesapeake Bay blue crab (*Callinectes sapidus*) fishery the catch is almost entirely age-0 and age-1. If there is a very weak incoming year class (almost no age-0 animals) the mean length will become large (all age 1); leading the mean-length based mortality estimator to falsely interpret this as good news with a decreased total mortality rate.

**Software**

Software is available for the mean length-only estimator assuming continuous recruitment in the fishmethods package in R (the function name is bhnoneq). The mean length with effort estimator is available at https://github.com/quang-huynh/MLZ. Example R code to run this model is available at https://github.com/ices-tools-dev/ICES_MSY.

## Length-based Spawning Potential Ratio (LB-SPR) approach

A well-documented explanation of the method, code, data requirements and settings needed for the LB-SPR approach is available at: https://cran.r-project.org/LBSPR_comparing_observed_length_data_to_target_size_structure. The LB-SPR package can be used in two ways: 1) simulating the expected length composition, growth curve, and SPR and yield curves using the LB-SPR model and 2) fitting to empirical length data to provide an estimate of the SPR.

### Information required

The length-based SPR method was developed for data-limited fisheries where few data are available other than the size structure of the catch (*i.e.* a representative sample of the size structure of the vulnerable portion of the population) and life history of the species. Knowledge of the natural mortality rate ($M$) is not required as it uses the ratio of natural mortality and the von Bertalanffy growth coefficient ($K$) ($M/K$), which is thought to vary less across stocks and species than $M$ (Prince *et al.,* 2015).

**Table 5** Explanation of the information required for ICES length-based SPR methods to estimate current equilibrium YPR and SPR..

| Parameter | Abbreviation | Notes |
|---|---|---|
| Length composition data of the catch | | |
| Ratio of natural mortality and the von Bertalanffy growth coefficient | M/K ratio | M is not required. M/K is thought to vary less across stocks and species than M. |
| Maximum length | $L_\infty$ | |
| CV[$L_\infty$][2] | | software default: 0.1 |
| Maturity-at-length | | software default: logistic parameters $L_{MAT50}$ and $L_{MAT95}$ |
| Proportion of animals surviving to maximum age | P | software default: 0.01 |
| Allometric exponent from the length–weight relationship | b | software default: 3 |

**Table 6** Information required for size based YPR and spawning biomass per recruit (SPR) reference points.

| Parameter | Abbreviation | Notes |
|---|---|---|
| Growth | $L_\infty$ and κ | von Bertalanffy parameters |
| Maximum length | $L_\infty$ | |
| Length-weight relationship | A, b in w=a $L_\infty$^ b | |
| Natural mortality rate | M | |
| Selectivity-at-length | | either knife-edged, logistic or domed (double-logistic) |
| Maturity-at-length | | for spawning biomass per recruit |

### Method description

Traditional approaches for estimating reference points for data-poor stocks compared size-based estimates of fishing mortality ($Z$, Beverton and Holt, 1956) with sized-based yield-per-recruit reference points ($F_{max}$ or $F_{0.1}$, Beverton and Holt, 1957; Gulland and Borema,1973), both of which assumed knife edged selectivity at $L_c$. Alternative selectivity functions can be assumed if the yield-per-recruit analysis is based on length at relative age (Cadima, 2003), and the size-based yield-per-recruit can be extended to spawning biomass per recruit (http://nft.nefsc.noaa.gov/).

The length-based per recruit analysis will derive YPR and spawning biomass per recruit as a function of F, maximum spawning potential (at F = 0), and $F$ reference points for maximum YPR ($F_{MAX}$), $^{1}/_{10th}$ of the initial rate of increase in YPR ($F_{0.1}$), and maintaining a portion of maximum spawning potential (%MSP, with 40%MSP being a common proxy for MSY). The primary

[2] Variation in size of fish close to the maximum age.

assumption of -per recruit models is that the stock is in equilibrium (*i.e.* constant recruitment, growth and mortality, including M and F at size).
Beverton and Holt (1957) found that the ratio of *M/K* largely determines productivity, resilience and overfishing limits. This life-history ratio is known to be relatively consistent between closely related stocks, and less variable between species than either of the individual parameters in the ratio (Beverton, 1992; Prince, 2015). Hordyk *et al*. (2015a, b) developed a size-based estimator that is based on the ratio *M/K*, for application to data-poor situations with no reliable age data or local estimates of growth or mortality. The method develops links between life-history ratios and the expected equilibrium size composition of the catch, and by comparing this expected size composition to the observe size composition, the method is able to estimate both *F/M* and selectivity parameters (assuming logistic selection). By further inclusion of information on maturity, the model estimates Spawning Potential Ratio (SPR), which can be used as a metric of stock status (similar to %MSP). The method incorporates variation in length-at-age by introducing a CV on $L_\infty$ under the assumption that variation in length-at-age follows a Normal distribution and is due to variation in $L_\infty$ alone.

The terminal (most recent) fishing mortality rate can be compared with reference points obtained from a length-based per-recruit analysis. Expert groups should decide whether yield-per-recruit or spawning potential ratio is preferable and define the appropriate reference point (e.g. F/M = 1).

*Method of operation*
A description of the LB-SPR method developed by Hordyk *et al*. (2015a, b, c), as it has been implemented by ICES, is provided in the WKLIFE V report (ICES, 2015). The method essentially involves fitting the expected length distributions, given life history, selectivity parameters and levels of exploitation to observed length distributions with values for F/M and the selectivity parameters ($L_{sel50}$ and $L_{sel95}$) adjusted (using a maximum likelihood approach) to obtain the closest match between these two length distributions.

**Assumptions**

**Table 7** LB-SPR model relies on a number of simplifying assumptions.

| Assumptions for LB-SPR | |
|---|---|
| Equilibrium-based method | |
| Differences between observed and expected length distributions | Not due to variability of recruitment or mortality (*i.e.* method assumes constant recruitment and fishing pressure) |
| Growth | Adequately described by von Bertalanffy equation |
| $L\infty$, CV[$L\infty$], M/K, and t0=0 | Known |
| Length composition data | Representative of the exploited population at steady state |
| Length structure of the catch | Representative (*i.e.* not subject to biased sampling) |
| Commercial selectivity follows a logistic curve | The method is not limited to this, and will take alternative forms, including domed selection; however, this requires knowledge of the shape of the selectivity curve, information that may not be readily available in data-poor situations |

**Outputs expected**

Estimates of F/*M* and selectivity parameters (e.g. $L_{sel50}$ and $L_{sel95}$) for logistic selection)
Estimates of SPR, which can be compared to SPR target (e.g. SPR = 35%)
A time-series of these estimates if length-frequency distributions available for consecutive years (although estimation is independent year-on-year)

**Caveats**

Method is equilibrium-based.

- if this assumption is a problem, it can be ameliorated by aggregating size data over generational time periods.

Method most likely limited to cases where asymptotic selectivity is a reasonable assumption (given difficulty of establishing the presence of doming for data-poor stocks).

Method cannot fit multimodal length compositions well, leading to unrealistic estimates of F/M, selectivity and SPR in these cases.

- traditional length-based methods may be more suitable.
- problem could be tackled by collecting data at a higher temporal resolution.

Number of age classes need to be high enough to approximate continuous dynamics well (thus it is not applicable to short-lives species).

Validity of assumptions need careful examination.

**Software**

Example R code to run this model can be found at https://github.com/ices-tools-dev/ICES_MSY.

For detailed information on the software and method, see https://cran.r-project.org/web/packages/LBSPR_plotting_the_simulation.

## Stochastic Surplus Production in Continuous Time (SPiCT)

**Information required**

The model uses observed data on landings or catches and CPUE indices either commercial or from surveys. The model can handle several CPUE time-series. The model does not include life history parameters. Production models like SPiCT generally work best when there is a lot of contrast (of effort, biomass, catch rate) in the data. When the time-series is short or there isn't much contrast in the data, it is advisable to reduce the number of parameters in the model to promote model stability.

**Method description**

Stochastic Production model in Continuous-Time (SPiCT) (Pedersen and Berg, 2017) was presented to WKLIFE as a traditional surplus production model with several advancements. SPiCT is formulated as a state-space model and incorporates dynamics related both to the fisheries (F) and to the biomass (B) in the form of Pella and Tomlinson (1969). These two latent processes are then related to the observed data (catches and Catch per Unit of Effort: CPUE - either commercial or from surveys) via observation equations, which include error terms.
The equations of the model are defined:

Process equations (random effects):

- Biomass: $dB_t = rB_t\left(1 - \left[\frac{B_t}{K}\right]^{n-1}\right)dt - F_tB_tdt + \sigma_BB_tdW_t$.
- Fishing: $d\log(F_t) = f(t, \sigma_F)$,

where $W_t$ is Brownian motion (noise term).

Observation equations:

- Index: $\log(I_t) = \log(qB_t) + e_t, \quad e_t \sim N(0, [\alpha\sigma_B]^2)$.
- Catch: $\log(C_t) = \log\left(\int_t^{t+\Delta} F_sB_sds\right) + \epsilon_t$,
  $\epsilon_t \sim N(0, [\beta\sigma_F]^2)$.

The model for the fishing mortality represented by $f\ (t,\ \sigma_F)$ is, when using annual data, a random walk (or diffusion). If subannual data are available a model for F incorporating a seasonal pattern is applied. The model parameters are defined:

- $B_t$: Exploitable stock biomass.
- $F_t$: Fishing mortality.
- $r$: Intrinsic growth rate: growth, recruitment, natural mortality.
- $K$: Carrying capacity or equilibrium biomass or virgin stock biomass.
- $n$: Parameter determining the shape of the production curve.
- $q$: Catchability.
- $\sigma_B$: Standard deviation of $B_t$.
- $\sigma_F$: Standard deviation of $F_t$.
- $\alpha$: Ratio of standard deviation of $I_t$ to standard deviation of $B_t$.
- $\beta$: Ratio of standard deviation of $C_t$ to standard deviation of $F_t$.

With limited information, it is often difficult to estimate n, in which case n is set to 2 resulting in the Schaefer model. Similarly it is not always possible to estimate $\alpha$ and/or $\beta$, in which case they are set to 1, which is a common assumption (Thorson *et al*., 2013). However, this default assumes equal error in catch and CPUE, which deviates from simpler observation error models that assume no error in the catch but may be appropriate to data-limited stocks.

The SPiCT formulation is a generalisation of previous surplus production models in that it includes the dynamics of the fishery and the uncertainty of the observed catches, which are commonly omitted in similar models. The SPiCT is therefore able to make short-term projections of biomass as well as both fishing mortality and catch including uncertainty.

The continuous-time formulation of SPiCT, as opposed to constant fixed time-steps, enables the model to accommodate arbitrary and irregular data sampling without a need for catch and index observations to match temporally. It is therefore straightforward to fit SPiCT to data containing a mix of annual, biannual and quarterly data. Such increased sampling frequencies will typically lead to larger sample size than the corresponding annual dataset. While autocorrelation between observations likely also increases at higher sampling frequencies, simulations have shown that increased sample size leads to increased precision on certain model parameters, in particular noise parameters.

The default configuration of SPiCT estimates all parameters but simpler configurations fix parameters n = 2, alpha, beta = 1, as well as B0/K (the ratio of the initial biomass to carrying capacity). See sections 2.8 and 2.9 of the user manual for help with this.

*Method of operation*
The SPiCT is implemented as an R-package and uses the Template Model Builder (TMB) package to obtain fast and efficient model estimation.

**Assumptions**

Important model assumptions shared by all production models include:
1) No migration takes place in and out of the stock as changes in biomass only occur through growth via r and K and through fishing.
2) No lagged effects in the dynamics of the biomass as caused by variability of the size/age-distribution.
3) Constant catchability *i.e.* no change in technology of fishing technique that changes q.
4) Gear selectivity can follow any pattern as long as it is constant over time.
5) No knowledge of natural mortality is required because it's included in the intrinsic growth rate, r.
6) There is no systematic under-reporting of catch and effort. A production model may or may not be robust to the failure of this assumption (see Omori *et al.,* 2016). For example, if catch and effort are each underestimated by the same amount over the entire time-series, the estimates of $B/B_{msy}$, $F/F_{msy}$ and catch/MSY are valid even as catch, MSY, and biomass are under estimated.

**Outputs expected**

In addition to parameter estimates, the model provides estimates of management reference points $B_{MSY}$, $F_{MSY}$, and MSY (maximum sustainable yield), where $B_{MSY}$ is the biomass that leads to maximum surplus production (*i.e.* MSY), similarly $F_{MSY}$ is the fishing mortality leading to MSY. All estimates of reference points include uncertainty (95% confidence intervals). A further benefit of the TMB package is that one-step-ahead residuals are provided automatically, which should be independent and standard normally distributed for the model output to be valid.

**Caveats (including problems, difficulties and issues with application)**

Departures from independence and standard normality of residuals indicate that model assumptions have been violated. It is therefore important to report residual diagnostics together with model results such that correct interpretations can be made.

*Process error*
The difference between a standard production model, and one including process error (such as SPiCT) is, in mathematical notation:

$$B_{y+1} = B_y + rB_y(1\text{-}B_y/K) - C_y \text{ ; or } B_{y+1} = B_y + P_y - C_y \text{ (in terms of production).}$$

vs

$$B_{y+1} = (B_y + rB_y(1\text{-}B_y/K) - C_y).\boldsymbol{e^{u\_y}} \text{ ; or } B_{y+1} = (B_y + P_y - C_y).\boldsymbol{e^{u\_y}}$$

To estimate the absolute size of the $e^{u\_y}$ process error term, one could calculate the annual production using two different approaches:

With process error: $P_y = B_{y+1} - B_y + C_y$

Without process error: $P_y = rB_y(1\text{-}B_y/K)$

With these values, it is possible to produce a graph such as the one below (Figure 2; not a SPiCT example, but a similar production model with process error), which indicates how changes in biomass were driven by process error vs the actual production function in the model. The example below, with significant fluctuations in biomass being driven primarily by the process error in recent years, indicates that the data may not be informative enough for the model. As such, the model may not be a good basis for advice.

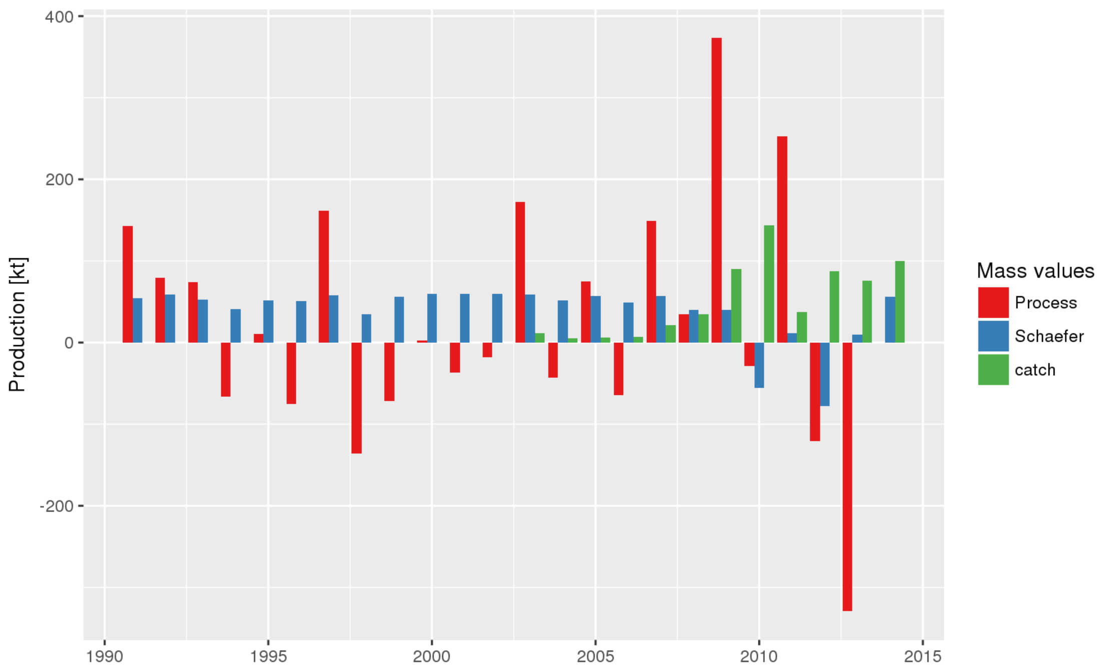


**Figure 2** Changes in biomass driven by process error.

**Software**

The SPiCT is implemented as an R-package and uses the Template Model Builder (TMB) package to obtain fast and efficient model estimation [https://github.com/mawp/spict.](https://github.com/mawp/spict) The user manual for SPiCT can be found here: [https://github.com/mawp/spict/blob/master/spict/vignettes/vignette.pdf](https://github.com/mawp/spict/blob/master/spict/vignettes/vignette.pdf).

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## Appendix 1: Example application on Cod (*Gadus morhua*) in NAFO Subarea 1, inshore (West Greenland cod)

The following examination of reference points was conducted at the North West Working Group (NWWG) in 2017. Each of the four methods - LBI, MLZ, LB-SPR, and SPiCT –-was attempted. The following section presents the input data, results, and interpretation of each method for this stock, along with the overall conclusion of the Expert Group and the choice of reference points used in the advice in 2017. The code can be found at https://github.com/ices-tools-dev/ICES_MSY

### 1. Length based indicators

#### Assumptions

Recruitment, selection and F constant over time

- Not fulfilled.

Asymtotic selection

- Not fulfilled. Selection in the pound-net fishery is probably dome-shaped.

#### Input data

**Table A1.1** Cod in NAFO Subarea 1, inshore. Input data for the LBI analysis

| Data type | Source | Years/Value | Notes |
|---|---|---|---|
| Length-frequency data | GINR (Greenland Institute of Natural Resources) | 2002–2016 | 1 cm grouping |
| Weight-at-length data | GINR | 2002–2016 | 1 cm grouping |
| $L_{mat}$ | GINR, 2002-2016, N = 5279 | $L_{50\%}$ = 47.1cm<br>$L_{95\%}$ = 66.6cm | Males and females combined |
| $L_{inf}$ | GINR, 2002-2016, N = 11 460 | $L_{inf}$ = 130.3.cm | |

The length-frequency shows a clear mode in all years, except 2003 and 2012 where no distinct peak is seen (Figure A.1).

The biological parameters were based on data from 2002-2016. Von Bertalanffy growth parameters (k and $L_{inf}$) were estimated by non-linear regression using the equation Length ~$L_{inf}$ * (1-exp(-k*Age)). A maturity ogive was estimated on data collected in April and May by a general linear model (GLM) with binomial errors.

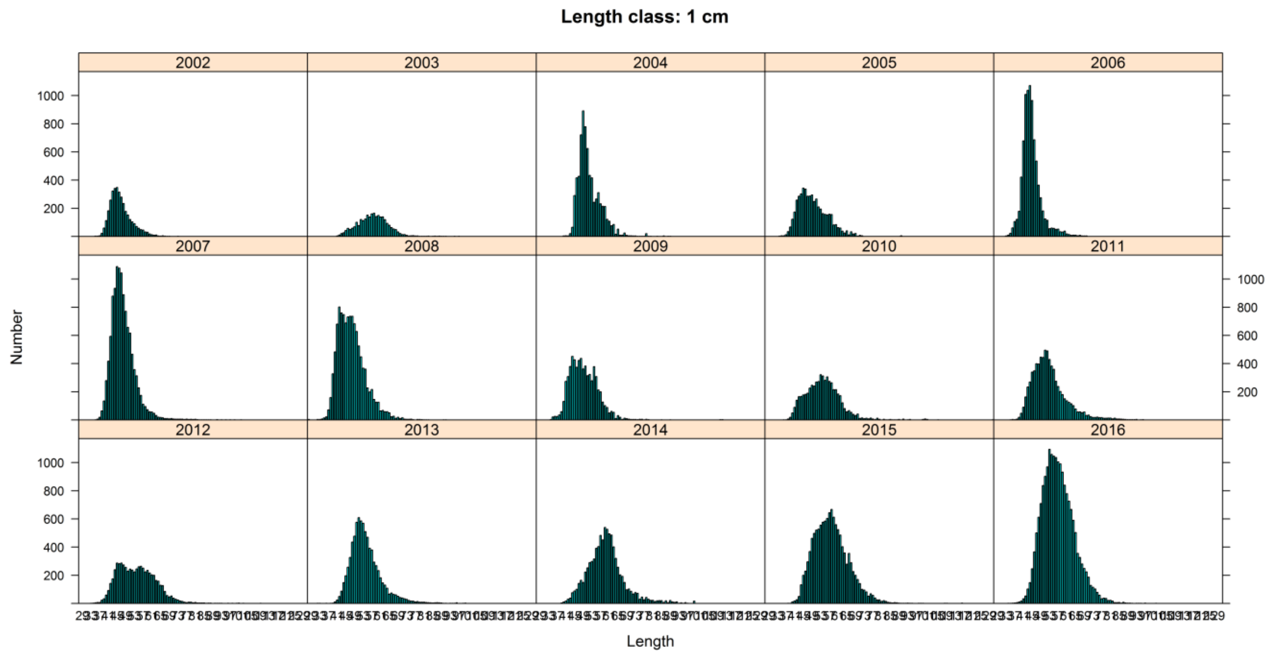



**Figure A1.1** Cod in NAFO Subarea 1, inshore. Length distribution from the inshore cod fishery

## Output

The results are compared to suggested reference points in the traffic light table (Table A1.2). If a cell is highlighted green, the indicator suggests that the stock is in a desirable state relative to the reference, and red a negative state.

**Table A1.2** Cod in NAFO Subarea 1, inshore. Output table with indications of status compared to reference points.

| | Conservation | | | | Optimizing Yield | MSY |
|---|---|---|---|---|---|---|
| | $l_c$ / $l_{mat}$ | $l_{25\%}$/ $l_{mat}$ | $l_{max\ 5\%}$/ $L_{inf}$ | $P_{mega}$ | $L_{mean}$ / $L_{opt}$ | $L_{mean}$ / $L_{F=M}$ |
| Reference | > 1 | > 1 | > 0.8 | > 30% | ~1(> 0.9) | ≥ 1 |
| 2014 | 0.95 | 1.14 | 0.63 | 0.2 | 0.68 | 0.9 |
| 2015 | 0.81 | 1.09 | 0.59 | 0.1 | 0.66 | 0.94 |
| 2016 | 1.02 | 1.09 | 0.57 | 0 | 0.67 | 0.84 |

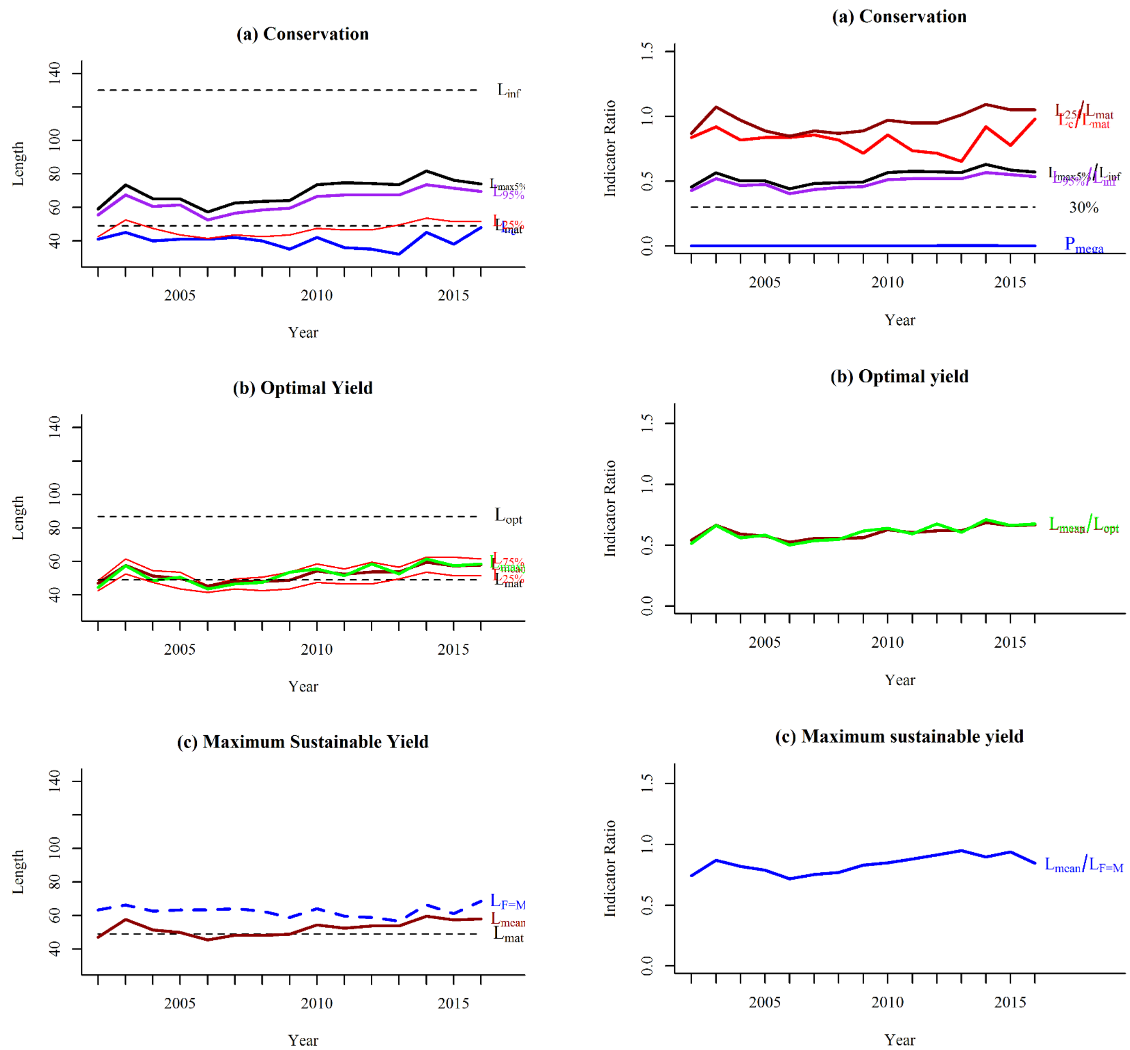



**Figure A1.2** Cod in NAFO Subarea 1, inshore. Time-series of indicators.

## Conclusion

The only green parameters in all three years is the $L_{25\%}/L_{mat}$. $L_c/L_{mat}$ is approximately 1, indicating that immature fish are well conserved. The large fish, however, constitute too small a part of the catch, either because the fishery is targeting smaller fish or because large fish are scarce. The optimizing yield and MSY indicators are below the desirable values of 0.9 and 1 showing that the fish caught may be too small and that some overexploitation is likely taking place.

The time-series of indicators (Figure A1.2) show that the levels of conservation and optimal and maximum sustainable yield indicators have been relatively stable throughout the time-series.

## 2. Mean length Z (MLZ)

### Assumptions

- Recruitment and selection are constant over time (probably **not** constant indicated by the yearly catch increasing 10-fold since 2002).
- Fishery selection is knife-edged (the fishery selection is not knife-edged in the most important fishery by pound net, where it is probably dome-shaped).

### Input data

In addition to length frequency distributions from the commercial fishery this method requires an effort time-series. The effort time-series was obtained from the ratio of catch and a CPUE time-series from the inshore pound net fishery in 2001–2016. The CPUE was estimated by dividing the total pound net catch with the number of pound net trades.
The CPUE has gradually increased since 2011 (Figure A1.4). Von Bertalanffy growth parameters (k and $L_{inf}$) were estimated by non-linear regression using the equation Length ~$L_{inf}$ * (1-exp(-k*Age)). The length-weight relation was estimated by linear regression. The reference points ($F_{0.1}$ and $F_{35\%}$) were estimated using the length-based Yield-Per-Recruit available at http://www.nft.nefsc.noaa.gov.

**Table A1.3** Cod in NAFO Subarea 1, inshore. Input data for the MLZ method

| Data type | Source | Years/value | Notes |
|---|---|---|---|
| Length Frequency data | GINR | 2002–2016 | 1 cm grouping |
| Fishing effort | Greenland Statistic | 2011–2016 | Derived from pound net fishery |
| Linf | GINR N = 11 460 | Linf = 130.3 cm | See LBI |
| Natural Mortality (M, $yr^{-1}$) | Based on literature | M = 0.2 | |
| k ($yr^{-1}$) | GINR | 0.11 | . |
| Length-weight, *a* | GINR, 2002–2016, N = 11 436 | $7.16*10^{-6}$ | $R^2$ = 0.98 |
| Length-weight, *b* | GINR, 2002–2016, N = 11 436 | 3.09 | $R^2$ = 0.98 |

### Conclusion

The main output is presented in Table A1.4. The length distribution changes little between years (Figure 5). The Gedamke-Hoenig model showed an improvement in AIC score from 46.3 to 37.0 when assuming a shift in Z in 2010, instead of one Z. Assuming two shifts in Z in 2003 and 2010 resulted in no further improvement in AIC (38.3). Therefore, one shift in Z from 0.92 in 2010 to 0.55 after 2 010 was chosen. Assuming M = 0.2, F shifted from 0.72 to 0.35 in 2010.

Applying the THoG model to estimate M resulted in an M estimate of 0.2. The $F_{2016}$ was estimated to be 0.54. $F_{0.1}$ ranged from 0.13 when estimated by the Gedamke-Hoenig method with a shift in 2010 of Z, to 1.15 when estimated by the THoG method with a shift in Z in 2010 and an estimated M of 0.21. $F_{0.35}$ was estimated to 0.14 using the YPRLen software, which does not allow a shift in Z.

**Table A1.4** Cod in NAFO Subarea 1, inshore. Results of the MLZ estimators

| Model | Parameter | Value (sexes combined) | |
|---|---|---|---|
| Gedamke-Hoenig | Z estimates ($yr^{-1}$) | 0.92 → 0.55 in 2010 | |
| | F ($yr^{-1}$), derived from Z | 0.72 → 0.35 in 2010 | |
| | $F_{0.1}$ with Z shift | 0.13 | |
| | $F_{0.35}$ from YPRLEN with no Z shift | 0.14 | |
| | | M estimated | M Fixed |
| THoG | M ($yr^{-1}$) | 0.21 | 0.2 |
| | $F_{2016}$ ($yr^{-1}$) | 0.54 | 0.56 |
| | $F_{0.1}$ with shift in Z/ YPREN no Z shift | 0.15 / 0.14 | 0.14 / 0.13 |
| | $F_{0.35}$ from YPRLEN no Z shift | 0.14 | 0.14 |

From the mean length-only analysis (Gedamke-Hoenig method) the estimated F-values appear high compared to $F_{0.1}$ and $F_{0.35}$, which may indicate overfishing. The same is indicated by the mean length and effort analysis (THoG).

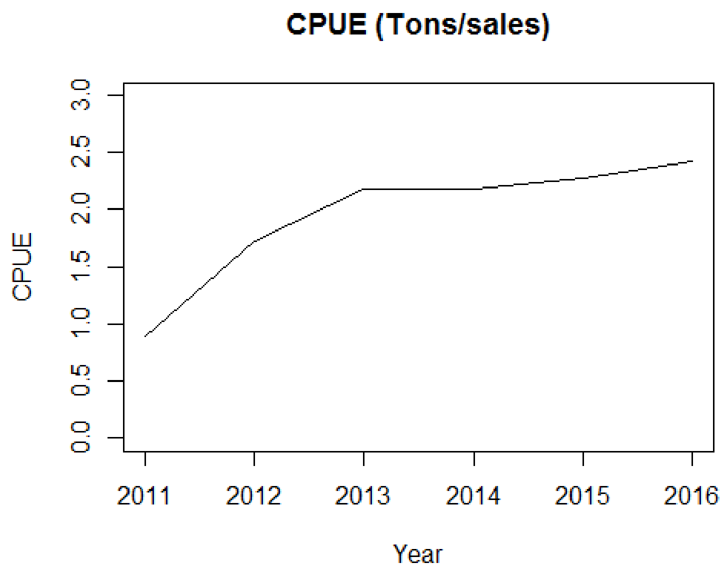



**Figure A1.3** Cod in NAFO Subarea 1, inshore. CPUE time-series of inshore pound net fishery

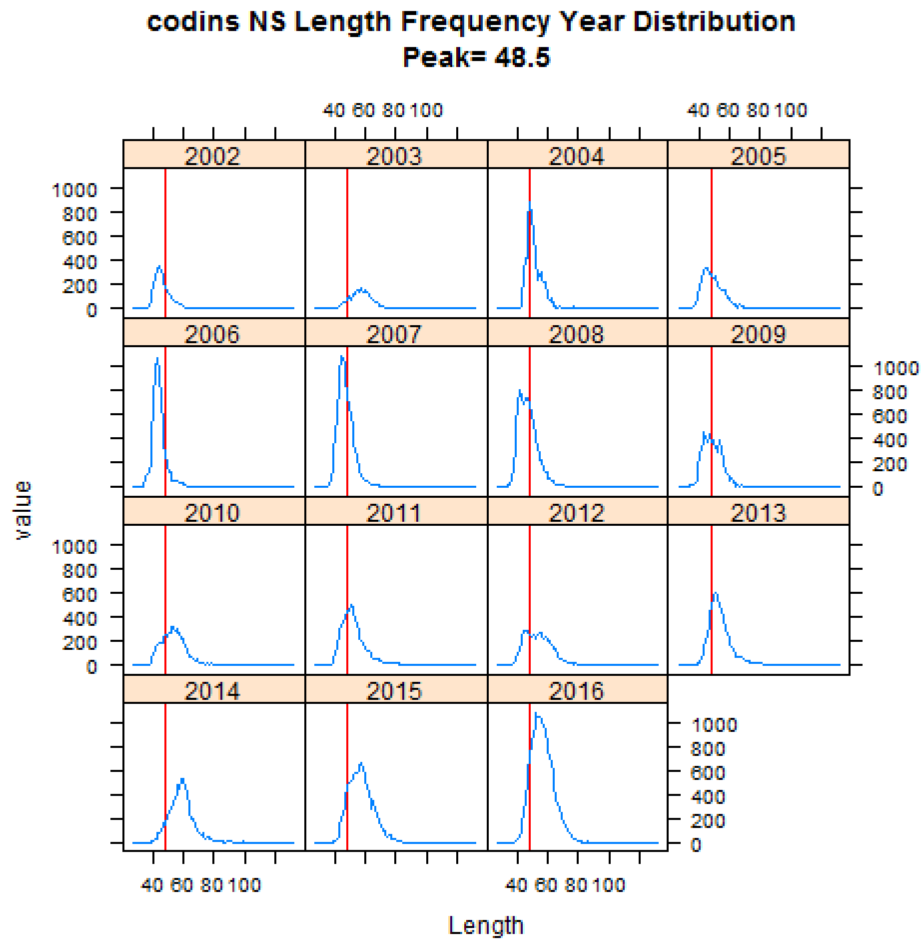



**Figure A1.4** Cod in NAFO Subarea 1, inshore. Length distribution by year from the inshore cod fishery. The red line indicates the overall mean.

### 3. Length-based Spawner Per Recruit (LB-SPR)

**Assumptions**

- Equilibrium based
- Difference between observed and expected length distributions are not due to variability in recruitment or mortality
- Constant recruitment
- Constant fishing pressure
- Known M/K ratio, $L_{inf}$, CV on $L_{inf}$, t0 =0
- Length structure of the catch is representative
- Selectivity follows a logistic curve

Beside the assumptions mentioned regarding the LBI and Mean-length Z methods, the assumption of equilibrium is not fulfilled as an exchange with the offshore area is known, although the extent is unknown.

**Table A1.5** Cod in NAFO Subarea 1, inshore. Input data for the LB-SPR method.

| Data type | Source | Years/value | Notes |
|---|---|---|---|
| Length Frequency data | GINR | 2012–2016 | 1 cm grouping |
| M/K ratio | GINR<br>Assumed | k = 0.11<br>M = 0.2<br>M/K = 1.82 | |
| $L_{inf}$ | GINR | $L_{inf}$ = 130.3 cm | $CV_{Linf}$ = 0.08 |
| $L_{mat}$ | GINR, 2002–2016, N=5279 | $L_{50\%}$ = 47.1 cm<br>$L_{95\%}$ = 66.6 cm | Males and females combined |
| Length-weight, *a* | GINR, 2002–2016, N=11 436 | $7.16*10^{-6}$ | $R^2$ = 0.98 |
| Length-weight, *b* | GINR, 2002–2016, N=11 436 | 3.09 | $R^2$ = 0.98 |
| Selectivity-at-length | Knife-edge, logistic or domed | logistic assumed<br>$SL_{50\%}$ = 40 cm<br>$SL_{95\%}$ = 45 cm | Assumed to be dome-shaped in ML analysis |

**Input data**

The LB-SPR method requires length frequency data and biological parameters. These are listed in Table A1.5. In addition to the data provided in the previous models, the LB-SPR requires information on selectivity (knife-edge, logistic or domed). The dominant fishery is pound net but some fishery with hand line, long line and gillnet are also taking place. A logistic relationship was used with a relatively sharp increase in selectivity.

**Ouput**

The model fitted length distributions are shown in Figure A1.7. In some years the length distribution fits are poor and less weight should be given to these years, e.g. 2012 and 2015. The SPR values were far below the SPR 30-40% range in all years (Figure A1.8) and therefore can be considered to be below proxies that would be consistent with high long-term yields. The F/M ratios are generally above F/M = 1 with a decreasing trend with time. This implies an exploitation above $F_{MSY}$.

Selectivity results are given in Figure A1.9, showing an increase of length in the catch in recent years.

**Conclusion**

The inshore cod stock appears overexploited. However, the size in the catch has increased in recent years. The assumption of equilibrium for this method may be violated if a migration from the offshore areas into the inshore areas is significant.

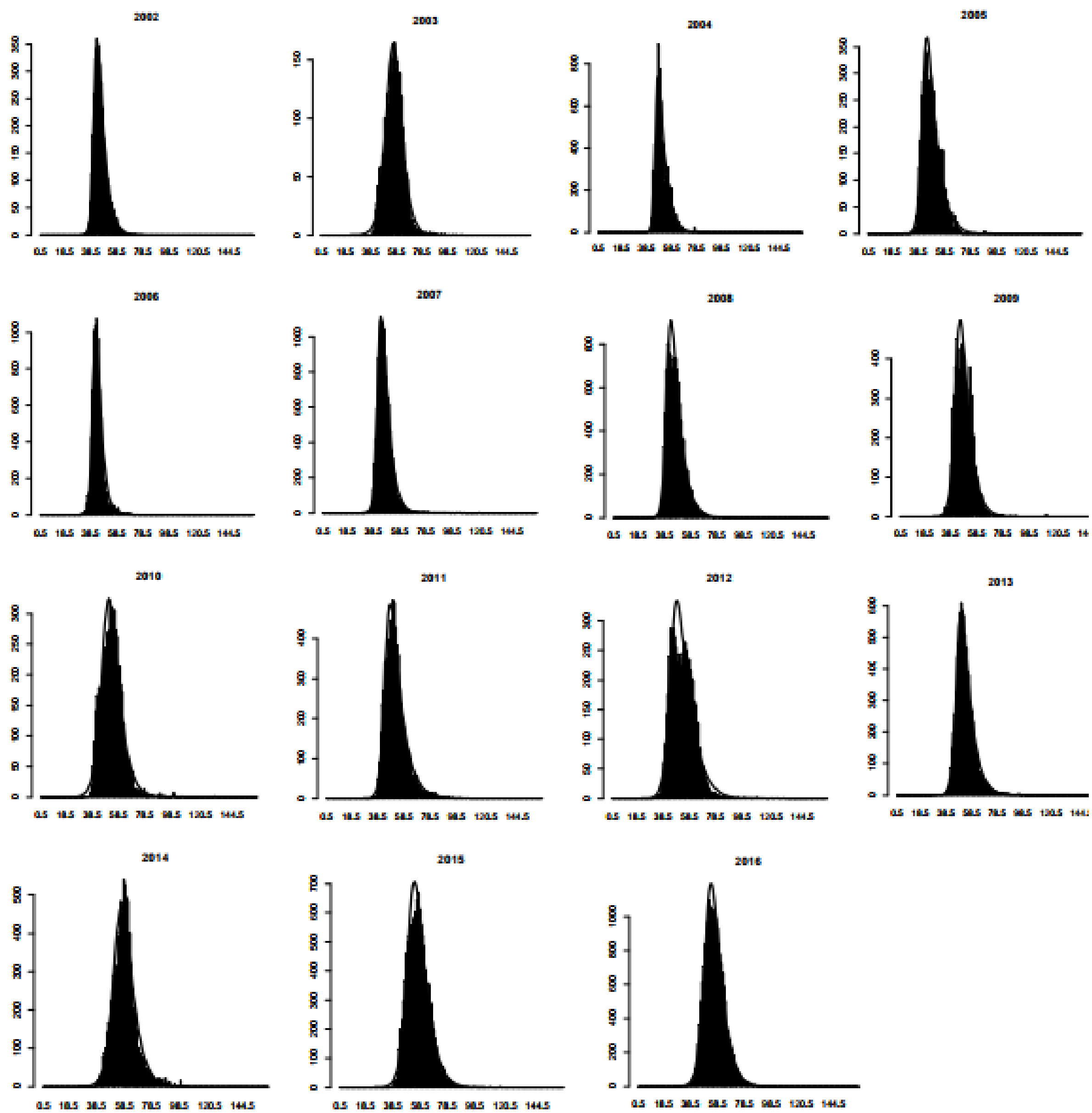


**Figure A1.5** Cod in NAFO Subarea 1, inshore. Length distributions and model fits

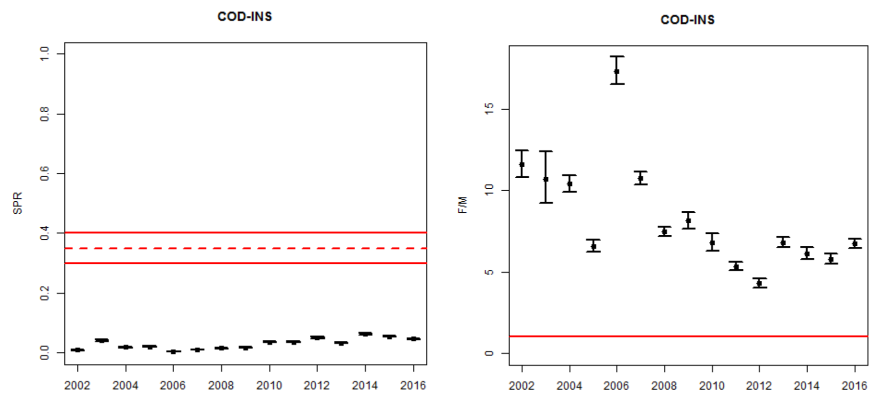



**Figure A1.6** Cod in NAFO Subarea 1, inshore. Left: SPR estimates by year with 95% confidence intervals. The dotted red line is SPR=35% and the solid red lines are SPR=30% and SPR=40%, respectively. Right: Estimates of F/M by year with 95% confidence intervals. The red line indicates F=M.

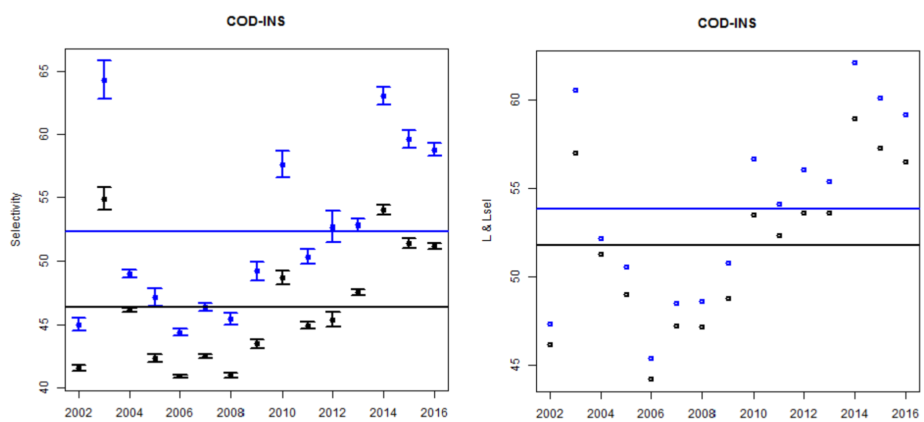



**Figure A1.7** Cod in NAFO Subarea 1, inshore. Left: Estimates of the selectivity parameters (Lsel50 in black and Lsel95 in blue). The horizontal lines indicate the means across all years. Right: Mean length in catch. The black circles are weighted means using midpoints of length bins weighted by the frequency of the bins for the entire catch. The blue circles apply a similar calculation, but with the midpoint of a length weighted by the product of the frequency and selection for that bin. The horizontal lines give the corresponding overall mean for each mean length calculation.

## 4. Surplus Production in Continuous Time (SpiCT)

### Input data

All input data are shown in Table A1.6 and Figure A1.10. Two surveys are conducted in the inshore area: the Sisimiut inshore gillnet survey and the Nuuk inshore gillnet survey. Both surveys cover the period 1985 to 2016 (Retzel, 2017). The Sisimiut survey have missing data in years 1999 to 2001 and in 2008–2009. The Nuuk survey has missing years in 2001 and 2007. The survey indices for 4+ are used to reflect the fishable part of the stock. Landings from 1970–2016 were used. Preliminary SPiCT runs extending the landing time-series further back in time did not converge properly. The landings peaked around 1980 and again in the late 1980s (Figure A1.10). After a sharp decline in the early 1990s the landings have slowly increased, with a third maximum in 2016.

The survey indices match the landings, however, the Nuuk survey did not reflect the peak in landings in the late 1980s.

**Table A1.6** Cod in NAFO Subarea 1, inshore. Input data for the SPiCT model.

| Data type | Source | Years/value | Notes |
|---|---|---|---|
| Survey time-series | Greenland survey (ICES, 2016)<br>Sisimiut inshore gillnet<br>Nuuk inshore gillnet | 1985–2016<br>1999–2002, 2008–2009<br>2001, 2007 | Biomass of 4+ used as input.<br>Missing years<br>Missing years |
| Landings | ICES, 2017 | 1970–2016 | |

**Model validation**

Model residuals and diagnostics are shown in Figure A1.11. The One Step Ahead (OSA) residuals were not significantly different from zero and are therefore unbiased. Testing of the autocorrelation of the residuals (ACF) was not significant when testing of multiple lags (here 4), however, testing individual lags were significant in the case of lag 2 in the catch residuals, and lag 1 in the Nuuk survey residuals (middle figure row). The residuals were not significantly different from being normal distributed in any case (bottom figure row).
Table A1.7 shows the correlations between model parameters. The correlations were relatively low *i.e.* the parameters are well separated. Only in the case of log q1 (catchability of survey index 1) and log q2 (catchability of survey index 2) was the correlation high (0.96).

**Table 12.4.3.2.A1.7** Cod in NAFO Subarea 1, inshore. Correlations between SPiCT parameter estimations.

```
             logm        logK       logq1      logq2       logn      logsdb
logm    1.00000000  0.65246309 -0.2559591 -0.2498299 -0.06628111  0.01350941
logK    0.65246309  1.00000000 -0.6683475 -0.6614146 -0.68031745  0.20949670
logq1  -0.25595907 -0.66834752  1.0000000  0.9649068  0.26947971 -0.24763890
logq2  -0.24982987 -0.66141462  0.9649068  1.0000000  0.26352521 -0.23633794
logn   -0.06628111 -0.68031745  0.2694797  0.2635252  1.00000000 -0.33888360
logsdb  0.01350941  0.20949670 -0.2476389 -0.2363379 -0.33888360  1.00000000
logsdf -0.12039743 -0.03281644 -0.1406858 -0.1581846  0.11008705 -0.42513292
logsdi  0.08317859  0.14204032 -0.1650197 -0.1595472 -0.07782103  0.08522477
logsdi -0.09567052 -0.16257060  0.2879263  0.2905813  0.01741373 -0.08924834
logsdc  0.03030428 -0.08446725  0.1609591  0.1612138  0.11144043 -0.30360849
           logsdf       logsdi      logsdi       logsdc
logm   -0.12039743  0.083178589 -0.09567052  0.030304278
logK   -0.03281644  0.142040320 -0.16257060 -0.084467250
logq1  -0.14068584 -0.165019663  0.28792632  0.160959081
logq2  -0.15818457 -0.159547197  0.29058132  0.161213815
logn    0.11008705 -0.077821034  0.01741373  0.111440426
logsdb -0.42513292  0.085224774 -0.08924834 -0.303608488
logsdf  1.00000000 -0.055363712 -0.06919684 -0.224111590
logsdi -0.05536371  1.000000000 -0.22799858  0.001648132
logsdi -0.06919684 -0.227998579  1.00000000  0.028766810
logsdc -0.22411159  0.001648132  0.02876681  1.000000000
```

**Output**

Figure A1.10 show the results of the SPiCT model. The relative biomass ($B_t/B_{MSY}$) was below 1 until 2009/2010 after which it was above 1. The relative fishing mortality ($F_t/F_{MSY}$) was in general above 1 until 1999 and since then it is around 1. The development of biomass and fishing mortality since 1970 have moved from the red square ($F_t/F_{MSY}$>1 and $B_t/B_{MSY}$<1) to the green square ($F_t/F_{MSY}$ <1 and $B_t/B_{MSY}$>1).

Retrospective plots with 5 scenarios with catch and survey time-series show high consistency between the scenarios, other than in the 1970s (Figure A1.11).

Table A1.8 show the stochastic reference points from the SPiCT model. The $B_{2016}/B_{MSY}$ is estimated to 1.67 and the $F_{2016}/F_{MSY}$ is estimated to be 0.75.

**Table A1.8** Cod in NAFO Subarea 1, inshore. Output from the SPiCT model with stochastic reference points.

| Parameter | Value |
|---|---|
| $B_{MSY}$ | 86 655 tonnes |
| $F_{MSY}$ | 0.27 |
| MSY | 22 417 tonnes |
| $B_{2016}$ | 144 476 tonnes |
| $F_{2016}$ | 0.20 |
| $B_{2016}/B_{MSY}$ | 1.67 |
| $F_{2016}/F_{MSY}$ | 0.75 |

The predicted catch in 2017 is 31 953 tonnes. The $B_{2017}/B_{MSY}$ is estimated at 1.73 and the $F_{2017}/F_{MSY}$ is estimated at 0.83 (Table A1.8).

**Forecast**

The forecast for the year 2018 is shown in Table 10. Six forecast scenarios are presented. The $B_{2017}/B_{MSY}$ are above 1 in all scenarios and the $F_{2017}/F_{MSY}$ are below 1 or 1 in all scenarios except for an 25% increase of F. The B decreases in all scenarios except with no fishing. The F increases if keeping the catch or fishing at $F_{MSY}$.

**Conclusion**

The SPiCT indicates no overexploitation of the inshore stock. The $B/B_{MSY}$ is well above 1 even when keeping the current catch at similar levels as in 2016 (34 204 tonnes). However, it should be noted that the model does not take into account recruitment.

**Table A1.9** Cod in NAFO Subarea 1, inshore. Detailed output from the SPiCT model.

```
Convergence: 0    MSG: relative convergence (4) Objective function at optimum: 115.8564291
Euler time step (years):    1/16 or 0.0625

  Nobs C: 47,  Nobs I1: 27,  Nobs I2: 30

Priors

               logn ~   dnorm[log(2), 2^2]
   logalpha ~   dnorm[log(1), 2^2] logbeta
                     ~  dnorm[log(1), 2^2]
```

```
Model parameter estimates w 95% CI
           estimate        cilow        ciupp    log.est
 alpha1  1.579389e+00  8.572737e-01  2.909769e+00  0.4570379  alpha2
 1.812747e+00 9.401841e-01 3.495115e+00 0.5948434 beta   4.412786e-
 01  1.468744e-01  1.325805e+00  -0.8180789   r         6.728863e-01
 6.543260e-02 6.919734e+00 -0.3961789  rc   6.300673e-01 1.659319e-
 01  2.392457e+00  -0.4619287   rold      5.923718e-01  2.347079e-01
 1.495068e+00  -0.5236208   m           3.370824e+04  1.163191e+04
 9.768342e+04  10.4254975   K           2.087023e+05  2.382980e+04
 1.827823e+06 12.2486642 q1    1.520800e-03 3.902000e-04 5.927600e-
 03  -6.4885038  q2       7.655000e-04 1.925000e-04 3.044900e-03 -
 7.1749668  n     2.135919e+00 6.586255e-01 6.926774e+00  0.7588969
 sdb    4.080340e-01  2.383649e-01  6.984742e-01  -0.8964048   sdf
 3.293799e-01 1.805852e-01 6.007752e-01 -1.1105435  sdi1 6.444443e-
 01   4.587277e-01   9.053484e-01   -0.4393669    sdi2  7.396624e-01
 5.307087e-01  1.030887e+00  -0.3015614   sdc         1.453483e-01
 6.553720e-02 3.223530e-01 -1.9286224

Deterministic reference points (Drp)

          estimate         cilow         ciupp    log.est  Bmsyd
 1.069988e+05   1.605170e+04   7.132424e+05   11.580573    Fmsyd
 3.150336e-01   8.296590e-02   1.196228e+00   -1.155076    MSYd
 3.370824e+04 1.163191e+04 9.768342e+04 10.425498

Stochastic reference points (Srp)

          estimate        cilow        ciupp   log.est rel.diff.Drp  Bmsys
 8.665504e+04 1.482291e+04 5.065871e+05 11.369691         -0.2347677

 Fmsys 2.694061e-01 6.805770e-02 1.066442e+00 -1.311535   -0.1693634

 MSYs  2.241716e+04 7.150567e+03 7.027822e+04 10.017582   -0.5036799

States w 95% CI (inp$msytype: s)

                  estimate      cilow      ciupp      log.est  B_2016.00
 1.444763e+05 3.095694e+04 6.742723e+05 11.8808708  F_2016.00 2.017156e-01
 4.207500e-02   9.670628e-01   -1.6008963    B_2016.00/Bmsy   1.667258e+00
 5.175268e-01 5.371217e+00 0.5111803 F_2016.00/Fmsy 7.487419e-01 3.230432e-
 01 1.735416e+00 -0.2893610

Predictions w 95% CI (inp$msytype: s)

prediction    cilow    ciupp    log.est B_2017.00 1.495826e+05 2.499080e+04 8.953273e+05
11.9156040 F_2017.00 2.244674e-01 4.178630e-02 1.205794e+00 -1.4940246  B_2017.00/Bmsy
1.726185e+00 5.848435e-01 5.094889e+00 0.5459135  F_2017.00/Fmsy 8.331936e-01 3.136252e-01
2.213506e+00 -0.1824893  Catch_2017.00 3.195252e+04 1.414985e+04 7.215368e+04 10.3720064
E(B_inf)       5.549005e+04         NA          NA 10.9239590
```

**Table A1.10** Cod in NAFO Subarea 1, inshore. Forecast scenarios for 2018 based on the SPiCT model.

```
 Observed interval, index:  1985.00 - 2016.00

 Observed interval, catch:  1970.00 - 2017.00

Fishing mortality (F) prediction: 2018.00
Biomass (B) prediction:           2018.00
Catch (C) prediction interval:    2017.00 - 2018.00

Predictions

                             C        B     F B/Bmsy F/Fmsy perc.dB perc.dF
 1. Keep current catch 33904.8 138671.5 0.234  1.600  0.870    -7.3     4.4
 2. Keep current F     31952.5 135493.4 0.224  1.564  0.833    -9.4     0.0
 3. Fish at Fmsy       37655.3 130561.0 0.269  1.507  1.000   -12.7    20.0
 4. No fishing            35.0 162528.0 0.000  1.876  0.001     8.7   -99.9
 5. Reduce F 25%       24519.7 141874.9 0.168  1.637  0.625    -5.2   -25.0
 6. Increase F 25%     39040.3 129358.2 0.281  1.493  1.041   -13.5    25.0

 95% CIs of absolute predictions

                          C.lo    C.hi    B.lo     B.hi  F.lo  F.hi
 1. Keep current catch 25896.6 44389.4 22137.2 868663.1 0.039 1.394
 2. Keep current F     14149.9 72153.7 18766.4 978263.4 0.037 1.359
 3. Fish at Fmsy       16718.3 84812.5 17223.7 989690.0 0.044 1.631
 4. No fishing            15.1    81.5 28043.7 941933.3 0.000 0.001
 5. Reduce F 25%       10806.9 55632.6 20839.1 965898.2 0.028 1.019
 6. Increase F 25%     17341.4 87890.5 16855.9 992741.0 0.046 1.699

 95% CIs of relative predictions

                       B/Bmsy.lo B/Bmsy.hi F/Fmsy.lo F/Fmsy.hi

 1. Keep current catch     0.565     4.534     0.289     2.614
 2. Keep current F         0.545     4.487     0.258     2.687
 3. Fish at Fmsy           0.509     4.463     0.310     3.225
 4. No fishing             0.737     4.773     0.000     0.003
 5. Reduce F 25%           0.591     4.532     0.194     2.016
 6. Increase F 25%         0.500     4.458     0.323     3.359
```

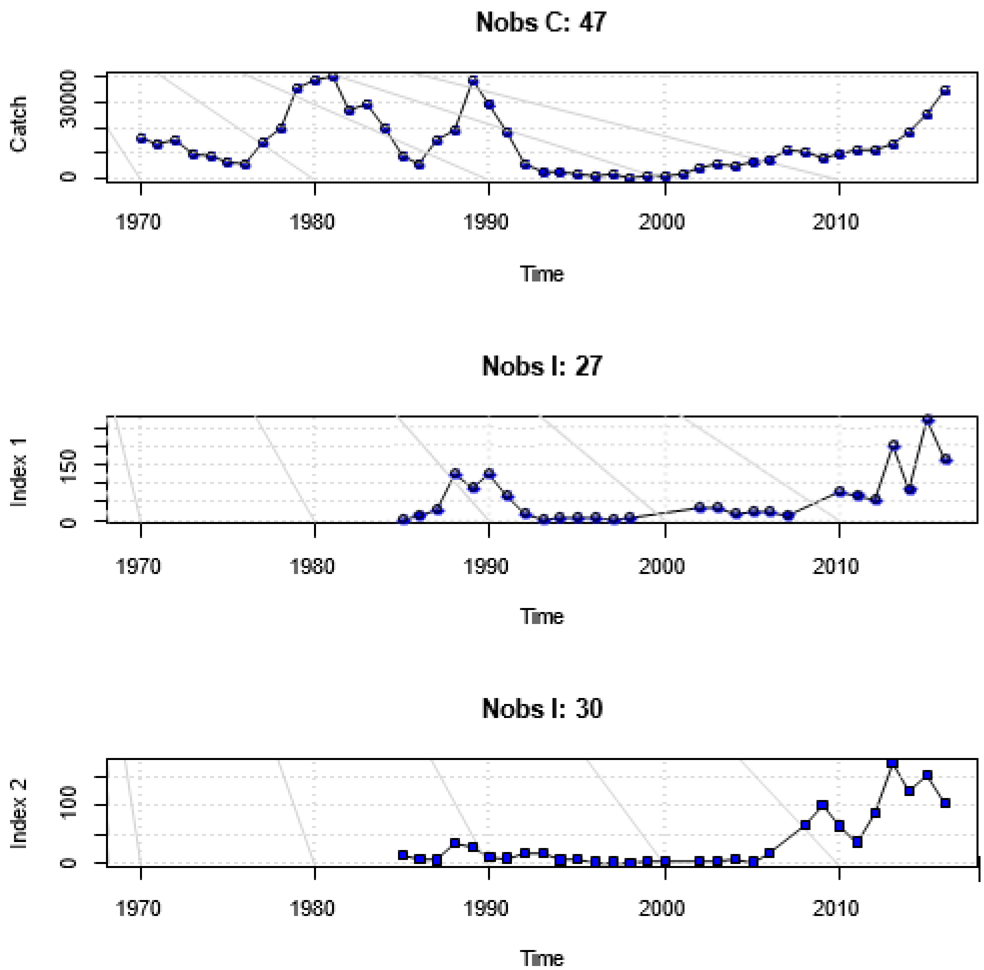



**Figure A1.8** Cod in NAFO Subarea 1, inshore. Input data for the SPiCT models. Top: landings. Middle: The Sisimiut survey data. Bottom: The Nuuk survey data.

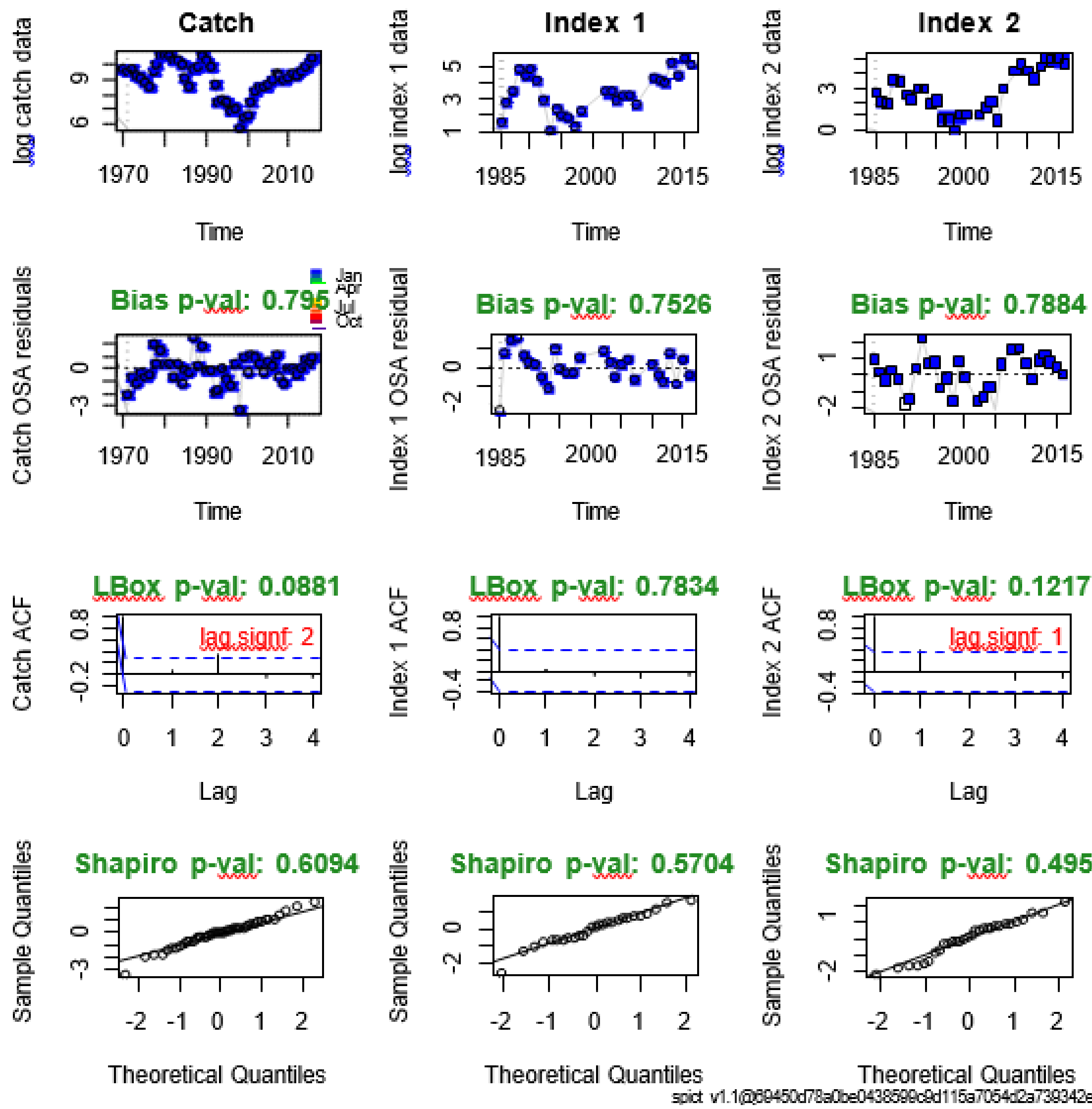



**Figure A1.9** Cod in NAFO Subarea 1, inshore. Plot of model diagnostics

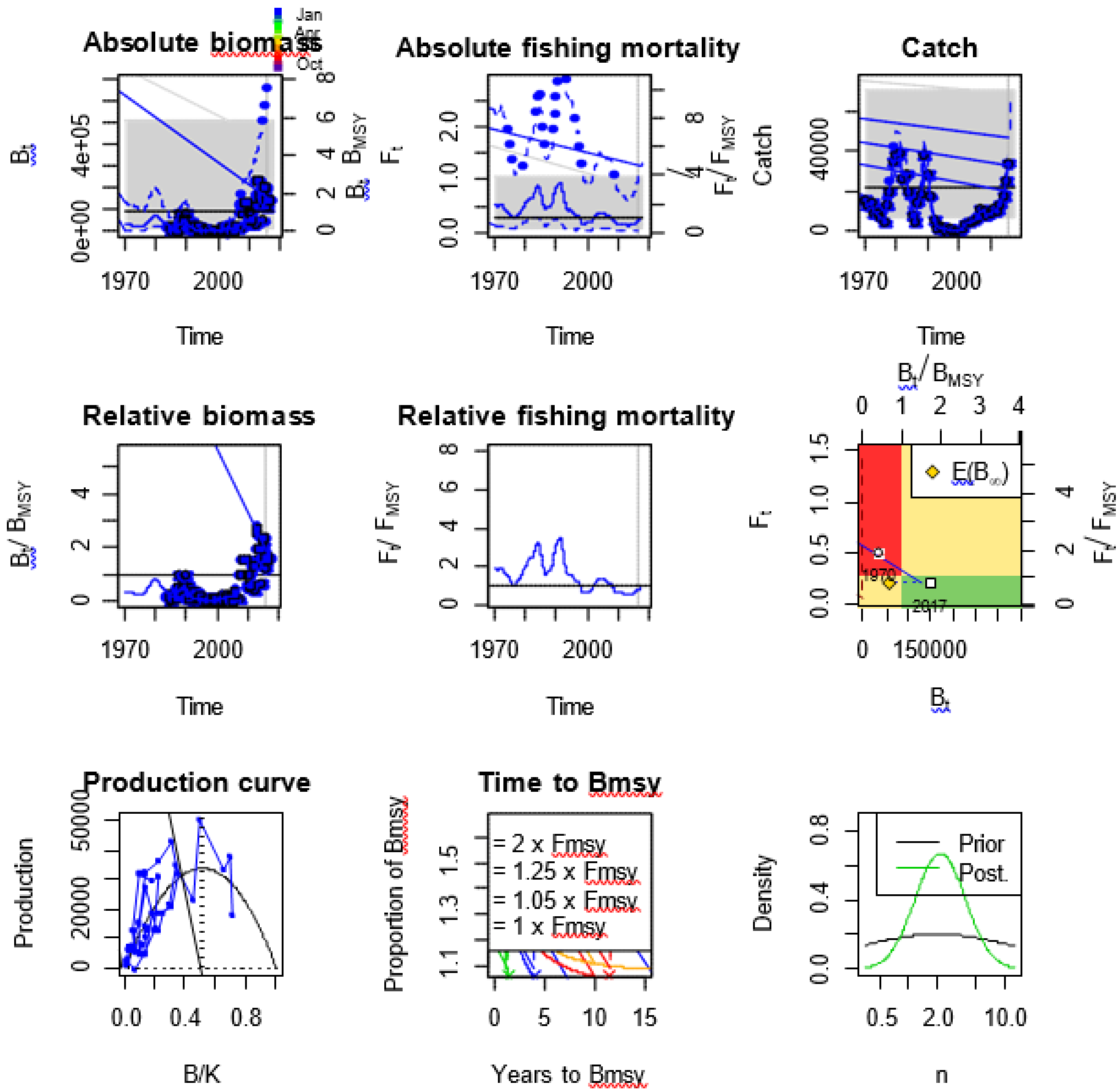



**Figure A1.10** Cod in NAFO Subarea 1, inshore. Results of the SPiCT model

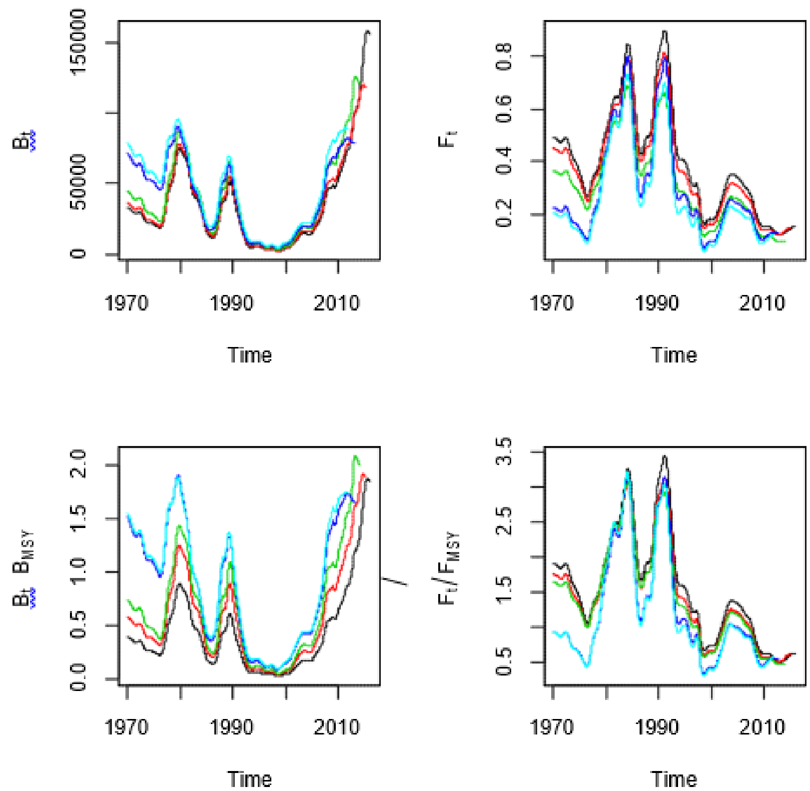



**Figure A1.11** Cod in NAFO Subarea 1, inshore. Retrospective plots. Catch and survey time-series are shortened by 1 to 5 last observations.

**Overall conclusions**

Four different methods (LBI, Mean-length Z, LB-SPR and SPiCT) are presented. All have different input data which in some cases are uncertain and crucial for the output of the method. They also have different assumptions about the fishery and the stock, which may not be valid. A key factor is to what extent migration of smaller fish from the offshore area to the inshore area occurs, but also to what extent a migration of large fish out of the inshore area occurs.

The LBI show “red” condition on the large-size related indicators, indicating the fishery targets smaller fish, but the smaller-size indicators were “green” or close to green. It also showed that this has been the situation since the beginning of the 2000s. However, this could be a consequence of the above mentioned migration in and out of the inshore area and not only a response of the fishery.

The Mean-Length Z estimated rather high $F_{2016}$ (0.56) compared to the reference points $F_{0.1}$ and $F_{0.35}$ but also a shift in F in 2010 (0.72 → 0.35). This indicates overfishing on the inshore stock from this analysis.

Overexploitation of the inshore stock was also indicated by the SPR, but at the same time the size in catch has increased.

The reference points derived from the SPiCT model showed no sign of overexploitation of the inshore stock

The catch history of the inshore stock should be kept in mind. Several times the catch has dropped during the years after a period with increasing catch. In 2016 the catch was of an historicalyl high level and a drop in the next few years may be likely.

## Appendix 2: Example application on *Nephrops* in FUs 28–29

Two of the methods were deemed appropriate for *Nephrops* in functional units 28 and 29: length-based indicators and mean-length Z (both the Gedamke-Hoening and THoG methods). The following section outlines the inputs and outputs of these methods estimated at WGBIE in 2017.

### 1. Length based indicators

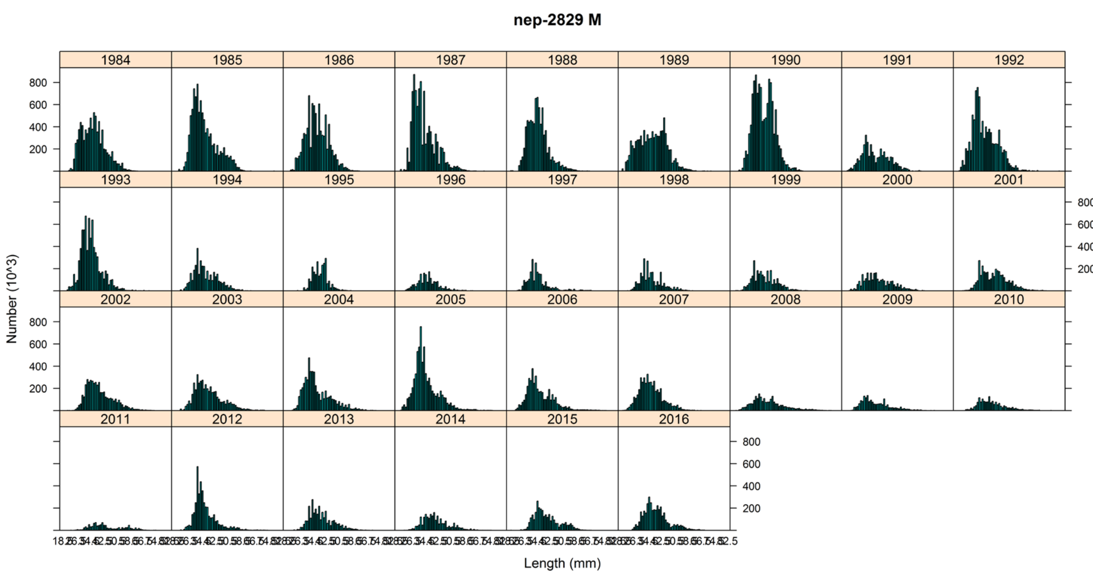
The LBI method was applied to *Nephrops* FUs 28–29 by sex.

#### Input data

**Table A2.1** Norway lobster in Division 9.a, functional units 28–29. Input parameters for LBI.

| Input (in mm) | Males | Females |
|---|---|---|
| $L_{inf}$ | 70 | 65 |
| $L_{MAT}$ | 28.4 | 30 |
| Start year, end year | 2000, 2016 | |
| Sex | M, F | |
| Type | L | |

#### Outputs



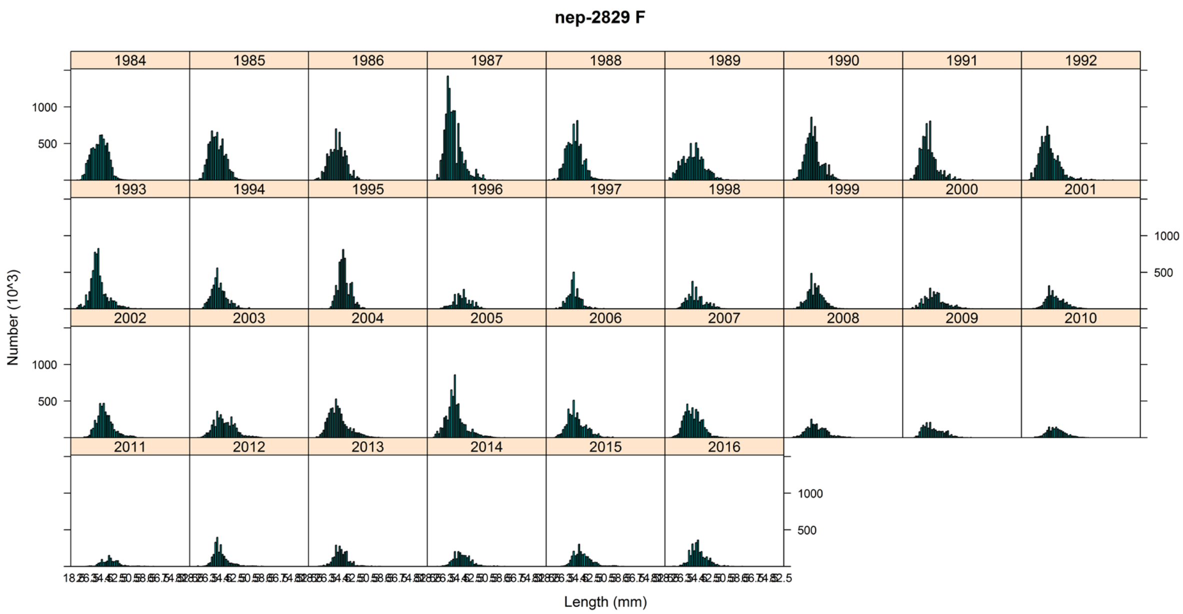



**Figure A2.1** Norway lobster in Division 9.a, functional units 28–29. Catch length composition for the period 2000–2014 at 1 mm carapace length classes (males top, females bottom).

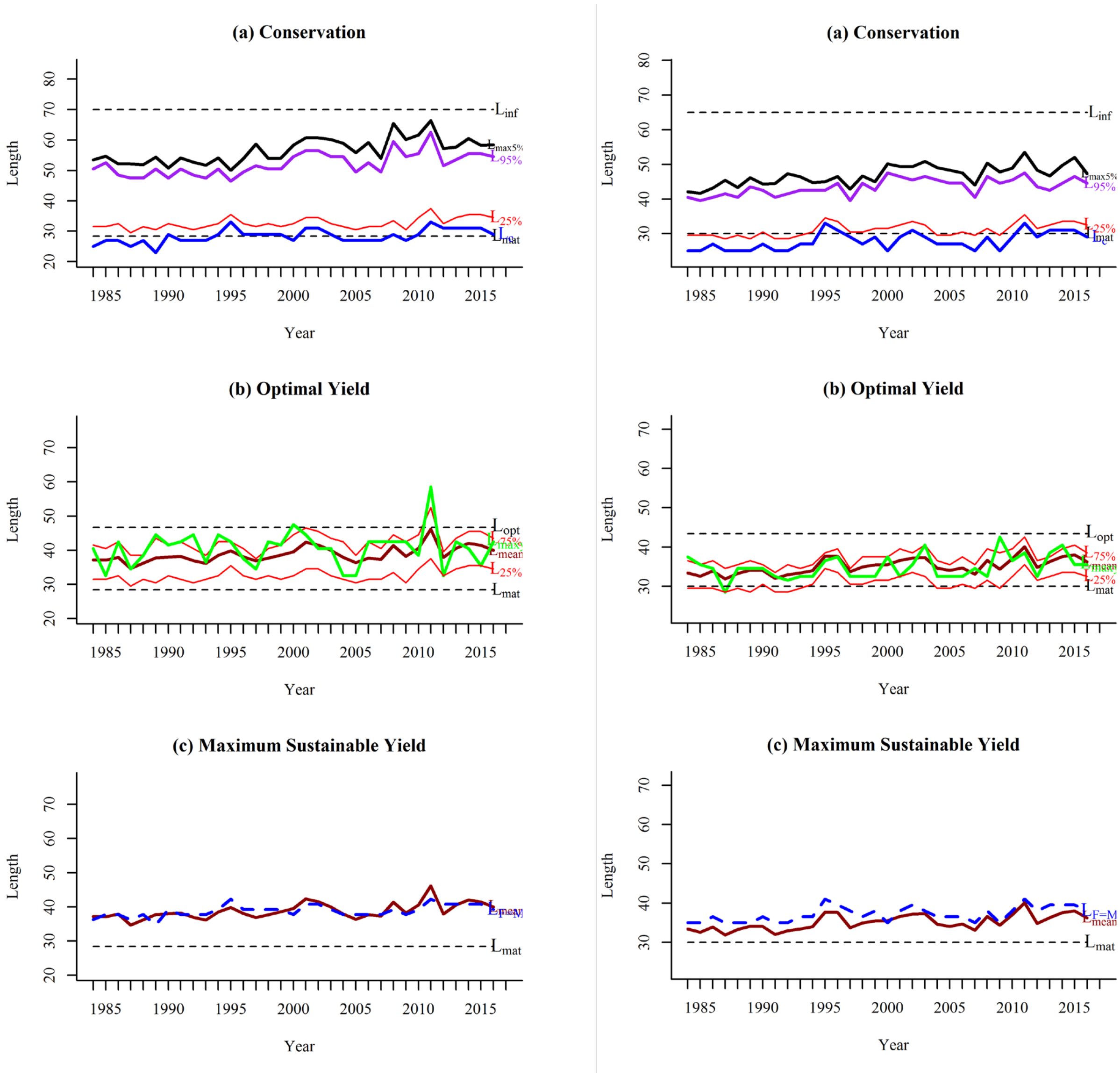



**Figure A2.2** Norway lobster in Division 9.a, functional units 28–29. Screening of length indicators for males (left) and females (right) under three scenarios: (a) Conservation, (b) Optimal yield, and (c) maximum sustainable yield.

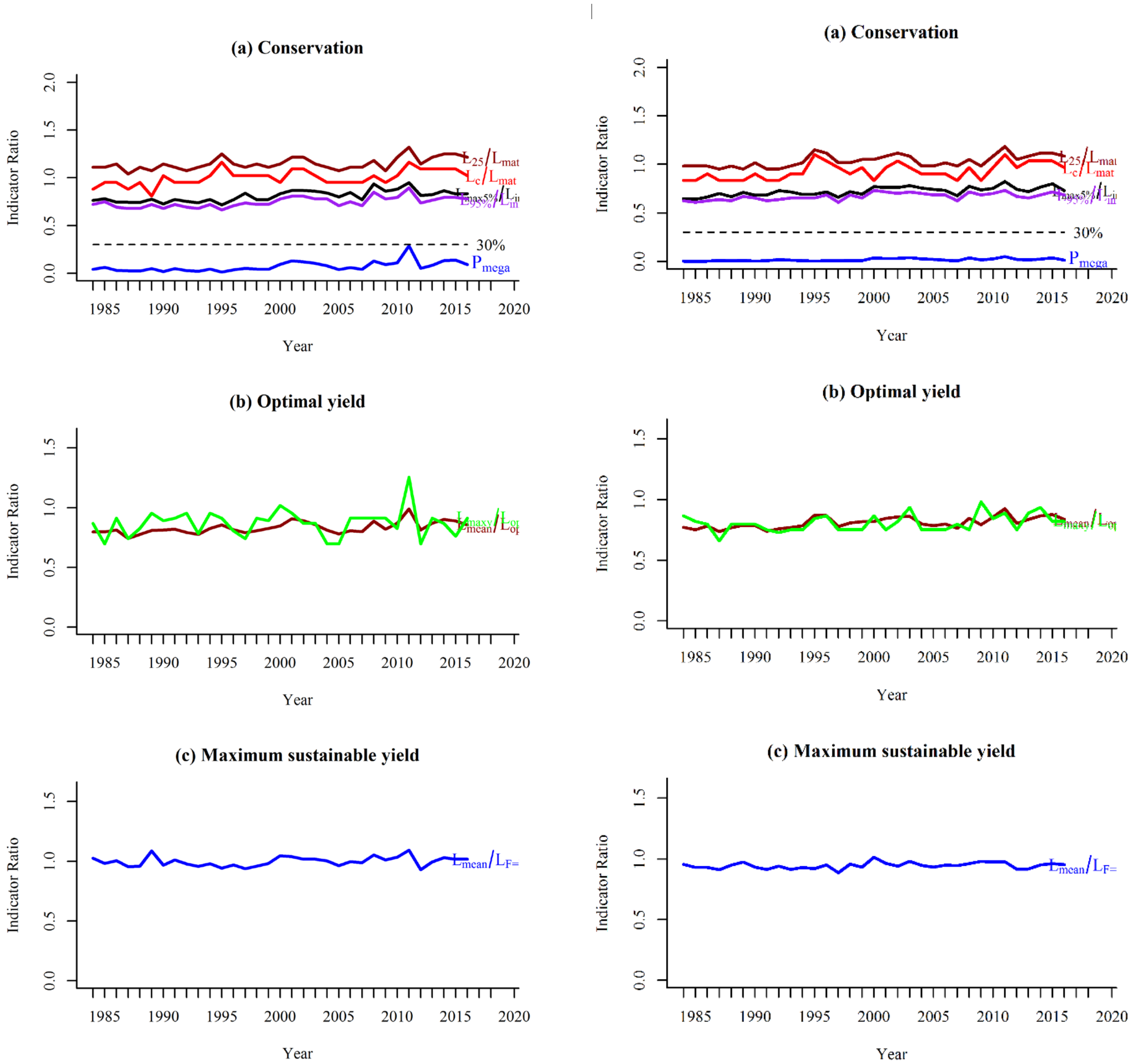



**Figure A2.3** Norway lobster in Division 9.a, functional units 28–29. Screening of length indicators ratios for males (left) and females (right) under three scenarios: (a) Conservation, (b) Optimal yield, and (c) maximum sustainable yield.

## Conclusion

Figures A2.1, A2.2, and A2.3 show no concerns regarding fishing on immature male *Nephrops* in FU 28-29. However, the lack of mega-spawners ($P_{mega}$) in the catches across the time-series and $L_{max5\%}$ being relatively close to the lower limit of 0.8. This indicates some truncation in length distribution in catches.

The mean length of the catch is stable across the time-series. The catch is close to the theoretical length of optimal yield. However, looking at A2.2(b) the core distribution (between 25th and 75th percentile) is below the optimal length. The mean length is close to the MSY proxy of $L_{F=M}$.

The results for three recent data years are presented by sex in a traffic light system according to conservation/sustainability, yield optimization and MSY considerations in Table A2.2. Reference levels (Ref) for the indicator ratios are indicated. In the case of the Optimizing Yield indicator ratio, with reference level around 1 (≈1), a threshold of 0.9 was adopted for the colour shading.

The overall perception from the length-based indicators analysis is that the stock is fished sustainably at levels close to optimum yield and with exploitation at the MSY level for males and slightly above MSY for females in 2016.

**Table A2.2** Norway lobster in Division 9.a, functional units 28-29. Traffic light indicators from LBI by sex for 2014, 2015, and 2016.

| | | Conservation | | | | Optimizing Yield | MSY |
|---|---|---|---|---|---|---|---|
| | | $L_c/L_{mat}$ | $L_{25\%}/L_{mat}$ | $L_{max5\%}/L_{inf}$ | $P_{mega}$ | $L_{mean}/L_{opt}$ | $L_{mean}/L_{F=M}$ |
| | Ref | >1 | >1 | >0.8 | >30% | ~1 (>0.9) | ≥1 |
| 2014 | M | 1.09 | 1.25 | 0.83 | 0.14 | 0.89 | 1.02 |
| | F | 1.03 | 1.12 | 0.80 | 0.04 | 0.88 | 0.96 |
| 2015 | M | 1.09 | 1.25 | 0.86 | 0.13 | 0.90 | 1.03 |
| | F | 1.03 | 1.12 | 0.76 | 0.02 | 0.87 | 0.95 |
| 2016 | M | 1.02 | 1.21 | 0.83 | 0.09 | 0.86 | 1.02 |
| | F | 0.97 | 1.08 | 0.73 | 0.01 | 0.84 | 0.95 |

* Berried females stay in burrows leading to lower catchability causing lack of larger individuals compared with males.

**Table A2.3** Norway lobster in Division 9.a, functional units 28-29. Stock status inferred from LBI for MSY. A green tick mark for MSY is provided because with exploitation at the MSY level for males and slightly above MSY for females. Stock size is unknown as this method only provides exploitation status.

| **Fishing pressure** | | | | | **Stock size** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2014 | 2015 | **2016** | | | 2014 | 2015 | **2016** | |
| **MSY ($F_{MSY}$)** proxy | ✓ | ✓ | ✓ | Below | **MSY** $B_{trigger}$ proxy | ? | ? | ? | Undefined |

## 2. Mean length Z (MLZ)

Reference points for the fishing mortality rate were obtained using the Length Based Yield per Recruit program (http://nft.nefsc.noaa.gov/YPRLEN.html) with the requisite life history information. From the Yield per Recruit (YPR) analysis, the $F_{0.1}$ was estimated. From the Spawning Potential Ratio (SPR) analysis, the $F_{35\%}$ was estimated.

For most stocks, discard information is only available beginning in 2005-2006, and so splitting the time-series to ensure only accurate catches are reflected was considered. Discards were determined to be negligible for *Nephrops* in FU 28–29 so the entire time-series was used for this stock.

Sexes can be considered separately or combined depending on the availability of data. When data is not separated by sex, life history parameters should be averaged - this may lead to sensitivity in the results due to the differences in life history characteristics for animals such as *Nephrops*.

**Input data**

**Table A2.4** Norway lobster in Division 9.a, functional units 28-29. Input parameters, data and information used for mean length Z.

| DATA TYPE | SOURCE | YEARS/VALUE | NOTES |
|---|---|---|---|
| Length frequency distribution | Portuguese commercial fishery landings | 1984–2016 | Discards considered to be zero/negligible |
| Fishing effort | | 1998–2016 | Standardized fishing effort time-series |
| Length-weight a | Portuguese data | 2.8 $10^{-4}$ males, 5.6 $10^{-4}$ females | |
| Length-weight b | Portuguese data | 3.2229 males, 3.0288 females | |
| $L_{MAT}$ | Portuguese data | 28.4 males, 30 females | |
| Von Bertalanffy $L_\infty$ (mm) | | 70 males, 65 females | |
| Natural mortality M ($yr^{-1}$) | | 0.3 males, 0.2 females | |
| Von Bertalanffy k ($yr^{-1}$) | | 0.2 males, 0.065 females | |

**Model and data exploration**

The length frequency distributions of each year did not indicate severe recruitment patterns, so applying mean length-based Z estimators are appropriate for this stock.

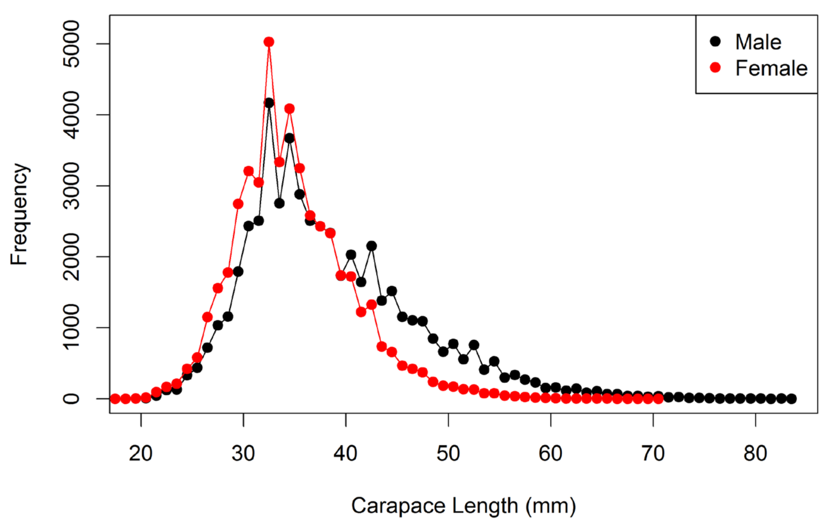



**Figure A2.4** Norway lobster in Division 9.a, functional units 28–29. Length frequency distribution of males and females aggregated over all years.

The peak of the length frequency distributions, or the assumed $L_c$, for both males and females was at the value of 32.5 mm. Estimates were stable to alternative $L_c$ inputs above 32.5 mm.

**Outputs**

Figures A2.5 and A2.6 show the output plots from the Gedamke-Hoenig and THoG models.

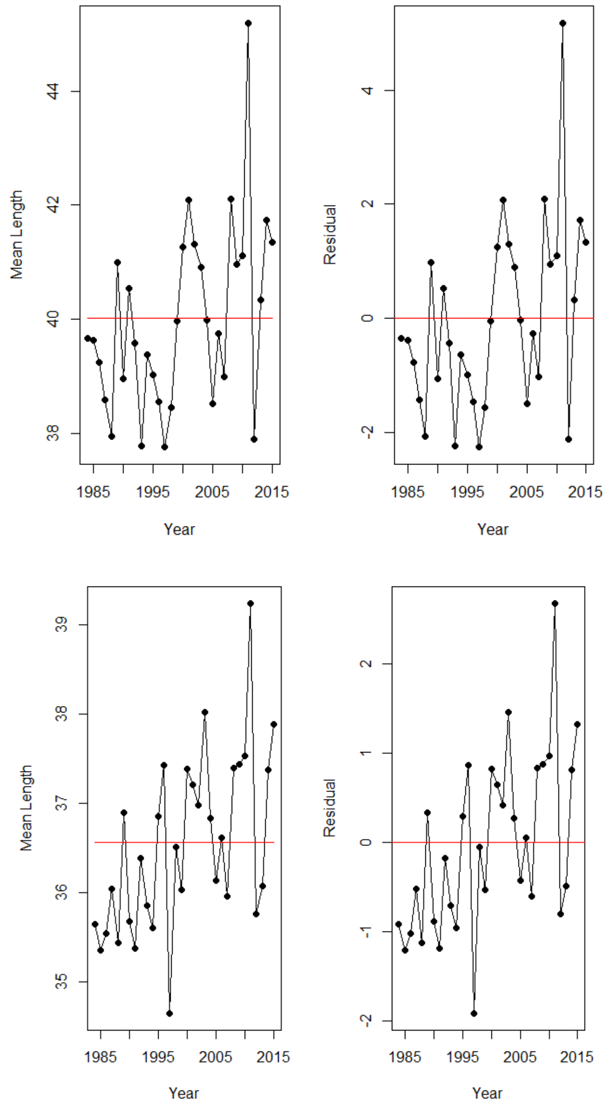



**Figure A2.5** Norway lobster in Division 9.a, functional units 28–29. Observed and fitted mean lengths for males (top) and females (bottom).


**Figure A2.6** Norway lobster in Division 9.a, functional units 28–29. Results of fitting the THoG model to males (left panels) and females (right panels). The observed (black line with dots) and predicted (red lines) mean lengths are shown.

The results are summarized in the table below.

**Table A2.5** Norway lobster in Division 9.a, functional units 28–29. Results of the mean-length Z estimators.

| Model | Parameter | Males | Females |
|---|---|---|---|
| Gedamke-Hoenig | Z estimate ($yr^{-1}$) | 0.44 | 0.29 |
| | F ($yr^{-1}$) (derived from Z estimate and external M) | 0.14 | 0.09 |
| | $F_{0.1}$ | 0.22 | 0.24 |
| THoG | M estimate ($yr^{-1}$) | 0.41 | 0.25 |
| | $F_{2016}$ estimate ($yr^{-1}$) | 0.03 | 0.02 |
| | $F_{0.1}$ | 0.22 | 0.24 |

**Conclusion**

From the mean length-only analysis (Gedamke-Hoenig method), it is inferred that overfishing is not occurring on the *Nephrops* stock. From the mean length and effort analysis (THoG method), it is again inferred that overfishing is not occurring on the *Nephrops* FU 28–29 stock.

The THoG (2014) model produced estimates of M that are slightly higher than the values of M used in the stock assessment. Both mean length estimators predict small changes in mean length over the course of the time-series, and both models predict small values of F. The two approaches are thus consistent with each other in the conclusions they provide.

The Then (2014) model produced estimates of M that are slightly higher than the values of M used in the stock assessment. Fixing the value of M in the Then model to the value used in the assessment results in slightly higher estimated fishing mortality rates.

The mean length Z estimator predicts small changes in mean length over the course of the time-series and small F values.

## Appendix 3: Example application on Beaked redfish (*Sebastes mentella*) in Division 14.b, demersal (Southeast Greenland)

### 1. Length based spawner per recruit (LBSPR)

**Input data**

The LB_SPR method requires length frequency data and biological parameters. When including 2010, the output result in unrealistic values for this year, and 2010 was excluded from further analysis. This is most likely a result of limited sampling in that year.

In addition to the data provided in the previous models, the LB-SPR requires information on selectivity (knife-edge, logistic or domed). This fishery is almost exclusively a trawled based fishery, and we used a logistic relationship, with a relatively sharp increase in selectivity.

**TableA3.1** Beaked redfish (*Sebastes mentella*) in Division 14.b, demersal. Input parameters, data and information used for LB-SPR.

| Data type | Source | Years/value | Notes |
|---|---|---|---|
| Length Frequency data | GINR | 2011–2016 | 1 cm grouping |
| M/K ratio | Fishbase, literature | k = 0.06<br>M = 0.1<br>M/K = 1.7 | M was set higher than in the MLZ method. This to make sure M/K ratio is within expected range. |
| $L_{inf}$ | FIshbase | $L_{inf}$ = 45.9 cm | $CV_{Linf}$ = 0.08 |
| $L_{mat}$ | GINR, 2015–2015,<br>N=1483 | $L_{50\%}$ = 26.2 cm<br>$L_{95\%}$ = 38.6 cm | Males and females combined |
| Length-weight, *a* | GINR, 2005–2015,<br>N=1 505 | $1.745*10^{-5}$ | $R^2$ = 0.9862 |
| Length-weight, *b* | GINR, 2002–2015,<br>N=1505 | 2.9251 | $R^2$ = 0.9862 |
| Natural mortalty, M | Guess | 0.1 | |
| Selectivity-at-length | Knife-edge, logistic or domed | logistic assumed<br>$SL_{50\%}$ = 30 cm<br>$SL_{95\%}$ = 35 cm | No basis |

**Output**

The model fitted the length distributions well in all years (Fig.1). The output for 2011 was outside the range of reasonable values for especially the F/M ratio. We are unsure of why this is the case, but for instance, the F/M range was estimated at [72–891] in 2011. Therefore, for graphical purposes and in our interpretation of the stock status, we only use 2012-2016 values.

The SPR values were above the SPR 30-40% range in all years (Fig. 2) suggesting that the stock is above the proxies associated with high long term yields. Similarly, the F/M ratio indicates the same in 2012-2014, but 2015 and 2016 the F/M ratio is ~1, indicating a fishery at around the optimal intensity in these years.

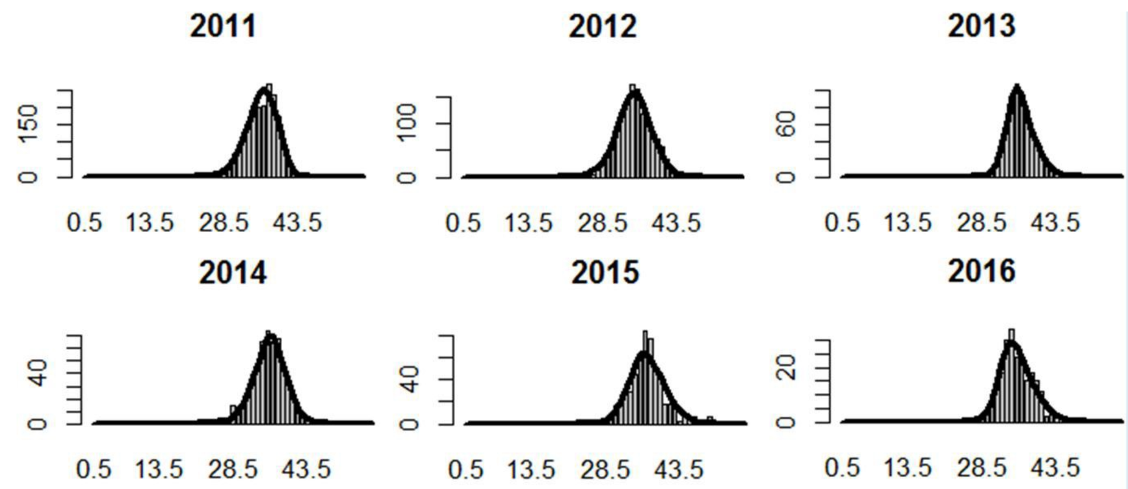



**Figure A3.1** Beaked redfish (*Sebastes mentella*) in Division 14.b, demersal. Length distributions and model fits.

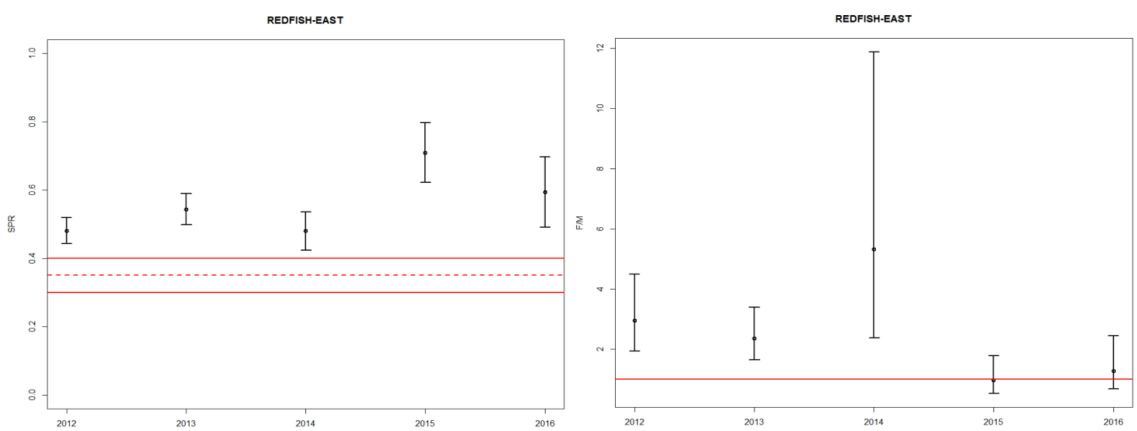



**Figure A3.2** Beaked redfish (*Sebastes mentella*) in Division 14.b, demersal. Left: SPR estimates by year with 95% confidence intervals. The dotted red line is SPR35% and the solid red lines are SPR=30% and SPR=40%, respectively. Right: Estimates of F/M by year with 95% confidence intervals. The red line indicates F=M.

## Conclusion

At first glance, the stock appears to be exploited at a reasonable level. The method is however highly dependent on input values, especially the M/K ratio. We report the output associated with a ratio of 1.67, as this is close to that seen for other stocks. This is based on Fishbase values. If we instead use the M used for the adjacent deep pelagic *S. mentella* stock, 0.05, and in other analyses described in this document, the conclusions change. If we keep the same k value, which seems consistent across stocks (Fishbase) the F/M ratio in 2016 changes from 1.27 to 3.83 and the SPR in 2016 changes from 0.59 to 0.24. Given this sensitivity any conclusions regarding stock status are tentative. In addition, the area is subject to an unknown inflow from other areas/stocks: the Icelandic slope, the deep pelagic stock and the shallow pelagic stock, and the assumption regarding "equilibrium" may not be met.

## Appendix 4: Example application on anglerfish (*Lophius budegassa*, *Lophius piscatorius*) in subareas 4 and 6 and Division 3.a (North Sea, Rockall and West of Scotland, Skagerrak and Kattegat)

### 1. SPiCT

**Input data**

A single survey was included in the SPiCT model (the Scottish and Irish anglerfish and megrim industry/science survey SCO-IV-VI-AMISS-Q2) a targeted survey covering ICES subareas 27.4 and 27.6. This was used as a relative or exploitable biomass index input. Landings data is available from 1973 however there are uncertainties associated with the catches between 1998-2006 after the introduction of a Total Allowable Catch (TAC) in 1998 and prior to the registration of fish sellers and buyers and designation of auction sites (Scotland) regulations of 2005. Landings during this period are assumed to be unreliable due to high levels of suspected area misreporting and possible black landings under a restrictive TAC. An effort series for Scottish demersal trawls (TR1) in subareas 27.4 and 27.6 was available from 2000 to present. The recording of Scottish hours fished data is not mandatory in log sheets and the data are incomplete therefore Scottish otter-trawl fleet effort data are provided in units of kWdays.

*Exploration*

The SPiCT model was applied to relative biomass index as a proxy for exploitable biomass and landings as a proxy for catches. SPiCT allows for fixing the noise parameters on data series, due to the short time-series the parameters of observation error of the landings (β) and survey biomass (α) were not estimated in the model therefore fixed values of $\beta = 0.65$ and $\alpha = 0.85$ were adopted from the WKPROXY report (ICES, 2016b). No priors were used. The method exploration conducted at WKPROXY discounted the survey years where the survey was not conducted in April (November, 2005–2007, 2013) however SPiCT allows for the time at which the observation was made and the intervals between observation to be specified so these years were included in all model runs reported here.

Several trials were run using various lengths and combinations of the available time-series as inputs.

**Output**

The output includes both stochastic and deterministic reference points. Both are shown but if a suitable model was agreed upon for the approximation of reference points then the more conservative of the two would likely be chosen.

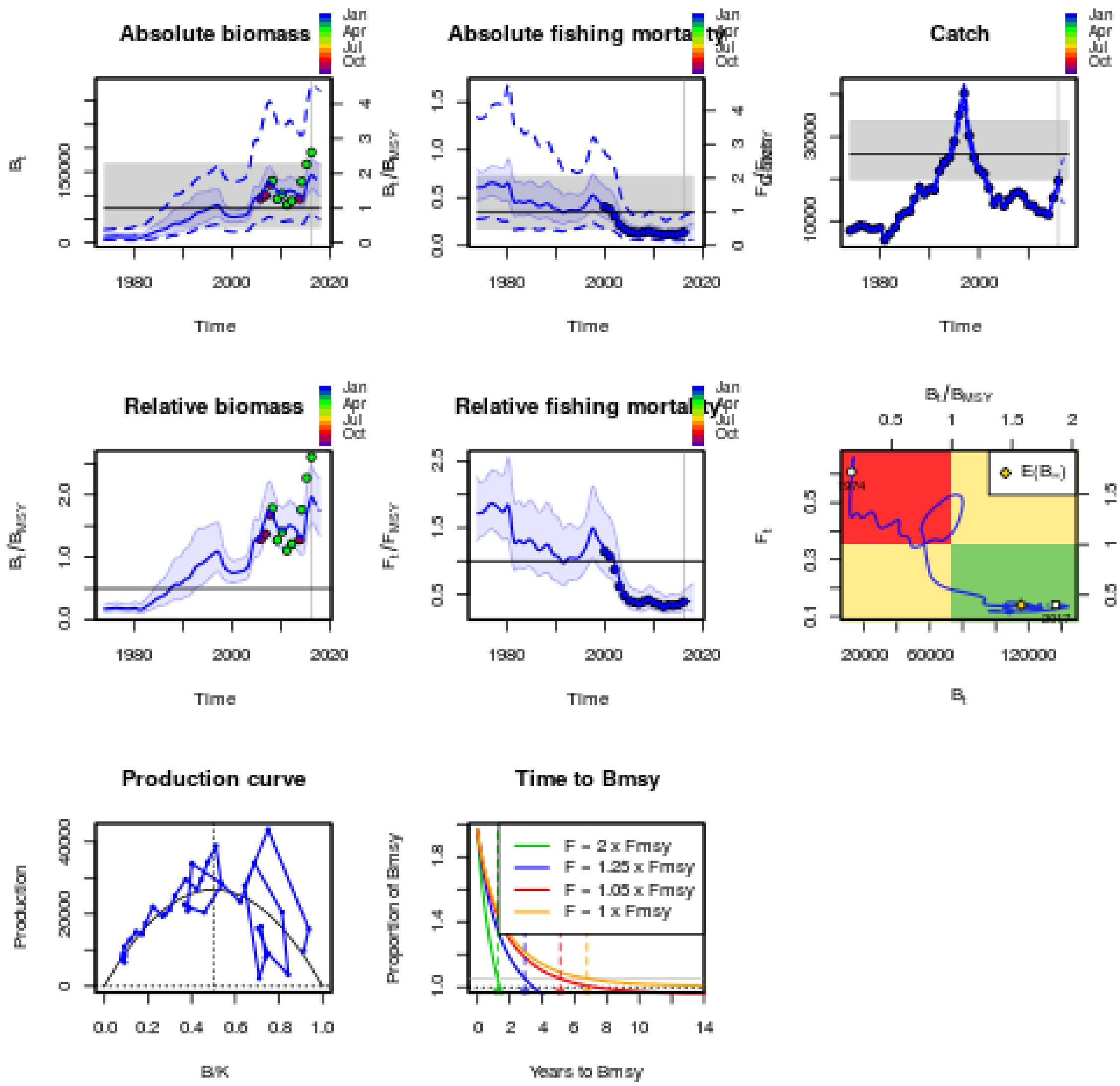



**Figure A4.1** Anglerfish in subareas 4 and 6 and Division 3a. Model diagnostics from the SPiCT model run.

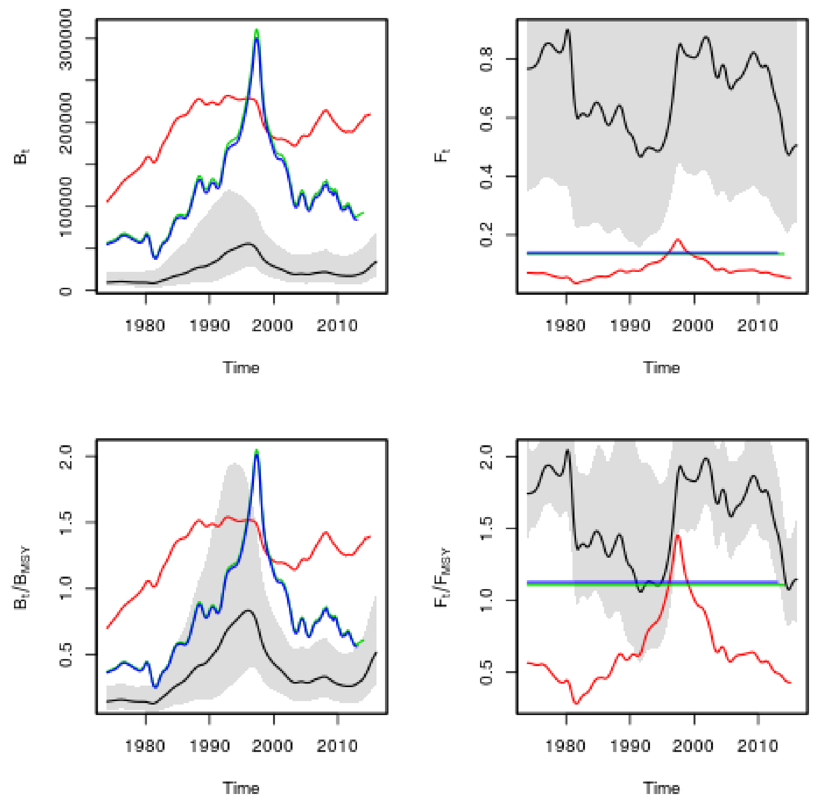



**Figure A4.2** Anglerfish in subareas 4 and 6 and Division 3a. 4-year retrospective of SPiCT run.

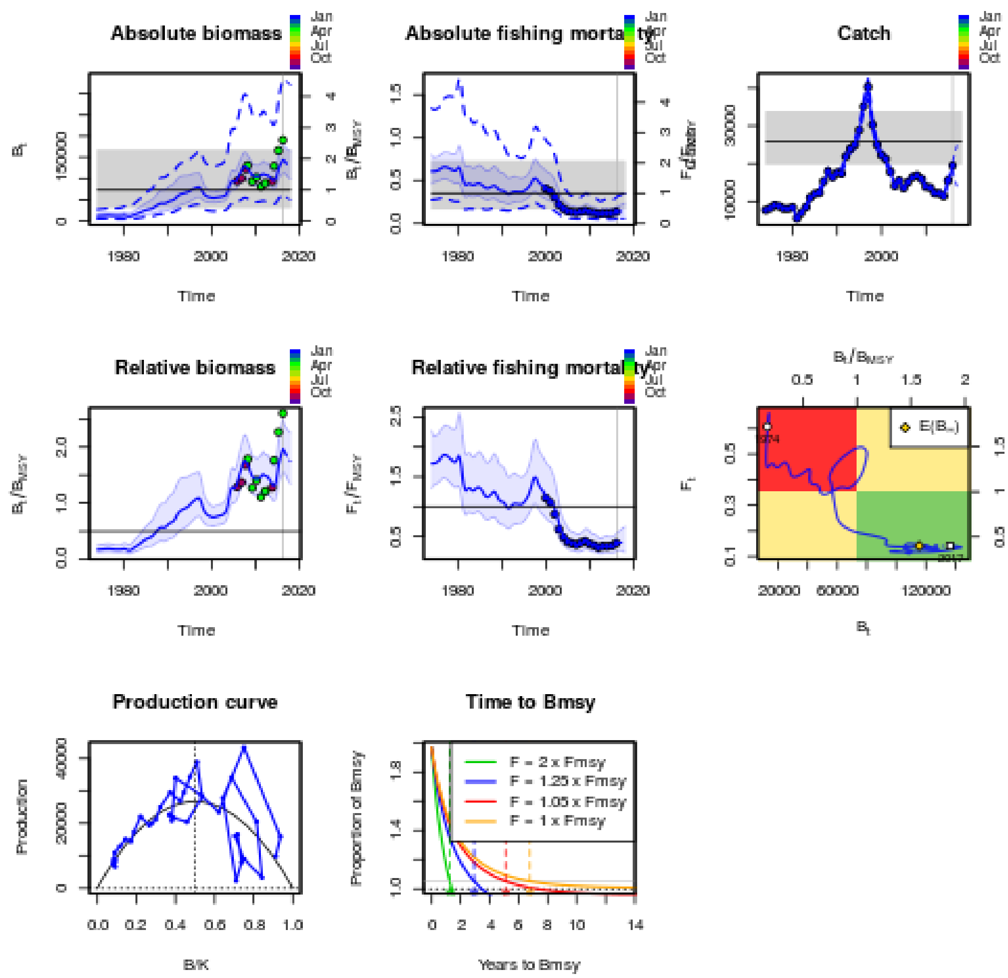



**Figure A4.3** Anglerfish in subareas 4 and 6 and Division 3a**.** Ouputs from the SPiCT model run.

**Table A4.1** Anglerfish in subareas 4 and 6 and Division 3a. Stochastic reference points from SPiCT

| Run 5 | Parameter | Type | Value |
|---|---|---|---|
| Landings: 1974–2016<br>Index: 2005–2016<br>Effort: 2000–2016 | $B_{MSY}$ | S | 73 284 tonnes |
| | | D | 74 713 tonnes |
| | $F_{MSY}$ | S | 0.353 |
| | | D | 0.357 |
| | MSY | S | 25 852 tonnes |
| | | D | 26 690 tonnes |
| | $B_{2016}$ | - | 144 144 |
| | $F_{2016}$ | - | 0.136 |
| | $B_{2016}/B_{MSY}$ | S | 1.967 |
| | $F_{2015}/F_{MSY}$ | S | 0.384 |

Caution is required when assessing the status of *Lophius budegassa* in Subarea 7 and divisions 8.a-b in relation to reference points given that the model includes the wanted catch component only and unwanted catch could be as much as 30% of the total catch.

The model is highly sensitive to the assumptions used and given the landings and CPUE are highly variable with minimal contrast this could account for the difficult the model had to converge.

**Conclusion**

Whilst the inclusion of an effort time-series and additional years of landings data have made the model predictions more representative of existing knowledge of this stock's exploitation the model retrospective fits in almost all instances only partially converge and show significant differences between the retrospective fits demonstrating a lack of robustness in the SPICT model estimates.

The survey biomass index used in the SPiCT assessment is too short to inform production parameters, despite having a long time-series of landings available; using the two together is not advisable as it creates a large mismatch in the series for which the model is making assumptions. The reported landings since 1998 have been driven by quota limitations and are therefore not reflective of stock size. In addition, there is considerable uncertainty around the reported landings during the period 1998 to 2006 - a period when underreporting is known to have occurred. The analysis conducted here supports the conclusions of the WKPROXY experts and external reviewers that given the currently available data, SPiCT does not provide a reliable indication of stock status or associated MSY reference points.