BENCHMARK WORKSHOP FOR HARP AND HOODED SEALS (WKBSEALS)

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Contents

i Executive summary

The benchmark was tasked with evaluating proposed developments to the assessment model used for two stocks of harp seals (East Ice [White Sea/Barents Sea, seh.27.1] and West Ice [Greenland, seh.27.125a14]) and one stock of hooded seals (West Ice [Greenland, sez.27.2514]) in the Northeast Atlantic. The benchmark concluded that there were sufficient data to produce an assessment model for the West Ice (Greenland Sea) stock of harp seals but that data were insufficient for the East Ice (Barents Sea / White Sea) harp seal stock and too weak a signal for the West Ice hooded seals for viable assessments for these stocks.

There has been no pup production survey for East Ice harp seals since 2013. In the absence of more recent survey data, the benchmark concludes that viable assessment of current stock status or catch advice cannot be produced. Furthermore, the most recent available pup production estimates indicated a poor status. There have been limited catches since 2019, and the benchmark recommends that a pup survey and subsequent revised assessment is required prior to the resumption of any substantial commercial hunt. The model version with capelin abundance informing model dynamics does perform well in the time period for which data exist.

For the West Ice harp seal stock, the benchmark proposes a revised assessment model using cod and capelin alongside a first order autocorrelation (AR1) process to drive the model dynamics. Owing to the provisional nature of the recent pup survey, Reference Points are not calculated here but will be evaluated at WGHARP 2023 when the final data is available. The historical modelled population absolute level is uncertain, but the overall recent trend is relatively flat and has not been adversely affected by recent catches. Although a harvest is taken, advice is not currently given through ICES. An existing HCR is used (see section 6.3., ICES, 2005) for advice outside ICES, and there is a desire to conduct an HCR evaluation to produce a basis for future ICES advice.

The benchmark notes the current low level of the hooded seal stock and that no commercial hunting has been conducted since 2007. No commercial hunting should be considered unless a clear upward trend in the pup abundance estimate can be observed, taking account of the uncertainty in these data. In the event of such an improving trend being observed, a new revised assessment would be needed prior to the resumption of hunting in order to give information on stock status and potential harvest levels.

The benchmark also performed a preliminary evaluation of the existing catch-at-age data for the different stocks. There was sufficient sign of signal in the data consistent with population structure (exponential decay with age, sign of recruitment failure tracking between years) to consider the possibility for using these data for model tuning. The benchmark strongly encourages such work.

ii Expert group information

Expert group name	Benchmark Workshop for Harp and Hooded Seal (WKBSEALS)
Expert group cycle	Annual
Year cycle started	2023
Reporting year in cycle	1/1
Chair(s)	Daniel Howell, Norway
	Alejandro Buren, Argentina
Meeting venue(s) and dates	22–26 May 2023, ICES HQ, Copenhagen, Denmark, 12 participants

1 Motivation for the Benchmark

WKBSEALS aimed to benchmark three different stocks of two arctic pinniped species: harp seals (*Pagophilus groenlandicus*) in the White Sea / Barents Sea (hereafter referred to as 'East Ice') and the Greenland Sea (hereafter 'West Ice'), and hooded seals (*Cystophora cristata*) in the Greenland Sea. This represents the first ever ICES benchmark for seals. The meeting was run as a hybrid meeting, with most participants present at the ICES Headquarters in Copenhagen and some participating via Microsoft Teams. The motivation for conducting a benchmark was the conclusion by the 2019 meeting of the joint NAFO/ICES/NAMMCO working group on harp and hooded seals (WGHARP), that the current assessment model fails to produce realistic estimates of population dynamics to form the basis for harvest advice using the harvest control rules (HCR) agreed upon in 2005 (see section 6.3., ICES, 2005). One reason for the poor model performance is its stiffness. It currently estimates only three parameters: initial population size in 1946 and constant mortalities for pups and 1+ animals. The argument for keeping the model relatively simple, and therefore inflexible, has been the relative sparsity of input data. WKBSEALS aimed to evaluate an updated model that allows for increased flexibility and the inclusion of environmental drivers on vital rates.

1.1 Definitions of data-rich vs. data-poor stocks, biological reference points, and harvest control rules

As stated in ICES (2005), WGHARP recommends that data-rich stocks should have data available for estimating abundance with the following characteristics:

- Accuracy of the data
    - Precision—abundance estimates should have a Coefficient of Variation about the estimate of 30% or less
    - Abundance estimates should be unbiased
- The most recent abundance estimates should be prepared from surveys and supporting data (e.g. birth and mortality estimates) that are no more than five years old

The management of both species is based on harvest control rules (HCRs) that are related to specific biological reference points (BRPs; see Figure 1). All BRPs are referred to as N_p, where subscript $_p$ refers to the percentage of the current estimated abundance relative to N_{max}, i.e. the maximum estimated historical total abundance. N_{lim} represents 30% of N_{max}.

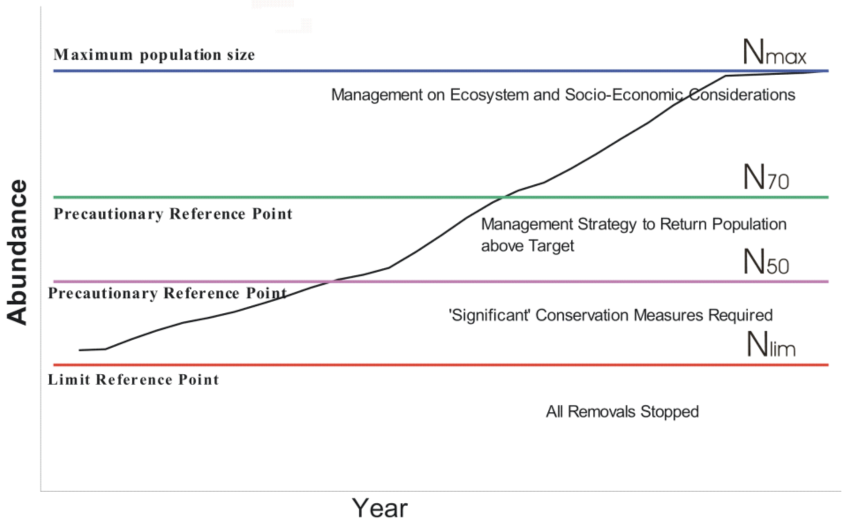

Figure 1. Reference points for a data rich stock, as defined in ICES (2005).

For data-rich stocks, the full set of control rules established under the multi-tier system would apply:

- If abundance is greater than N_{70}, management objectives would be based upon the appropriate WGHARP assessment model and would require that the population remains above the N_{70} level.
- If the abundance is greater than N_{50}, the management objective must include efforts to conserve the population. For WGHARP, projections of proposed management actions must have a > 0.8 probability of the population returning to N_{70} within 10 years.
- If abundance is greater than N_{lim} but less than N_{50}, significant conservation measures will be required, that would give a 95% probability of stock recovery.
- If the abundance is below N_{lim}, then no harvest should occur.

For data-poor stocks, the multi-tier system collapses to two levels:

- If a stock has no recent (i.e. within five years), accurate abundance estimates, then no harvest should occur.
- If a stock has 1–2 recent, accurate abundance estimates, then the control rules collapse to the point where the only concern is whether the abundance is less than or greater than N_{lim}, such that:
    - If abundance is greater than N_{lim}, then the potential biological removals (PBR) protocol (Wade, 1998) is used to set the total allowable catch (TAC).
    - If abundance is less than N_{lim}, then no harvest should occur.

2 Presentation of stocks

2.1 Harp seals (*Pagophilus groenlandicus*)

The harp seal is a pelagic, migratory species that occurs throughout the North Atlantic, from the Canadian coast in the west to the Barents Sea in the east and northward to pack-ice regions in Arctic waters (Figure 2). It is an obligatory ice-dependent species, relying on pack ice for most parts of the year, and is an important high trophic level predator. Based on geographically distinct whelping (pupping) locations, three putative populations of harp seals have been identified (see Sergeant, 1991). In the Northwest Atlantic, one population breeds on the drifting pack ice in Canadian waters. In the European Arctic, the Greenland Sea ('West Ice') population whelps off the east coast of Greenland, and the White Sea/Barents Sea ('East Ice') population whelps, as the name implies, in the White Sea. These harp seal populations all have their own distribution and migration patterns throughout the North Atlantic, although there is some overlap between Northwest Atlantic and Greenland Sea harp seals along the coast of East Greenland (Stenson et al., 2020), and substantial overlap between feeding areas of Greenland Sea and Barents Sea / White Sea harp seals within the Barents Sea (Folkow et al., 2004; Nordøy et al., 2008; Svetochev et al., 2016).

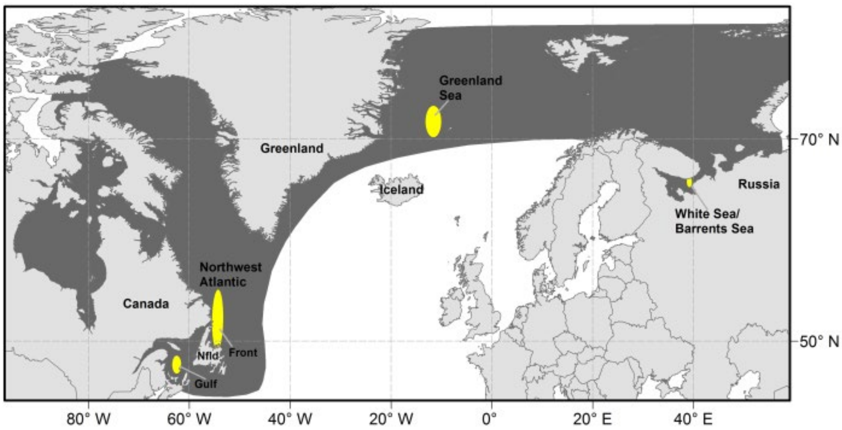

Figure 2. General distribution of harp seals in the North Atlantic. Yellow regions indicate breeding and moulting sites, while the shaded grey area represents distribution also including feeding migrations at sea. The two stocks under consideration here are the White Sea / Barents Sea (East Ice) and Greenland Sea (West Ice) stocks. Figure taken from Stenson *et al*. (2020).

Whelping occurs on drifting pack ice from late February through early April, depending upon location (Sergeant, 1991), whereas moulting of adults and immatures takes place slightly north of each whelping location approximately 3–4 weeks after weaning with immature seals and adult males moulting before adult females. After the moult, seals generally migrate northwards to their summer and autumn feeding grounds. Figure 3 shows a schematic annual timeline of key events.

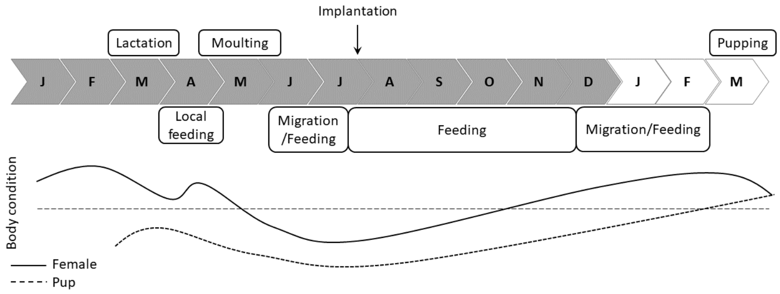

Figure 3. Schematic annual timeline of key events related to pup production, moulting, pregnancy and feeding in harp seals.

While the Northwest Atlantic stock is currently by far the most numerous (~7 000 000 animals compared to ~1 500 000 for the East Ice and ~430 000 for the West Ice), it is not the subject of this benchmark. Below we present general information and stock status for the East Ice and West Ice stocks. These two stocks have historically been subject to commercial harvest, and they have been managed jointly by Norway and Russian Federation via the Joint Russian–Norwegian Fisheries Commission since the 1980s.

2.2 East Ice stock, seh.27.1, Harp seals (*Pagophilus groenlandicus*) in Subarea 1 (Barents and White sea stock)

Harp seals in the Barents Sea has constituted an important harvested resource for centuries, with annual catches during the 1940s and 1950s generally exceeding 100 000 seals. Despite a gradually reduced harvest over recent decades, there was a significant drop in pup production from 2003 to 2005 (ICES 2019a). While the reasons for this decline remain unknown, Øigård et al. (2013) found that harp seal body condition was significantly lower in 2011 than 10–15 years earlier, and they identified possible links between seal body condition and the abundance of several spatially overlapping potential competitors and prey including capelin, polar cod and northeast Arctic cod. Changes in prey availability and maternal body condition is likely to influence reproductive output by affecting e.g. abortion rates or pup survival. In extreme situations, limitations in prey availability might even lead to increased adult mortality, such as that observed during the 'seal invasion' years during periods of capelin collapse in the 1980s and, to a lesser degree, 1990s. Due to the sharp decline in pup production, ICES (2016) recommended that removals be restricted to the estimated sustainable equilibrium level, which was 10 090 1+ (i.e. aged 1 year and older) animals in 2017–2019. In the case of pups being harvested, the removal of two pups count as one 1+ animal. The Joint Norwegian-Russian Fisheries Commission has followed this request and allocated 7,000 seals of this TAC to Norway and 3,090 to Russia. A ban implemented on all pup catches prevented Russian harvest in the White Sea during the period 2009–2013. This ban was removed prior to the 2014 season. However, the availability of ice was too restricted to permit sealing, resulting in no commercial Russian harp seal catches in the White Sea in 2014–2019. While recent catches have been modest (see Figure 8; also, Annex 7, Table 2 in ICES, 2019), there is no sign that pup production has increased, and WGHARP (2019) concluded that the current assessment model fails to fit to the time series of pup production (Figure 4). This is mostly due to the inflexibility of the model is very inflexible with only three parameters, very informative priors, scarce population data and no drivers of variation in vital rates and thereby the population dynamics. Hence, the model is unable to adapt to rapid changes.

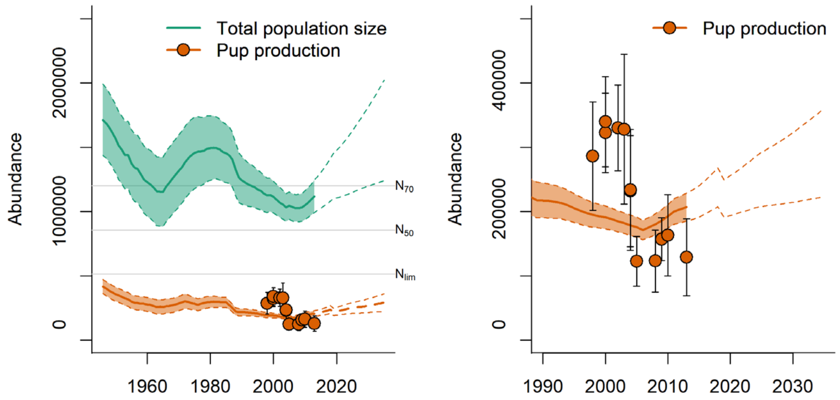

Figure 4. Modelled total adult (green) and pup (orange) abundance, and the model fit to the estimated pup production (right panel) for harp seals breeding in the Barents Sea/White Sea. Full lines show historical trajectory, dashed lines show the future predictions, and shaded area shows the 95% confidence intervals.

In particular, WGHARP (2019) noted that forward projections of population trends were not consistent with observed pup production. Since the current harvest control rules are based on predicting future population trends in relation to biological reference points, WGHARP (2019) concluded that the model needs revising and re-evaluation prior to being proposed for use in future assessments. In particular, WGHARP (2019) suggested that the inclusion of potential environmental drivers be explored, and they recommended that effects of variations in the biomass of key prey and competitor species on harp seal vital rates be tested.

2.3 West Ice stock, Harp seals (*Pagophilus groenlandicus*) in subareas 1, 2, and 14 and Division 5.a (Greenland Sea stock), seh.27.125a14

Similar to the East Ice population, West Ice harp seals have been commercially harvested for centuries, with total annual catches in the 1940s and 1950s of around 30 000–40 000 seals. Both Norwegian and Russian Federation vessels have historically been involved, and the stock have therefore been managed jointly between the two countries. Catches have decreased substantially in recent decades, averaging < 10 000 seals annually since 2000, and no Russian Federation vessels have been involved in the harvest since 1994. While this stock did not display the dramatic decline in pup production as that seen in the East Ice population, substantial year-to-year variations in pup production is evident in the time series, especially during the 1980s and 1990s when observations were carried out much more frequently than in subsequent years (Figure 5).

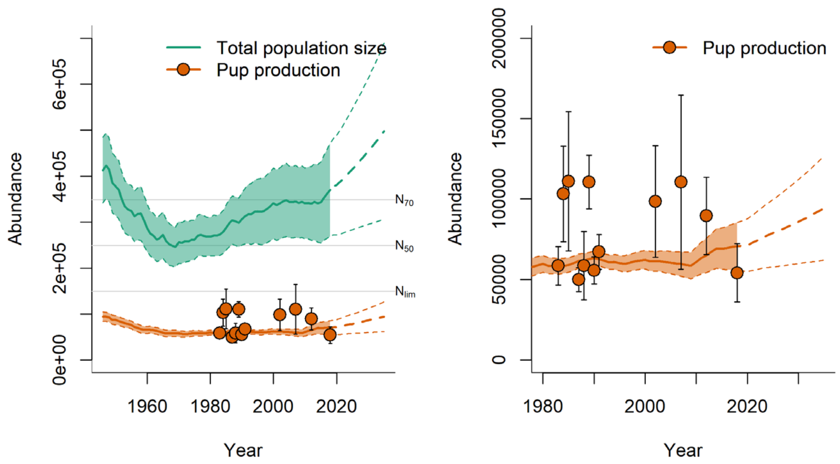

Figure 5. Modelled total adult (green) and pup (orange) abundance, and the model fit to the estimated pup production (right panel) for harp seals breeding in the Greenland Sea. Full lines show historical trajectory, dashed lines show the future predictions, and shaded area shows the 95% confidence intervals.

As in the case of the East Ice stock, WGHARP (2019) concluded that there was a substantial lack of fit of the current assessment model to the pup production estimates obtained from surveys. In particular, the failure of the model to reconstruct the apparent short-term fluctuations in pup production in the 1980s and 1990s was noted.

2.4 West Ice hooded seals, Hooded seals (Cystophora cristata) in subareas 2, 5, and 14 (Greenland Sea stock), sez.27.2514

This stock has historically been harvested in numbers similar to those for West Ice harp seals, fluctuating between about 30 000 and 80 000 annually until the early 1960's before decreasing gradually until the harvest was discontinued in 2007 due to concerns regarding their population status. Specifically, the harvest control rules agreed upon by WGHARP in 2005 (ICES, 2005) states that: "If the abundance is less than N_{lim}, then no harvest should occur", where N_{lim} was set at 30% of the estimated historical maximum total abundance. Figure 6 presents the estimates of pup production and modelled population trajectories, based on the assessment model runs presented at WGHARP 2019.

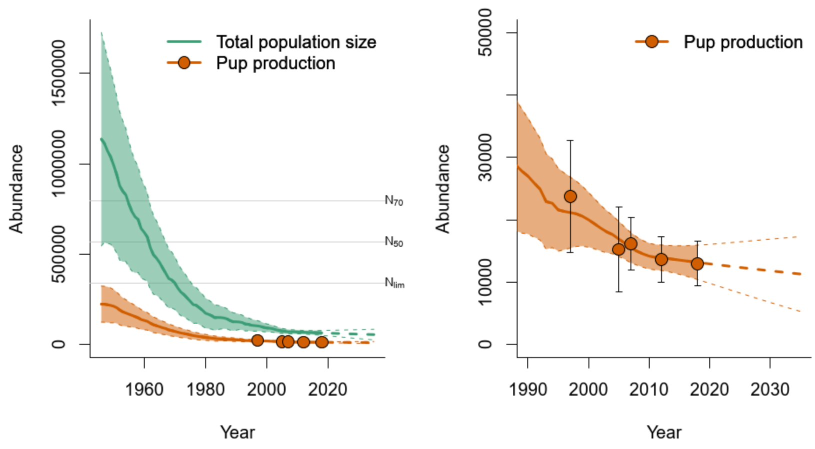

Figure 6. Modelled total adult (green) and pup (orange) abundance, and the model fit to the estimated pup production (right panel) for hooded seals breeding in the Greenland Sea. Full lines show historical trajectory, dashed lines show the future predictions, and shaded area shows the 95% confidence intervals.

For this stock, the model is able to fit well to the time series of estimated pup production. The likely reason for this good fit is the consistent overall trend in pup production, where the lack of model flexibility is not an issue. However, if pup production starts changing in ways that do not follow the historical trend, it is unlikely that the current assessment model will be appropriate for this stock.

3 Population model

The population (assessment) model is age-structured, but data are only given for two age groups, age 0 (pups) and age 1 and older (1+). Yearly catch data are available separately for these two groups and are regarded as error free. Population monitoring follows common methodology for other pinniped species with a land- or ice-based lactation period, in that abundance surveys focus on counts of pups. This is due to the assumption that this represents the period when the majority of the population gathers on whelping grounds, and that pup counts represent the most accurate estimate of a particular demographic group. Estimates of pup production (age 0) are given at roughly 5-year intervals for the past 3–4 decades, with estimation uncertainty given as coefficient of variation (cv). Estimates of proportion mature females by age as well as fecundity rate for sexually mature females are given for certain years at less regular intervals, also with cv's. In addition, we have yearly data for other species that may constitute prey resources (positive impact, e.g. capelin) or competitors (negative impact, e.g. cod), which can influence various vital rates in the model (e.g. fecundity, abortion rate, pup or adult mortality).

It should be noted that the yearly catch data is currently only used as total catch (rather than catch at age), while the periodic surveys only give estimates for age zero. One consequence of this is that many of diagnostics available to a catch-at-age model cannot be produced for these models. Residual plots are not available owing to an absence of age data. The c. five-year gap between the survey data points makes retrospective plots problematic, especially as recent catches are either zero or at a low level compared to earlier in the time series. This report therefore concentrates on presenting the model fit to the available data, as well as the likelihood and AIC scores for different model variants. Of the three stocks examined here, only the West Ice harp seals were considered to have sufficient information to support an assessment model, and we therefore focus on this stock when presenting diagnostics.

3.1 Current, pre-benchmark, official model

The official model (see Box 1 for notations and Box 2 for general model structure) currently used for assessment purposes is a special version of the general model presented in Box 2, where mortalities are independent of year and constant for seals of age 0 and of age 1+ separately, and where the fecundity is assumed to be known and interpolated as described in Box 2 This model has three parameters:

- $M_{0,normal}$: The mortality rate for pups, $M_{0,y} = M_{0,normal}$ for all years.
- $M_{1,normal}$: The mortality rate for age 1 and older, $M_{a,y} = M_{1,normal}$ for all years and for ages greater or equal to 1.
- N_{1+,y_0}: 1+ stock size in initial year y_0.

3.2 Submodels

In preparation for the benchmark process, we have considered a suite of different submodels for four compartments of the model: 1) the natural pup mortality rate, 2) the natural adult mortality rate, 3) the fecundity rate and finally 4) an abortion rate to modify the fecundity rate (Box 2), i.e. a realized fecundity rate. Because of the scarce data for all these seal stocks, there was a limitation to the number of parameters to be estimated in the models. The four processes would be otherwise confounded given that the time series of data is only on number of pups. Hence, we fitted different candidate models differing only in one submodel of one of these compartments at a time. It should be noted that one consequence of this focus on a single process is that the estimated rates may not be physically realistic. The model is forcing all of the variability that, in reality, occurs in the four different processes (pup mortality, adult mortality, fecundity rate, abortion rate) into a single modelled variable. This does not impact on the reliability of the model population, but it does mean that care needs to be taken in interpreting the specific process rate values.

Models are numbered and generally follow an increasing scale of complexity, while the letter prefix represents the vital rate modelled (M0 = pup mortality, M1 = adult mortality, F = fecundity, A = abortion rate).

3.2.1 Natural pup mortality rate

For the benchmark process we considered the following submodels for the natural pup mortality rate, $M_{0,y}$:

$$
\begin{aligned}
\text{M01: } \log(M_{0,y}) &= \log(M_{0,normal}),\\
\text{M02: } \log(M_{0,y}) &= \log(M_{0,normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp},\\
\text{M03: } \log(M_{0,y}) &= \log(M_{0,normal}) + \omega_y,\\
\text{M04: } \log(M_{0,y}) &= \log(M_{0,normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp} + \omega_y;
\end{aligned}
$$

Note that here, and below, ω_y constitute an AR(1) process given by

$$
\begin{aligned}
\omega_y &= \phi\omega_{y-1} + \varepsilon_y,\\
\varepsilon_y &\sim N(0,\sigma^2).
\end{aligned}
$$

The set of alternative submodels means that the natural pup mortality rate is assumed to either (i) be a constant (cf. M01), (ii) depend on a resource and a competitor index (cf. M02), (iii) follow a stochastic AR(1) process (cf. M03), or (iv) be a combination of the two latter (cf. M04). In submodels M02 and M04, as in similar submodels below, the regression coefficients β_{res} and β_{comp} are restricted to be non-negative. Since both x_y^{res}, x_y^{comp} and ω_y varies around 0, the natural pup mortality rate, $M_{0,y}$, varies around $M_{0,normal}$. Hence, $M_{0,normal}$ can be interpreted as the mortality in a normal situation. This also applies to $M_{1,normal}$, F_{normal} and A_{normal}, respectively.

3.2.2 Natural adult mortality rate

For age 1 and older, we considered the same submodels as for pups. However, in addition we considered two additional variants with age-dependence:

$$
\begin{aligned}
\text{M11: } \log(M_{a,y}) &= \log(M_{1,normal}),\\
\text{M12: } \log(M_{a,y}) &= \log(M_{1,normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp},\\
\text{M13: } \log(M_{a,y}) &= \log(M_{1,normal}) + \omega_y;\\
\text{M14: } \log(M_{a,y}) &= \log(M_{1,normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp} + \omega_y;\\
\text{M15: } \log(M_{a,y}) &= \log(M_{1,normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp}, a = 1, \dots A^{old} - 1,\\
\log(M_{a,y}) &= \log(M_{A^{old},normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp}, a = A^{old}, \dots A,\\
\text{M16: } \log(M_{1,y}) &= \log(M_{1,normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp},\\
\log(M_{a,y}) &= \log(M_{A^{old},normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp}, a = A^{old}, \dots A,\\
&\text{and } S_{a,y} \text{ linearly interpolated between } a = 1 \text{ and } a = A^{old}.
\end{aligned}
$$

In submodel M15, the natural mortality for the 1+ age classes is similar to submodel M12, but varies around one level for age classes up to $A^{old} - 1$ and around another level for older ages. Submodel M16 is similar to submodel M15, but the natural mortality changes linearly from age 1 to age A^{old}. We chose $A^{old} = 7$, to reflect the average age-at-maturity (Frie *et al.*, 2003).

3.2.3 Fecundity rates

For fecundity, we considered the following four submodels:

F0: $\text{logit}(F_y)$ = assumed known and interpolated between observations,
F1: $\text{logit}(F_y) = \text{logit}(F_{normal})$,
F2: $\text{logit}(F_y) = \text{logit}(F_{normal}) + \beta_{res}x_y^{res} - \beta_{comp}x_y^{comp}$,
F3: $\text{logit}(F_y) = \text{logit}(F_{normal}) + \omega_y$,
F4: $\text{logit}(F_y) = \text{logit}(F_{normal}) + \beta_{res}x_y^{res} - \beta_{comp}x_y^{comp} + \omega_y$.

Note that in submodel F0, the fecundity is assumed to be known and without error. Moreover, the fecundity is linearly interpolated between observed estimates of fecundity and extrapolated up until the first estimate and after the last estimate (see upper left panel in Figure 10 for an example).

3.2.4 Abortion rates

For the abortion rate (A_y), we considered the following four submodels:

A0: $\text{logit}(A_y) = 0$,
A1: $\text{logit}(A_y) = \text{logit}(A_{normal})$,
A2: $\text{logit}(A_y) = \text{logit}(A_{normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp}$,
A3: $\text{logit}(A_y) = \text{logit}(A_{normal}) + \omega_y$,
A4: $\text{logit}(A_y) = \text{logit}(A_{normal}) - \beta_{res}x_y^{res} + \beta_{comp}x_y^{comp} + \omega_y$.

Note that here fecundity rates are more reflective of pregnancy rates and that abortion rates are a cumulative measure of several different causes of mortality of pups, such as reabsorption of the fetus, late abortions, stillborn pups and early mortality from birth to the time surveys are conducted. Hence, the product of fecundity and abortion rates reflects the realized reproductive rate.

Note also that the current official model (see above and Box 2) consists of the combination of submodels M01, M11, F0, and A0, while the model presented by Øigård and Skaug (2014) consists of the combination of submodels M01, M11, F3, and A0.

3.3 Estimation

The different model variants are estimated by maximum likelihood, with a Bayesian flavor, using Template Model Builder (TMB). The likelihood components include the contribution from pup production estimates, fecundity estimates (except for submodel F0, where fecundity is assumed to be known) and the priors for the parameters. All likelihood components are based on the normal distribution. The priors used in the different model variants are provided in Table 1.

Assuming normality for the pup production counts, their contribution to the log-likelihood function is:

$$\sum_{y=y_{E_1}}^{y=y_{E_Y}} -log(cv_{0,y}) - \frac{1}{2}\frac{(N_{0,y} - n_{0,y})}{(cv_{0,y}n_{0,y})} \quad (7)$$

where $y_{E_1} \ldots y_{E_Y}$ are the Y years with available pup production estimates, $n_{0,y}$ and $cv_{0,y}$ denotes the survey pup production count and corresponding coefficient of variation (CV) for year y, respectively (Table 3).

The population dynamics model has a 'Bayesian flavour', as priors are imposed on the parameters. The priors used are found in Table 4. The combined likelihood-contributions for these priors are:

$$-\frac{1}{2}(\mathbf{b}-\mathbf{m})^T \Sigma^- 1(\mathbf{b}-\mathbf{m}) - \frac{1}{2} ln|\Sigma| - \frac{3}{2} ln(2\pi) \quad (8)$$

where $\mathbf{b}$ constitute a vector containing the parameters estimated by the model, T denotes the vector transpose, $\mathbf{m}$ is a vector containing the respective mean values of the normal priors for the parameters in $\mathbf{b}$, and Σ is a diagonal matrix with the variance of the respective prior distributions on the diagonal.

All parameter estimates are found by minimizing the likelihood function using the statistical software TMB (Kristensen *et al.*, 2016). TMB uses a quasi-Newton optimization algorithm with bounds on the parameters, and calculates estimates of standard errors of model parameters using the "delta-method" (Skaug *et al.*, 2007). The catch data enters the model through catch equation (see box 2), but do not otherwise contribute to the objective function. All data processing and analyses were done using R (R Core Team, 2018). Model fitting was done using the R package TMB (Kristensen *et al.*, 2016).

Table 1: Mean and standard deviation of the normal priors for model parameters

Parameter	Mean	Sd
$N_{1+,y0}$	10^6	$2 \cdot 10^7$
$M_{0,normal}$	0.27	0.2
$M_{1,normal}$	0.09	0.1
$M_{Aold,normal}$	0.09	0.1
β_{rec}	0.00	0.2
β_{comp}	0.00	0.2
ϕ	0.50	0.3
σ	0.00	0.5

A jitter analysis was conducted on the models for all three stocks. This indicated stable convergence to an optimum, however there was instances where convergence occurred at much higher (worse) likelihood scores and clearly poor fit to the data. These local optima were readily identifiable and could be rejected as part of a suite of jitter analyses. It is therefore important that at any assessment a jitter analysis be run to confirm the validity of the final model estimate.

3.4 Model selection

For each stock, one specific combination of the various submodels were chosen as the preferred model based on its fit to the data (likelihood and AIC values) and subsequently, its biological plausibility. For the models with environmental drivers both resource and competitor were included in the model formulation for all stocks. For the hooded seals this was not found to improve the model, and was therefore excluded. For the East Ice the competitor (cod) effect was estimated to zero by the model and we therefore refer to this as ‘capelin only’, while for the West Ice harp seals both the cod and the capelin were estimated as having an impact and are retained in the diagnostics presented below.

The appropriate lag to use for the resource/competitor index was investigated using an analysis of the best fit (on the likelihood score) for different lags. For the East Ice a lag of one year (i.e. food abundance in the previous year) was preferred, and (as discussed below) fits with the timing of the data and the seal feeding. For West Ice a lag of zero years produced the best fit, which was considered to make biological sense given the timing of the survey and the impacts of cod predation (see below for details).

We also investigated the impact of adding AR1 process in addition to the resource/competitor. AR1 alone was not considered for candidate assessment models, as this could account for variability in the hindcast but would have zero predictive power.

3.5 Re-evaluation of catch-at-age data

The benchmark discussed the data limitations common to the three stocks, and requested that existing catch-at-age data be collated to evaluate the potential benefit of including these data in the updated assessment model. The inclusion of these data has previously been considered by WGHARP, but the conclusion has been that potential unrepresentative sampling may bias any results in terms of assessing the age structure in the population. Upon request from the benchmark, catch-at-age data for all three stocks were collated and presented by Anne-Kristine Frie at the IMR.

A preliminary evaluation of the catch-at-age data was conducted for each stock. For all stocks the benchmark concluded that there was signal relating to the population dynamics in the data (in terms of showing mortality in ages and in some cases of following cohorts), and that model development should test the effects of including catch-at-age data as tuning data. However, there was insufficient time to conduct this analysis at the present benchmark. The models presented here therefore use aggregated catch data. The conclusions presented here will obviously be subject to revision if and when the catch-at-age data are included.

4 The three different stocks

This benchmark covers three stocks of seals. There are two stocks of harp seals, one in the Barents and White Sea (the East Ice harp seals) and one between Greenland and Iceland (the West Ice harp seals). In addition, the hooded seal stock between Greenland and Iceland is included. Of these stocks there is an ongoing hunt for the West Ice harp seals (at a lower level than in earlier decades, very limited hunting for the East Ice harp seals in recent years, and a moratorium on the hooded seal population (which is believed to be at a low level). The model framework described above is applied to all three stocks, although the data availability varies between stocks. An ICES group, WGHARP, considers these populations although there is currently no official ICES advice for any of them. The work presented here can be considered as an attempt to improve the previous poor performance of the assessment models, and as a step towards a potential future ICES advice.

4.1 Harp seals (*Pagophilus groenlandicus*) in Subarea 1 (Barents and White sea stock), the East Ice harp seal stock

Figure 7 shows the schematic annual timeline of events, where the timing of surveys for Barents Sea capelin and cod are indicated. Time series plots of fecundity estimates, pup production estimates, resource and competitor indices and catch data used as input data into the models are shown in Figure 8. How the proportion at maturity changes across years is depicted in Figure 9 for a selection of age classes of harp seals in the East Ice. And finally, Figure 10 depicts the output and fit of the preferred model from the benchmark process. However, because the last pup production estimate was as long ago as 2013, this model was not deemed suitable for stock assessment and consequently for providing advice on harvest levels. Hence, the benchmark has recommended that if new pup production estimates are made available, a new model evaluation should be conducted to decide on the best assessment model for this stock.

However, the chosen model for modelling the harp seals in the East Ice was the model that consisted of the following submodels; constant pup mortality (M01), constant 1+ mortality (M11), fixed fecundity (F0) and the abortion rate depending on capelin as a resource index with an additional AR(1) process (A4), i.e., M01-M11-F0-A4 (see subsection Submodels for a detailed explanation behind the codes for the different submodels). As the estimate of $\beta comp$ (i.e., cod) was 0, meaning that the cod index had no effect, this predictor was removed from the model. Hence, the resource index in the model was chosen to be capelin per 1st of October in year y - 1, i.e., the capelin biomass roughly a 1/4 year before the pup births. This is the approximate timing of the survey and fits with the feeding time of the seals; therefore, it is likely that this gives direct information on the food availability (in contrast to the later capelin survey in the West Ice stock). The parameter estimates with standard deviation are given in Table 2. Note that the chosen model was initiated with a narrow prior for $N_{1+,y0}$ (i.e. relatively low sd around the mean value). It should be stressed again that while this was the best available model, in the absence of recent data it was not considered suitable as a basis for catch advice.

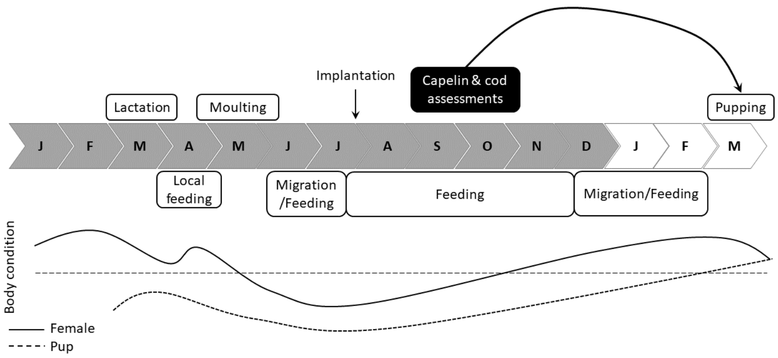

Figure 7. Timeline of key annual life history events for harp seals, with the timing of environmental drivers considered in the modelling for the East Ice stock is indicated. The black box represents the time represented by the environmental driver assessments. In this case, assessments represent the situation around Sep-Oct in the calendar year prior to the year of the whelping season, hence the y-1 lag in these driver data matches the resource and competitor data to the period of pregnancy.

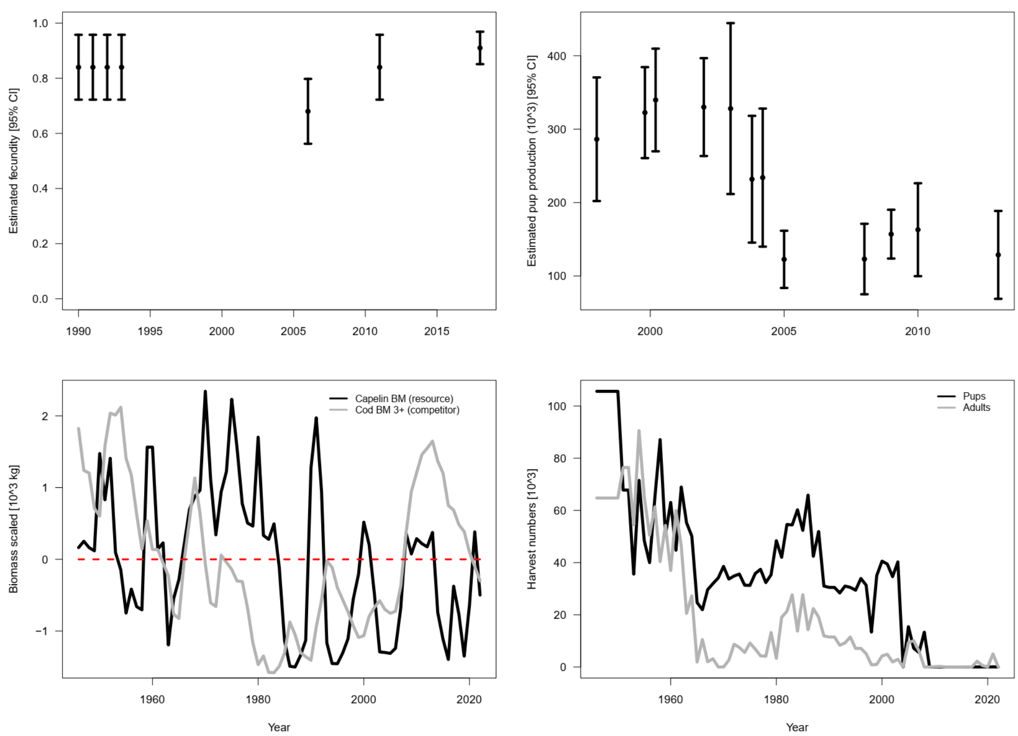

Figure 8. Timeseries of the different sources of input data to the model. The upper left panel shows the fecundity estimates, the upper right panel shows the pup production estimates, the lower left panel shows the scaled biomass timeseries of capelin (resource, black) and cod (competitor, gray), where the red stippled line indicates the mean, and the lower right panel shows the catch data (in thousands) for pups (black) and adults (1+, gray).

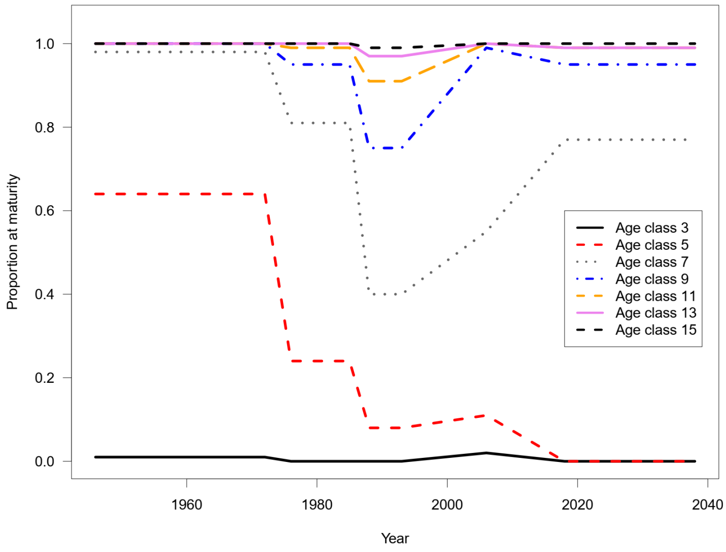

Figure 9. Proportion at maturity across years for a selection of age classes of harp seals in the East Ice.

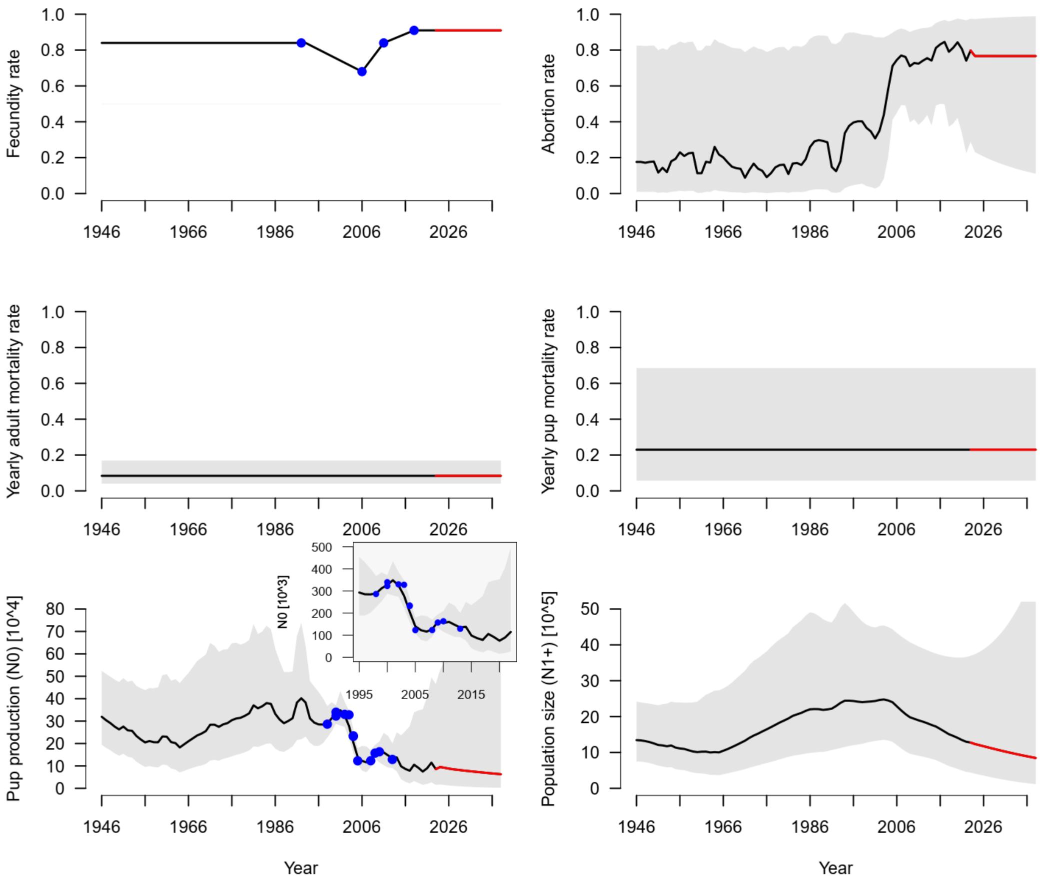

Figure 10. Shows the output from the chosen model (i.e., M01-M11-F0-A4), where submodel A4 indicates that abortion rates are modelled as a function of capelin biomass at t-1 and an additional AR(1) process. In all panels, black lines indicate estimated values, and the grey areas indicate the 95% confidence bands. The inset in the lower left panel shows the fit of the model to the period with pup production estimates (blue points). Note that the red segments indicate a period of forecast of 16 years, based on average values of vital rates and drivers. Note also, the different scale of the y-axis in the different panels.

Table 2. Parameter estimates with standard deviation for the current best model for Harp seals in the East Ice.

Parameter	Estimate	sd
$N_{1+,y0}$ (in millions)	1.34	0.40
$M_{0,normal}$	0.26	0.20
$M_{1,normal}$	0.09	0.03
A_{normal}	0.19	0.24
β^{A}_{cap}	1.43	0.92
β^{A}_{cod}	0	0
Φ	0.99	0.0006
Σ	0.31	0.92

WKBSEALS Recommendation

The benchmark concludes that there is insufficient data to conduct a reliable assessment of the East Ice harp seal stock. The key issue is the lack of any pup survey since 2013. This lack of data makes any assessment of current stock or trends unacceptably uncertain, and this is unlikely to be improved without a new pup survey. A new survey would therefore be required in order to provide an assessment of this stock to support any catch advice.

The benchmark notes that the current best available model for the East Ice harp seal stock (seh.27.1) is the version presented with abortion rate informed by capelin abundance, and recommends that the possibility of including age-structured catch data as tuning data is explored. Future model development should concentrate on including catch-at-age data. The model estimates prior to the late 1990s are very uncertain, and it is hoped that the inclusion of catch-at-age data may be able to inform these estimates.

4.2 Harp seals (*Pagophilus groenlandicus*) in subareas 1, 2, and 14 and Division 5.a (Greenland Sea stock), the West Ice harp seal stock

Figure 11 shows the schematic annual timeline of events, where the timing of surveys for Iceland and Greenland capelin and cod are indicated. Time series plots of fecundity estimates, pup production estimates, resource and competitor indices and catch data used as input data into the models for Harp seals in the West Ice are shown in figure 12. How the proportion at maturity changes across years is depicted in Figure 13 for a selection of age classes of harp seals in the West Ice. Moreover, Figure 14 depicts the output and fit of the preferred model from the benchmark process. It should be noted that the most recent pup production survey point is preliminary data, these will be revised prior to the assessment being conducted at WGHARP 2023.

Table 3 shows the likelihood scores and AIC values for a range of candidate assessment models for the West Ice harp seals. In the interests of brevity we focus on the model formulation using abortion rates, since that was the best performing across the different model options.

It can be seen that adding capelin and cod as tuning series improves the model fit over that available prior to the benchmark, with variability on abortion rate being the most successful. Adding an AR1 process in addition improves the fit, and the AIC, for all the model options. These conclusions were borne out by a visual examination of the model fits for all the options. Adding either cod or capelin alone produced worse likelihood and AIC values than the combination presented here (discussed below). In addition to the numerical analysis, it was considered a plausible hypothesis that the abortion rate is the process most sensitive to food availability. This can be considered as a sanity check on these results.

The chosen assessment model for modelling the harp seals in the West Ice was therefore the model that consisted of the following submodels; constant pup mortality (M01), constant 1+ mortality (M11), fixed fecundity (F0) and the abortion rate depending on capelin as a resource index and cod as a competition index and with an additional AR(1) process (A4), i.e., M01-M11-F0-A4 (see Submodels for a detailed explanation behind the codes for the different submodels). The resource and competition index in the model for abortion rates was chosen to be capelin and cod, respectively, and with no time lag. The parameter estimates are given in Table 4.[1]

The capelin abundance estimates are obtained in Jan-Feb while the main feeding season occurred in the preceding autumn months (Fig 11). The benchmark discussed this and it seems likely that the inclusion of cod as well as capelin as tuning series is producing more representative information on the food availability in the feeding period in the previous autumn than the capelin abundance in Jan-Feb alone. This explains the zero time lag (in contrast to the East Ice): in the absence of direct information on capelin abundance in the previous year's feeding time the best available information on feeding conditions the previous year is obtained from this year's cod and capelin information. This interpretation is supported by comparison with the East Ice model where the best fit was obtained with just capelin lagged one year but where the capelin survey occurs at a similar time to seal feeding. In that case simply lagging the capelin data gives direct information on feeding conditions at the correct time. The benchmark suggested that further work should be carried out to attempt to directly reconstruct the summer-autumn capelin biomass, based on estimated predation by cod.

Given that the recent pup estimate are preliminary numbers, no reference points are computed here. These will be estimated at the 2023 WGHARP when the final data is available.

[1] Note that the model for harp seals (West ice) selected at the benchmark was not accepted by WGHARP 2023 or the Benhmark Oversight Group (BOG). This was mainly because the estimated population abundance by the model was influenced by the choice of the standard deviation of the prior on the initial population. See Annex 5.

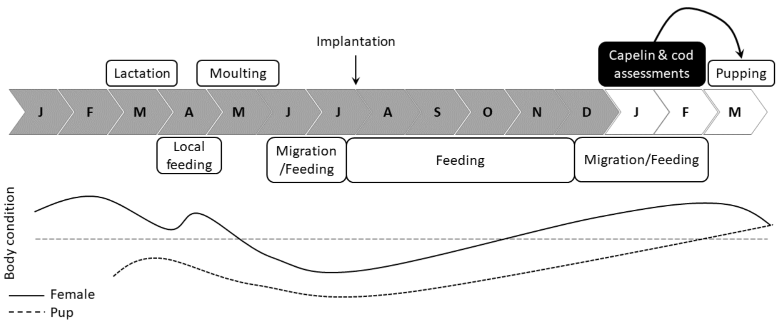

Figure 11. Timeline of key annual life history events of harp seals, with the timing of environmental drivers considered in the modelling for the West Ice stock is indicated. Note that resource and competitor assessments are obtained in Jan–Feb in the same year as whelping, but are considered representative also of the period of pregnancy in the preceding autumn. Hence, no lag means drivers and pup production are temporally matched.

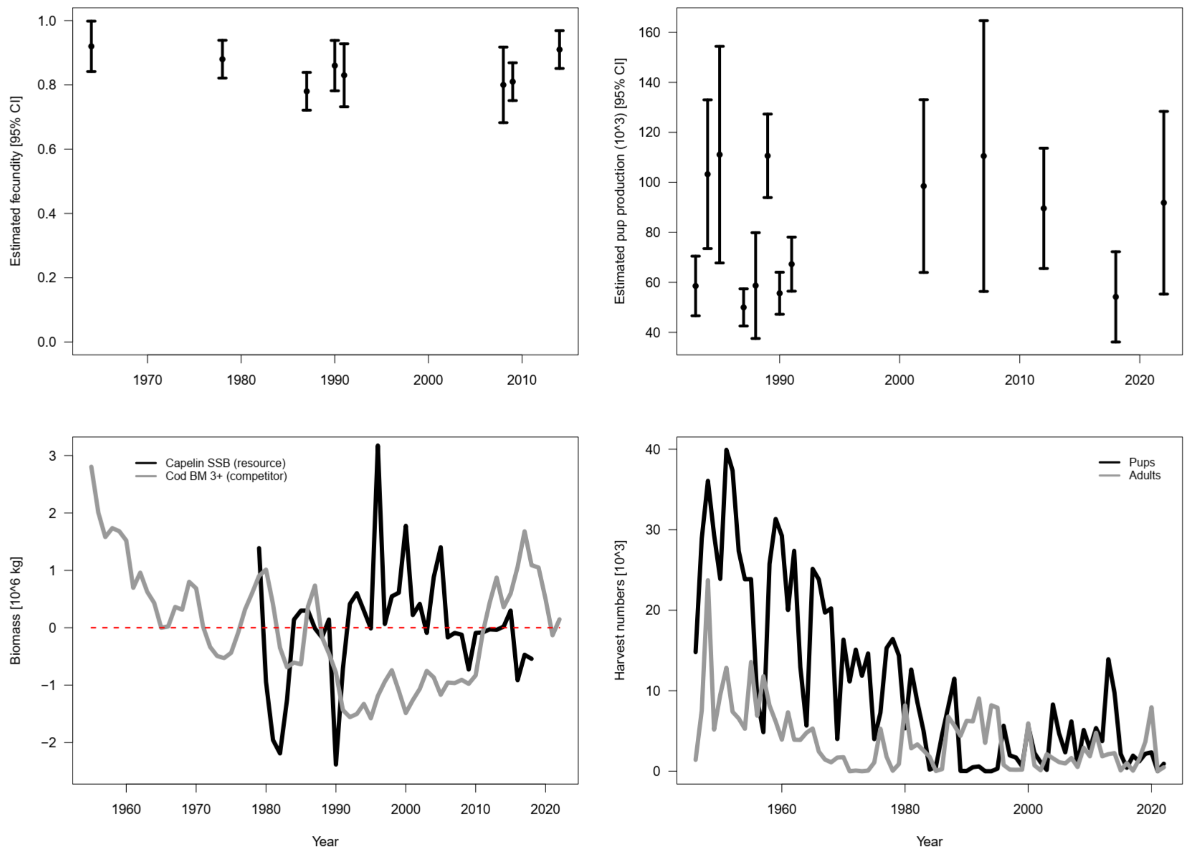

Figure 12. Timeseries of the different sources of input data to the model of Harp seals in the West Ice. The upper left panel shows the fecundity estimates, the upper right panel shows the pup production estimates, the lower left panel shows the scaled timeseries of SSB capelin (resource, black) and cod biomass (competitor, gray), where the red stippled line indicates the mean, and the lower right panel shows the catch data (in thousands) for pups (black) and adults (1+, gray).

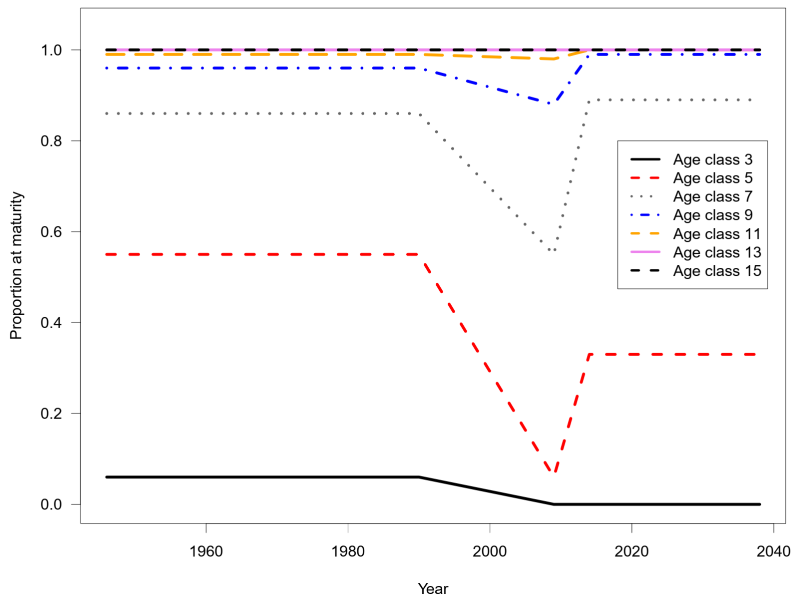

Figure 13. Proportion at maturity across years for a selection of age classes of harp seals in the West Ice.

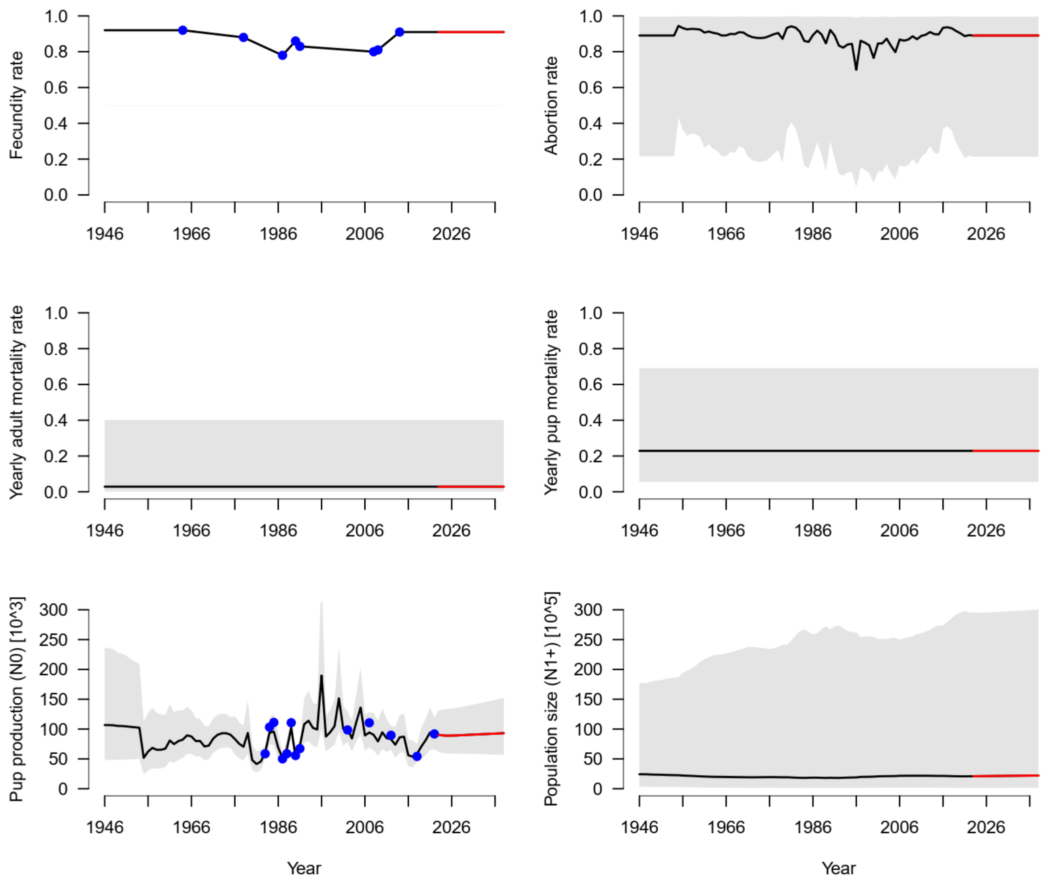

Figure 14. Shows the output from the chosen model (i.e. M01-M11-F0-A4), where submodel A4 indicates that abortion rates are modelled as a function of capelin SSB, cod biomass and an additional AR(1) process. In all panels, black lines indicate estimated values, and the grey areas indicate the 95% confidence bands. In the lower left panel, the blue points show the years

with pup production estimates. Note that the red segments indicate a period of forecast of 16 years, based on average values of vital rates and drivers. Note also the different scale of the y-axis in the different panels.

Table 3. Likelihood scores and AIC for different candidate assessment models for the West Ice harp seal stock. Asterisk denotes the selected model.

Area	Species	Model.ID	Likelihood	AIC	Specifics	
West Ice	Harp seal	M0.1M1.1F.0A.0	169.8147	345.6294	Standard model	
West Ice	Harp seal	M0.2M1.1F.0A.0	169.3833	348.7666	Pups ~ cap + cod	
West Ice	Harp seal	M0.1M1.2F.0A.0	162.1222	334.2444	Adults ~ cap + cod	
West Ice	Harp seal	M0.1M1.1F.2A.0	163.3009	338.6018	Fecundity ~ cap + cod	
West Ice	Harp seal	M0.1M1.1F.0A.2	147.4636	306.9271	Abortion ~ cap + cod	
West Ice	Harp seal	M0.4M1.1F.0A.0	169.3833	352.7666	Pups ~ cap + cod + AR[1]	
West Ice	Harp seal	M0.1M1.4F.0A.0	145.6999	305.3997	Adults ~ cap + cod + AR[1]	
West Ice	Harp seal	M0.1M1.1F.4A.0	155.0325	326.0650	Fecundity ~ cap + cod + AR[1]	
West Ice	Harp seal	M0.1M1.1F.0A.4	134.6367	285.2734	Abortion ~ cap + cod + AR[1]	*

Table 4. Parameter estimates with standard deviation for the best assessment model for Harp seals in the West Ice.

Parameter	**Estimate**	**sd**
$N_{1+,y0}$ (in millions)	2.42	2.46
$M_{0,normal}$	0.26	0.20
$M_{1,normal}$	0.03	0.04
A_{normal}	0.89	0.17
β^{A}_{cap}	1.91	0.57
β^{A}_{cod}	1.59	0.66
φ	0.28	0.23
σ	0.15	0.06

WKBSEALS Recommendation

The benchmark recommends that a viable assessment is the current best available model for the West Ice harp seal stock (seh.27.125a14) using the version presented with abortion rate informed by cod and capelin as drivers of model dynamics, alongside an AR1 process, and recommends that the possibility of including age-structured catch data as tuning data[2].

4.3 Hooded seals (*Cystophora cristata*) in subareas 2, 5, and 14 (Greenland Sea stock)

Figure 15 shows the schematic annual timeline of events, where the timing of assessments for Iceland and Greenland Sea halibut and redfish are indicated. Time series plots of fecundity estimates, pup production estimates, resource and competitor indices and catch data used as input data into the models for Hooded seals in the West Ice are shown in Figure 16. How the proportion at maturity changes across years is depicted in Figure 17 for a selection of age classes of hooded seals in the West Ice. Moreover, Figure 18 depicts the output and fit of the preferred model from the benchmark process, which is the standard model. This stock has had no catch since the late 2000s, and the recent recruitment surveys are all low and very similar to each other (figure 16). This lack of contrast in the population data makes modelling the stock level problematic.

The chosen assessment model for modelling the hooded seals in the West Ice was the standard model that consisted of the following submodels; constant pup mortality (M01), constant 1+ mortality (M11), fixed fecundity (F0) and a fixed abortion rate of zero (A0), i.e., M01-M11-F0-A0 (see Submodels for a detailed explanation behind the codes for the different submodels). Hence, neither including resource indexes (Redfish and Greenland halibut), an AR(1) process, or any combination of those in any of the submodels provided models with a markedly better fit to the pup production estimates than the standard model. This is mainly because pup production estimates for hooded seals are almost on a flat line but could also be due to a lack of suitable biotic or abiotic drivers considered during the benchmark. The parameter estimates are given in Table 5. Note that the commercial harvest of this stock was stopped in 2007/2008, due to the population being considered well below the N_{30} reference point (see above). Any new assessment of harvest potential for this stock would depend on a marked increase in pup production over several consecutive surveys. However, such a marked increase in pup production would need to be accompanied by a new model assessment before commercial harvest could be recommended.

[2] Note that the model for harp seals (West ice) selected at the benchmark was not accepted by WGHARP 2023 or the Benhmark Oversight Group (BOG). This was mainly because the estimated population abundance by the model was influenced by the choice of the standard deviation of the prior on the initial population. See Annex 5.

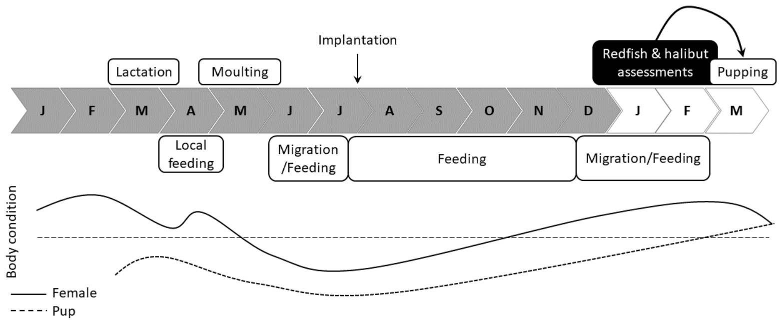

Figure 15. Timeline of key annual life history events of hooded seals, with the timing of environmental drivers considered in the modelling is indicated.

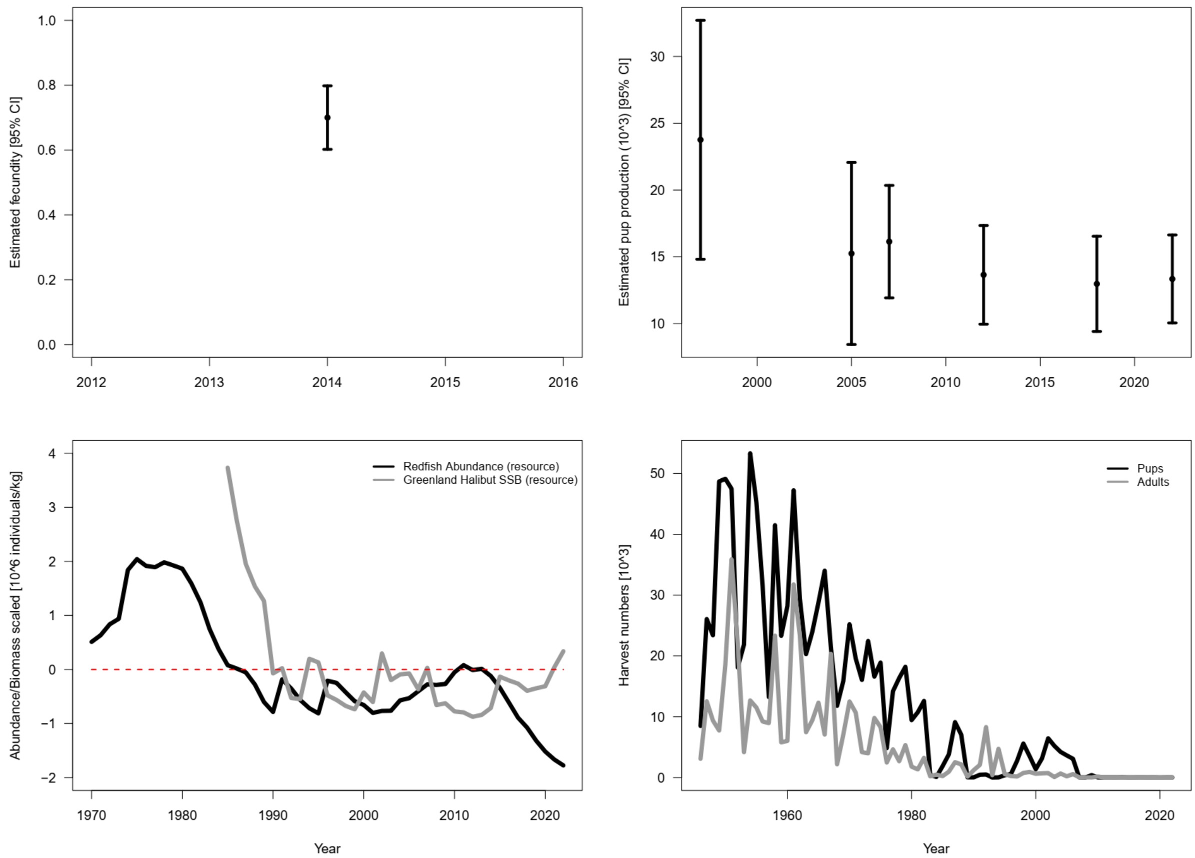

Figure 16. Timeseries of the different sources of input data to the model of Hooded seals in the West Ice. The upper left panel shows the single fecundity estimate, the upper right panel shows the pup production estimates, the lower left panel shows the scaled timeseries of abundance of redfish (resource, black) and Greenland halibut SSB (resource, gray) outside Iceland and in the Greenland Sea, where the red stippled line indicates the mean, and the lower right panel shows the catch data (in thousands) for pups (black) and adults (1+, gray).

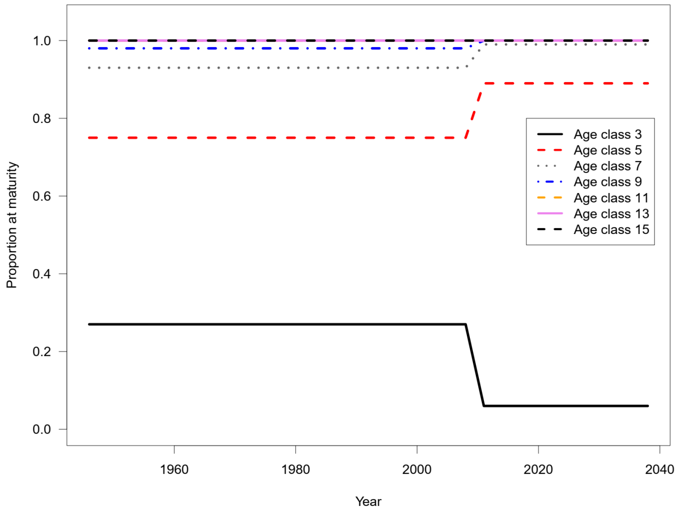

Figure 17. Proportion at maturity across years for a selection of age classes of hooded seals in the West Ice.

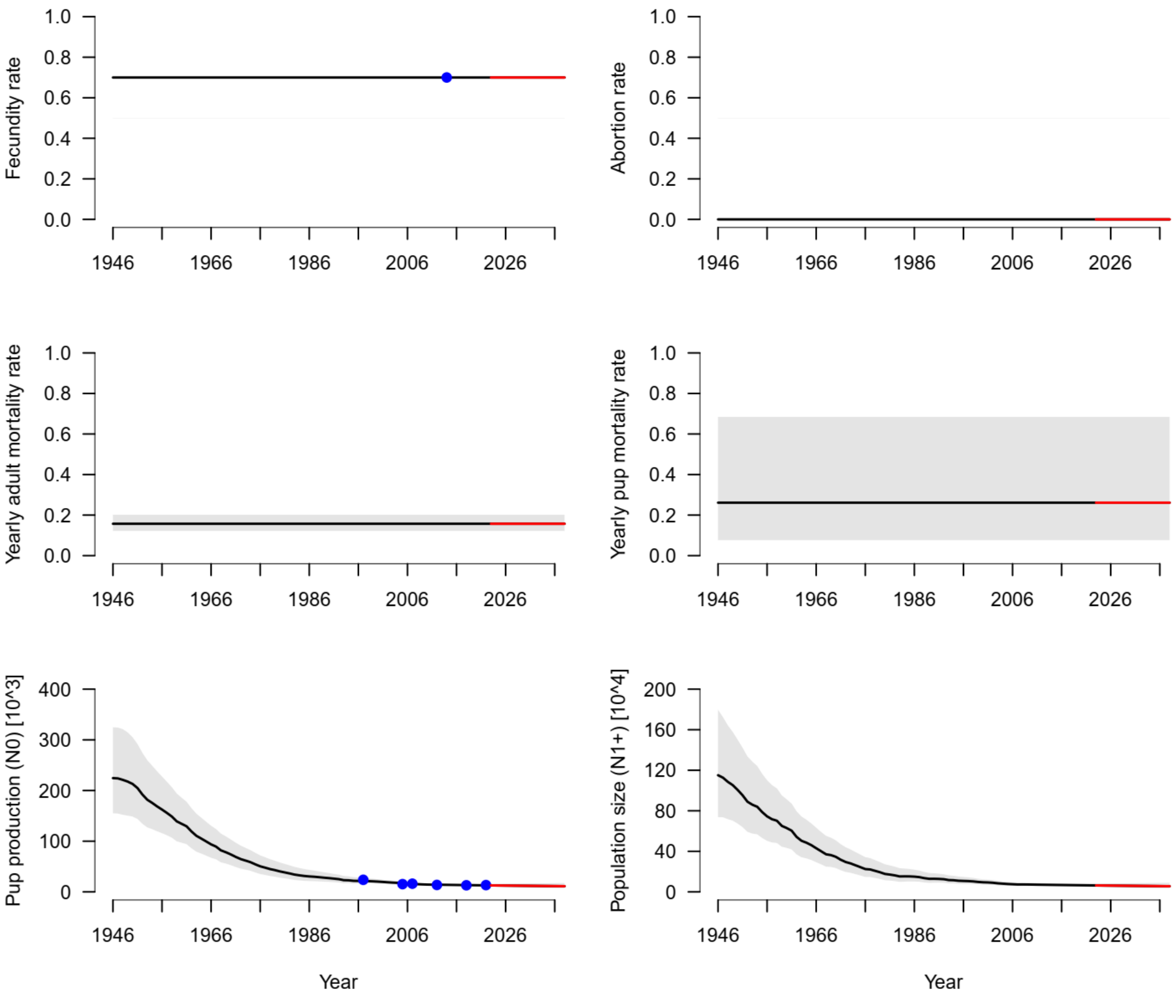

Figure 18. Shows the output from the chosen assessment model (i.e., M01-M11-F0-A0). In all panels, black lines indicate estimated values, and the grey areas indicate the 95% confidence bands. In the lower left panel, the blue points show the years

with pup production estimates. Note that the red segments indicate a period of forecast of 16 years, based on average values of vital rates and drivers. Note also, the different scale of the y-axis in the different panels.

Table 5. Parameter estimates with standard deviation for the best assessment model for Hooded seals in the West Ice.

Parameter	Estimate	Sd
$N_{1+,y0}$ (in millions)	1.15	0.26
$M_{0,normal}$	0.30	0.21
$M_{1,normal}$	0.17	0.02

WKBSEALS Recommendation

The benchmark concludes that there is currently insufficient information to conduct a reliable assessment for this stock, and recommends that no commercial hunting be undertaken until an improvement in recruitment be observed in the survey (taking account of the uncertainty in these data). In the event of such an improvement being observed, a new revised assessment would be needed prior to the resumption of hunting.

The benchmark notes that for hooded seals in the West Ice (sez.27.2514) there is very little contrast in the pup estimate data, and therefore little information to inform the model estimation. Adding in catch-at-age data may help to improve the estimation.

5 Investigation into catch-at-age data

During the benchmark, discussions were held regarding the availability of age-structure data from harvested seals (i.e. catch-at-age data) that could be used to tune the age structure of the model, adult mortality rates and recruitment. As such data exist, though with varying temporal coverage and representativeness to the real population structure, a preliminary bubble plot of the catch-at-age data for the different stocks was presented to the benchmark (Figure 19).

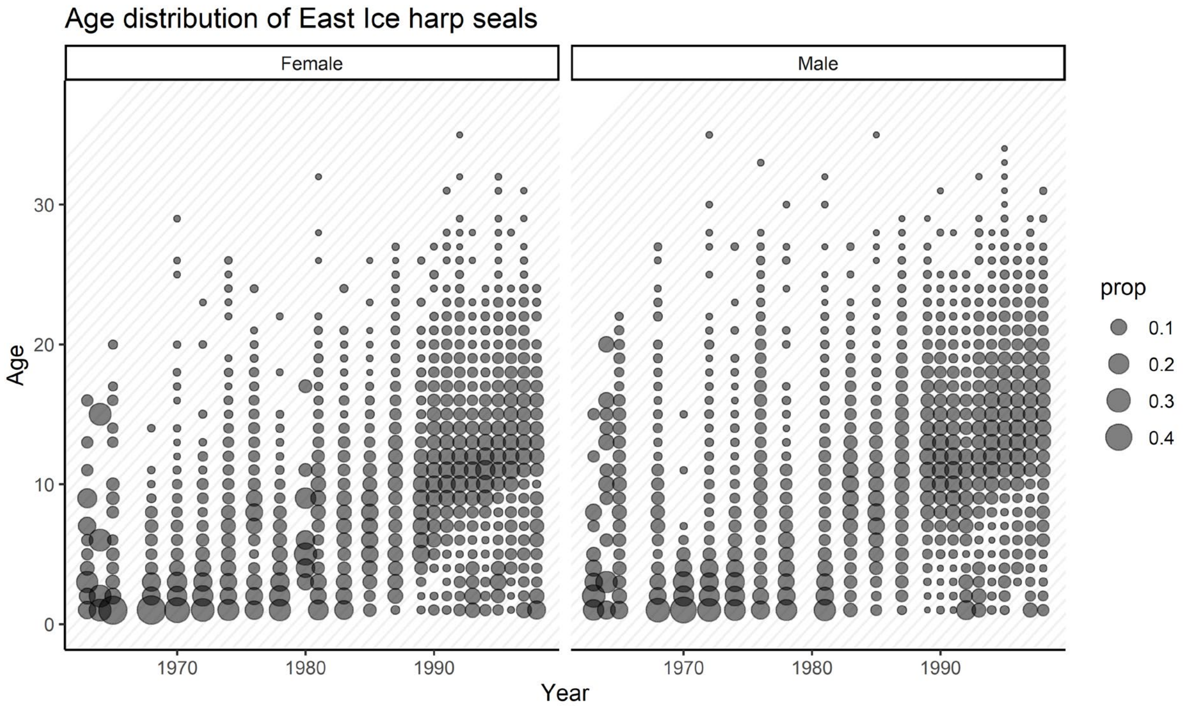

Figure 19. Bubble plot of the year-specific relative proportion of seals in each age class for female and male East Ice harp seals. Note that cohorts can be traced along the diagonal by following the pale grey lines. Cohorts with weak recruitment can be clearly seen starting in the mid-1980s.

the benchmark concluded that there is sufficient sign of signal in the data consistent with population structure (exponential decay with age, sign of recruitment failure tracking between years) to consider the possibility for using this data for model tuning, especially for the East Ice harp seals. Since the benchmark strongly encouraged such work, we performed a preliminary analysis of these data (i.e., a simple multinomial model for the catch-at-age data) to assess the relevance of including these data in the model. This analysis indicates a strong decline in recruitment that started in the 1970s and escalated from the 1980s onward. This preliminary analysis suggests that recruitment has not recovered subsequently, remaining at a fairly low level (Figure 20). Interestingly, this recruitment decline occurs more or less simultaneously with the capelin dynamics switching from more stable low-amplitude dynamics with a high mean prior to the early 1980s, to high-amplitude oscillating dynamics with a low mean. This change in capelin dynamics in turn coincides with the onset of substantial commercial harvest of capelin following the herring collapse. Hence, the inclusion of these data as tuning data in the model is therefore very encouraging and in the process of being completed.

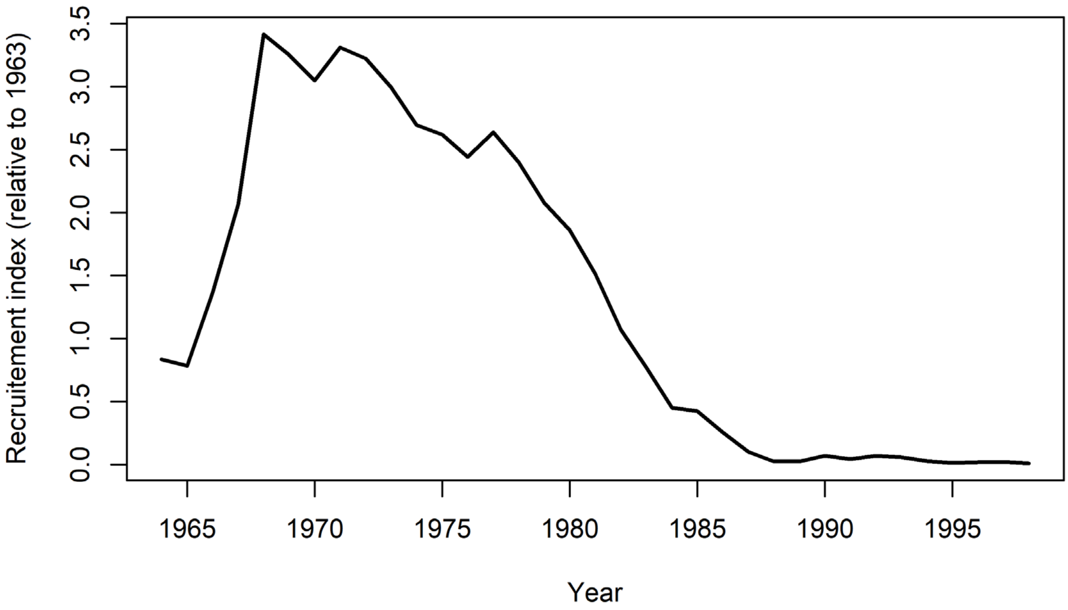

Figure 20. Estimated pup recruitment relative to 1963, based on a preliminary multinomial model of the catch-at-age data for east Ice harp seals.

Box 1. Notation

- $\boldsymbol{A}$: Maximum age class, representing seals of age A and older. Here, we set $A = 20$.
- $\boldsymbol{N_{a,y}}$: Number of seals in age class a in year y. Estimates of the reproduction, $N_{0,y}$, based on observations available at roughly 5-year intervals for the past 3-4 decades.
- $\boldsymbol{N_{1+,y}} = \sum_{a=1}^{A} N_{a,y}$: Number of seals of age 1 or older in year y.
- $\boldsymbol{C_{a,y}}$: Catch, the number of seals of age class a caught in year y. Observed separately for age 0 ($C_{0,y}$) and age 1+ ($C_{1+,y}$).
- $\boldsymbol{S_{a,y}} = \exp(-M_{a,y})$: Yearly survival probability in year y for age class $a, a = 0, \ldots, A$, where $M_{a,y}$ is the corresponding mortality rate and $1 - S_{a,y}$ is the corresponding yearly mortality probability.
- $\boldsymbol{p_{a,y}}$: Proportion of sexually mature seals of age a in year y. Estimates based on observations that are available for a few years.
- $\boldsymbol{F_y}$: Fecundity, the proportion of sexually mature females that actually are pregnant in year y. Estimates based on observations are available for the same years as maturity, $p_{a,y}$.
- $\boldsymbol{A_y}$: Abortion rate, the proportion of pregnancies that resulted in an abortion.
- $\boldsymbol{x_y^{res}}$: An observed resource index (e.g. capelin biomass), i.e. an explanatory variable with assumed positive or non-negative impact on a particular vital rate. This is scaled and centred: If z_y's are the raw data, then $z'_y = z_y/\max_i(z_i)$ and $x^{res} = z'_y - \text{mean}_i(z'_y)$.
- $\boldsymbol{x_y^{comp}}$: An observed competitor index (e.g. adult cod biomass), i.e. an explanatory variable with assumed negative or non-positive impact on a particular vital rate. Scaled and centred.
- $\boldsymbol{N_{1+,y_0}}$: 1+ stock size in an initial year y_0, a parameter to be estimated.

Box 2. General model structure

In the general population model

$$\begin{aligned} N_{a,y} &= \left(N_{a-1,y-1} - C_{a-1,y-1}\right)S_{a-1,y-1}, \qquad a = 2, \dots, A-1, \\ N_{A,y} &= [(N_{A-1,y-1} - C_{A-1,y-1}) + (N_{A,y-1} - C_{A,y-1})]S_{A,y-1}, \end{aligned}$$

where the observed catch of age 1 and older in year y ($C_{a,y}$) is assumed to be distributed between age classes proportional to their abundance, i.e.

$$C_{a,y} = C_{1+,y} N_{a,y} / N_{1+,}.$$

It is further assumed that half of the population are females, and reproduction, i.e., the number of seal pups born in year y, is given by:

$$N_{0,y} = (1 - A_y)F_y \sum_{a=1}^{A} p_{a,y}\, N_{a,y}/2.$$

In the initial year y_0, it is assumed that the population has stable age distribution, which means that the N_{1+,y_0}seals are distributed among age classes according to the mortality in year y_0, as described in Øygård and Skaug (2015).

The maturity-by-age, $p_{a,y}$, is assumed to to be known and i) equal to the estimates in the years with observations, ii) equal to the first estimate in the years before the first observation, iii) linearly interpolated between the years with observations, and iv) equal to the last estimate in the years after the last observation.

The fecundity, F_y, is either interpolated and extrapolated in the same way as the maturity-by-age and then assumed to be known, modelled as a stochastic process or as a function of resource and competitor indices.

6 References

Folkow, L. P., Nordøy, E. S., & Blix, A. S. 2004. Distribution and diving behaviour of harp seals (Pagophilus groenlandicus) from the Greenland Sea stock. Polar Biology, 27: 281–298. https://doi.org/10.1007/s00300-004-0591-7

Frie, A. K., Potelov, V. A., Kingsley, M. C. S., & Haug, T. 2003. Trends in age-at-maturity and growth parameters of female Northeast Atlantic harp seals, *Pagophilus groenlandicus* (Erxleben, 1777). ICES Journal of Marine Science, 60: 1018–1032. https://doi.org/10.1016/S1054-3139(03)00123-1

ICES. 2005. Report of the ICES/NAFO Working Group on Harp and Hooded Seals (WGHARP), 30 August–3 September 2005, St Johns, Newfoundland, Canada. ICES CM 2006/ACFM:06. 54 pp. http://ices.dk/sites/pub/CM%20Doccuments/2006/ACFM/ACFM0606.pdf

ICES. 2016. Report of the Joint ICES/NAFO Working Group on Harp and Hooded Seals (WGHARP), 26–30 Sept. 2016, ICES Headquarters, Copenhagen, Denmark. ICES CM 2016 / ACOM:21. 85 pp.

ICES. 2019. ICES/NAFO/NAMMCO Working Group on Harp and Hooded Seals (WGHARP). ICES Scientific Reports. 1:72. 193 pp. http://doi.org/10.17895/ices.pub.5617

Nordøy, E. S., Folkow, L. P., Potelov, V., Prischemikhin, V., & Blix, A. S. 2008. Seasonal distribution and dive behaviour of harp seals (Pagophilus groenlandicus) of the White Sea–Barents Sea stock. Polar Biology, 31: 1119–1135. https://doi.org/10.1007/s00300-008-0453-9

Sergeant, D. E. 1991. Harp seals, man and ice. Canadian Special Publication of Fisheries and Aquatic Sciences, 114. Department of Fisheries and Oceans, Ottawa, Canada. 153 pp.

Stenson, G. B., Haug, T., & Hammill, M. O. 2020. Harp Seals: Monitors of Change in Differing Ecosystems. Frontiers in Marine Science, 7. https://doi.org/10.3389/fmars.2020.569258

Svetochev, V. N., Kavtsevich, N. N., & Svetocheva, O. N. 2016. Satellite tagging and seasonal distribution of harp seal (juveniles) of the White sea–Barents sea stock. Czech Polar Reports, 6: 31–42. https://doi.org/10.5817/CPR2016-1-4

Wade, P. R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science*, 14: 1–37. https://doi.org/10.1111/j.1748-7692.1998.tb00688.x

Øigård, T. A. and Skaug, H. J. 2014. Fitting state–space models to seal populations with scarce data. ICES Journal of Marine Science, 72: 1462–1469. https://doi.org/10.1093/icesjms/fsu195

Annex 1: List of participants

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Annex 2: Resolutions

- **BWKSEALS2023 - 22**

Approved on the Resolutions Forum in March 2021

2022/2/FRSG31 **A Benchmark Workshop for harp and hooded seals (BWKSEALS2023),** chaired by External Chair Alejandro Buren, Argentina, and ICES Chair Daniel Howell, Norway, and attended by two invited external experts Phil Hammond, UK, and Hans Skaug, Norway, will be established and will meet:

- by correspondence on 8 December 2021, for a Modelling planning workshop
- online throughout 2022 as needed
- in a physical meeting held at ICES Headquarters, Copenhagen, on 22-26 May 2023 for a Benchmark Workshop

BWKSEALS2023 will:

a) Evaluate the appropriateness of data and methods to determine stock status and investigate methods for providing harvest advice for the stocks listed in the text table below. The evaluation shall include consideration of:

   i. Stock identity and migration issues;

   ii. Life-history data;

   iii. Hunt dependent and hunt independent data;

   iv. Further inclusion of environmental drivers, multi-species information, and ecosystem impacts for stock dynamics in the assessments and outlook;

b) For each stock, agree and document the preferred methods for evaluating stock status and harvest advice and produce stock annexes as appropriate. Knowledge about environmental drivers, including multispecies interactions, and ecosystem impacts should be integrated in the methodology to the extent possible;

c) Re-examine and update (if necessary) the methods for setting biological limits for seal harvest as defined by ICES in 2005[3];

d) Review and summarise the evidence currently available to support the implementation of harvest control rules, identifying important knowledge gaps, especially in connection with potential changes to assessment model general formulation and/or specifics.

e) Develop recommendations for future improvements to the assessment methodology and data collection.

[3] Request from the Norwegian Government regarding Greenland Sea harp and hooded seals and White Sea/Barents Sea harp seals. *In* Report of the ICES Advisory Committee on Fishery Management, Advisory Committee on the Marine Environment and Advisory Committee on Ecosystems, 2005. ICES Advice 2005, Volume 3, Section 1.4.1.2. http://www.ices.dk/sites/pub/Publication%20Reports/ICES%20Advice/2005/ICES%20Advice%202005%20Volume%203.pdf

- and, will meet by correspondence in June 2023 to:

f) Evaluate whether the current harvest control rules (see section 6.3. of ICES 2005)[4] are precautionary in light of potential acceptance of alternative model formulations and reference points from the benchmark.

Working documents to be reviewed during the Benchmark meeting at least 7 days prior to the meeting.

Stocks	Stock leader
Harp seals (*Pagophilus groenlandicus*) in subarea 1 (Barents and White sea stock)	Martin Biuw
Harp seals (*Pagophilus groenlandicus*) in subareas 1, 2 and 14 and Division 5.a (Greenland Sea stock)	Martin Biuw
Hooded seals (*Cystophora cristata*) in subareas 2, 5 and 14 (Greenland Sea stock)	Martin Biuw

The Benchmark Workshop will report by 31 August 2023 for the attention of the FRSG, ACOM and SCICOM.

[4] ICES. 2005. Report of the ICES/NAFO Working Group on Harp and Hooded Seals (WGHARP), 30 August–3 September 2005, St Johns, Newfoundland, Canada. ICES CM 2006/ACFM:06. 54 pp. http://ices.dk/sites/pub/CM%20Doccuments/2006/ACFM/ACFM0606.pdf

Annex 3: External Chair and Reviewer Reports

External chair report from BWKSEALS

I acted as the external chair for the BWKSEALS benchmark for harp and hooded seals. We evaluated the methods used for the assessment of three stocks: 1. Barents and White Sea Harp seals, 2. Greenland Sea harp seals, 3. Greenland Sea hooded seals.

I would like to commend the workshop participants for their efforts during the benchmark process. The assessment team was asked to provide many additional analyses during the meeting. Their response to the requests was helpful in furthering our understanding of the assessment models and were successful in bringing useful information to the management process.

The background for this meeting were the 2019 WGHARP meeting (ICES, 2019), and the 2020 NAMMCO-ICES workshop on seal modelling (Smout et al., 2022). Currently, assessments of the population status and hunting potential for harp and hooded seals in the Greenland Sea and harp seals in the Barents Sea/White Sea are carried out using a deterministic age-structured population dynamics (Skaug et al., 2007). The Barents/Sea harp seal population model in particular showed a poor fit to the pup production data and produced overly optimistic forecasts. Given the poor fit of the model and the lack of pup production estimates (the last estimate was from 2013), WGHARP suggested to take a precautionary approach to recommending catch options and did so based on the concept of Potential Biological Removals (PBR) (ICES, 2019). WGHARP recognized that the inability of the population model to account for rapid decline in pup production in the mid-2000s was not surprising, given the deterministic nature of the model, and the fact that only three parameters are estimated. WGHARP therefore suggested to incorporate potential ecosystem drivers in an attempt to improve model fit.

The current assessment model is fit to a time series of pup production data. It is informed by catch data, and maturity and fecundity rates – these are informed by sparse data and linearly interpolated between the years with observations. This model has three parameters: i) mortality rate for pups, ii) mortality rate for age 1 and older, iii) 1+ stock size in initial year. The assessment team presented a suite of different models that represent different hypotheses on how environmental variables may affect vital rates: 1) the natural pup mortality rate, 2) the natural adult mortality rate, 3) the fecundity rate and 4) an abortion rate to modify the fecundity rate, i.e., a realized fecundity rate. The suite of models was created by making these four vital rates either: 1) constant, 2) a function of capelin (resource) and cod (competitor), 3) an autoregressive term, or 4) a combination of capelin, cod, and an autoregressive term.

The model results were dependent on the initial parameter values. Therefore, the models were run multiple times, starting each time from a different position in parameter space. The benchmark suggested that this procedure be followed moving forward in the assessment. Additionally, the model results were influenced by the choice of prior distribution of the model parameters, particularly the 1+ stock size in initial year. The narrow range provided for the prior distribution of this parameter affected the model trajectory. Several combinations of priors and starting points (i.e. first year considered in the model) of the model runs were explored during the meeting. The final model runs were not affected by the choice of prior distributions. However, the meeting participants agreed that this an element that should be considered in modelling efforts moving forward.

Catch-at-age data was collated during the benchmark meeting. The participants of the meeting carried out a preliminary analysis of these data. There are patterns in the data of cohort tracking and coherent reductions in numbers at age. These data therefore have the potential to inform mortality of individuals 1 year and older. The meeting suggested that the assessment team should try to incorporate catch-at-age data into the modelling efforts, considering their potential limitations and biases.

The benchmark meeting reached consensus advice for the three stocks:

Hooded seal

"The benchmark notes the current low level of the hooded seal stock, and that no commercial hunting has been conducted since 2007. No commercial hunting should be considered unless a clear upward trend in the pup abundance estimate can be observed, taking account of the uncertainty in this data. In the event of such an improving trend being observed, a new assessment would be needed prior to the resumption of hunting in order to give information on stock status and potential harvest levels."

I support this conclusion.

East ice harp seals

"There has been no pup production survey for the East ice harp seals since 2013. In the absence of more recent survey data, the benchmark concludes that viable assessment of current stock status or catch advice cannot be produced. Furthermore, the most recent available pup production estimates indicated a poor status. There have been limited catches since 2019, and the benchmark recommends that a pup survey and subsequent assessment is required prior to the resumption of any substantial commercial hunt. The model version with capelin abundance informing model dynamics does perform well in the time period with the data."

I support this conclusion.

West ice harp seals

"For the west ice stock, the benchmark proposes a revised assessment model using cod and capelin alongside an AR1 process to drive the model dynamics. The historical modelled population level is uncertain, but the overall trend is relatively flat, and has not been adversely affected by recent catches. The group considers that the change in model has not impacted on the precautionary nature of the agreed HCR described in ICES (2006), and therefore recommends that this can continue to be used until a new HCR is evaluated."

I support this conclusion. It is worth noting here that there was discussion around the meaning of each of the terms included in the model, particularly cod and capelin. The estimates of capelin biomass used as input to the model were provided by Icelandic colleagues at the Marine and Freshwater Research Institute. This estimate is produced using data collected during winter surveys (January and February), and it represents the biomass of the mature component of the stock after predation by three important predators (including cod) has occurred. The relevant estimate of capelin biomass for harp seals would be the biomass before predation occurs during January and February. We discussed that the cod term in the model may represent capelin that this predator consumes. The assessment team was therefore suggested to try to collaborate with Icelandic colleagues to reconstruct capelin biomass before predation occurs, and use that estimate as input to the model. I support this research recommendation.

Buenos Aires, July 6, 2023.

Alejandro Buren

References

ICES. 2019. ICES/NAFO/NAMMCO Working Group on Harp and Hooded Seals (WGHARP). ICES Scientific Reports, 1:72. http://doi.org/10.17895/ices.pub.5617.

Skaug, H. J., Frimannslund, L., and Øien, N. I. 2007. Historical population assessment of Barents Sea harp seals (Pagophilus groenlandicus). ICES Journal of Marine Science, 64: 1356–1365.

Smout, S., Murray, K., Aarts, G., Biuw, M., Brasseur, S., Buren, A., Empacher, F., et al. 2022. Report of the NAMMCO-ICES Workshop on Seal Modelling (WKSEALS 2020). NAMMCO Scientific Publications, 12. https://septentrio.uit.no/index.php/NAMMCOSP/article/view/5794.

Reviewers' Report for WKBSEALS

Model

An assessment model, common to the three populations, was presented to the Benchmark meeting. This model was an extension of the model previously used by WGHARP, with increased flexibility based on recommendations made by the NAMMCO-ICES Workshop held in 2020 (Smout et al., 2020). The new model allows explanatory variables to affect recruitment and mortality parameters. In addition, unexplained variability can be modelled as an autoregressive process. The model also produced standard deviations for all quantities of interest and could be fitted to data in a few seconds. The latter meant that a large number of different model configurations could be tested during the meeting.

However, the data that have thus far been used by WGHARP to tune the model are limited and consist only of estimates of fecundity and pup production. This amount of data is at the lower end (for all three populations) for fitting such a flexible model. The approach taken by WGHARP has been to put priors on the parameters, and thus it is important to check the sensitivity of model output to these priors.

During the benchmark meeting it was discussed whether existing catch-at-age data could be used in the tuning of the model. Such data may be subject to selectivity biases but if they are sufficiently representative of the age distribution in the population, they should be very informative, improving estimation of model parameters, and hence reducing the need for inclusion of priors. Improved model outputs would then provide a better basis for providing advice.

During the benchmark meeting, a large number of models runs were made, with different configurations and, for the better performing models, "Jitter analyses" based on different starting points for the optimizer to check for consistency of results. Both the point estimates and the associated uncertainty were useful for comparing different model runs. The practice of exploring the fit of many model runs is useful when assessing these three populations because there are insufficient data to support fitting models with all parameters.

Hooded seal

We support the conclusions of the benchmark, that no commercial hunting should be considered unless a clear upward trend in the pup abundance estimate can be observed, taking account of the uncertainty in these data.

East ice harp seals

We support the conclusions made by the benchmark that 1) in the absence of more recent survey data, viable assessment of current stock status or catch advice cannot be produced 2) the model with capelin abundance informing model dynamics does perform well in the time period with the data.

West ice harp seals

We support the conclusions made by the benchmark, of using cod and capelin alongside an AR1 process to drive the model dynamics, and that these changes have not impacted on the precautionary nature of the agreed harvest control rules described in ICES (2006).

References

ICES. 2006. Report of the Joint Ices/Nafo Working Group On Harp And Hooded Seals (WGHARP) St. John's, Newfoundland, Canada 30 August – 3 September, 2005. ICES CM 2006/ACFM, 46 pp.

Smout, S., Kimberly Murray, K., Aarts, G., Biuw, M., Brasseur, S., Buren, A., Empacher, F., Frie, A. K., Grecian, J., Hammill, M., Mikkelsen, B., Mosnier, A., Rosing-Asvid, A., Russell, D., Skaug, H., Stenson, G., Thomas, L., ver Hoef, J., Witting, L., Zabavnikov, V., Øigård, T. A., Fernandez, R. & Wickson, F. 2021. Report of the NAMMCO-ICES Workshop on Seal Modelling (WKSEALS 2020). NAMMCO Scientific Publications 12. https://doi.org/10.7557/3.5794

St. Andrews and Bergen, June 23, 2023,

Phil Hammond

Hans J. Skaug

Annex 4: Working Documents

A population model for seals, with focus on harp seals in the east ice
Working paper to BWKSEALS2023, Copenhagen, May 2023

Magne Aldrin, Norwegian Computing Center Martin Biuw, Institute of Marine Research, Norway
John-André Henden, Institute of Marine Research, Norway

May 20, 2023

1 Introduction

This paper gives an overview of a population model for seals that here is used on three different stocks: harp seals in the Barents Sea / White Sea (East Ice), harp seals in the Greenland Sea (West Ice) and hooded seals in the West Ice. The model is age-structured, but data are only given for two age groups, age 0 (pups) and age 1 and older (1+). Yearly catch data are available separately for these two groups, and are regarded as error free. Estimates of pup production (age 0) are given at roughly 5-year intervals for the past 3-4 decades, with estimation uncertainty given as coefficient of variation (cv). Estimates of proportion mature females by age as well as fecundity rate for sexually mature females are given for certain years at less regular intervals, also with cv's.

In addition, we have yearly data for other species that may constitute a prey resource (positive impact, e.g. capelin) or a competitor (negative impact, e.g. cod), which can influence various vital rates in the model (e.g. fecundity, abortion rate as well as pup or adult mortality).

We first present the general model with the current official model as a special case. Then we fit various model configurations to the three seal stocks, with focus on the harp seals in the East ice.

2 Population model

2.1 Notation

We first define some notation:

- A: Maximum age, representing seals of age A and older. Here, we set $A = 20$.
- $N_{a,y}$: Number of seals of age a in year y. Estimates of the reproduction, $N_{0,y}$, based on observations available at roughly 5-year intervals for the past 3-4 decades.
- $N_{1+,y} = \sum_{a=1}^{A} N_{a,y}$: Number of seals of age 1 or older in year y.
- $C_{a,y}$: Catch, the number of seals of age a caught in year y. Observed separately for age 0 ($C_{0,y}$) and age 1+ ($C_{1+,y}$).
- $S_{a,y} = \exp(-M_{a,y})$: Yearly survival probability in year y for age a, $a = 0, \ldots, A$, where $M_{a,y}$ is the corresponding mortality rate and $1 - S_{a,y}$ is the corresponding yearly mortality probability.
- $p_{a,y}$: Proportion of sexually mature of age a in year y. Estimates based on observations are available for a few years.
- F_y: Proportion of sexually mature females that actually reproduce in year y. Estimates based on observations are available for the same years as maturity, $p_{a,y}$.
- x_y^{res}: An observed resource index (e.g. capelin biomass), i.e. an explanatory variable with assumed positive or non-negative impact on a particular vital rate. This is scaled and centred: If z_y's are the raw data, then $z_y^l = z_y/\max_i(z_i)$ and $x_y^{res} = z_y^l - \text{mean}_i(z_y^l)$.
- x_y^{comp}: An observed competitor index (e.g. adult cod biomass), i.e. an explanatory variable with assumed negative or non-positive impact on a particular vital rate. Scaled and centred.
- $K = N_{1+,y_0}$: 1+ stock size in initial year y_0=1945, a parameter to be estimated.

2.2 General model structure

The general population model is

$$N_{a,y} = (N_{a-1,y-1} - C_{a-1,y-1})S_{a-1,y-1}, 1 = 2, \ldots, A-1, \quad (1)$$
$$N_{A,y} = [(N_{A-1,y-1} - C_{A-1,y-1}) + (N_{A,y-1} - C_{A,y-1})]S_{A,y-1}, \quad (2)$$

where the observed catch of age 1 and older in year y is assumed to be distributed between ages proportional to their abundance, i.e.

$$C_{a,y} = C_{1+,y}N_{a,y}/N_{1+,}. \quad (3)$$

Reproduction, i.e. the number of seal pups born in year y is given by

$$N_{0,y} = F_y \sum_{a=1}^{A} p_{a,y}N_{a,y}/2. \quad (4)$$

Stable age distribution is assumed in the initial year y_0, which means that the K 1+ seals are distributed among ages according to the mortality in year y_0, as described in Øygård and Skaug (2015).

The maturity-by-age, $p_{a,y}$, is assumed to to be known and i) equal to the estimates in the years with observations, ii) equal to the first estimate in the years before the first observation, iii) linearly interpolated between the years with observations, and iv) equal to the last estimate in the years after the last observation.

The fecundity, F_y, is either interpolated and extrapolated in the same way as the maturity-by-age and then assumed to be known, or modelled as a stochastic process or a function of resource and competitor indices.

2.3 Current official model

The official model currently used for assessment purposes is a special version of the general model presented above, where mortalities are independent of year and constant for seals of age 0 and of age 1+ separately, and where the fecundity is assumed to be known and interpolated as described above. This model has three parameters:

- $M_{0,normal}$: The mortality rate for pups, $M_{0,y} = M_{0,normal}$ for all years.
- $M_{1,normal}$: The mortality rate for age 1 and older, $M_{a,y} = M_{1,normal}$ for all years and for ages greater or equal to 1.
- K: 1+ stock size in initial year y_0=1945.

2.4 Model variants to be explored

We will consider the following submodels for the natural mortality rate $M_{0,y}$ for pups:

M01: $\log(M_{0,y}) = \log(M_{0,normal})$,
M02: $\log(M_{0,y}) = \log(M_{0,normal}) - \beta_{res}x^{res}_y + \beta_{comp}x^{comp}_y$,
M03: $\log(M_{0,y}) = \log(M_{0,normal}) + \omega_y$;
$\omega_y = \varphi\omega_{y-1} + \varepsilon_y;\ \varepsilon_y \sim N(0, \sigma^2)$,

The natural mortality for pups is assumed either constant (model M01), depends on a resource and a competitor index (model M02) or as a stochastic AR(1) process (model M03). The regression coefficients β_{res} and β_{comp} are restricted to be non-negative. Since both x^{res}_y, x^{comp}_y and ω_y varies around 0, $M_{0,y}$ varies around $M_{0,normal}$, and $M_{0,normal}$ can therefore be interpreted as the mortality in a normal situation.

For age 1 and older, we consider the same three submodels as for pups, and in addition we consider two models with age-dependence:

M11: $\log(M_{a,y}) = \log(M_{1,normal})$,
M12: $\log(M_{a,y}) = \log(M_{1,normal}) - \beta_{res}x^{res}_y + \beta_{comp}x^{comp}_y$,
M13: $\log(M_{a,y}) = \log(M_{1,normal}) + \omega_y$;
$\omega_y = \varphi\omega_{y-1} + \varepsilon_y;\ \varepsilon_y \sim N(0, \sigma^2)$,
M14: $\log(M_{a,y}) = \log(M_{1,normal}) - \beta_{res}x^{res}_y + \beta_{comp}x^{comp}_y,\ a = 1, \ldots A^{old} - 1$,
$\log(M_{a,y}) = \log(M_{A^{old},normal}) - \beta_{res}x^{res}_y + \beta_{comp}x^{comp}_y,\ a = A^{old}, \ldots A$,
M15: $\log(M_{1,y}) = \log(M_{1,normal}) - \beta_{res}x^{res}_y + \beta_{comp}x^{comp}_y$,
$\log(M_{a,y}) = \log(M_{A^{old},normal}) - \beta_{res}x^{res}_y + \beta_{comp}x^{comp}_y,\ a = A^{old}, \ldots A$,

and $S_{a,y}$ linearly interpolated between $a = 1$ and $a = A^{old}$.

In submodel M14, the natural mortality for age 1 and older is similar to submodel M12, but varies around one level for ages up to $A^{old} - 1$ and around another level for older ages. Submodel M15 is similar to submodel M14, but the natural mortality changes linearly from age 1 to age A^{old}. In the models fitted here, $A^{old} = 7$.

For fecundity, we consider the following four submodels:

F0: $\text{logit}(F_{a,y})$ = assumed known and interpolated between observations, F1: $\text{logit}(F_{a,y}) = \text{logit}(F_{normal})$,
F2: $\text{logit}(F_{a,y}) = \text{logit}(F_{normal}) + \beta_{res}x^{res}_y - \beta_{comp}x^{comp}_y$,
F3: $\text{logit}(F_{a,y}) = \text{logit}(F_{normal}) + \omega_y;\ \omega_y = \varphi\omega_{y-1} + \varepsilon_y$.

The current official model is the combination M01, M11 and F0. The combination M01, M11 and F3 is the model presented by Øygård and Skaug (2015).

2.5 Estimation

The model variants are estimated by maximum likelihood with a Bayesian flavour, using the TMB software. The likelihood components include the contribution from pup production estimates, the contribution from fecundity estimates except for submodel F0 where fecundity is assumed to be known, and priors for the parameters. All likelihood components are based on the normal distribution. Priors are given in Table 1.

Table 1: Means and standard deviations in the normal priors for the model parameters.

Parameter	0 Mean	Standard deviation
K	10^6	$0.5 \cdot 10^6$
$M_{0,normal}$	0.27	0.2
$M_{1,normal}$	0.09	0.1
$M_{A^{old},normal}$	0.09	0.1
β_{rec}	0	2
β_{comp}	0	2
φ	0.5	0.3
σ	0	0.5

2.6 AIC

For each variant of the model we will compute the Akaike Information Criterion (AIC) as

AIC = -2 log likelihood + 2 number of fixed parameters,

where the log likelihood in AIC here only includes the pup production data, whereas the fecundity data and prior distributions are ignored. AIC for models with latent processes may not be directly compared to AIC without such processes.

3 Harp seals in the East ice

3.1 Fixed data

Time plots of catch, resource and competitor indices and proportion of maturity are given in Figure 1.

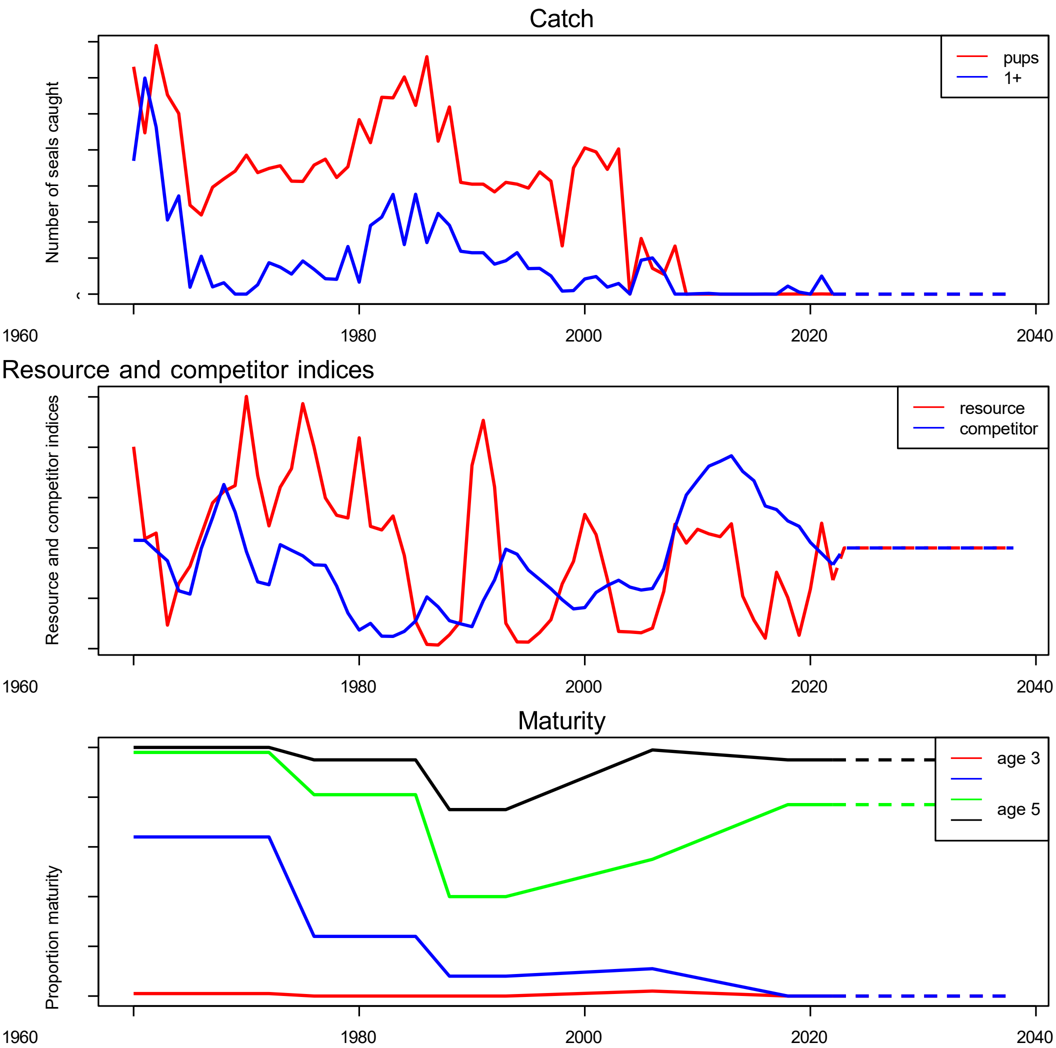

Figure 1: Fixed data for harp seals in the East ice. Upper panel: catch. Middle panel: Resource (capelin) and competitor (cod) indices. Lower panel: Proportion of maturity for selected ages.

3.2 M0 and M+ models

Consider first the models where fecundity is assumed to be known (submodel F0). Table 1 shows parameter estimates and AIC values for selected models. The three models with constant M0 (submodel M01) and where M+ depends on the indices for the resource capelin and the competitor cod (submodels M12, M14 and M15) have similar fit to the pup production data (similar AIC). Note that cod have no effect in any of these models. The model with constant M0 (submodel M01) and AR(1) process for M+ (submodel M13) has the lowest AIC of all models, i.e. best fit to the pup production data, due to the flexibility by using a stochastic model with latent variables. Figs. 2-8 show the corresponding model fits.

Table 1: Estimated models for M0 and M+

M0 model	1	2	1	1	1	1
M+ model	1	1	2	3	4	5
F model	0	0	0	0	0	0
Parameter	Est. (se)	Est. (se)	Est. (se)	Est. (se)	Est. (se)	Est. (se)
K in mill.	2.7(0.3)	2.2(0.3)	1.7(0.3)	1.3(0.4)	1.8(0.3)	1.8(0.3)
$M_{0,normal}$	0.20(0.20)	0.65(0.15)	0.16(0.19)	0.27(0.20)	0.17(0.18)	0.14(0.18)
φ^{M_0}	NA	NA	NA	NA	NA	NA
σ^{M_0}	NA	NA	NA	NA	NA	NA
cap β^{M_0} cod	NA	5.05(1.15)	NA	NA	NA	NA
β^{M_0}	NA	0(0)	NA	NA	NA	NA
$M_{1,normal}$	0.15(0.02)	0.12(0.01)	0.11(0.02)	0.10(0.03)	0.09(0.02)	0.07(0.04)
$M_{A^{old},normal}$	NA	0(NA)	NA	0(NA)	0.15(0.05)	0.15(0.04)
φ^{M+}	NA	NA	NA	0.37(0.33)	NA	NA
cap σ^{M+} cod	NA	NA	NA	0.71(0.28)	NA	NA
β^{M+}	NA	NA	3.63(0.66)	NA	NA	NA
β^{M+}	NA	NA	0(0)	NA	NA	NA
F_0	NA	NA	NA	NA	NA	NA
cap φ^{F} cod	NA	NA	NA	NA	NA	NA
σ^{F}	NA	NA	NA	NA	NA	NA
β^{F}	NA	NA	NA	NA	NA	NA
β^{F}	NA	NA	NA	NA	NA	NA
No fixed par.	3	5	5	5	6	6
Latent process	No	No	No	Yes	No	No
AIC (pup prod.)	344.2	321.7	293.2	283.9	293.9	293.2

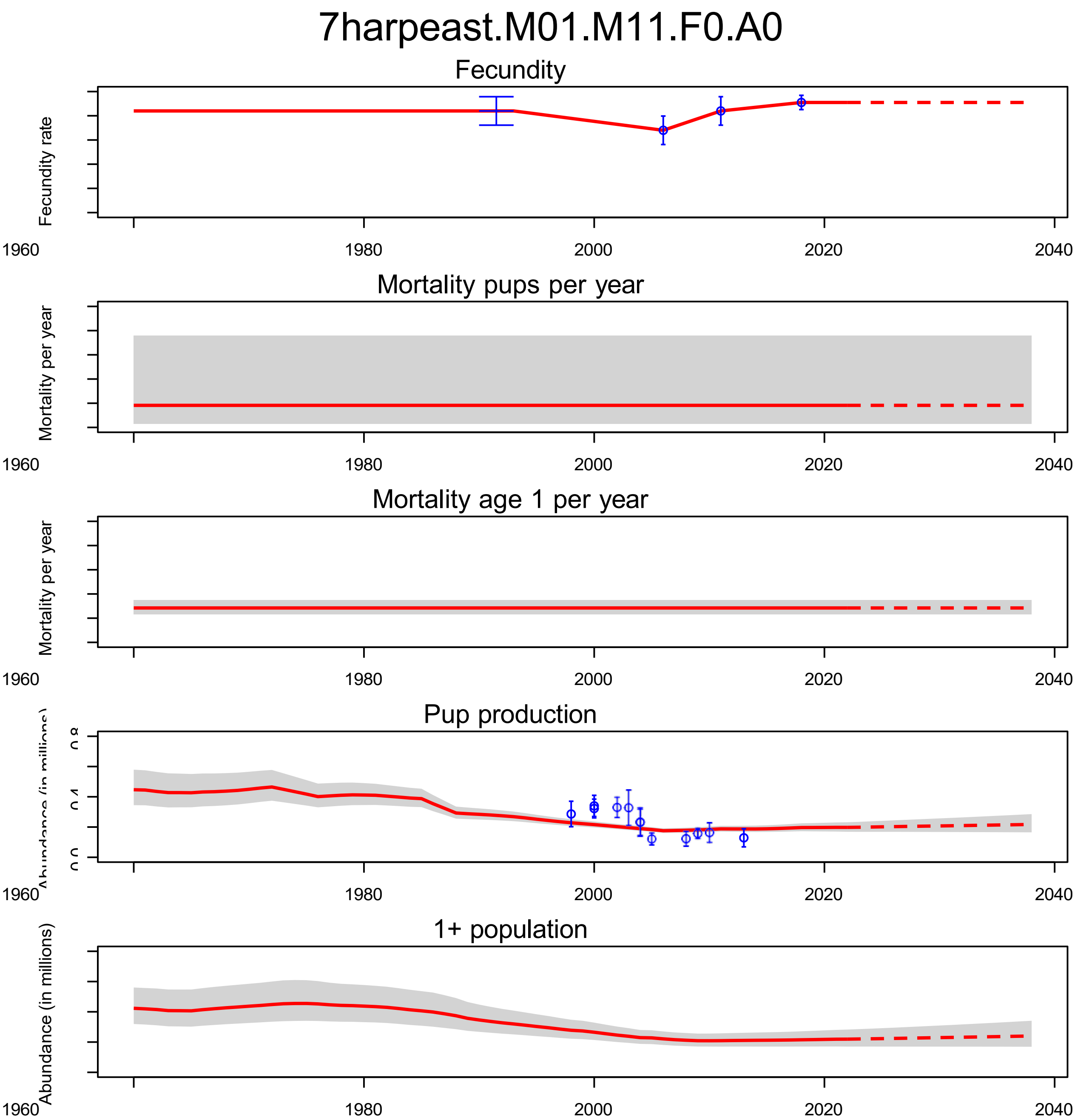

Figure 2: Model fit for harp seals in the East ice, with constant M0 (submodel M01) and M+ (submodel M11) and with fixed fecundity.

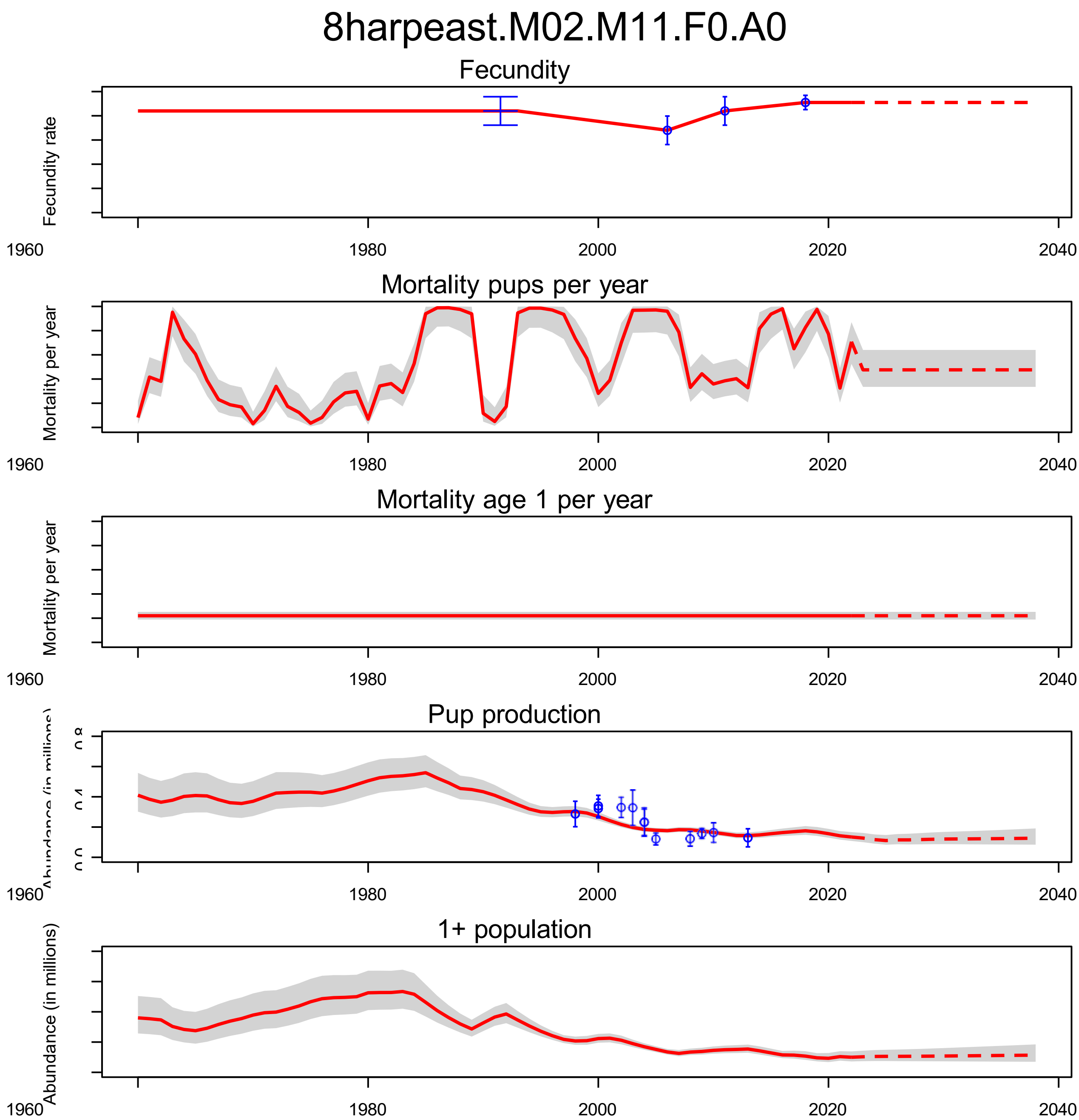

Figure 3: Model fit for harp seals in the East ice, with M0 dependent of indices for resource (capelin) and competitor (cod) (submodel M02), with constant M+ (submodel M11) and with fixed fecundity.

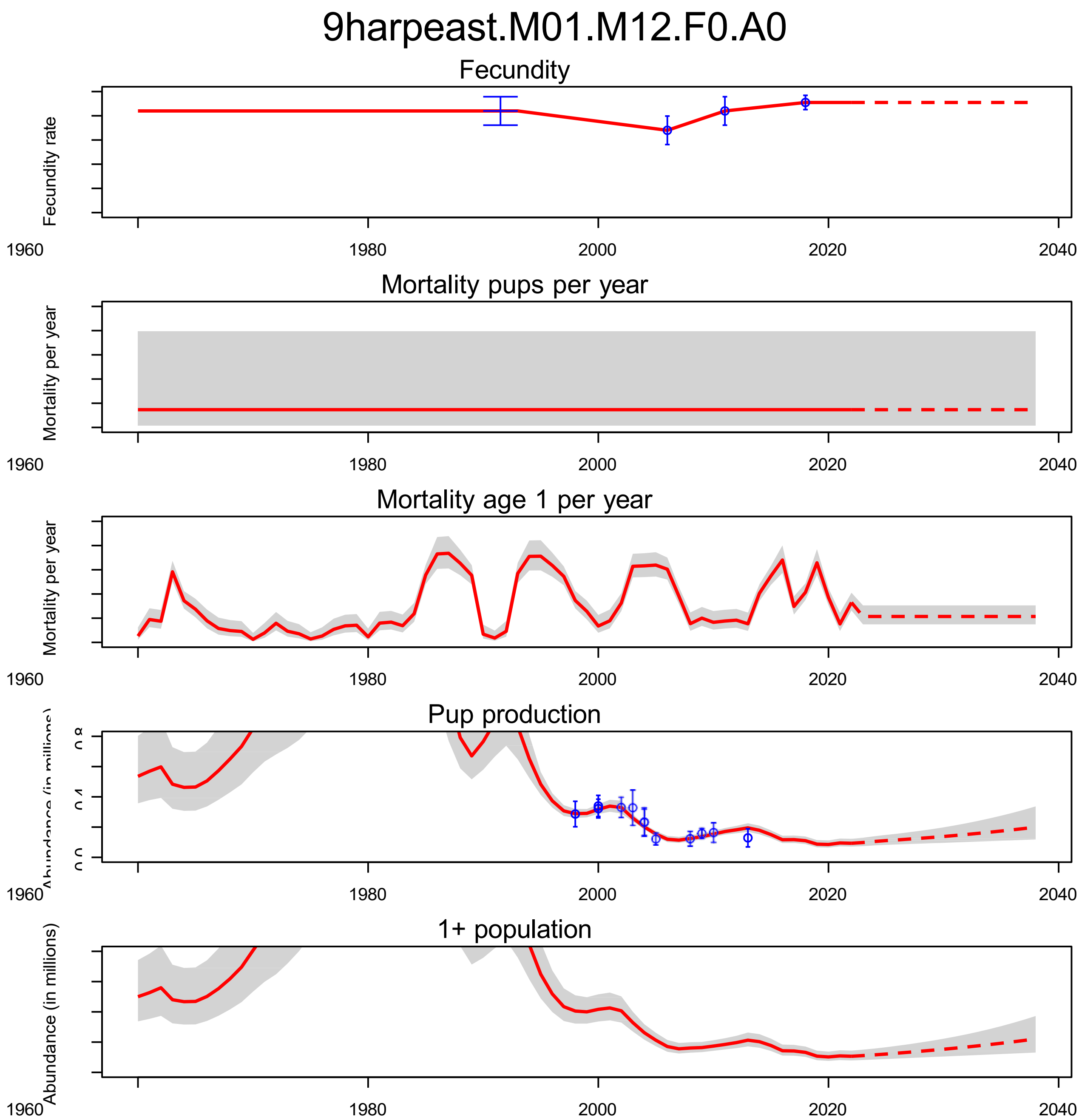

Figure 4: Model fit for harp seals in the East ice, with constant M0, with M+ dependent of indices for resource (capelin) and competitor (cod) equal for all ages (submodel M12) and with fixed fecundity.

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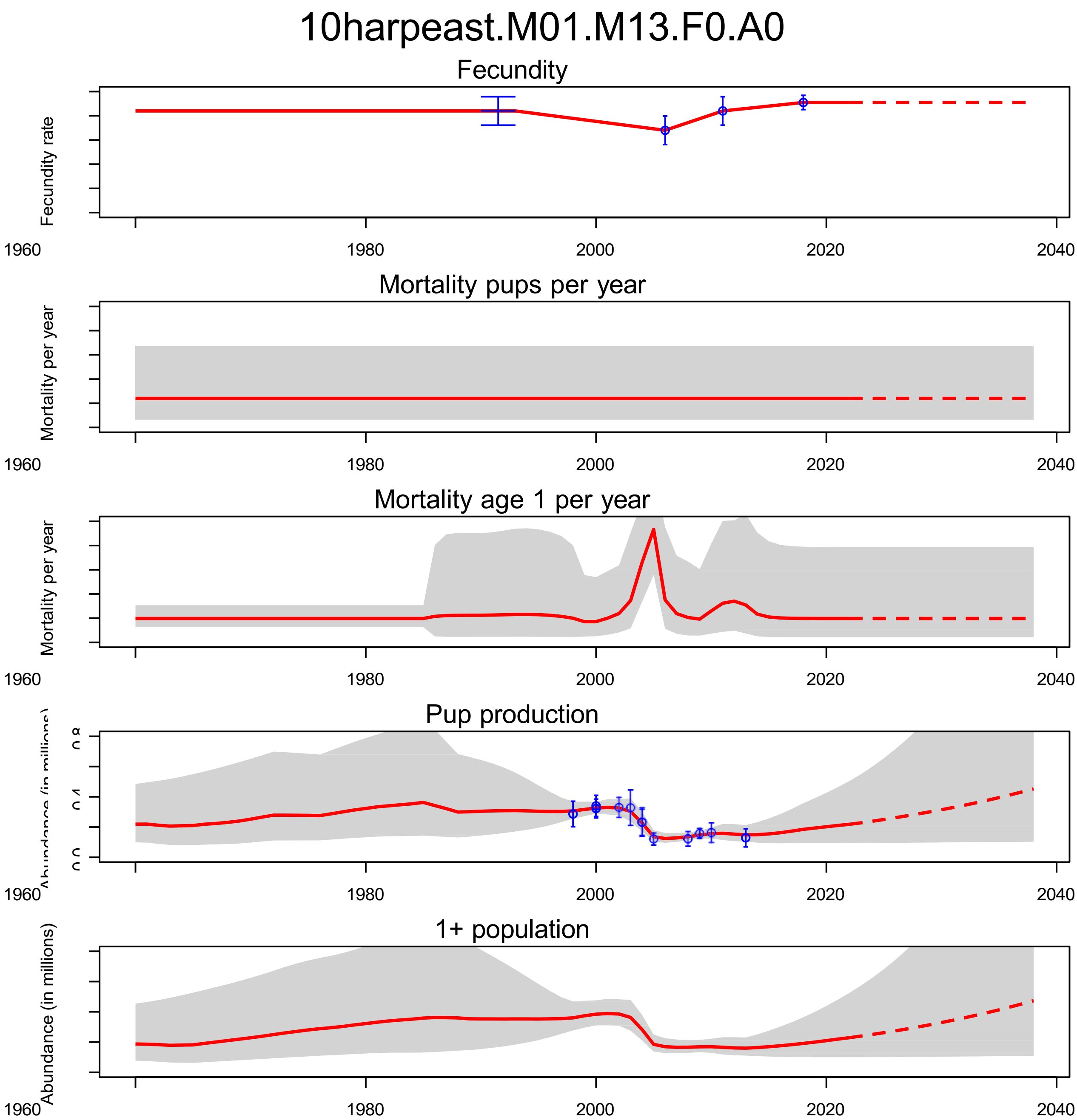

Figure 5: Model fit for harp seals in the East ice, with constant M0, with M+ modelled as an AR(1) process (submodel M13) and with fixed fecundity.

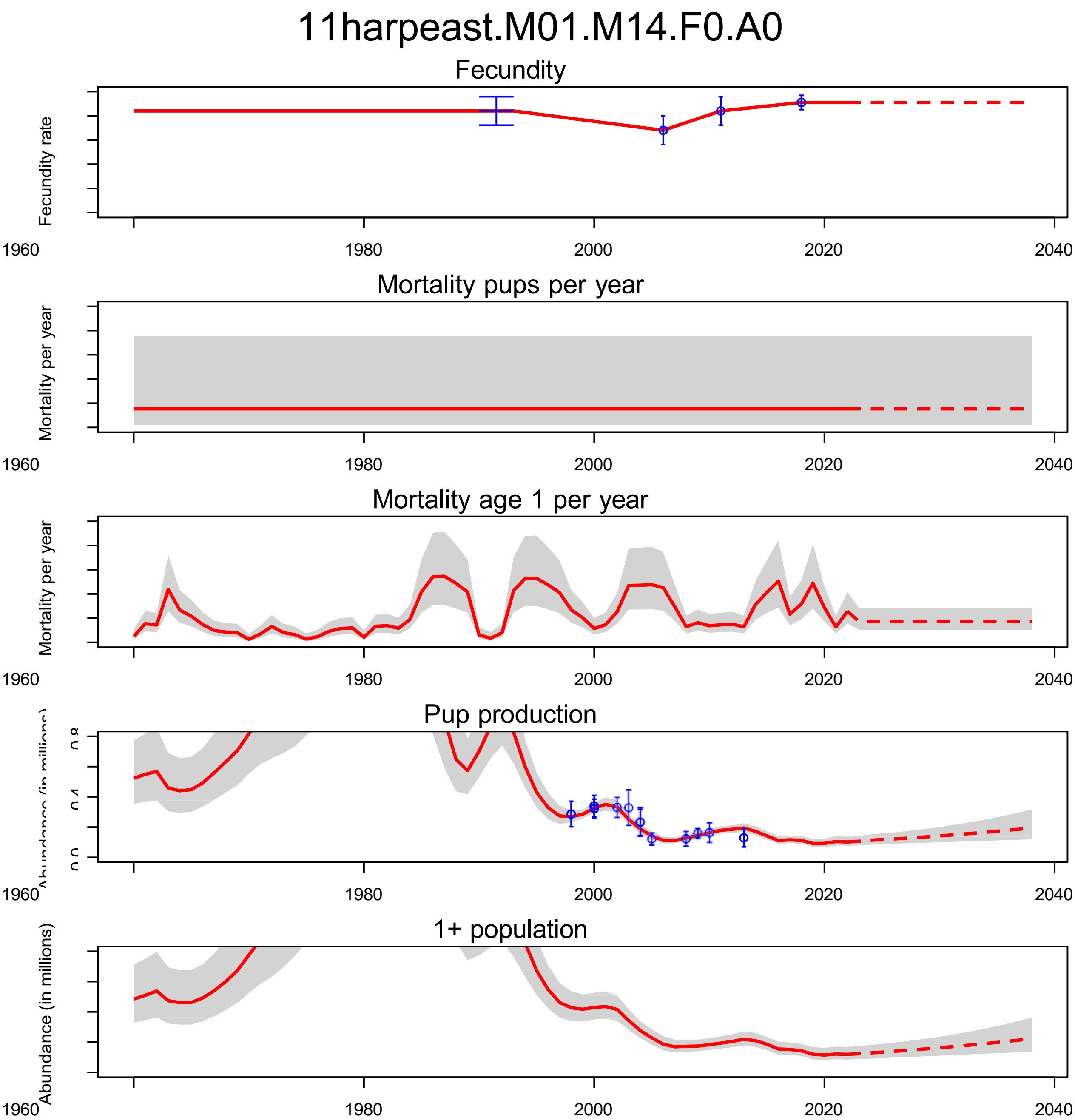

Figure 6: Model fit for harp seals in the East ice, with constant M0, with M+ dependent of indices for resource (capelin) and competitor (cod) separate for young (age 1-6) and old (age 7 and older) seals (submodel M14) and with fixed fecundity.

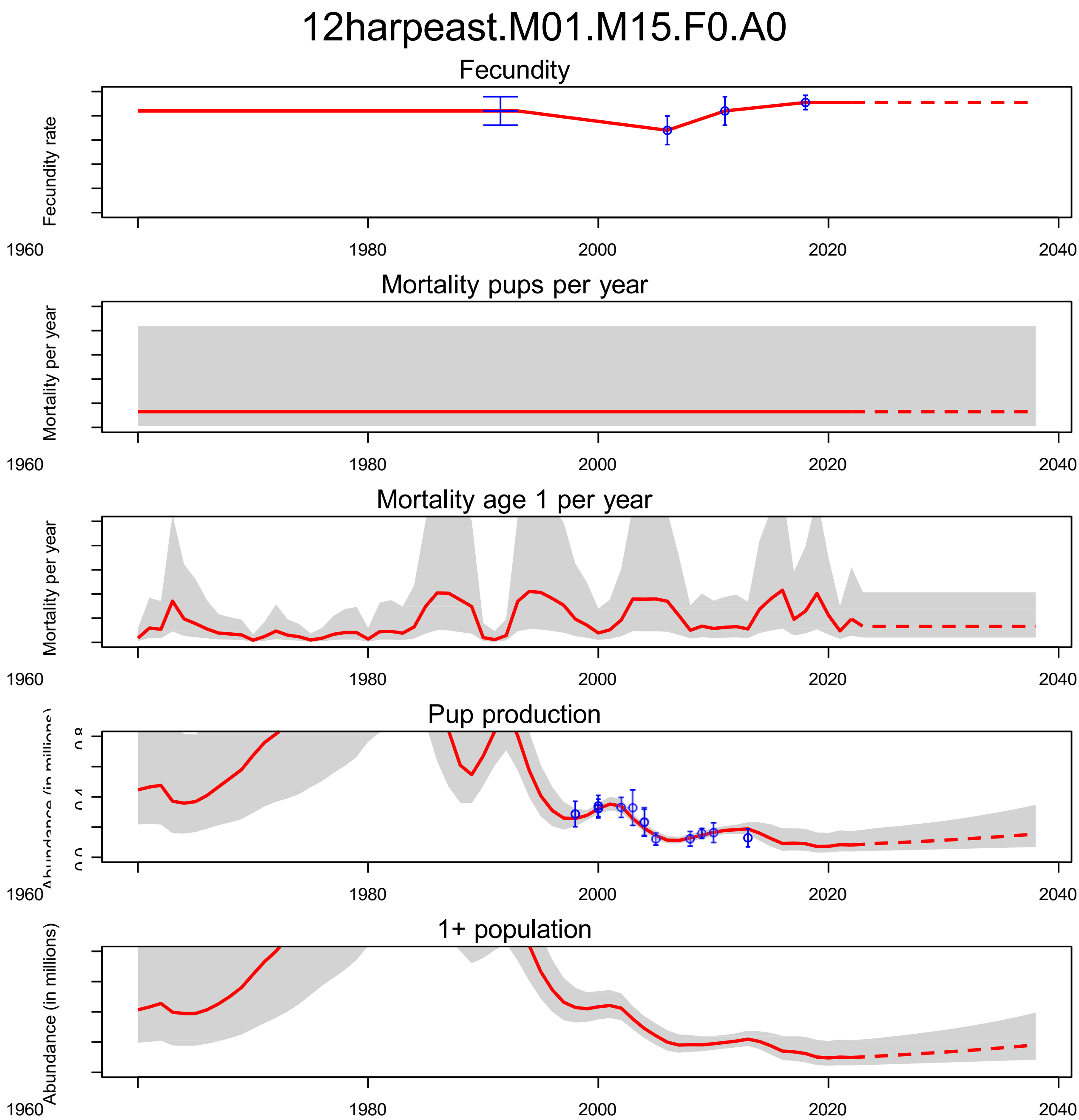

Figure 7: Constant M+, M0 follows AR(1).

Figure 8: Model fit for harp seals in the East ice, with constant M0, with M+ dependent of indices for resource (capelin) and competitor (cod) and linearly changing from age 1 to age 7 (submodel M15) and with fixed fecundity.

3.3 Fecundity models

Table 2: Estimated models for F, with constant M0 and M+

M0 model	1	1
M+ model	1	1
F model	2	3
Parameter	Est. (se)	Est. (se)
K in mill.	2.6(0.3)	1.8(0.4)
M_0	0.23(0.20)	0.28(0.20)
φ^{M0}	NA	NA
σ^{M0}	NA	NA
β^{M0}_{cap}	NA	NA
β^{M0}_{cod}	NA	NA
$M+$	0.16(0.02)	0.13(0.02)
φ^{M+}	NA	NA
σ^{M+}	NA	NA
β^{M+}_{cap}	NA	NA
β^{M+}_{cod}	NA	NA
F_{normal}	0.91(0.03)	0.86(0.08)
φ^{F}	NA	0.66(0.19)
σ^{F}	NA	0.90(0.19)
β^{F}_{cap}	3.28(1.34)	NA
β^{F}_{cod}	0(0)	NA
No fixed par.	6	6
Latent process	No	Yes
AIC (pup prod.)	343.0	286.2

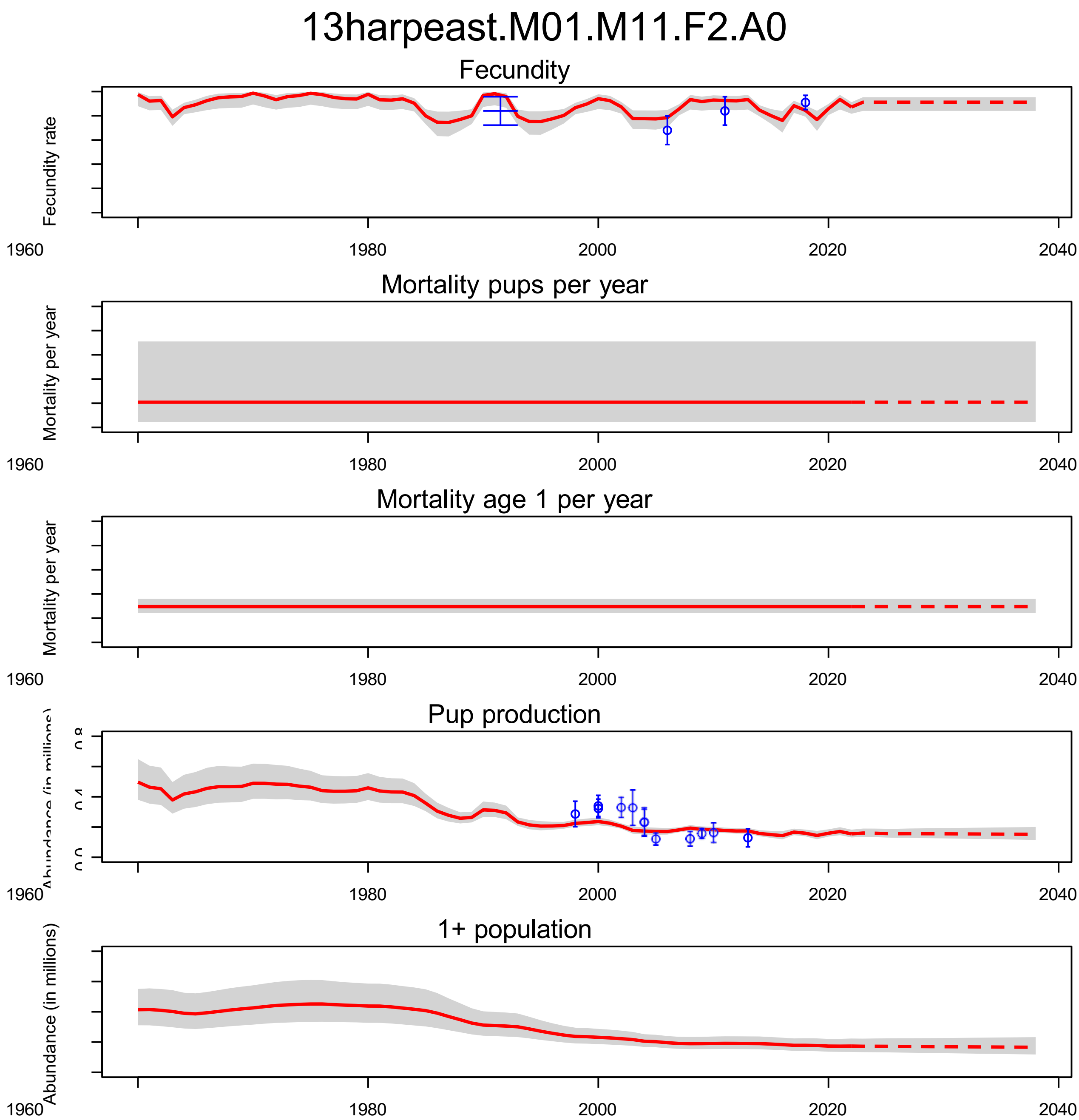

Figure 9: Constant M0 and M+, F depends on resource (capelin) and competitor (cod) indices.

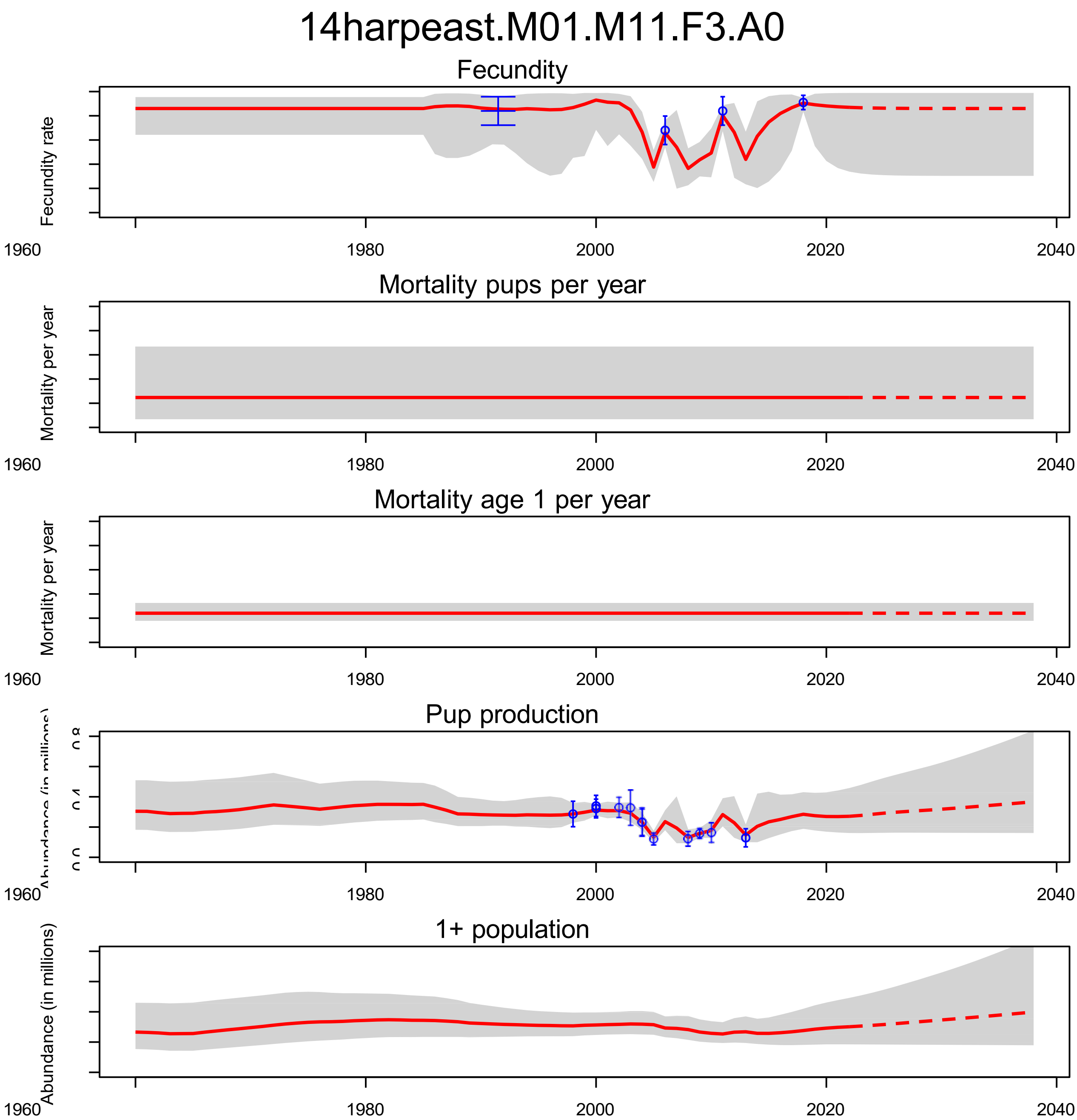

Figure 10: Constant M0 and M+, F follows an AR(1) process.

4 Harp seals in the West ice

4.1 Fixed data

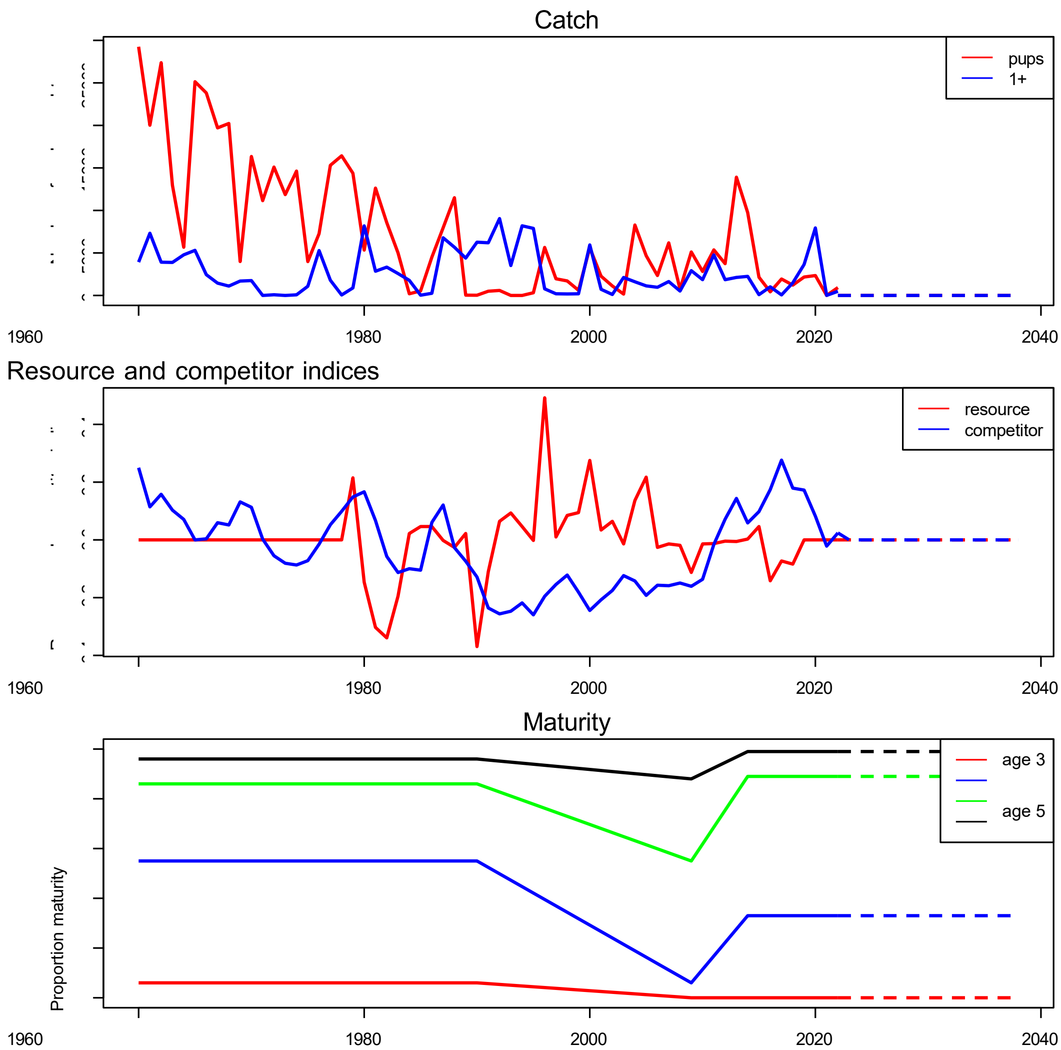

Figure 11: Fixed data for harp seals in the West ice. Upper panel: catch. Middle panel: Resource (capelin) and competitor (cod) indices. Lower panel: Proportion of maturity for selected ages.

4.2 M0 and M+ models

Assume first the models where fecundity is assumed to be known (submodel F0). Table 1 shows parameter estimates and AIC values for selected models. Figs. 12-19 show the corresponding model fits.

Table 1: Estimated models for M0 and M+

M0 model	1	2	1	1	1	1
M+ model	1	1	2	3	4	5
F model	0	0	0	0	0	0
Parameter	Est. (se)	Est. (se)	Est. (se)	Est. (se)	Est. (se)	Est. (se)
K in mill.	0.36(0.03)	0.39(0.06)	1.1(0.3)	0.24(0.01)	1.0(0.3)	1.0(0.3)
$M_{0,normal}$	0.25(0.19)	0.30(0.19)	0.22(0.20)	0.09(NA)	0.33(0.20)	0.23(0.17)
φ^{M0}	NA	NA	NA	NA	NA	NA
σ^{M0}	NA	NA	NA	NA	NA	NA
β^{M0}_{capcod}	NA	0.92(1.79)	NA	NA	NA	NA
β^{M0}	NA	0.92(1,78)	NA	NA	NA	NA
$M_{1,normal}$	0.13(0.02)	0.13(0.02)	0.16(0.02)	0.11(0.03)	0.07(0.06)	0.06(0.08)
$M_{A^{old},normal}$	NA	0(NA)	NA	0(NA)	0.28(0.08)	0.26(0.04)
φ^{M+}	NA	NA	NA	0.02(NA)	NA	NA
σ^{M+}_{capcod}	NA	NA	NA	1.10(0.23)	NA	NA
β^{M+}	NA	NA	1.24(0.86)	NA	1.81(0.92)	1.76(0.63)
β^{M+}	NA	NA	1.70(0.42)	NA	2.31(0.80)	2.13(0.44)
F_0	NA	NA	NA	NA	NA	NA
φ^{F}_{capcod}	NA	NA	NA	NA	NA	NA
σ^{F}	NA	NA	NA	NA	NA	NA
β^{F}	NA	NA	NA	NA	NA	NA
β^{F}	NA	NA	NA	NA	NA	NA
No fixed par.	3	5	5	5	6	6
Latent process	No	No	No	Yes	No	No
AIC (pup prod.)	345.6	348.8	334.2	304.7	329.7	328.2

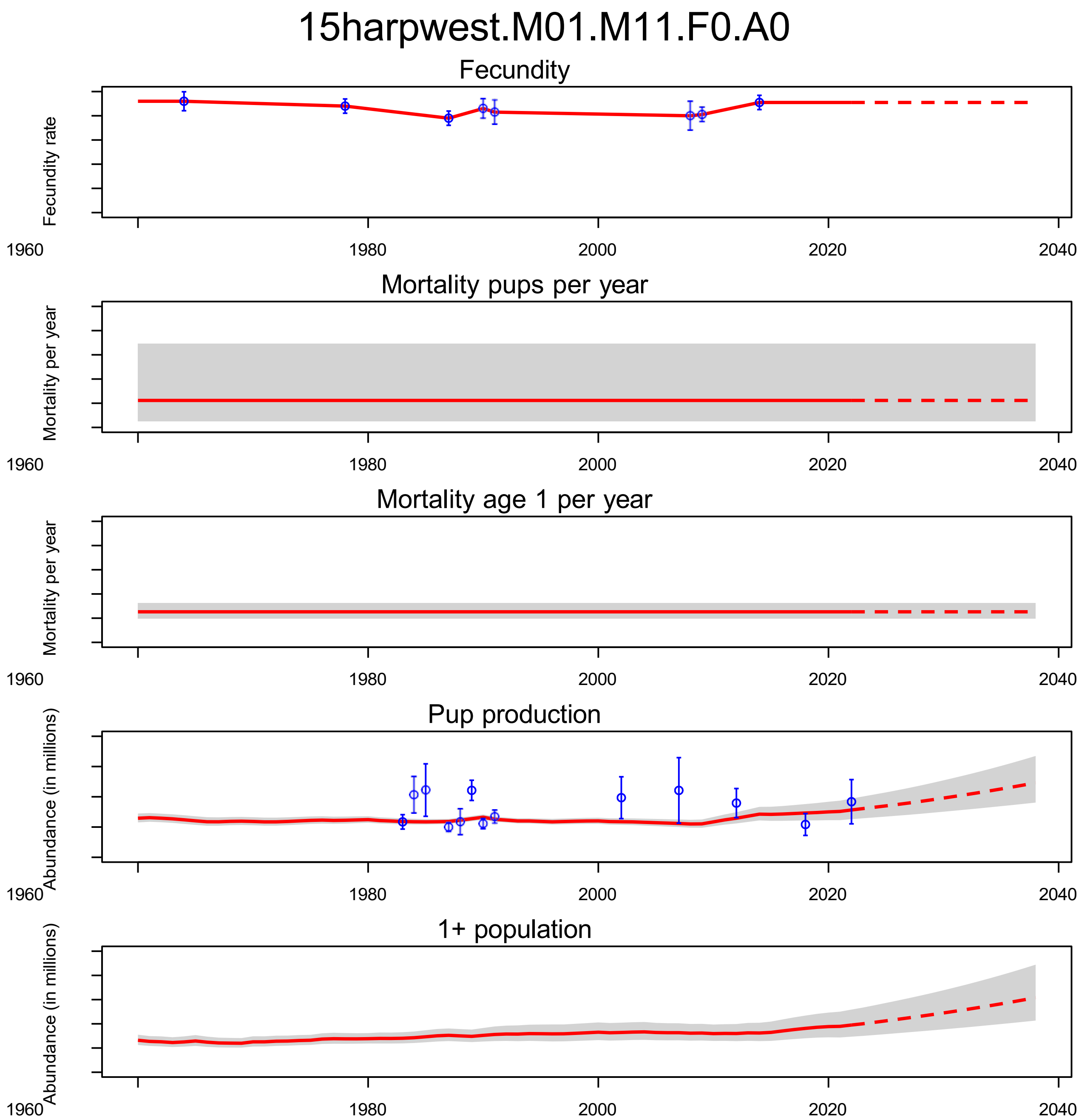

Figure 12: Model fit for harp seals in the West ice, with constant M0 (submodel M01) and M+ (submodel M11) and with fixed fecundity.

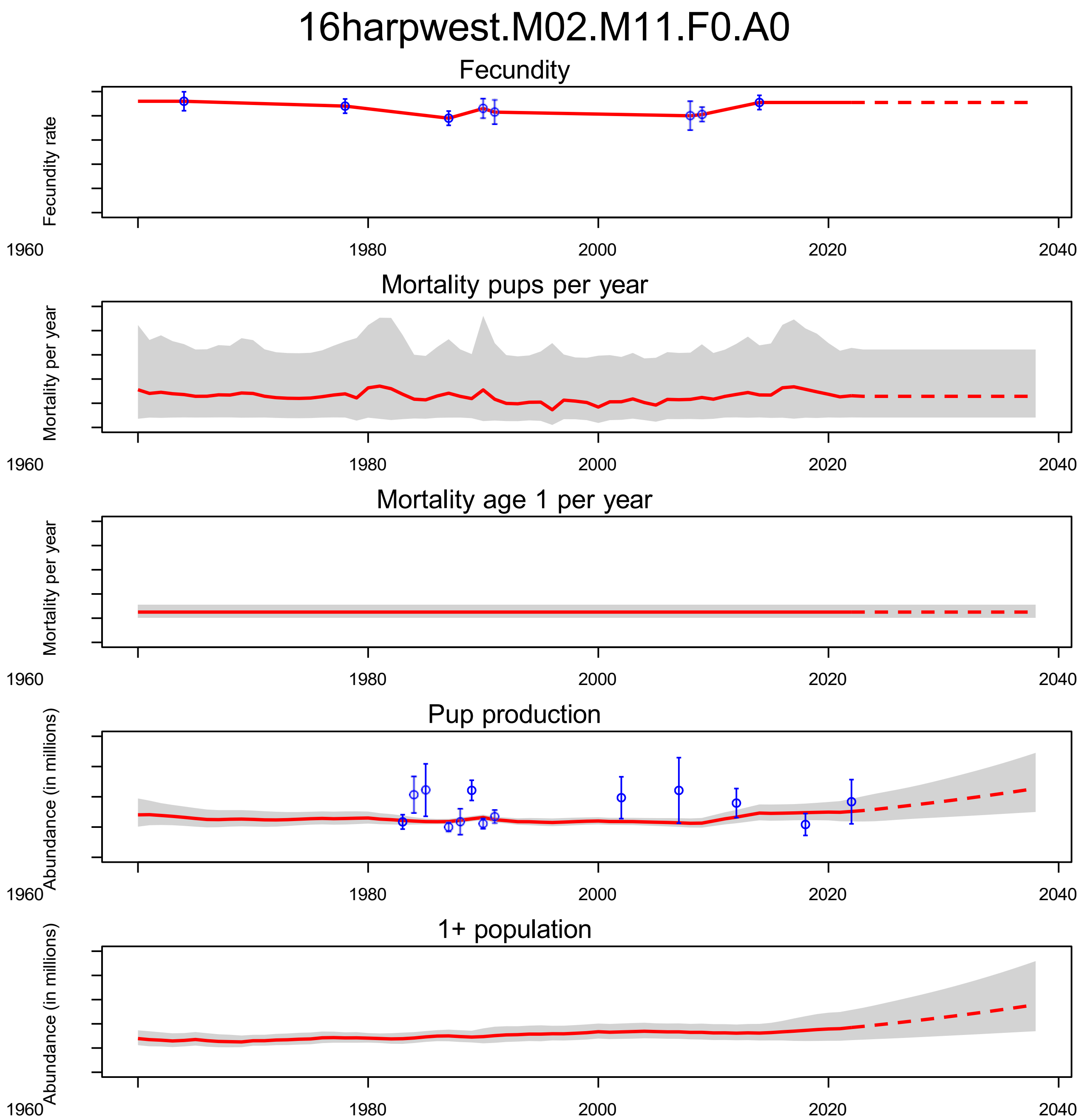

Figure 13: Model fit for harp seals in the West ice, with M0 dependent of indices for resource (capelin) and competitor (cod) (submodel M01), with constant M+ (submodel M11) and with fixed fecundity.

Figure 14: Constant M0, M+ depends on on resource (capelin) and competitor (cod) indices.

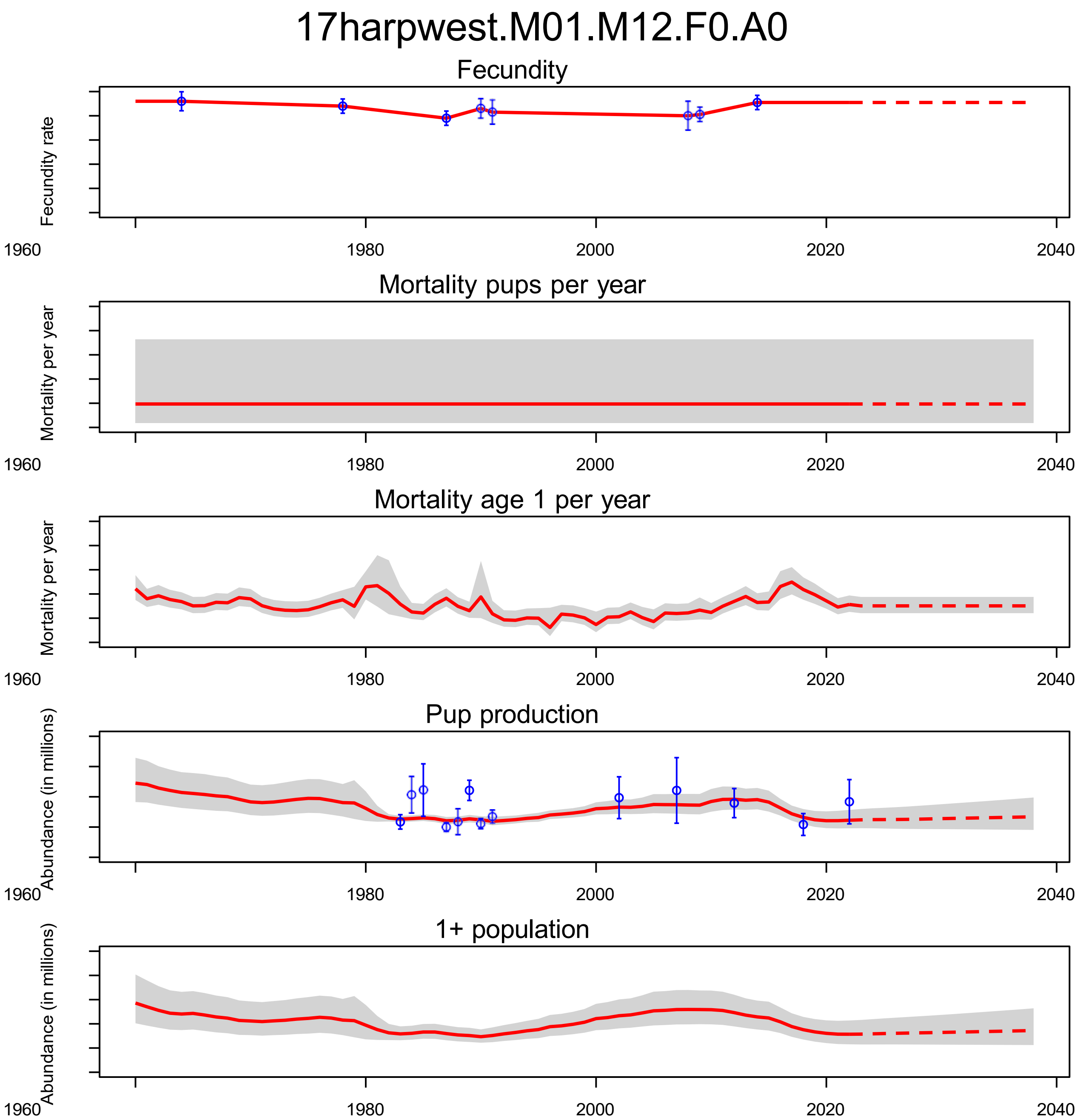

Figure 15: Model fit for harp seals in the West ice, with constant M0, with M+ dependent of indices for resource (capelin) and competitor (cod) equal for all ages (submodel M12) and with fixed fecundity.

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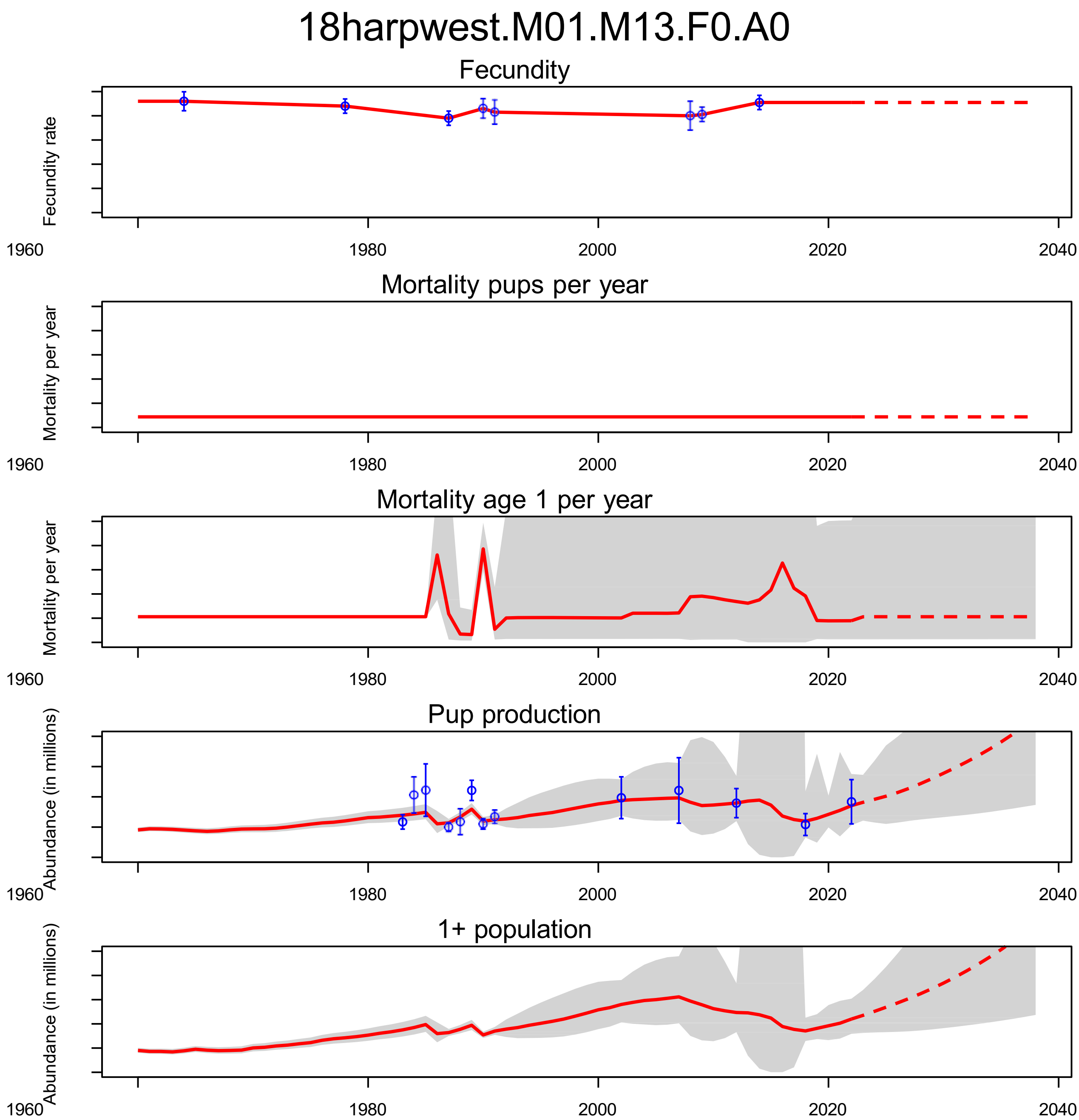

Figure 16: Model fit for harp seals in the West ice, with constant M0, with M+ modelled as an AR(1) process (submodel M13) and with fixed fecundity.

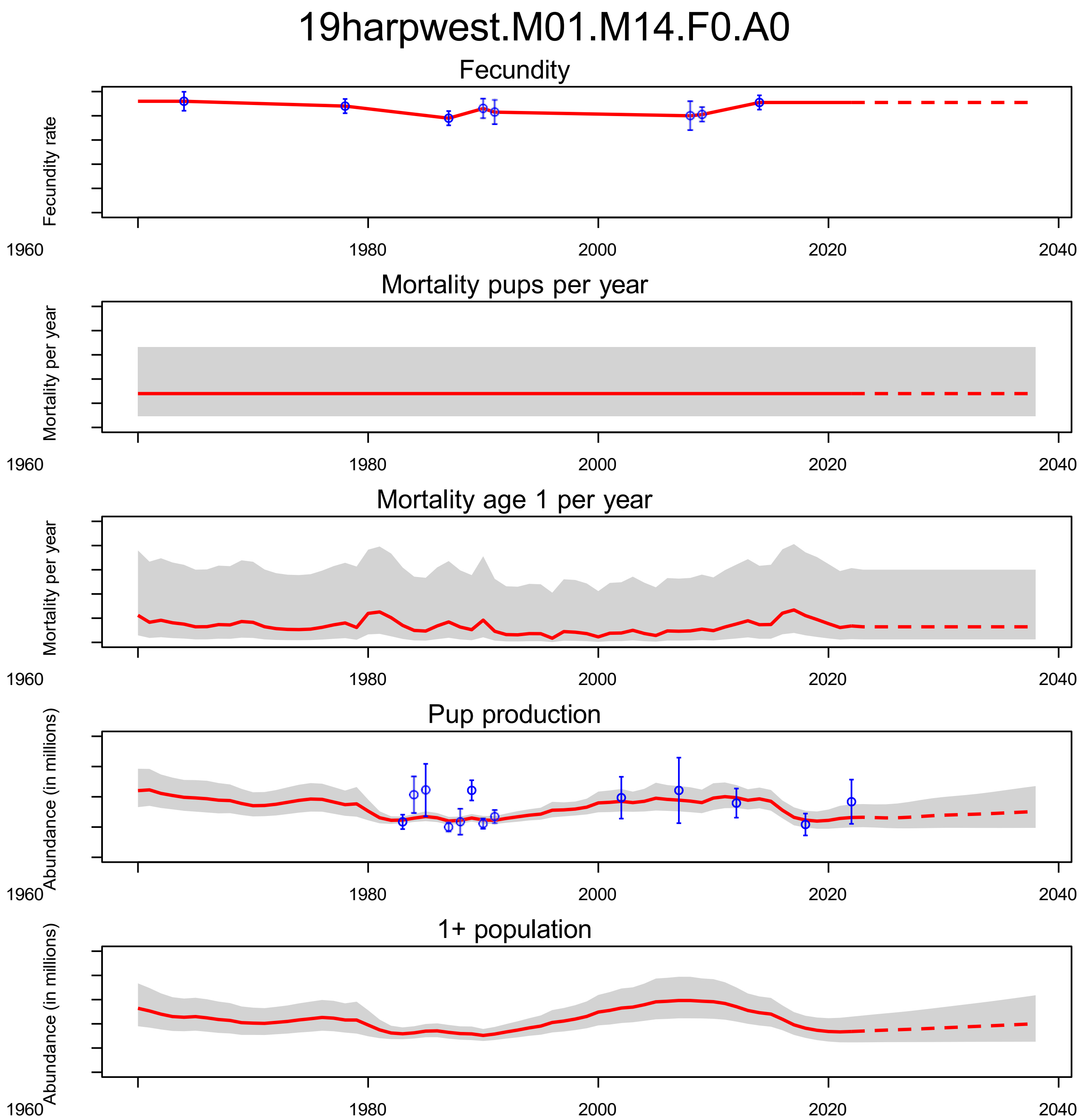

Figure 17: Model fit for harp seals in the West ice, with constant M0, with M+ dependent of indices for resource (capelin) and competitor (cod) separate for young (age 1-6) and old (age 7 and older) seals (submodel M14) and with fixed fecundity.

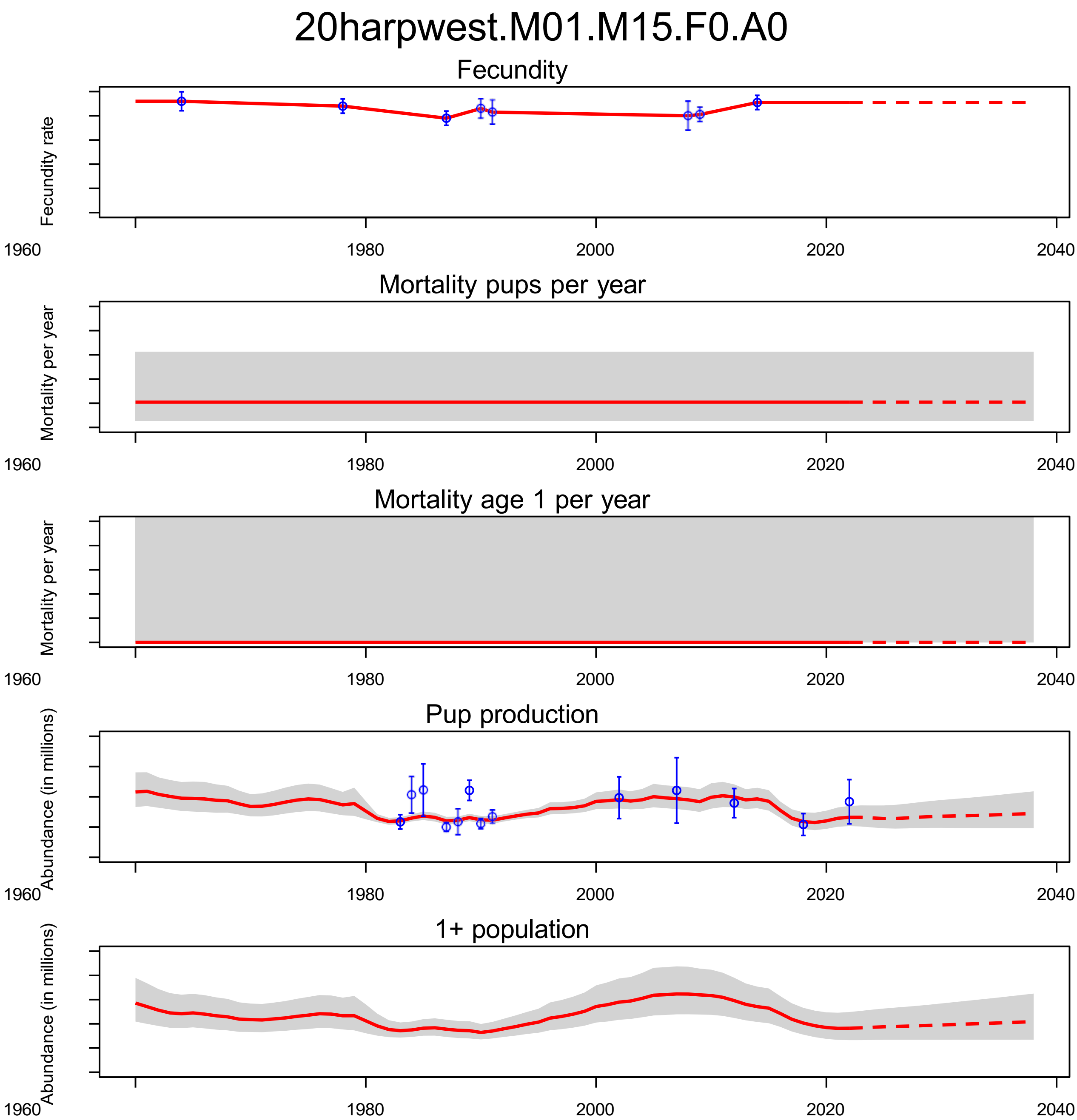

Figure 18: Constant M+, M0 follows AR(1).

Figure 19: Model fit for harp seals in the West ice, with constant M0, with M+ dependent of indices for resource (capelin) and competitor (cod) and linearly changing from age 1 to age 7 (submodel M15) and with fixed fecundity.

4.3 Fecundity models

Table 2: Estimated models for F, with constant M0 and M+

M0 model	1	1
M+ model	1	1
F model	2	3
Parameter	Est. (se)	Est. (se)
K in mill.	0.43(0.04)	0.38(0.04)
M_0	0.20(0.20)	0.26(0.19)
φ^{M0}	NA	NA
σ^{M0}	NA	NA
β^{M0}_{cap}	NA	NA
β^{M0}_{cod}	NA	NA
$M+$	0.14(0.02)	0.14(0.02)
φ^{M+}	NA	NA
σ^{M+}	NA	NA
β^{M+}_{cap}	NA	NA
β^{M+}_{cod}	NA	NA
F_{normal}	0.86(0.03)	0.88(0.08)
φ^{F}	NA	0.33(0.25)
σ^{F}	NA	0.60(0.27)
β^{F}_{cap}	1.88(0.72)	NA
β^{F}_{cod}	1.55(0.92)	NA
No fixed par.	6	6
Latent process	No	Yes
AIC (pup prod.)	338.6	325.1

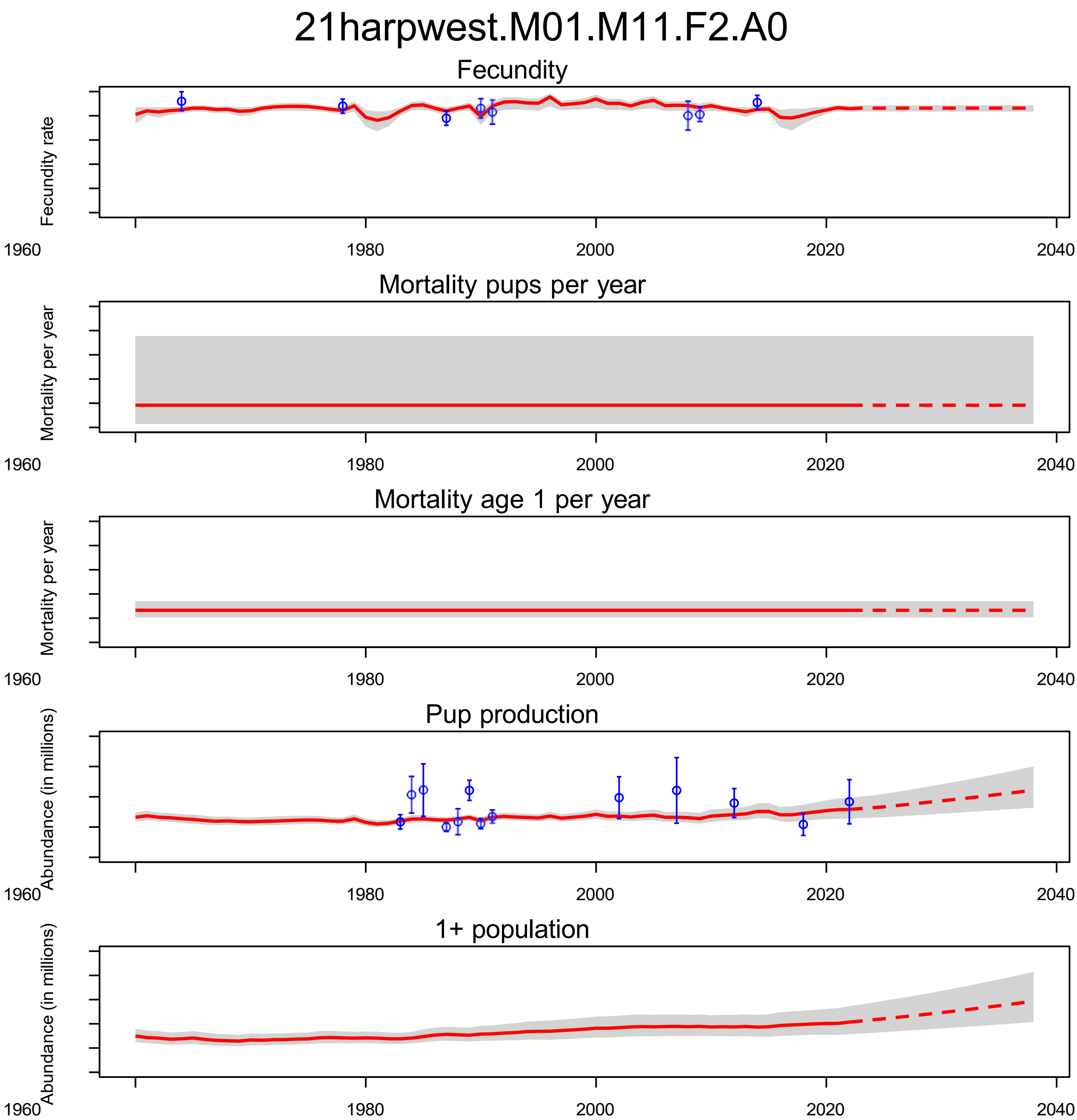

Figure 20: Constant M0 and M+, F depends on cap/cod.

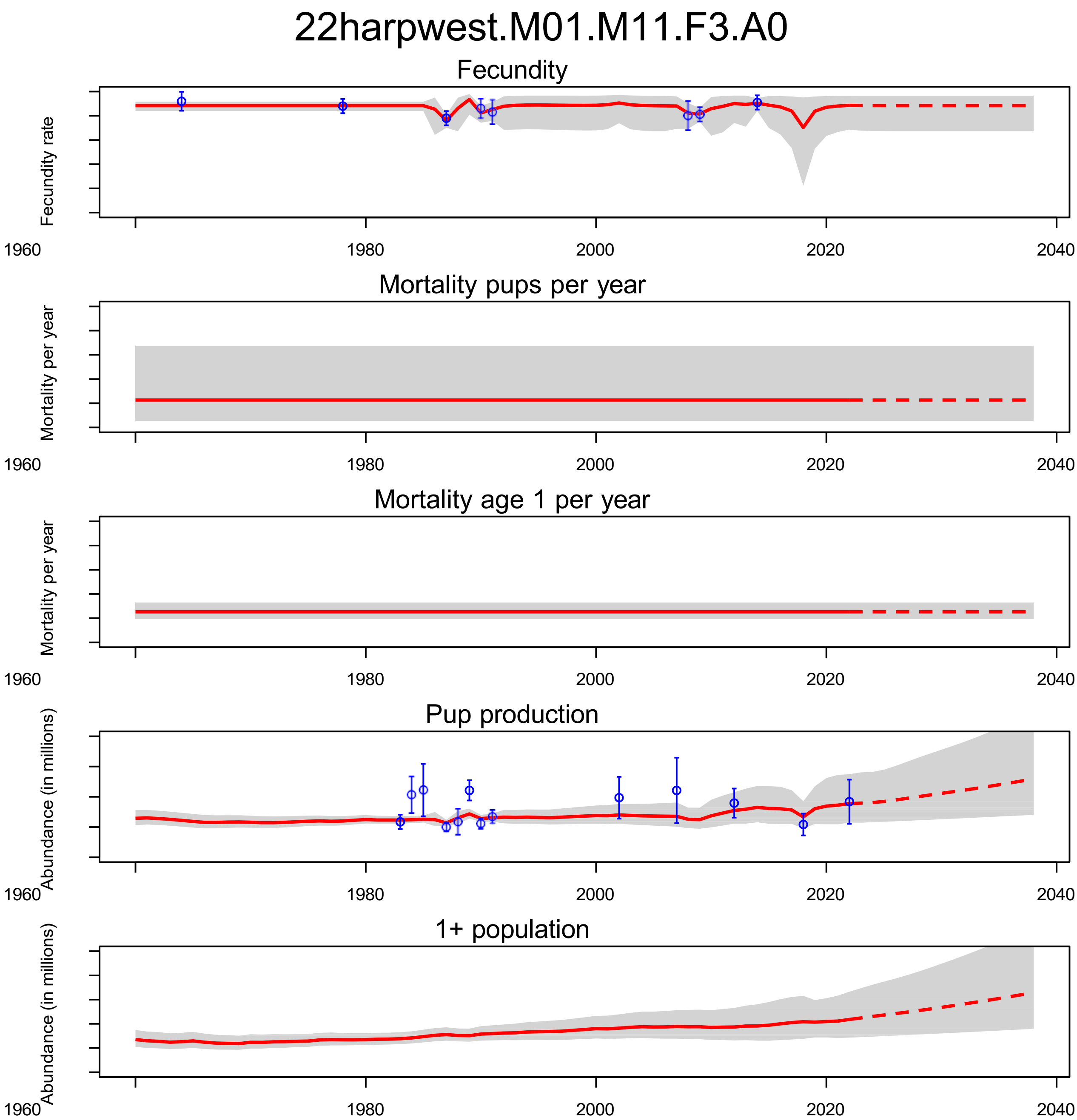

Figure 21: Constant M0 and M+, F follows AR(1).

5 Hooded seals in the West ice

5.1 Fixed data

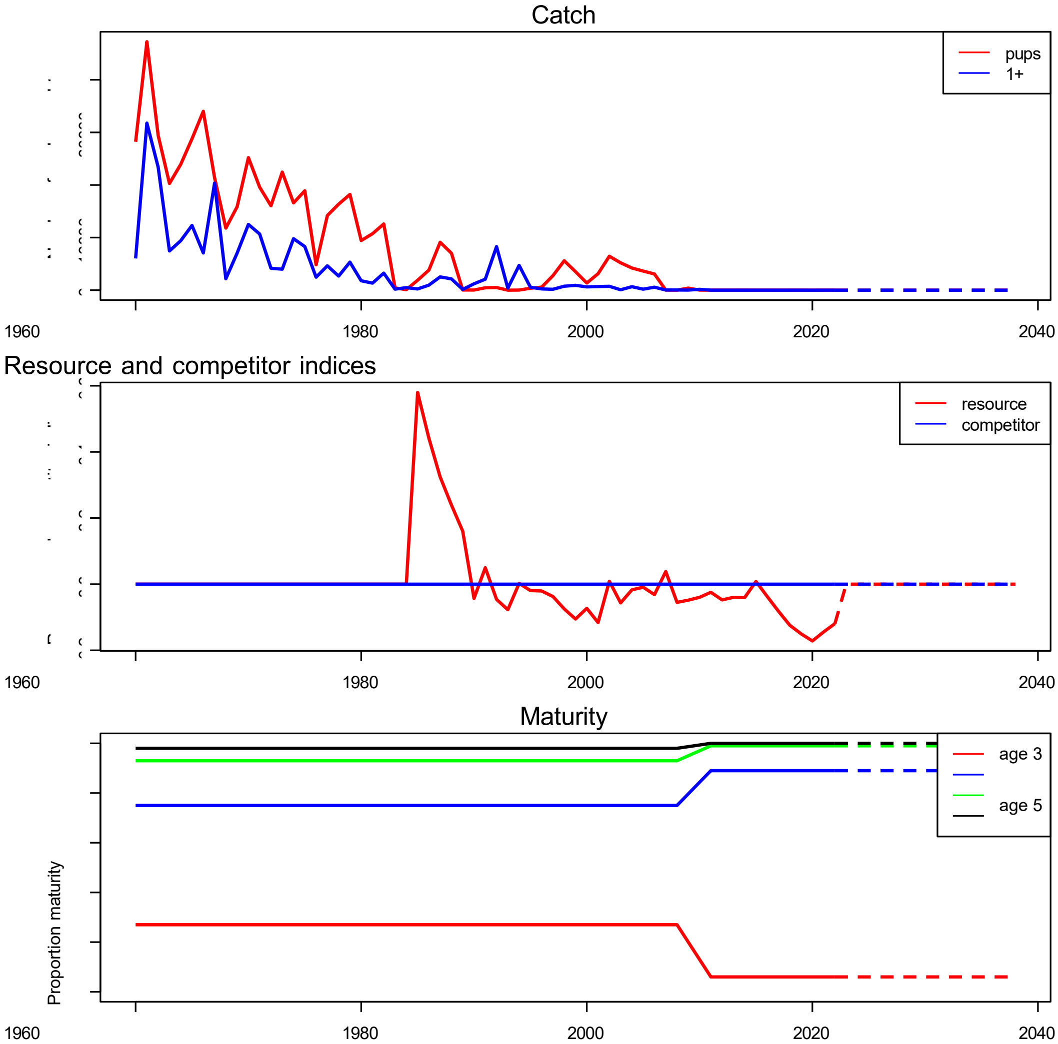

Figure 22: Fixed data for hooded seals in the West ice. Upper panel: catch. Middle panel: Resource (combination of redfish and halibut) index. Lower panel: Proportion of maturity for selected ages.

5.2 M0 and M+ models

The official model with constant mortalities for M0 and M+ has the lowest AIC of model we have tried, and Fig. 23 shows the model fit.

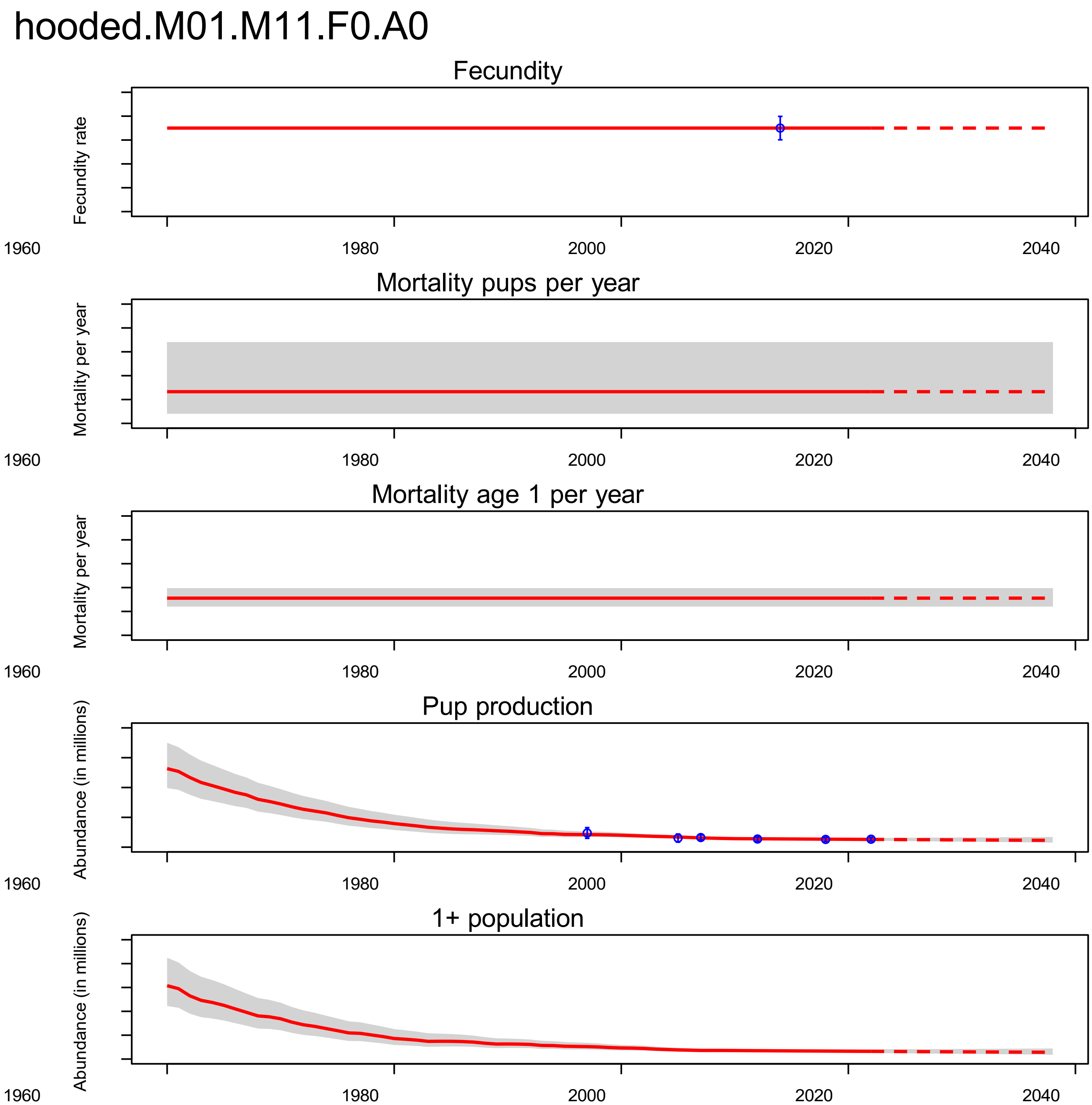

Figure 23: Model fit for hooded seals in the West ice, with constant M0 (submodel M01) and M+ (submodel M11) and with fixed fecundity.

Overview of diet composition of Northeast Atlantic harp and hooded seals

Martin Biuw

2023-05-23

This summary is adapted from Skern-Mauritzen *et al.* (2022), which in turn relies on primary publications for estimates of prey species proportions in the diet of a range of marine mammal species in the Northeast Atlantic.

1 Harp seals

For harp seals, diet composition data for various regions are taken from references listed in Table 1. Full citations can be found in the reference list to Skern-Mauritzen *et al.* (2022).

Region.observed	Ref
Iceland	Hauksson and Bogason 1997
EastGreenland	Enoksen et al. 2017
GreenlandSea	Potelov et al. 2002
BarentsSea,west	Lindstrom et.al. 2013
BarentsSea	Lindstrom et.al. 1998
BarentsSea	Lindstrom et.al. 1998
BarentsSea	Wathne et al. 2000
BarentsSea	Lydersen et al. 1991
CanadianArctic	Ogloff et al. 2019
BarentsSea	Nilssen et al. 1995
BarentsSea	Nilssen et al. 1995
BarentsSea	Nilssen et al. 1995

Due to the relatively limited sample sizes in all studies, we follow Skern-Mauritzen *et al.* (2022) and calculate summary statistics for all studies combined, irrespective of the region from which samples were collected. These are presented in Table 2. Numbers refer to percent of biomass consumed.

Prey	mean	sd
Copepods	0	0
Krill	5.25	10.96
Amphipods	28.83	35.16
Myctophids	0	0
Ammodytes	4.67	15.23
Blue.whiting	0.08	0.29
Herring	3.75	9.54
Capelin	12.77	23.43
Polar.cod	18.25	20.46
Mackerels	0	0
Gadoids	6.61	9.67
Flatfish	1.76	2.95
Redfish	0	0
Cephalopods	0.25	0.62
Shrimp	4.1	7.41
Other.inverts	5.51	12.77
Mammals	0	0
Other.fish	8.18	7.8

In terms of the relative importance of capelin, they make up about 12.8% of the diet by biomass. By comparison, polar cod and amphipods make up roughly 18.3% and 28.8% of the diet, respectively. To instead estimate their relative importance energetically, we need to collate the best estimates of energy content of all prey species/groups identified.

If we break this down by region where samples were obtained, the relative importance of these three key components vary dramatically. In the Barents Sea, capelin, polar cod and amphipods make up about 14.4%, 22.5% and 19.4% of the diet, respectively. In the Greenland Sea, these proportions are 0%, 6% and 91.5%.

2 Hooded seals

For hooded seals, diet composition data for various regions are taken from references listed in Table 3. Full citations can be found in the reference list to Skern-Mauritzen *et al.* (2022).

Region.observed	Ref
Iceland	Hauksson and Bogasson 1997
EastGreeland	Enoksen et al. 2017
GreenlandSea	Potelov et al. 2002
NWAtlantic	Hammill and Stenson 2000
NWAtlantic	Hammill and Stenson 2000
EastGreeland	Haug et al. 2004
EastGreeland	Haug et al. 2004

Due to the relatively limited sample sizes in all studies, we follow Skern-Mauritzen *et al.* (2022) and calculate summary statistics for all studies combined, irrespective of the region from which samples were collected. These are presented in Table 4. Numbers refer to percent of biomass consumed.

Prey	mean	sd
Copepods	0	0
Krill	5.66	14.97
Amphipods	4.71	8.77
Myctophids	0	0
Ammodytes	2.71	7.18
Blue.whiting	0	0
Herring	2	5.29
Capelin	4.39	11.17
Polar.cod	21.71	31.82
Mackerels	0	0
Gadoids	5.71	8.88
Flatfish	12	19.83
Redfish	14.14	27.47
Cephalopods	20.97	26.97
Shrimp	0	0
Other.inverts	0.42	1.12
Mammals	0	0
Other.fish	5.57	12.3

In terms of the relative importance of halibut and redfish, they make up about 12% and 14.1% of the diet. By comparison, cephalopods make up roughly 21% of the diet.

Again, to estimate their relative importance energetically, we need to collate the best estimates of energy content of all prey species/groups identified.

23References

Skern-Mauritzen, M., Lindstrøm, U., Biuw, M., Elvarsson, B., Gunnlaugsson, T., Haug, T., Kovacs, K. M., *et al.* 2022. Marine mammal consumption and fisheries removals in the nordic and barents seas. ICES J. Mar. Sci., 0: 1–21.

Annex 5: Benchmark Steering Group (BOG) and WGHARP recommendation

After the completion of WKSEALS, BOG and WGHARP[**] separately concluded that the assessment model for harp seals in the Greenland Sea proposed by the benchmark should be not accepted as basis for scientific advice. This is mainly because estimated population abundance is influenced by the choice of the standard deviation of the prior on initial population size in 1946 (i.e. increasing the standard deviation of the prior in effect increases the mean).

While WGHARP trusted the trend in population size over time, the absolute level was deemed unrealistic.

[**] ICES, 2023. ICES/NAFO/NAMMCO Working Group on Harp and Hooded Seals (WGHARP). ICES Scientific Reports. In preparation.