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Abundance Estimate of Northwest Atlantic Harp Seals, *Pagophilus groenlandicus*, and Harvest Advice for 2025-2029

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

ABSTRACT

The Northwest Atlantic (NWA) harp seal population is harvested for commercial and subsistence purposes in Canada and Greenland, and is caught incidentally in commercial fisheries. A new pup production survey in 2022 estimated total pup production at 614,100, the lowest estimate since 1994. Stock status is estimated using a Bayesian Integrated Population Model (IPM) which incorporates periodic estimates of pup production along with updated data on age composition, age-specific reproductive rates, total removals, and environmental conditions. Based on the IPM, NWA harp seal abundance increased rapidly from the 1970s through the 1990s, peaking at an estimated abundance of 7.5 million seals (95% Credible Interval, CrI: 6.75-8.42) in 1998. The population declined from 1998-2024 with the exception of a period of relative stability between 2009-2019. The estimated 2024 total abundance was 4.4 million seals (95% CrI: 3.65-5.35). This represents a decline in abundance from 2019 (5.6 million, 95% CrI: 4.78-6.63) at a rate of 4.7% (95% CrI: 2.14-7.45%) per year.

Harp seals are managed under the Atlantic Seal Management Strategy (ASMS). Under the current ASMS, N_{max} (largest population observed or estimated) was estimated to be 7.5 million seals (95% CrI: 6.81-8.35).This results in a Precautionary Reference Point (PRP, 70% of N_{max}) of 5.3 million seals and a Limit Reference Point, (LRP, 30% of N_{max}) of 2.2 million seals. The estimated 2024 total abundance has a 96% probability of being below this PRP and is, therefore, in the Cautious Zone. Under the current ASMS, there is no harvest level that would have an 80% probability of the population increasing above the PRP in 10 years. Under the proposed Revised ASMS (R-ASMS), the environmental carrying capacity (K) was estimated to be 6.9 million seals (95% CrI: 5.27-8.48). This results in a PRP (70% of K) of 4.8 million seals and a LRP (30% of K) of 2.1 million seals. The estimated 2024 total abundance has a 80% probability of being below this PRP and is, therefore, in the Cautious Zone. Under the proposed R-ASMS, we estimated the sustainable harvest levels for the next five years (2025-2029) that would have an 80% probability of the population increasing above the PRP in 1.5 generations (30 years). The annual Atlantic Canadia sustainable harvest levels which meet this criteria are 253,000, 222,000, and 113,000 seals assuming harvest age compositions of 95%, 90%, and 50% young of the year, respectively. These harvest projections assume that ice conditions and environmental variables will remain similar to recently observed conditions. Harvest levels compatible with the harvest control rule would be less assuming future ice conditions were to deteriorate further as projected due to climate change.

INTRODUCTION

The harp seal (*Pagophilus groenlandicus*) is a medium sized, migratory phocid distributed over continental shelf regions of the North Atlantic. It is the most abundant pinniped in the North Atlantic (Hammill and Stenson 2022). Three populations are recognized based on whelping location; the Greenland Sea, the White Sea and the Northwest Atlantic (NWA) populations. The NWA is the most abundant of the three populations (Stenson et al. 2020b). This population summers in the eastern Canadian Arctic and west Greenland. In the fall, NWA harp seals migrate southward to the Newfoundland Shelf and the Gulf of St. Lawrence, where they feed, prior to whelping on the pack-ice off the southeast coast of Labrador/northeast coast of Newfoundland, an area referred to as the “Front” and in the Gulf of St. Lawrence (Gulf; Figure 1). They migrate back to the Arctic in early summer (Sergeant 1991, Stenson and Hammill 2014).

The Northwest Atlantic harp seal population is harvested commercially and for subsistence in Canada and Greenland, and is caught incidentally in commercial fisheries. The Atlantic Canada commercial harvest, traditionally the largest source of removals, is mainly directed towards animals in their first year (hereafter referred to as young-of-the-year, YOY; Stenson and Upward 2020).

The harp seal is an ice-obligate species, requiring ice as a platform to give birth and nurse their pup (Sergeant 1991). Weaned pups, referred to as “beaters”, remain on the ice for several weeks while they develop their physiological capacity to forage independently (Burns et al. 2007). Good ice conditions during this period are crucial, and years of poor ice conditions can result in high pup mortality (Stenson and Hammill 2014). The timing of ice breakup can also have implications for prey abundance that can, in turn, affect body condition and reproductive performance (Buren et al. 2014, Stenson et al. 2016, Hammill and Sauvé 2017). The frequency of poor ice conditions in the harp seal whelping areas has increased, particularly over the last decade (Han et al. 2015) and climate change is projected to continue to impact ocean and ice conditions in the NWA. Under the Representative Climate Pathway 8.5 (RCP 8.5) climate change scenario, Brickman et al. (2016) and Lavoie et al. (2020) predicted in 2061-2080 a drastic reduction in sea ice extent in the Northwest Atlantic. Annual primary production in the Gulf is also projected to decline by 13.4% in less than 70 years (Han et al. 2019, Mei et al. 2024). As for the waters off Newfoundland and Labrador, Han et al. (2015) predicted that they could be ice free by 2060.

Abundance of the NWA harp seal population is estimated using a Bayesian Integrated Population Model (IPM; Tinker et al. 2023). In this model, population abundance is estimated from multiple sources of information including periodic estimates of pup production, and annual information on age-specific reproductive rates (Stenson et al. 2016, Stenson et al. 2020a), age structure of the population (Tinker et al. 2023) and total removals from harvesting and bycatch (Stenson and Upward 2020).

In order to provide an estimate of current abundance, a new pup production survey was conducted in 2022 (Goulet et al. In press). Here, we use this new survey information, along with recent and updated data on age composition, reproductive rates (1979-2022), removals and environmental conditions to provide an updated population estimate for the NWA harp seal population from 1952-2024. We used the IPM formulation presented in Tinker et al. (2023) to estimate population size and trends, and account for the different levels of uncertainties in removals over time and across removal categories.

In this assessment, we also provide advice on sustainable harvest levels. Specifically, we provide advice on the sustainable harvest levels for the Atlantic Canada commercial harp seal fishery for the next 5 years (2025-2029) which respects management objectives under the Precautionary Approach for three harvest age structures: 5% adults / 95% young of the year (YOY), 10% adults / 90% YOY and 50% adults / 50% YOY.

The Atlantic Seal Management Strategy (ASMS) was accepted in 2003 (DFO 2003). The strategy was initially developed for species taken in the commercial seal hunt in Atlantic Canada (harp, hooded, and grey seals) but has since been applied to the management of other marine mammals in Canada. Under the ASMS, harp seals are considered to be a “data rich” species. As such, the management objective under ASMS is to have an 80% probability that the population remains above a Precautionary Reference point (PRP) referred to as N_{70}, a threshold representing 70% of the maximum population abundance observed in the time series (N_{max}). If the population falls below N_{70}, then management efforts are to be undertaken to return the population above the PRP within 10 years (DFO 2006). A revision of the strategy, hereafter referred to as the Revised ASMS (R-ASMS), has been proposed (Lang et al. In Press). The R-ASMS sets N_{70} with respect to *K*, the environmental carrying capacity, instead of N_{max}. The ASMS and R-ASMS also differ in their Harvest Control Rules (HCR) in cases where current population size falls below the PRP with the time frames for a population in the upper half of the cautious zone to have an 80% probability of increasing above N_{70} set at 10 years and 1.5 generations for the ASMS and R-ASMS, respectively. In this document, harvest advice is provided to meet the objectives under both strategies (ASMS and R-ASMS). A Potential Biological Removal (PBR) level is also provided to meet requirements under the US *Marine Mammal Protection Act* (MMPA) Imports Provisions Rule (81 FR 54389; National Oceanic and Atmospheric Administration (NOAA) 2016).

METHODS

DATA SOURCES

The harp seal IPM relies on six sources of data:

1. Periodic pup production estimates, and annual information on
2. Reproductive rates;
3. Age composition;
4. Total removals (harvest and bycatch);
5. Ice anomalies; and,
6. The Newfoundland and Labrador Climate Index (NLCI).

The latter two data sets represent co-variates for vital rates, while the first four data sets represent observations used for model fitting.

Pup production

Whelping occurs on the pack ice between late February and early March. We used 14 independent estimates of pup production from 1951 to 2022, derived using a combination of mark-recapture and aerial-survey methods (Table 1). Pup counts from the three whelping patches (Southern Gulf, Northern Gulf and Front) were combined to produce a population-wide survey estimate (Goulet et al. In press).

Reproductive rates

We used annual information on age-specific reproductive rates, based on 4,417 samples collected since 1952 (Fisher 1954, Bowen et al. 1981, Sjare and Stenson 2010, Stenson et al. 2016, Stenson et al. 2020). Seal ovaries are collected around Newfoundland and southern Labrador by Fisheries and Oceans Canada (DFO) personnel and experienced seal hunters under licenses issued by DFO (Stenson et al. 2020). Detection of pregnancy in sampled females was performed as per Stenson et al. (2016). Females were deemed pregnant if a foetus in the uterus was detected and/or if a large and fully luteinized corpus luteum was present in one of the ovaries. Only samples collected from October through February, which corresponds to late-term pregnancy (Bowen et al. 1981), were used in the model. Years 1951-1954 were combined due to low sample sizes.

The age of each seal sampled was determined to the nearest year by sectioning a lower canine tooth and counting dentine annuli (Fisher 1954, Bowen and Sergeant 1983, Frie et al. 2011). The age was used to calculate age-specific reproductive rates. Harp seals can start giving birth at four years-old and females less than four years-old were assumed to be immature. At age eight years-old, all females were considered to be sexually mature and reproductive rates are assumed to have reached a consistent value. For this reason, we calculated reproductive rates for females of age 4, 5, 6, 7, and ≥8 years-old (Table 2). We updated the age-specific reproductive data used by Tinker et al. (2023) to include recent years (2020-2022).

Age composition

Age composition data were obtained from seals collected for reproductive rates (described above) or as part of other sampling programs carried out by DFO since 1979. We calculated age composition for seals collected from October through February to match the timing of reproductive data collection (Table 3). Age sampling included both males and females. We revised age data throughout the time series presented in Tinker et al. (2023) and added years 2020-2022 (Figure 2). Because of a concern that younger seals may have been under- or over-represented in the sampling in some years, we only used data for seals five years of age and older for model fitting (Tinker et al. 2023).

Removals

Removals of harp seals are from four distinct sources:

1. Commercial and personal use seal hunt in Atlantic Canada;
2. Subsistence harvest in Greenland;
3. Subsistence harvest in Arctic Canada; and,
4. Incidental by-catch in commercial fishing gear (Stenson and Upward 2020) (Figure 3).

We updated the removal data used by Tinker et al. (2023) to include recent years (2020-2022). Removals are separated between young-of-the-year (YOY) and adults (Table 4). To simplify terminology we refer to seals one year and older as “adults” throughout.

There are uncertainties in the estimates of removals and in the proportion of YOY versus adults removed by each source. In addition, these uncertainties have varied over the time series. In the previous model run, a Coefficient of Variation (CV) of 0.1 was assumed to account for uncertainties in reporting (Tinker et al. 2023). Here, based on previous studies (Stenson and Upward 2020; Hammill et al. 2021; Tinker et al. 2023, 2025 (under review)) and expert opinion from authors G. Stenson and M.O. Hammill, we assessed our confidence in total removals and the proportion of YOY for each source and year of the time series. We used three categories of uncertainties; “high”, “moderate” and “low” (Table 5). High uncertainty was given a CV value of 0.2, moderate uncertainty a value of 0.1 and low uncertainty a value of 0.05. These CVs were then used to set uncertainty levels for each data series during model fitting to estimate true values for human-caused mortality (see Section “Survival” below). How annual removals attributed to each source were obtained since 1952 and the level of confidence in those numbers (or their estimates) is fully explained in Stenson and Upward (2020) and Stenson (2010). Moreover, we provide additional details and explanations as to how the different levels of uncertainty were attributed per source of removal and time period in Appendix 2.

Not all animals that are killed during harvest activities are successfully recovered and reported, a phenomenon referred to as “struck and loss”. The rate of struck and loss varies by age class (YOY versus adults) and harvest source. Accordingly, we assigned a time-varying struck and loss rate for each harvest source based on previously published estimates and expert opinion (see Stenson 2010). Struck and loss rate of YOY was set to 50% (i.e., 50% of the YOY that are killed are not recovered and reported) for the Arctic and Greenland hunts and for Atlantic Canada hunt it was set to 1% prior to 1983 and then 5% from 1983 onward. Struck and loss rate of adults was set to 50% in all sources of harvest. Struck and loss rate was set to 0% for removals from bycatch.

Ice anomalies

Suitable ice is needed during pupping and nursing, and for approximately one month during the pups post-weaning fast, otherwise mortality of YOY can be high (Sergeant 1991, Stenson and Hammill 2014). To account for the impact of ice conditions on YOY survival, we used ice anomalies as a covariate in the IPM. Ice anomalies describe annual deviations from historical ice conditions. We used data from the beginning of the ice records in 1969 until 2000 as the basis for historical baseline levels and focused on two periods of high ice dependency for pups: the pupping and post-weaning fast periods. Because of differences in the timing of pupping in the southern Gulf, these periods correspond to weeks of 28 February and 26 March. In the northern Gulf and the Front, these periods correspond to the weeks of 5 March and 9 April. For each of these weeks and areas, we extracted total first-year ice cover from the Gulf of St Lawrence and southern Labrador ice charts available from the Canadian Ice Service of Environment Canada (Ice Graph).The ice anomaly index (IC) is calculated for each year (t) and breeding area (a) as the average of the ice cover anomalies over the two periods (p). The anomalies are the deviation in % total ice from the average % ice cover (μ) for breeding area and the historical reference period (h) divided by the standard deviation in mean ice cover during the period σ, as follows:

$$IC_{a,t} = \frac{1}{2}\sum_{p}(ICE_{a,t,p} - \mu_{a,h,p})/\sigma_{a,h,p} \qquad (1)$$

Values of the IC index below 0 indicate anomalously low ice cover compared to historical observations (Figure 4A). Ice anomalies were calculated for years 1951-2023. The Northern Gulf whelping area is closer to the Front whelping area and as such seals there may encounter ice conditions more similar to the Front. Further, the timing of pupping and weaning in Northern Gulf is more similar to the Front than the Gulf (e.g., Goulet et al. In press). For these reasons, we used the Front anomalies for the northern Gulf and Front whelping areas, and the Gulf anomalies for the southern Gulf.

Newfoundland and Labrador Climate Index, NLCI

The NLCI provides a measure of the overall state of environmental conditions and ecosystem variability in the Northwest Atlantic. It is a mosaic of 10 environmental components including the winter North Atlantic Oscillation, sea ice season duration and maximum cover area, air temperature, iceberg count, sea surface temperature, salinity, temperature and cold intermediate layer measurements from a variety of sites in the Northwest Atlantic covering the period of 1951-2023 (Figure 4B; Cyr and Galbraith 2021).

INTEGRATED POPULATION MODEL

The methods for analyzing the harp seal population can be described in three parts:

1. The process model, a series of equations that describe demographic transitions and which, when solved, predict dynamics in the variables of interest (e.g., population abundance) based on the values of the input parameters;
2. The data model, which describes how empirical data sets are related to the predicted dynamics of the process model; and,
3. Model fitting, which describes how input parameters are estimated.

Process model

Summary

Population dynamics are described using a female-based, age-structured, pre-breeding matrix model with discrete annual time steps. The abundance of animals in each age class for a given year corresponds to the population state in late winter, i.e., just prior to the annual pup survey. This formulation simplified interpretation of age samples and pregnancy rate data, as pup counts could be compared with expected births given the pregnancy rate of sampled females. The population vector $\boldsymbol{n}(t)$ describes the number of individuals in each age class, i ($i = 1, 2 \ldots 36$), at year t, and $N(t)$ is the sum of $\boldsymbol{n}(t)$ across all age classes. The first entry in the population vector ($n(1,t)$) corresponds to 1-year olds: that is, pups born the previous year that have survived to their first birthday. The last age class, $i = 36$, represents a multi-year class comprised of all animals older than 35 years of age. Although YOY are not directly included in the population vector $\boldsymbol{n}$, their numbers are separately tracked as the summed reproductive output of adult females.

Demographic transitions between $\boldsymbol{n}(t)$ and $\boldsymbol{n}(t+1)$ are calculated from annually varying vital rates: fecundity (F; the probability that a female gives birth at year t), YOY survival (S_0, the probability that a newborn survives to its first birthday), and adult survival (S_A). Fecundity and adult survival rates are allowed to vary by age. Vital rate calculations are described in detail in the following sections, and concise definitions of all model parameters are provided in Table 6.

Survival

We used a proportional hazards formulation to model survival, as this provides a mathematically coherent way to incorporate and estimate multiple competing hazards (e.g., Gelfand et al. 2000, Heisey and Patterson 2006, Beyersmann et al. 2009, Brodie et al. 2013). Annual survival rates for both YOY (S_0) and adults (S_A), represent the joint probability of surviving multiple competing hazards (h), and are calculated as:

$$S_0(t) = exp\left(-1 \cdot \left[h_0(t) + h_{IC} + \sum_j h_{H0,j}(t)\right]\right) \quad (2)$$

$$S_A(i,t) = exp\left(-1 \cdot \left[h_A(i,t) + \sum_j h_{HA,j}(t)\right]\right) \quad (3)$$

The instantaneous hazard terms in equations (2) and (3) are assumed to be additive, and include baseline hazards for YOY (h_0) and adults (h_A), hazards associated with poor ice conditions for YOY (h_{IC}), and hazards associated with human removals (harvest or bycatch) for YOY (h_{H0}) and adults (h_{HA}). Equations are presented in terms of log-transformed hazards (γ), as this allows various effects to be expressed as simple additive linear equations.

Baseline hazards include all sources of "natural mortality" (excluding ice-related mortality for YOY), and for adults (γ_A) we also allow for an age (i) effect:

$$\gamma_A(i) = \alpha_0 + \alpha_1 \cdot max(0,10 - i) + \alpha_2 \cdot max(0, i - 10) \quad (4)$$

The age vector in equation (4) is re-centered by subtracting 10 to simplify fitting and parameter interpretation: specifically, α_0 represents baseline log hazards for a 10 yr-old adult (assuming that survival should have peaked at this age), α_1 represents additional log hazards for younger animals and α_2 represents additional log hazards for older animals.

For YOY we assume that baseline log hazards (γ_0) are equivalent to those of a 1-year-old juvenile with an added risk component (υ):

$$\gamma_0 = \gamma_A(1) + \upsilon \quad (5)$$

We next incorporate effects of density-dependence, environmental factors (as captured by the NLCI) and additional stochasticity:

$$\gamma_D = \phi_S \cdot N'(t) \cdot exp\big(\delta \cdot NLCI(t) + \epsilon_S(t)\big) \quad (6)$$

where parameter ϕ_S determines the strength of density-dependent effects (for computational tractability we re-scale N to units of millions of animals, designated at N'), δ determines the effect of environmental conditions, while ϵ_S accounts for stochasticity (unexplained variance) in survival and is drawn as a random normal variate with mean of 0 and standard deviation σ_S. In constructing equation (6) we assumed that the magnitude of $NLCI$ and other unexplained variance are density-dependent in nature (i.e., the greatest impacts are expected to occur at higher population densities), and thus these effects are included as exponentiated modifiers of the density-dependent effects term.

For long lived species such as harp seals, adult survival is typically buffered from effects of environmental variation and density dependence (Gaillard et al. 1998, Eberhardt 2002). We therefore assume that the effects described by equation (6) apply to YOY, and we define a corresponding log hazard term for adults:

$$\gamma_{DA} = log((exp(\gamma_D) - 1) \cdot \zeta + 1) \quad (7)$$

where parameter ζ scales the magnitude of density-dependent and environmental effects for older age classes relative to YOY (e.g., when ζ = 1 the effects are equivalent for YOY and adults, when ζ = 0 there are no density-dependent and environmental impacts on adult survival).

We sum the log-hazard effects described in equations (4) - (7) and transform by exponentiation to derive the baseline hazard terms for YOY (h_0) and adults (h_A):

$$h_0(t) = exp(\omega + \gamma_0 + \gamma_D) \tag{8}$$

$$h_A(i,t) = exp(\omega + \gamma_A(i) + \gamma_{DA}) \tag{9}$$

where ω is a constant (arbitrarily fixed at -10) that determines a minimum possible mortality rate (~0) so that the other terms summed within the exponentials represent log hazard ratios relative to this minimum.

The hazards of ice-related mortality for YOY are calculated as a function of the "ice anomaly index" (IC). The form of the functional relationship was defined based on the recognition that in years with average or above-average ice cover, there is little or no mortality, but in years when the ice cover is significantly below average the mortality rate may increase sharply. Accordingly, we calculate ice-related log hazards (γ_{IC}) for each breeding area, a, and year, t, using a scaled logit function:

$$\gamma_{IC}(a,t) = (-\omega + 1) \cdot logit^{-1}\big(-3 - \psi_a \cdot IC(a,t)\big) \tag{10}$$

where parameters ψ_a determine the relative impact of ice anomalies on mortality for each breeding area (ψ_{Gulf} and ψ_{Front}), and ω is the constant defined above ($\omega = -10$). To calculate the population-level hazards from ice anomalies, we transform by exponentiation and take the weighted average across breeding areas, with weighting determined by the proportion of YOY born in each breeding area ($P(a,t)$):

$$h_{IC}(t) = \sum_{a=1}^{3} P(a,t) \ \cdot exp(\omega + \gamma_{IC}(a,t)) \tag{11}$$

For years in which YOY surveys were conducted (t_S) the values of $P(a,t)$ were calculated from survey data: for all other years, $P(a,t)$ was drawn from a Dirichlet distribution with parameters calculated by pre-fitting a Dirichlet distribution (using maximum likelihood methods) to the observed values of $P(a,t)$.

For YOY and adults, we calculate the hazards associated with each of the four sources of human mortality (j) as hierarchical random effects:

$$\gamma_{H0,j}(t) \sim normal\big(\bar{\gamma}_{H0,j}, \sigma_{H,j}\big) \tag{12}$$

$$\gamma_{HA,j}(t) \sim normal\big(\bar{\gamma}_{HA,j}, \sigma_{H,j}\big) \tag{13}$$

where the parameters to be estimated include average log-hazards from human removals for YOY ($\bar{\gamma}_{H0,j}$) and adults ($\bar{\gamma}_{HA,j}$), and the magnitude of variance in hazards from year to year ($\sigma_{H,J}$). We then convert to hazard rates by exponentiation:

$$h_{H0,j} = exp\left(\omega + \gamma_{H0,j}(t)\right) \quad (14)$$

$$h_{HA,j} = exp\left(\omega + \gamma_{HA,j}(t)\right) \quad (15)$$

Fecundity

Fecundity was calculated using an instantaneous hazards function, for consistency with the formulation of survival rates. Typically, harp seals start producing pups as 5 year-olds, which means they can start to mate as 4 year-olds (Stenson et al. 2020). Fecundity-by-age is structured such that fecundity reaches a maximum at age 8 years old. Fecundity for females aged > 8 years is set equal to $F(8, t)$ as in Tinker et al. (2023). Therefore,

For $1 \leq i \leq 3$:

$$F(i, t) = 0 \quad (16)$$

For $4 \leq i \leq 8$:

$$F(i, t) = exp(-exp(\Omega + \beta_1 + \beta_2 \cdot (8 - i)^2 + \phi_F \cdot N'(t) \cdot exp(\delta \cdot NLCI(t-1) + \epsilon_F(t))) \quad (17)$$

For $i > 8$:

$$F(i, t) = F(8, t) \quad (18)$$

In equation (17), parameter Ω is a constant set arbitrarily to -3 (corresponding to a pregnancy rate of 0.95), and the additive terms to the right of Ω can be interpreted as log hazard ratios, increasing (in the case of terms > 0) or decreasing (terms < 0) the inverse of pregnancy probability. Parameter β_1 determines the average pregnancy rate in the absence of other effects, relative to Ω, β_2 determines the effect of age, ϕ_F determines the strength of density-dependent effects, δ determines the effect of environmental conditions, assuming a 1-year lag (i.e., female fecundity in year t is primarily affected by the $NLCI$ value in year $t - 1$), while ϵ_F accounts for stochasticity (unexplained variance) in reproductive rates and is modeled as a normally distributed random effect with mean of 0 and standard deviation σ_F. As for survival rates in equation 6, the magnitude of $NLCI$ and other unexplained variance in equation 17 were assumed as density-dependent and thus these effects are included as exponentiated modifiers of the density-dependent effects term.

Estimated population dynamics

Vital rates are organized into an age-structured and time-varying projection matrix, $\boldsymbol{M}(t)$ (Caswell 2001) of dimensions 36×36, that describes all demographic transitions at year t:

$$\boldsymbol{M}(t) = \begin{bmatrix} R(1,t) & \cdots & R(34,t) & R(35,t) & R(36,t) \\ S_A(1,t) & \cdots & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & 0 & 0 \\ 0 & \cdots & S_A(34,t) & \vdots & \vdots \\ 0 & \cdots & 0 & S_A(35,t) & S_A(36,t) \end{bmatrix} \quad (19)$$

In $\boldsymbol{M}(t)$, the terms $R(i,t)$ in the first row represent reproductive contributions of females to the 1 yr old age class the following year (assuming a 50:50 sex ratio), and thus are calculated as the product of age-specific fecundity and YOY survival:

$$R(i,t) = 0.5 \cdot F(i,t) \cdot S_0(t) \tag{20}$$

We calculate the expected age vector in the following year, $\boldsymbol{n}(t+1)$, via matrix multiplication:

$$\boldsymbol{n}(t+1) = \boldsymbol{M}(t) \times \boldsymbol{n}(t) \tag{21}$$

To initiate the population vector at $t = 0$ we multiply the estimated starting abundance (N_0, a parameter to be estimated) by the stationary age distribution (SAD) associated with the demographic schedule for $t = 1$, considering harvest mortality prevailing at that time. The SAD was calculated by projecting the $\boldsymbol{M}(t)$ matrix forward in time until the stage distribution stabilized.

Predicted YOY counts, age distribution, and harvest/bycatch mortality

The predicted number of YOY available to be counted during a survey in year t is calculated as:

$$YOY.pred(t) = 0.5 \cdot \left(\sum_{i=1}^{36} n(i,t) \cdot F(i,t) \right) \cdot (S_0(t))^{\pi(t)} \tag{22}$$

Equation (22) assumes a 50:50 sex ratio, and allows for a small amount of newborn mortality to occur prior to the pup survey: specifically, the fraction of first year mortality occurring before the survey is determined by annually varying parameter $\pi(t)$, drawn from a prior distribution with mean of 0.05 based on previous work suggesting that newborn mortality is generally quite low (Sergeant 1991).

The predicted age frequency distribution at year t is calculated as a linear array:

$$Agedist.pred(t) = \frac{n(q,t)}{\sum_{i=m}^{36} n(i,t)}, m \leq q \leq 36 \tag{23}$$

where m is the minimum age of adults to be considered for comparison with observed age distributions (set to 5 yrs based on expert opinion).

The predicted YOY harvest mortality from source j is calculated in two steps: first, the fraction of all YOY deaths accounted for by source j in year t, $f_{H0,j}(t)$ is calculated:

$$f_{H0,j}(t) = \frac{h_{H0,j}(t)}{\left(h_0(t) + h_{IC}(t) + \sum_j h_{H0,j}(t)\right)} \tag{24}$$

Second, this fraction is used to calculate the expected reported harvest/bycatch of YOY ($Hv_{0,j}.pred(t)$) from source j in year t, by removing struck and loss animals from the total:

$$Hv_{0,j}.pred(t) = 0.5 \cdot \left(\sum_{i=1}^{36} n(i,t) \cdot F(i,t) \right) \cdot (1 - S_0(t)) \cdot f_{H0,j}(t) \cdot Q_{0,j}(t) \tag{25}$$

where $Q_{0,j}(t)$ represents the proportion of killed YOY that are recovered in the harvest (i.e., 1-struck and loss rate) in year t (Supplementary Materials).

Similarly, the fraction of total adult deaths in each age class represented by harvest/bycatch from source j in year t ($f_{HA,j}(i,t)$) is calculated as:

$$f_{HA,j}(i,t) = \frac{h_{HA,j}(t)}{\left(h_A(i,t) + \sum_j h_{HA,j}(t)\right)} \tag{26}$$

We note that equation (26) implicitly assumes that for adults, removals from harvest for each age class are proportional to the living age structure (excluding YOY harvests), and thus does not account for any age bias in adult harvests. This value is then used to calculate the predicted reported total harvest/bycatch of adults in year t from source j, by removing struck and loss animals from the total:

$$Hv_{A,j}.pred(t) = \sum_{i=1}^{36}\left(n(i,t) \cdot (1 - S_A(i,t)) \cdot f_{HA,j}(i,t)\right) \cdot Q_{A,j}(t) \tag{27}$$

where $Q_{A,j}(t)$ is the proportion of killed adults from source j that are recovered in the harvest (i.e., 1- struck and loss rate) in year t. The total expected annual harvest from each source ($Hv_j.pred(t)$) is calculated as the sum of $Hv_{0,j}.pred(t)$and $Hv_{A,j}.pred(t)$.

Data model

The observed YOY abundance estimates ($YOY.obs$) at time t are assumed to follow a gamma distribution:

$$YOY.obs(t) \sim gamma\left(a = \frac{(YOY.pred(t))^2}{(SE_{sv}(t))^2}, b = \frac{YOY.pred(t)}{(SE_{sv}(t))^2}\right) \tag{28}$$

where the error estimates associated with each YOY survey point estimate (SE_{sv}) were computed prior to model fitting according to the survey analysis methods (Table 1).

Data on pregnancy rates of sampled females are treated as a beta-binomial variable: specifically, given a sample of N females of age i in year t ($NF(i,t)$), the observed number of pregnant females ($NPr.obs(i,t)$) is assumed to follow a beta-binomial distribution with probability determined by the model-estimated fecundity rates and inverse scale parameter η:

$$NPr.obs(i,t) = beta.binomial\ (NF(i,t), \eta \cdot F(i,t), \eta \cdot (1 - F(i,t))) \tag{29}$$

Counts of adult animals of age i sampled in year t ($NC(i,t)$) were compiled into linear arrays for each year, $\boldsymbol{Agedist.obs(t)} = [NC(m,t), NC(m+1,t) \ldots\ NC(36,t)]$, where $m = 5$. These observed age distribution arrays are compared to the model-predicted age distribution vectors ($\boldsymbol{Agedist.pred}(t)$). To account for additional noise and sampling error in the age counts, we use a Dirichlet-multinomial formulation:

$$\boldsymbol{Agedist.obs}(t) \sim Dirichlet.multinomial\left(\sum_{i=m}^{36} NC(i,t), \tau \cdot \boldsymbol{Agedist.pred}(t)\right) \tag{30}$$

where τ is an estimated precision parameter.

The annual reported harvest/bycatch numbers from source j are assumed to follow negative-binomial distributions parameterized with a mean and precision parameter:

$$Hv_j.obs(t) = negative.binomial\left(\bar{x} = Hv_j.pred(t), \xi_j(t)\right) \tag{31}$$

In equation (31), the annually-varying precision parameter (ξ) is calculated from the CV associated with each harvest/bycatch source:

$$\xi_j(t) = \frac{\left(Hv_j.pred(t)\right)^2}{(CV_j(t)\ \cdot HV_j.pred(t))^2\ -\ HV_j.pred(t)} \tag{32}$$

Next, to account for varying levels of uncertainty in the reported age composition of removal numbers from each source (i.e., YOY vs. adults), we treat reported numbers of harvested or by-caught YOY as draws from a beta-binomial distribution:

$$Hv_{0,j}.obs(t) = beta.binomial\left(Hv_j.obs(t), \kappa_j(t) \cdot \frac{Hv_{0,j}.pred(t)}{Hv_j.pred(t)}, \kappa_j(t) \cdot \left(1 - \frac{Hv_{0,j}.pred(t)}{Hv_j.pred(t)}\right)\right) \tag{33}$$

In equation (33) the precision parameter $\kappa_j(t)$ was set for each source and year based on the level of certainty around the proportion of YOY versus adults reported in the harvest.

Priors and model fitting

We use vague prior distributions for most parameters (i.e., scaled based on biological feasibility but having no information specific to the analysis). For ice-anomaly effects (ψ_a) we used a normal prior distribution allowing for a broad range of feasible relationships between ice anomalies and YOY mortality (the inter-quartile range for expected YOY survival from a strong ice anomaly, $IC\ =\ -2.5$, was 0.50 – 0.99). For parameter ζ, which scales the magnitude of density-dependent and environmental impacts on survival for older age classes relative to YOY, we used a gamma prior with mean = 0.1 and SD = 0.03, reflecting our assumption that density-dependent and environmental impacts primarily affect YOY and not adults (Gaillard et al. 1998). For parameter π, which determines the annual fraction of YOY mortality occurring before the pup survey, we used a beta prior with mean = 0.05 and SD = 0.03, reflecting our assumption that mortality of newborn pups is generally low prior to the survey (Sergeant 1991). For parameter υ, which scales YOY base log hazards relative to those of older animals, we used a normal prior with mean = 1.1 and SD = 0.2, which corresponds to previously reported estimates of the ratio of pup mortality to adult mortality at low population density (mean = 3x, range = 1-5x; Roff and Bowen 1983). See Table 6 for the full list of priors.

Posterior distributions for parameters were estimated using standard Markov Chain Monte Carlo (MCMC) methods. We used R (R Core Team 2024) and Stan software (Carpenter et al. 2017) to code and fit the model, saving 5,000 samples after a burn-in of 300 samples. We evaluated model convergence by graphical examination of trace plots from 18 independent chains and by ensuring that Gelman-Rubin convergence diagnostic ($\hat{R}$) was <1.1 for all fitted model parameters. We plotted and visually compared prior and posterior distributions for all parameters to assess the degree to which posteriors were distinct from priors. We conducted graphical posterior predictive checking to evaluate model goodness-of-fit, ensuring that out-of-sample predictive distributions of YOY abundance, female pregnancy rates and age distributions were consistent with distributions of observed data. We also calculated the posterior predictive Bayesian-P values for each data set (using Pearson residuals as the test statistic to compare observed vs. out-of-sample predicted data), with good model fit indicated by 0.05 < Bayesian-P < 0.95. We next employed Leave-One-Out cross validation approximation (R library "Loo"; Vehtari et al. 2017) to estimate the expected log predictive density (ELPD) for a new dataset and used the Pareto-k diagnostic to identify data observations exerting excessive influence on the joint posterior.

As an additional goodness-of-fit check, we created "out-of-sample" hindcast projections of population dynamics to compare to the fitted model projections. Specifically, for each out-of-sample projection we initiated a "new" 1951 population at N_0, and then projected forward for T years with the process model parameterized by drawing from the joint posteriors of all parameters and with hierarchical random effects drawn from their appropriate sampling distributions (except for hierarchical harvest hazard parameters, which were set to their mean estimated values). In the case of a well-fit model, the best-fit abundance trend should fall within the distribution of out-of-sample hindcast projections.

We summarize model fitting results by presenting the mean, standard deviation, median and 95% Credible intervals for parameter posterior distributions (Table 7).

MODEL ANALYSIS AND HARVEST PROJECTIONS

First, the model was used to estimate pup production in 2022 (pup survey year) as well as population abundance, N, in 2024 (current year). Second, we evaluated the stock status under the ASMS (DFO 2003) and the R-ASMS (DFO 2025). Third, we projected the IPM forward in time under various scenarios of commercial (Atlantic Canada) harvest levels and composition, while accounting for expected variation in other sources of human mortality and environmental and ice conditions (see below for details). We then estimated harvest levels that would respect the management objectives and Harvest Control Rules (HCR) under the R-ASMS and the ASMS. Finally, we calculated the PBR.

Atlantic Seal Management Strategy (ASMS)

Under the current ASMS, the objective is to ensure, with an 80% probability, that the population remains above the Precautionary Refence Point (PRP) corresponding to 70% of maximum population size estimated over the time series (N_{max}, $N_{70} = 0.7 \cdot N_{max}$), for a period of 15 years into the future (hereafter referred to as the projection interval). N_{max} was calculated as the maximum population size predicted by the IPM over the time series. If $N_{current} < N_{70}$, the HCR is to set harvest to a level that would allow the population to reach and surpass N_{70} within 10 years, with an 80% probability.

Revised Atlantic Seal Management Strategy (R-ASMS)

Under the R-ASMS, N_{max} is replaced by K. K is estimated by projecting the population model forward in time in the absence of harvest until stability in population abundance achieves a dynamic equilibrium with environmental stochasticity, climate effects (NLCI) and ice anomalies (IC) all varying according to their observed distributions over the entire historical time series. The mean asymptotic value at this dynamic equilibrium corresponds to the long-term average K. The PRP remains N_{70}, but here it is defined as 70% of K. As with the ASMS, the management objective is that the population remains above N_{70} for a period of 15 years in the future. The HCR is to bring the population back to the PRP within 1.5 generations (T) with an 80% probability. Generation time, T, represents the average age of reproducing females in the population and is calculated following Bienvenu and Legendre (2015):

$$T = 1 + \frac{\boldsymbol{vSw}}{\boldsymbol{vFw}} \tag{34}$$

Where $\boldsymbol{w}$ and $\boldsymbol{v}$ are the right and left eigenvectors associated with the dominant eigenvalue of matrix $\boldsymbol{A}$. $\boldsymbol{S}$ and $\boldsymbol{F}$ are the survival and fecundity matrices obtained by decomposing the matrix $\boldsymbol{A}$, with $\boldsymbol{A} = \boldsymbol{F} + \boldsymbol{S}$. Importantly, survival and fecundity values are not fixed across the time series but rather they vary according to environmental conditions and density. Consequently the matrices $\boldsymbol{S}$ and $\boldsymbol{F}$, as well as $\boldsymbol{v}$ and $\boldsymbol{w}$ are also time varying, resulting in variation in T. In general, T is expected to be positively correlated with population density. For a population near carrying capacity, we calculated generation time (using equation 35) as T = 19 years. Multiplying T by 1.5 results in a projection interval of 29 years, which was rounded up to 30 years in the projections.

Harvest projections under ASMS and R-ASMS

Harvest projections under the ASMS and R-ASMS were made by simulating Atlantic Canada harvest levels ranging from 1,000 to 500,000 seals per year and assuming three potential age compositions for the harvest:

1. 95% YOY/5% adults;
2. 90% YOY/10% adults; and
3. 50% YOY/50% adults.

For each combination of harvest level and composition, we ran 1,000 simulations. For each simulation, projections were made based on the IPM structure with parameters drawn randomly from the joint posterior distribution obtained from fitting the IPM.

Several assumptions had to be made about future states of variables over the projection interval:

- Removals: Removals from bycatch, Greenland harvest and the Arctic Canada harvest were drawn randomly from the distributions of observed values over the last 10 years of the time series in the projections. We thus assumed that there would be no change in removals from those sources. However, for the Atlantic Canada harvest, we projected the model forward under different harvest levels in the future.
- Whelping distribution for ice cover impacts on YOY mortality: based on pup counts, the mean proportion of pups born in each whelping area were, on average, 0.17, 0.07 and 0.76 for the Southern Gulf, Northern Gulf and Front, respectively. For projections, those proportions were rounded to 0.15, 0.05, and 0.80, respectively, and allowed to vary across years by drawing from a Dirichlet distribution with precision determined by historically observed variation.
- Environmental conditions: values for NLCI, IC, and environmental stochasticity were drawn from the distribution of historically observed values over the time series. However, a regime shift occurred in the Northwest Atlantic between early to mid-1990s, with a brief period of transient climatic forcing (Buren et al. 2014). Because of the regime shift, we expect that future environmental conditions are more likely to be comparable to the post-1995 period. To account for this, we used a logistic weighting function with an inflexion point set to 1995 (Figure 5) to adjust the probability of sampling past values. This ensured that environmental conditions in simulated projections were more similar to those prevailing during the post-1995 period than the pre-1995 period.

- Ice anomalies (IC): In addition to the logistic weighting function, we also explored the impact of accounting for forecasted changes in ice conditions associated with climate change. Several scenarios of climate change exist (IPCC 2023). The Representative Concentration Pathway 8.5 (RCP 8.5) is considered a very high greenhouse gas emission scenario, with a radiative forcing up to 8.5W/m^2 by 2100. RCP 8.5 is a worst case scenario, however, it matches well with the observed declining trend in ice conditions in harp seal whelping areas for the period 1980-2015 (Han et al. 2015, 2019). Therefore, in our projections of ice anomalies in the future, we calculated the linear trend in our index of ice anomalies between 1980-2024 and extrapolated that trend to the projection interval to simulate the RCP 8.5 scenario. The slope of the reduction in ice anomalies was -0.33 in our dataset. We present results using both unadjusted (but time-weighted) ice conditions (which we refer to as "Future ice conditions reflecting recent variability") and climate-change-projected ice conditions (which we refer to as "Future ice conditions under RCP 8.5") in our projections.

Management objectives are either to have an 80% probability that the population remains above N_{70} over the projection interval or, if below, to allow the population to reach or surpass N_{70} at the end of the projection interval. The calculation of the harvest level differs between the two approaches. The population is assumed to remain above N_{70} over the projection interval if 80% of the simulations across all years are above N_{70}. The population is assumed to have reached or surpassed N_{70} if 80% of the simulations at the final year of the projection interval are above N_{70}.

Positive Growth Scenario

We also explored an alternative approach that would ensure a 95% probability of net positive growth. For each simulation, asymptotic population growth rate (λ) was calculated each year by dividing population size at $t+1$ by population size at time t. Instantaneous population growth rate, r, was calculated as $r = log(\lambda)$. A positive growth rate was assumed over the projection interval if 95% of the distribution of the mean value of r (over the projection period) was above 0.

POTENTIAL BIOLOGICAL REMOVAL (PBR)

The Potential Biological Removal (PBR) approach aims to identify removal levels that have a 95% probability of the population increasing above the Maximum Net Productivity Level (MNPL), or if above, to remain there with a 100 year time frame. PBR is estimated as follows:

$$PBR = 0.5 \cdot R_{max} \cdot F_R \cdot N_{min} \tag{35}$$

where R_{max} is the maximum rate of population increase, F_R is a recovery factor (between 0 and 1), and N_{min} is the 20th percentile of the log-normal distribution of the most recent estimate of population size (Wade 1998). The default value used for R_{max} for pinnipeds is 12% (Wade and Angliss 1997). In the revised guidelines for the calculation of PBR in Canada (Lang et al. In Press) it has been recommended that, where it is possible to obtain a reliable estimate, the value of R_{max} for the stock being assessed should be used to calculate the PBR. Therefore, we used the IPM to estimate R_{max} ($R_{max,est}$), and calculated the PBR using both the default R_{max} (R_{max_theo}) and the model-based estimate (R_{max_est}). The value for F_R is chosen based on stock status, following decision rules in Table 1 of DFO (2025).

RESULTS

Model fitting resulted in well-mixed chains, with $\hat{R} \leq 1.1$ for all parameters (Table 7). Bayesian-P values and graphical posterior predictive checks indicated consistency between observed and out-of-sample distributions for pregnancy rate and age distribution data, but posterior predictive checks failed for pup survey data (Bayesian P value = 0.96; Figure A1) and there were 3 observations having Pareto-k values >1. Re-scaling the observer variance by a factor of 3 in the pup production dataset resulted in all observations having Pareto-k values <1, with negligible impacts on most parameter estimates (Tinker et al. under review). Therefore, we kept the observer variance unchanged here. Posterior distributions were distinct from prior distributions for all parameters (Figure A2) except ζ and υ (both of which had strongly informative priors), as well as α_0 and ψ_1(where both prior and posterior distributions indicated minimal mortality for prime age adults in the absence of other effects and expected increase in survival when ice anomalies are positive). The distribution of out-of-sample hind-cast projections of population trends were consistent with the best-fit projection (Figure A3). Data on removal had a greater contribution to model results that other sources of data (Figure A4). Detailed statistics for model parameters are provided in Table 7.

Ice anomalies showed significant inter-annual fluctuations, with a noticeable trend towards more anomalous years over time. Since 2000, 18 and 20 years (out of 23) were below the 1969-2000 baseline in the Gulf and Front, respectively (Figure 4A). The slope of the reduction in ice anomalies for the period 1998-2024 was -0.33 ice anomaly unit per year. This value was used to project future ice conditions under the “Future ice conditions under RCP 8.5” scenario.

The Newfoundland and Labrador Climate Index (NLCI) also varied across the time series (Figure 4B). There was a period of lower than average values during 1970-1995. Since then, the NLCI has been predominantly above the average (17 out of 28 years) indicating warmer conditions in recent years.

Negative ice anomalies (negative values of the IC index, indicating poorer ice conditions) were associated with significant increases in YOY mortality, especially in the Front (Figure 6). NLCI also explained variation in vital rates: there was a negative relationship between NLCI and pregnancy rates and YOY survival (Figure 7).

Model-based estimates of total removals matched well with observations (Figure 6). The model showed several shifts in the composition of removals across time. In recent years, the proportions of adults in total annual removals were near 50%. This is because on one hand the Greenland hunt, which is mostly directed towards adults, has increased over the time series and on the other hand, the Atlantic Canada hunt, which is mostly directed towards YOY, has declined since 2008 (Table 4). Averaged over the entire time series, removals represented the most important source of mortality for YOY (Figure 7A). However, density-dependent mortality has increased substantially since 1995, and ice anomalies and climate effects (NLCI) have also accounted for an increasing fraction of YOY mortality since 2000 (Figure 7A). For adults, density-dependence, ice anomalies and the NLCI contributed very little to fluctuations in adult mortality (Figure 7B). Removals from the Atlantic Canada harvest represented the main source of mortality up until approximately 1982, when removals from the Greenland harvest increased in importance as the Canadian take of adults declined. In recent years, the Greenland harvest is the most important contributor to adult mortality in NWA harp seals. Very few adults are taken in the Canadian harvest.

A significant shift in age structure occurred between 2000-2015 (Figure 2): both empirical data and model estimates indicate that the proportion of adults aged between 5 and 15 years (i.e., young adults) declined sharply over this period (Figure 10). Model estimates and empirical data suggest there may be an increasing proportion of young adults in the population since approximately 2019.

Reproductive rates have declined since the beginning of the time series (Figure 11). Over the last 20 years, model-based estimates show larger, and less regular, fluctuations in reproductive rates, although the overall average appears to have stabilized around 0.55.

Overall, model-based predictions of pup production were consistent with aerial survey estimates (Figure 12). In-between survey years, the model often predicted an increasing trend that did not match the following pup production survey. However, during the survey years, the model adjusted pup production to match observations, resulting in several spikes in model-based predictions across the time series. Pup production in 2022 (survey year) was estimated at 618,600 (95% CrI = [494,900, 735,500]; Figure 12).

Based on all sources of information, the model estimated that population abundance increased rapidly in the 1970s and peaked in 1998 at 7.54 (95% CrI = [6.75, 8.42]) million (Figure 13). Since then the population has declined with a short period of relative stability between 2009-2019. Model-based estimate of population abundance in 2019 was 5.65 (95% CI = [4.78, 6.63]). Population abundance in 2024 (current year) was estimated at 4.44 (95% CrI: [3.65; 5.35]) million (Figure 13). This represents a decline in abundance from 2019 at a rate of 4.7% (95% CrI: 2.14-7.45%) per year.

HARVEST PROJECTIONS

Reference parameters and harvest levels that would respect the ASMS and R-ASMS objectives and HCRs are presented in Table 8 and Table 9, respectively.

Atlantic Seal Management Strategy (ASMS)

N_{max} and PRP ($N_{70} = 0.7 \times N_{max}$) were 7.52 (95% CrI = [6.81, 8.35]) and 5.26 (95% CrI = [4.77, 5.84]) million, respectively. The LRP ($N_{30} = 0.3 \times N_{max}$) was estimated at 2.26 (95% CrI = [2.04, 2.50]) million. There is a 96% probability that the 2024 population abundance is below the PRP and is, therefore, in the cautious zone (Figure 13A). Projecting forward assuming ice conditions remain similar to past observations ("Future ice conditions reflecting recent variability") or would decline over time ("Future ice conditions under RCP 8.5"), there are no harvest levels that would allow the population to reach or surpass the PRP in a 10 year timeframe with an 80% probability (Table 9; Figure 14A, 14C).

Revised Atlantic Seal Management Strategy (R-ASMS)

K and PRP ($N_{70} = 0.7 \times K$) were 6.86 (95% CrI = [5.27, 8.48]) and 4.80 (95% CrI = [3.69, 5.94]) million, respectively (Table 8). The LRL ($N_{30} = 0.3 \times K$) was estimated at 2.06 (95% CrI = [1.58, 2.55]) million. There is an 80% probability that the estimated 2024 population abundance is below the PRP and is, therefore, in the cautious zone (Figure 13B).

Under the "Future ice conditions reflecting recent variability" scenario, harvest levels ranging between 113,000 (50% YOY) and 253,000 (95% YOY) seals per year would result in an 80% probability that the population would reach or surpass the PRP in 1.5 generations (Table 9; Figure 14B). Those levels would drop to 90,000 (50% YOY) and 208,000 (95% YOY) animals under the "Future ice conditions under RCP 8.5" scenario (Table 9, Figure 14D).

Positive Growth Scenario

Under the "Future ice conditions reflecting recent variability" scenario, harvest levels ranging between 57,000 (50% YOY) and 134,000 (95% YOY) seals per year would allow, with a 95%

probability, the population to show a positive growth (Table 9). Those levels would drop to 40,000 (50% YOY) and 87,000 (95% YOY) under the “Future ice conditions under RCP 8.5” scenario.

POTENTIAL BIOLOGICAL REMOVAL (PBR)

The estimated minimum population size (N_{min}) for 2024 was 4.1 million seals. The R_{max_est} was 0.15 (95% CrI: [0.14, 0.16]; Table 8), which is higher that the default R_{max_theo} for pinnipeds (0.12).

The F_R was selected following the revised guidelines for the calculation of PBR in Canada (Lang et al. In Press). For a population with a declining trend whose current stock status is greater than $0.5K$ but less than $0.7K$, the F_R is 0.75 for an estimated R_{max_est} that is greater than the default and 0.5 when the default R_{max_theo} is used.

PBR calculated using the R_{max_est} (0.15) and an F_R of 0.75 was 228,400 (rounded to the nearest hundred). PBR calculated using the default R_{max} (R_{max_theo} , 0.12) and an F_R of 0.5 was 121,800. These values include removals from all sources including reported harvest (Atlantic Canada, Arctic Canada and Greenland), struck and lost (killed but not recovered or reported), and bycatch in Canada and Greenland, and assumes that the age and sex composition of the harvest match those of the population.

DISCUSSION

The Integrated Population Model incorporates information from several sources (pup production, removals, age structure, reproductive rates and ice and climate indices) to predict population abundance and trends in the Northwest Atlantic harp seal population (Tinker et al. 2023). In this assessment, maximum population size was estimated at 7.5 million animals, which is greater than what was predicted in the last assessment (6.6 million; Tinker et al. 2023). This results from the inclusion of updated information in the model. However, the peak in abundance was predicted to have occurred at a similar time (1998 in the current assessment versus 1997 in the last assessment). In the previous assessment, the model predicted a period of stability from 2010-2019. A similar period of stability was evident in the new assessment, but after 2019, the estimated trend again becomes negative, consistent with the lower estimated pup production in 2022 (Goulet et al. In press).

In this assessment, ice anomalies were calculated as the averaged anomalies between two periods, the pupping and the post-weaning periods, thus approximating an integrated measure of platform stability. Our calculation of ice anomalies accounts for the fact that pups need a stable ice platform at birth and during their first few weeks of life while they develop the physiological capacity to feed independently and that, in some years, the ice conditions deteriorated during the post pupping season. The objective of this calculation was to better reflect the quality of the ice platform and to provide insights into ice longevity, which is affected by storm activity and approaching spring breakup, during the critical period for YOY (Tinker et al. 2023). We found that years with anomalously low ice cover in the Gulf of St. Lawrence and the Front are associated with increases in YOY mortality, although ice anomaly effects appear to be most significant for the Front likely due to the fact that most pupping occurs there. These findings are in line with the latest assessment that used an ice anomaly over the entire winter season (Tinker et al. 2023).

Offshore Newfoundland and Labrador is projected to be ice-free by 2060 (Han et al. 2015) and the Gulf has already entered a period with occasional ice-free winters (Galbraith et al. 2024). Our simulations are based on two hypotheses regarding the state of ice conditions in the future:

1. Ice conditions will remain similar to recently-observed conditions; or,
2. Ice conditions will further deteriorate, as forecasted by Han et al. (2015).

Depending on the hypothesis, harvest levels that would meet the R-ASMS vary considerably, with a greater potential harvest under conditions which reflect recent variability versus the future ice conditions predicted under climate change scenarios, such as RCP 8.5.

The future scenarios presented here are consistent with previously observed vital rate dynamics and environmental and anthropogenic effects. Yet, they could be considered as overly optimistic. This is because although we incorporated the impact of changing ice conditions in response to climate change in our projections, we made no attempts to account for future trends in the NLCI. The NLCI incorporates data from 10 environmental metrics over the NWA and as such provides a general index of environmental conditions on an annual basis (Cyr and Galbraith 2021). Climate change is expected to impact the future dynamics of several of the environmental variables included in the NLCI index and, consequently, future NLCI values. For instance, predicted increases in water temperature (Han et al. 2015, Lavoie et al. 2020), which is one component of the NLCI, will likely result in further increases in the NLCI. Our results show that the NLCI has a strong impact on both YOY survival and pregnancy rates and as such influences recruitment rates in harp seals. Further, in recent years, the NLCI has had a much greater impact on YOY survival than ice conditions and even removals in some years. Considering the negative impacts of positive NLCI values on harp seal demography, an increasing trend in this environmental index is likely to have further negative consequences for NWA harp seals that warrants close monitoring.

The current population contains a high proportion of older females (>23 years of age; Tinker et al. 2023). This is likely a result of multiple factors. First, and most importantly, intense harvest directed towards YOY during 1995-2008 contributed to curtailing those cohorts. Second, when a population approaches carrying capacity, juvenile survival and adult fecundity decreases (Gaillard et al. 1998, Festa-Bianchet et al. 2003), and age of first reproduction increases (Jorgenson et al. 1993). As a result, age structure shifts towards older age classes as a regulatory mechanism (Eberhardt 2002). The environmental context in which the NWA harp seal population lives now has drastically changed since it peaked in abundance in the late 1990s. Its ability to recover is now constrained by the interplay between environmental change, removals and low recruitment rates. If older females are not replaced by younger adults before they die or undergo reproductive senescence, it will reduce the ability of the population to recover under current environmental pressures.

Despite the current negative trends and increasing impacts of environmental factors, there may be some reasons for optimism about future recovery potential. Over the last 5 years there are indications that the age structure has begun to shift back towards younger animals (Figure 8). If these younger seals survive to sexual maturity, it will increase the future potential for pup production. Continued monitoring of the age structure over the next decade will help to resolve uncertainty, with a return to a high proportion of young animals (i.e., the age structure that prevailed prior to 2000) signaling increased growth potential.

The relative importance of mortality factors for YOY has changed considerably over the time series (Tinker et al. under review). Between 1950 and 1985, removals were the single most important contributor to YOY mortality in the NWA harp seal. Since the 2000s, YOY mortality is explained by a combination of factors, including removals, environmental factors, density dependence and other unexplained causes. Removals are no longer the most important cause of YOY mortality and we now see a much greater contribution of environmental conditions (NLCI and ice anomalies) to overall YOY mortality than removals.

The advice provided here is for the Atlantic Canada harvest. It assumes that the hunts in Arctic Canada and Greenland remain as they have been over the past 10 years. Currently, it is estimated that the Greenland hunt (~50 thousand animals per year) accounts for ~55% of the total removals and we assumed that 75% of removals in Greenland are adults. Considering that adult survival is the demographic parameter for which population growth rate is the most sensitive (Gaillard et al. 1998), the Greenland harvest is the removals component that should have the largest impact on current population recovery. However, the percentage of YOY (and conversely, of adults) in the Greenland harvest after 1984 is unknown. We assumed it to be 25%, which represents the average for the five previous years (1980-1984). This was based on indications of a change in the Greenland harvest towards fewer YOY post-1984 (Kapel 1999). Challenging this assumption results in large impacts on past and current abundance and trends. Indeed, a sensitivity analysis shows that if the Greenland harvest was comprised of 0% YOY (i.e., 100% adults), population abundance in 2024 would be 2.9 million seals. In contrast, if the Greenland harvest was comprised of 40% YOY (i.e., 60% adults), population abundance in 2024 would be 4.9 million seals (Figure 15). Improving our ability to categorize animals harvested in Greenland into YOY versus adults would be important to better understand past and current population status, but also to predict future abundance of the stock.

Another source of uncertainty is that harvest projections were based on random draws of environmental conditions from the distribution of historically observed values over the time series. This method of selection does not account for the possibility of temporal autocorrelation in environmental conditions and, thus, a series of consecutive years of either good or poor conditions would not have been captured in the projections.

The current management objective, which is to have an 80% probability that the population abundance remains above the PRP (N_{70}) for 15 years, cannot be met considering the current population status and trend. Indeed, population abundance in 2024 is already below the PRP regardless of the definition of the PRP used (ASMS or R-ASMS). Both management strategies stipulate that when population abundance falls below the PRP, actions have to be undertaken to bring the population above the PRP. Our simulations indicate that the HRC proposed under the ASMS, which is to allow the population to reach or surpass the PRP in a 10 year interval, is not achievable.

The R-ASMS and associated HCR presents more flexibility in terms of harvest levels. For a harvest comprising 90% or 95% YOY, harvest levels of 177,000 or 205,000 seals would allow the R-ASMS objectives under the most pessimistic scenario of future climate to be met. These HRC values are higher than corresponding HRC values recommended for ASMS for two reasons. First, the PRP is set at a lower value in the R-ASMS because the estimated K is below N_{max}. Following DFO guidance, K should be calculated over the longest possible time period while accounting for variation in contemporary environmental conditions (Lang et al. In Press). Because of this, it is possible that population abundance has reached above the averaged K at some point over the time series. Second, under the R-ASMS, the timeframe to reach the different objectives is greater with a 30 year period (1.5 generation time) to reach or surpass the PRP. An alternative objective based on the projection model specific to the NWA harp seal population and the projected climate, would be to simply have a high likelihood (95% probability) of population increase. This would also allow an Atlantic Canada commercial harvest, although it would be lower than the HRC proposed under the R-ASMS. The harvest levels allowing for positive growth would be 70,000 and 82,000 seals annually considering a harvest composition of 90% and 95% YOY, respectively, under the most pessimistic scenario of future climate.

In estimating the PBR, following recommendations in DFO (2025), we used the IPM to estimate the maximum population growth rate ($R_{max,est}$) as an alternative to the default value of 0.12 used for pinnipeds. Based on the IPM, $R_{max,est}$ was estimated at 0.15. Härkönen et al. (2002)

estimated that the intrinsic rate of population growth λ_{max} should not exceed 13% in true seals, or, equivalently, R_{max} should not exceed 12% and that a reported R_{max} above this value should be considered as indicative of nonstable population structure. The higher model-based R_{max} estimate reflects the very high sustained rate of increase observed between 1980-1995, a trend more consistent with the estimated R_{max} of 0.15 than the theoretical pinniped value of 0.12. However, that period of rapid increase appears to have been possible due to a combination of factors including a relaxation of harvest mortality and a period of very favorable environmental conditions and high ice cover. Under current conditions, $R_{max,est}$ is likely an overestimate. Also, there is more uncertainty in the data collected earlier in the time series. This could have led to a bias in our understanding on population dynamics at the time, including population growth. For these reasons, PBR calculated using $R_{max,theo}$ should be used instead. A difference of 3% in annual growth has large impacts for the calculation of PBR as PBR calculated using $R_{max,est}$ would allow for 106,600 more seals to be removed annually. Further work could aim at re-evaluating what the maximum population growth rate is and when it should be calculated for the NWA harp seal and for other pinniped populations in general.

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TABLES

Table 1. Pup production estimates (SE) at the three harp seal whelping patches and in total, obtained from aerial survey (A) and mark-recapture (M-R) methods.

Year	Type	Southern Gulf	Northern Gulf	Front	Total	Reference
1951	A	-	-	-	645,000 (322,500)[1]	Sergeant and Fisher (1960)
1960	A	-	-	-	235,000 (117,500)[1]	
1978	M-R	-	-	-	497,000 (68,000)[2]	Roff and Bowen (1986)
1979	M-R	-	-	-	478,000 (70,000)[2]	
1980	M-R	-	-	-	475,500 (94,000)[2]	
1983	M-R	-	-	-	534,000 (66,000)[2]	
1990	A	106,000 (23,000)	4,400 (1,300)	467,000 (31,000)	577,900 (38,800)	Stenson et al. (1993)
1994	A	198,600 (24,200)	57,600 (13,700)	446,700 (57,200)	702,900 (63,600)	Stenson et al. (2002)
1999	A	176,200 (25,400)	82,600 (22,500)	739,100 (96,300)	997,900 (102,100)	Stenson et al. (2003)
2004	A	261,000 (25,700)	89,600 (22,500)	640,800 (46,900)	991,400 (58,200)	Stenson et al. (2014)
2008	A	287,000 (27,600)	172,600 (22,300)	1,185,000 (112,000)	1,644,500 (117,900)	Stenson et al. (2014)
2012	A	115,500 (15,100)	741,000 (12,400)	626,200 (66,700)	815,900 (69,500)	Stenson et al. (2020)
2017	A	18,300 (1,500)	13,600 (3,000)	714,600 (89,700)	746,500 (89,800)	Stenson et al. (2020)
2022	A	63,900 (28,600)	46,200 (8,600)	504,000 (62,800)	614,100 (69,500)	Goulet et al. (In Press)

[1]Assumed a coefficient of variation of 50% (see Hammill et al. 2021)
[2]Standard errors have been doubled after Roff and Bowen (1986)

Table 2. Number of harp seal females sampled and proportion of females pregnant by age and year.

Year	Age	N	Preg	Year	Age	N	Preg	Year	Age	N	Preg	Year	Age	N	Preg	Year	Age	N	Preg
1954	4	4	0	1980	4	2	0	1992	4	10	2	2002	4	2	0	2012	4	2	0
1954	5	3	1	1980	5	2	1	1992	5	11	3	2002	5	4	1	2012	5	1	0
1954	6	3	2	1980	6	1	1	1992	6	9	4	2002	6	5	3	2012	6	0	0
1954	7	16	12	1980	7	0	0	1992	7	8	6	2002	7	17	10	2012	7	0	0
1954	8	33	29	1980	8	12	9	1992	8	33	21	2002	8	71	32	2012	8	12	5
1964	4	11	0	1981	4	5	1	1993	4	11	0	2003	4	1	0	2013	4	1	0
1964	5	9	1	1981	5	4	3	1993	5	17	2	2003	5	3	2	2013	5	0	0
1964	6	2	1	1981	6	2	1	1993	6	7	0	2003	6	2	1	2013	6	0	0
1964	7	4	3	1981	7	8	6	1993	7	5	4	2003	7	3	2	2013	7	1	0
1964	8	25	22	1981	8	19	14	1993	8	35	16	2003	8	91	58	2013	8	10	6
1965	4	30	1	1982	4	4	0	1994	4	23	1	2004	4	2	0	2014	4	2	0
1965	5	44	5	1982	5	5	2	1994	5	16	2	2004	5	5	0	2014	5	0	0
1965	6	37	20	1982	6	1	1	1994	6	14	6	2004	6	5	1	2014	6	1	0
1965	7	38	27	1982	7	4	3	1994	7	7	3	2004	7	1	0	2014	7	1	0
1965	8	109	96	1982	8	3	1	1994	8	41	34	2004	8	76	23	2014	8	76	65
1966	4	7	0	1985	4	4	0	1995	4	10	0	2005	4	9	1	2015	4	0	0
1966	5	9	1	1985	5	3	1	1995	5	13	6	2005	5	9	0	2015	5	1	0
1966	6	17	6	1985	6	5	2	1995	6	4	2	2005	6	13	2	2015	6	0	0
1966	7	11	8	1985	7	3	3	1995	7	5	2	2005	7	7	0	2015	7	3	0
1966	8	49	43	1985	8	1	1	1995	8	24	14	2005	8	86	55	2015	8	15	15
1967	4	10	0	1986	4	1	1	1996	4	8	0	2006	4	2	0	2016	4	7	0
1967	5	19	4	1986	5	0	0	1996	5	6	0	2006	5	0	0	2016	5	4	1
1967	6	33	20	1986	6	2	1	1996	6	4	1	2006	6	0	0	2016	6	6	2
1967	7	29	28	1986	7	1	0	1996	7	1	1	2006	7	0	0	2016	7	4	3
1967	8	123	109	1986	8	7	7	1996	8	36	24	2006	8	119	57	2016	8	91	69
1968	4	27	0	1987	4	12	2	1997	4	6	0	2007	4	1	0	2017	4	7	0
1968	5	19	6	1987	5	8	3	1997	5	4	0	2007	5	5	0	2017	5	8	0
1968	6	20	14	1987	6	9	7	1997	6	10	3	2007	6	3	1	2017	6	0	0
1968	7	12	11	1987	7	4	4	1997	7	2	2	2007	7	2	2	2017	7	2	0
1968	8	55	48	1987	8	25	15	1997	8	36	27	2007	8	84	62	2017	8	49	28
1969	4	25	1	1988	4	17	2	1998	4	6	0	2008	4	6	0	2018	4	11	0
1969	5	25	4	1988	5	6	1	1998	5	10	3	2008	5	3	0	2018	5	6	0
1969	6	16	7	1988	6	3	3	1998	6	9	2	2008	6	2	0	2018	6	2	1
1969	7	28	23	1988	7	0	0	1998	7	4	2	2008	7	0	0	2018	7	2	1
1969	8	165	146	1988	8	19	14	1998	8	36	21	2008	8	61	43	2018	8	70	52
1970	4	13	0	1989	4	8	0	1999	4	6	0	2009	4	1	0	2019	4	4	0
1970	5	13	3	1989	5	9	0	1999	5	7	0	2009	5	1	0	2019	5	2	0
1970	6	12	6	1989	6	6	2	1999	6	17	4	2009	6	1	0	2019	6	1	0
1970	7	10	9	1989	7	3	2	1999	7	15	6	2009	7	1	1	2019	7	2	2
1970	8	107	92	1989	8	23	21	1999	8	60	35	2009	8	104	59	2019	8	110	80
1978	4	40	1	1990	4	8	0	2000	4	1	0	2010	4	0	0	2020	4	6	0
1978	5	38	23	1990	5	7	1	2000	5	9	3	2010	5	0	0	2020	5	11	1
1978	6	20	18	1990	6	3	1	2000	6	6	4	2010	6	0	0	2020	6	10	0
1978	7	9	6	1990	7	1	0	2000	7	5	2	2010	7	1	0	2020	7	2	2
1978	8	0	NA	1990	8	11	6	2000	8	43	29	2010	8	114	35	2020	8	125	62
1979	4	4	1	1991	4	10	0	2001	4	2	0	2011	4	3	0	2021	4	3	0
1979	5	1	1	1991	5	11	2	2001	5	0	0	2011	5	2	0	2021	5	2	0
1979	6	0	0	1991	6	7	4	2001	6	2	2	2011	6	0	0	2021	6	7	3
1979	7	1	1	1991	7	3	1	2001	7	3	0	2011	7	0	0	2021	7	11	3
1979	8	3	2	1991	8	29	18	2001	8	39	26	2011	8	153	30	2021	8	150	65
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2022	4	0	0
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2022	5	5	0
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2022	6	6	1
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2022	7	6	0
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2022	8	103	68

Table 3. Age composition of harp seals sampled 1979-2022.

	Age																															
Year	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1979	17	9	8	5	5	2	2	3	2	3	2	1	4	1	3	1	2	2	0	1	1	1	0	0	0	0	0	1	0	0	0	0
1980	39	27	27	19	12	7	7	8	5	9	8	6	8	0	2	7	6	6	4	0	3	3	0	2	1	1	0	0	0	0	0	1
1981	28	22	18	14	8	12	5	7	3	4	11	5	6	4	4	5	6	2	2	2	0	1	1	2	0	1	0	0	0	0	0	0
1982	29	12	7	9	3	1	4	3	3	3	3	0	2	0	1	3	2	0	2	2	2	2	1	2	1	1	0	0	0	0	0	0
1983	11	2	4	2	1	2	0	1	2	0	2	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1984	9	4	6	2	2	2	2	3	0	2	2	1	1	0	0	1	3	0	3	2	1	1	0	1	1	0	0	0	0	0	0	0
1985	11	9	6	6	3	4	0	0	1	4	3	0	0	1	1	2	0	0	0	0	0	0	2	1	0	1	0	0	0	0	0	0
1986	23	19	9	9	10	5	7	7	3	4	5	5	1	6	4	5	6	4	5	4	3	0	2	2	2	0	2	1	0	3	0	0
1987	35	31	16	10	11	10	12	4	5	6	7	5	5	4	3	9	5	2	6	4	4	4	7	4	3	1	8	2	3	0	1	2
1988	28	16	11	13	8	7	4	5	8	4	7	5	3	3	5	5	0	0	1	5	6	2	1	0	1	3	1	0	0	1	0	0
1989	31	16	5	4	6	2	2	2	6	3	4	4	3	4	2	3	4	5	4	2	0	0	1	1	1	0	0	0	0	0	0	0
1990	19	12	5	1	2	3	3	3	2	1	1	2	1	3	0	4	0	2	3	0	3	1	1	0	0	1	2	0	0	0	0	0
1991	34	18	7	5	4	3	6	8	5	2	6	1	3	1	0	1	0	1	0	1	1	1	0	2	0	0	1	2	0	1	0	1
1992	18	17	12	6	9	4	3	2	1	1	0	3	3	1	5	2	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	0
1993	40	29	16	17	12	6	6	4	7	2	2	4	4	0	2	2	6	4	2	2	1	3	2	4	0	4	1	0	1	0	0	0
1994	37	29	15	15	9	7	9	2	4	3	6	1	6	6	2	0	4	2	2	3	0	0	0	3	1	1	0	1	0	0	0	0
1995	24	10	11	3	3	2	3	0	0	2	2	2	2	5	3	4	3	1	3	0	0	0	0	1	0	0	1	0	0	0	0	0
1996	19	7	4	0	1	4	4	1	2	4	3	7	10	3	2	2	4	3	2	5	1	3	1	2	0	0	0	1	0	0	1	0
1997	8	11	5	3	2	7	7	3	3	1	2	4	1	2	0	7	3	3	2	2	0	0	1	0	0	2	1	0	0	0	0	0
1998	16	13	6	12	5	0	4	3	0	4	2	0	3	2	0	2	3	0	2	2	1	2	1	2	0	0	1	1	0	0	0	0
1999	21	28	19	13	17	3	7	8	8	5	4	4	2	3	5	3	0	0	3	2	1	0	1	2	1	1	2	0	0	1	0	1
2000	15	14	7	11	7	10	6	6	5	5	4	3	2	4	2	2	1	1	1	3	0	1	0	0	0	0	1	0	1	0	0	0
2001	2	6	4	7	6	9	7	4	4	3	7	6	2	1	2	1	1	2	2	2	1	0	1	0	0	0	1	0	0	0	0	0
2002	4	7	20	7	16	3	5	6	10	7	6	4	0	2	2	5	2	2	0	2	2	1	0	1	0	0	0	0	0	0	0	0
2003	5	8	4	5	4	11	2	12	12	17	9	5	9	5	9	2	3	1	2	0	1	1	1	0	0	0	3	1	0	0	0	0
2004	7	9	2	13	8	1	11	7	7	7	11	11	14	9	8	11	3	5	6	2	3	1	2	1	1	3	1	0	0	0	1	1
2005	11	16	8	7	5	11	4	8	8	17	3	13	14	12	5	6	3	4	1	3	3	0	2	0	0	0	0	0	0	0	0	1
2006	3	5	0	8	8	15	7	13	18	17	23	22	18	17	13	15	12	0	4	4	2	3	2	3	3	1	0	0	0	0	0	1
2007	5	3	2	2	5	4	4	5	8	13	7	17	10	7	15	7	5	4	3	2	2	1	1	0	1	1	0	0	0	0	0	0
2008	5	3	0	4	3	3	6	1	1	3	11	7	6	6	3	8	3	3	0	2	4	0	1	1	0	1	0	0	0	1	0	0
2009	1	1	1	1	1	3	1	5	7	4	11	10	16	18	6	16	13	6	5	10	11	7	1	5	2	2	0	1	1	0	0	0
2010	1	2	1	0	1	0	1	1	2	0	9	11	10	17	17	15	19	22	10	15	16	9	3	6	0	4	2	0	4	2	0	0
2011	5	2	1	0	0	0	1	1	3	5	6	4	14	11	16	25	25	29	22	21	24	16	15	13	5	9	5	3	1	0	0	0
2012	2	0	0	0	0	0	0	0	0	1	0	1	2	3	2	6	2	6	6	4	7	6	2	4	2	2	0	1	0	0	0	0
2013	0	0	1	0	1	0	0	0	0	0	0	0	1	2	0	1	1	1	2	2	0	0	1	1	1	0	0	0	0	0	0	0
2014	1	2	2	2	4	0	2	2	0	1	1	1	0	2	4	8	7	14	9	14	14	11	16	8	9	7	5	0	3	0	0	0
2015	1	1	4	0	0	0	0	2	1	0	0	2	0	0	0	1	1	0	3	1	11	2	2	1	0	2	2	0	0	0	0	0
2016	6	8	5	4	1	1	0	0	3	1	1	2	2	4	3	8	6	12	8	13	25	25	15	12	10	10	2	2	2	1	3	0
2017	17	2	2	2	1	0	1	0	0	0	0	0	1	0	3	9	2	9	5	11	11	8	3	3	3	8	0	2	2	1	2	0
2018	19	15	4	1	2	1	2	0	2	3	0	0	1	1	1	7	1	3	4	7	11	4	7	2	3	11	3	2	1	0	1	1
2019	9	10	7	1	0	2	1	2	2	0	1	0	0	3	0	5	3	11	8	5	18	15	12	22	9	21	12	17	17	7	11	6
2020	13	14	4	2	2	2	0	0	2	0	3	0	1	3	3	7	4	8	6	13	23	11	16	17	16	24	11	5	10	9	5	0
2021	9	15	22	7	9	6	0	3	1	2	4	7	12	7	3	7	6	10	14	9	32	14	20	17	15	19	12	10	8	4	0	0
2022	10	7	8	7	3	6	2	4	4	1	1	1	0	2	1	6	3	8	5	4	17	6	12	10	13	12	15	18	7	1	0	0

Table 4. *Total catches and proportion of young-of-the-year (YOY) for each source of removal. Details on data collection for catches can be found in Stenson and Upward (2020).*

Year	Total catches					Proportion YOY			
	Arctic Canada	Bycatch	Atlantic Canada	Greenland	Total	Arctic Canada	Bycatch	Atlantic Canada	Greenland
1951	1,784	0	289,997	16,400	308,181	0.03	0.00	0.69	0.59
1952	1,784	0	307,108	16,400	325,292	0.03	0.00	0.64	0.59
1953	1,784	0	272,886	16,400	291,070	0.03	0.00	0.73	0.59
1954	1,784	0	264,416	19,150	285,350	0.03	0.00	0.66	0.59
1955	1,784	0	333,369	15,534	350,687	0.03	0.00	0.76	0.59
1956	1,784	0	389,410	10,973	402,167	0.03	0.00	0.88	0.59
1957	1,784	0	245,480	12,884	260,148	0.03	0.00	0.67	0.59
1958	1,784	0	297,786	16,885	316,455	0.03	0.00	0.47	0.59
1959	1,784	0	320,134	8,928	330,846	0.03	0.00	0.75	0.59
1960	1,784	0	277,350	16,154	295,288	0.03	0.00	0.56	0.59
1961	1,784	0	187,866	11,996	201,646	0.03	0.00	0.90	0.59
1962	1,784	0	319,989	8,500	330,273	0.03	0.00	0.65	0.59
1963	1,784	0	342,042	10,111	353,937	0.03	0.00	0.79	0.58
1964	1,784	0	341,663	9,203	352,650	0.03	0.00	0.78	0.58
1965	1,784	0	234,253	9,289	245,326	0.03	0.00	0.78	0.58
1966	1,784	0	323,139	7,057	331,980	0.03	0.00	0.78	0.58
1967	1,784	0	334,356	4,242	340,382	0.03	0.00	0.83	0.58
1968	1,784	0	192,696	7,116	201,596	0.03	0.00	0.81	0.58
1969	1,784	0	288,812	6,438	297,034	0.03	0.00	0.81	0.58
1970	1,784	77	257,495	6,269	265,625	0.03	0.78	0.84	0.53
1971	1,784	525	230,966	5,572	238,847	0.03	0.84	0.91	0.63
1972	1,784	622	129,883	5,994	138,283	0.03	0.77	0.90	0.57
1973	1,784	468	123,832	9,212	135,296	0.03	0.77	0.79	0.55
1974	1,784	183	147,635	7,145	156,747	0.03	0.77	0.78	0.64
1975	1,784	286	174,363	6,752	183,185	0.03	0.77	0.81	0.62
1976	1,784	1,095	165,002	11,956	179,837	0.03	0.85	0.80	0.60
1977	1,784	1,633	155,143	12,866	171,426	0.03	0.81	0.82	0.77
1978	2,129	3,376	161,723	16,638	183,866	0.03	0.82	0.72	0.42
1979	3,620	3,603	160,541	17,545	185,309	0.03	0.84	0.83	0.50
1980	6,350	2,814	169,526	15,255	193,945	0.03	0.90	0.78	0.26
1981	4,672	4,181	202,169	22,974	233,996	0.03	0.90	0.88	0.26
1982	4,881	3,817	166,739	26,927	202,364	0.03	0.91	0.87	0.31
1983	4,881	5,009	57,889	24,785	92,564	0.03	0.91	0.86	0.27
1984	4,881	4,143	31,544	25,829	66,397	0.03	0.90	0.76	0.14
1985	4,881	4,987	19,035	20,785	49,688	0.03	0.87	0.70	0.25
1986	4,881	6,109	25,934	26,099	63,023	0.03	0.85	0.84	0.25
1987	4,881	10,911	46,796	37,859	100,447	0.03	0.83	0.78	0.25
1988	4,881	8,399	94,046	40,415	147,741	0.03	0.83	0.71	0.25
1989	4,881	8,644	65,304	42,971	121,800	0.03	0.92	0.86	0.25
1990	4,881	2,769	60,162	45,526	113,338	0.03	0.71	0.57	0.25
1991	4,881	8,702	52,588	48,082	114,253	0.03	0.93	0.81	0.25
1992	4,881	23,035	68,668	50,638	147,222	0.03	0.72	0.64	0.25
1993	4,881	26,976	27,003	53,432	112,292	0.03	0.71	0.61	0.25
1994	4,881	47,604	61,379	57,068	170,932	0.03	0.77	0.41	0.25
1995	4,881	20,593	65,767	59,789	151,030	0.03	0.69	0.52	0.25
1996	4,881	29,641	242,906	74,122	351,550	0.03	0.37	0.76	0.25
1997	2,500	19,048	264,210	68,715	354,473	0.03	0.73	0.83	0.25
1998	1,000	4,557	282,624	81,249	369,430	0.03	0.79	0.89	0.25
1999	500	16,168	244,552	91,456	352,676	0.03	0.61	0.97	0.25
2000	400	11,522	92,055	97,797	201,774	0.03	0.86	0.92	0.25
2001	600	20,064	226,493	84,706	331,863	0.03	0.75	0.95	0.25
2002	1,000	9,543	312,367	65,990	388,900	0.03	0.59	0.95	0.25
2003	1,000	5,445	289,512	66,404	362,361	0.03	0.65	0.97	0.25
2004	1,000	35,870	365,971	69,892	472,733	0.03	0.69	0.97	0.25
2005	1,000	26,378	323,826	90,424	441,628	0.03	0.69	0.99	0.25
2006	1,000	21,656	354,867	93,695	471,218	0.03	0.74	0.98	0.25
2007	1,000	9,450	224,745	82,822	318,017	0.03	0.68	0.99	0.25
2008	1,000	7,280	217,850	79,110	305,240	0.03	0.68	1.00	0.25
2009	1,000	2,275	76,668	71,482	151,425	0.03	0.57	1.00	0.25
2010	1,000	3,956	69,101	88,921	162,978	0.03	0.66	0.99	0.25
2011	1,000	2,114	40,389	72,663	116,166	0.03	0.66	1.00	0.25
2012	1,000	2,886	71,460	54,730	130,076	0.03	0.72	1.00	0.25

Year	Total catches					Proportion YOY			
	Arctic Canada	Bycatch	Atlantic Canada	Greenland	Total	Arctic Canada	Bycatch	Atlantic Canada	Greenland
2013	1,000	177	97,922	64,130	163,229	0.03	0.85	0.96	0.25
2014	1,000	1,166	59,666	62,681	124,513	0.03	0.82	1.00	0.25
2015	1,000	1,040	35,382	58,876	96,298	0.03	0.81	1.00	0.25
2016	1,000	603	68,360	54,621	124,584	0.03	0.77	0.89	0.25
2017	1,000	214	81,742	47,726	130,682	0.03	0.76	0.86	0.25
2018	1,000	568	61,022	47,014	109,604	0.03	0.74	0.92	0.25
2019	1,000	1,612	32,679	48,824	84,115	0.03	0.73	0.94	0.25
2020	1,000	2,148	2,418	48,749	54,315	0.03	0.74	0.79	0.25
2021	1,000	1,682	29,724	53,934	86,340	0.03	0.71	0.98	0.25
2022	1,000	1,986	31,844	49,249	84,079	0.03	0.81	0.97	0.25
2023	1,000	1,344	42,954	49,249	94,547	0.03	0.77	0.99	0.25

Table 5. Uncertainty levels in removals and proportion of young-of-the-year (YOY) by source and year.

	Total catches				Proportion of YOY			
Year	Arctic Canada	Bycatch	Atlantic Canada	Greenland	Arctic Canada	Bycatch	Atlantic Canada	Greenland
1951	High	High	High	High	High	High	High	High
1952	High	Moderate	Moderate	Moderate	High	Low	Moderate	Moderate
1953	High	Moderate	Moderate	Moderate	High	Low	Moderate	Moderate
1954	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1955	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1956	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1957	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1958	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1959	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1960	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1961	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1962	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1963	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1964	High	Moderate	Moderate	Low	High	Low	Moderate	Moderate
1965	High	Moderate	Moderate	Low	High	Low	Low	Moderate
1966	High	Moderate	Moderate	Low	High	Low	Low	Moderate
1967	High	Moderate	Moderate	Low	High	Low	Low	Moderate
1968	High	Moderate	Moderate	Low	High	Low	Low	Moderate
1969	High	Moderate	Moderate	Low	High	Low	Low	Moderate
1970	High	Moderate	Moderate	Low	High	Low	Low	Low
1971	High	Moderate	Low	Low	High	Low	Low	Low
1972	High	Moderate	Low	Low	High	Low	Low	Low
1973	High	Moderate	Low	Low	High	Low	Low	Low
1974	High	Moderate	Low	Low	High	Low	Low	Low
1975	High	Moderate	Low	Low	High	Low	Low	Low
1976	High	Moderate	Low	Low	High	Low	Low	Low
1977	High	Moderate	Low	Low	High	Low	Low	Low
1978	High	Moderate	Low	Low	High	Low	Low	Low
1979	High	Moderate	Low	Low	High	Low	Low	Low
1980	High	Moderate	Low	Low	High	Low	Low	Low
1981	High	Moderate	Low	Low	High	Low	Low	Low
1982	High	Moderate	Low	Low	High	Low	Low	Low
1983	High	Moderate	Low	Low	High	Low	Low	Low
1984	High	Moderate	Low	Low	High	Low	Low	High
1985	High	Moderate	Low	Low	High	Low	Low	High
1986	High	Moderate	Low	Low	High	Low	Low	High
1987	High	Moderate	Low	Low	High	Low	Low	High
1988	High	Moderate	Low	High	High	Low	Low	High
1989	High	Low	Low	High	High	Low	Low	High
1990	High	Low	Low	High	High	Low	Low	High
1991	High	Low	Low	High	High	Low	Low	High
1992	High	Low	Low	High	High	Low	Low	High
1993	High	Low	Low	Moderate	High	Low	Low	High
1994	High	Low	Low	Moderate	High	Low	Low	High
1995	High	Low	Low	Moderate	High	Low	Low	High
1996	High	Low	Low	Moderate	High	Low	Low	High
1997	High	Low	Low	Moderate	High	Low	Low	High
1998	High	Low	Low	Moderate	High	Low	Low	High
1999	High	Low	Low	Moderate	High	Low	Low	High
2000	High	Low	Low	Moderate	High	Low	Low	High
2001	High	Low	Low	Moderate	High	Low	Low	High
2002	High	Low	Low	Moderate	High	Low	Low	High
2003	High	Low	Low	Moderate	High	Low	Low	High
2004	High	Moderate	Low	Moderate	High	Low	Low	High
2005	High	Moderate	Low	Moderate	High	Low	Low	High
2006	High	Moderate	Low	Moderate	High	Low	Low	High
2007	High	Moderate	Low	Moderate	High	Low	Low	High
2008	High	Moderate	Low	Moderate	High	Low	Low	High
2009	High	Moderate	Low	Moderate	High	Low	Low	High
2010	High	Moderate	Low	Moderate	High	Low	Low	High
2011	High	Moderate	Low	Moderate	High	Low	Low	High
2012	High	Moderate	Low	Moderate	High	Low	Low	High
2013	High	Moderate	Low	Moderate	High	Low	Low	High
2014	High	Moderate	Low	Moderate	High	Low	Low	High
2015	High	Moderate	Low	Moderate	High	Low	Low	High
2016	High	Moderate	Low	Moderate	High	Low	Low	High
2017	High	Moderate	Low	Moderate	High	Low	Low	High
2018	High	Moderate	Low	Moderate	High	Low	Low	High
2019	High	Moderate	Low	Moderate	High	Low	Low	High
2020	High	Moderate	Low	Moderate	High	Low	Low	High
2021	High	Moderate	Low	Moderate	High	Low	Low	High
2022	High	Moderate	Low	Moderate	High	Low	Low	High

Table 6. Description of model parameters and prior distributions.

Parameter	Name	Description	Prior distribution	Value
N_0	N0	Initial population size at time $t = 1$ (1952)	Cauchy	Location: 1; scale=0.5
η	Eta	Inverse scale parameter for beta-binomial distribution of female pregnancy status	Cauchy	Location: 0; scale=2.5
τ	Tau	Precision parameter for age distribution (divided by ten)	Cauchy	Location: 0; scale: 5
ϕ_F	phi[1]	Scale of density-dependent and environmental effects on fecundity	Cauchy	Location: 0; scale=0.1
ϕ_S	phi[2]	Scale of density-dependent and environmental effects on survival	Cauchy	Location: 0; scale=0.1
ψ_{Gulf}	psi[1]	Effect of ice anomalies on YOY survival for the Gulf	Normal	μ: 1.5; σ: 0.7
ψ_{Front}	psi[2]	Effect of ice anomalies on YOY survival for the Front	Normal	μ: 1.5; σ: 0.7
ζ	zeta	Proportional strength of density-dependent impacts for adults vs YOY	Gamma	α (shape): 16; β (rate): 160
π	pi	Annual fraction of YOY mortality occurring before the pup survey	Beta	α: 2.5; β: 47.5
υ	upsilon	Scaling factor for YOY base log hazards relative to those of older animals	Normal	μ: 1.1; σ: 0.2
σ_S	sigS	Environmental stochasticity in YOY survival	Cauchy	Location: 0; scale:0.05
σ_H	sigH	Variance in harvest log hazard rate	Cauchy	Location: 0; scale:0.5
σ_{Fx}	sigFx	Environmental stochasticity in pregnancy rates	Cauchy	Location:0; scale:0.05
β_1	beta1	Added to Ω, gives average fecundity rate in the absence of any other effect	Cauchy	Location: 0; scale: 0.1
β_2	beta2	Impact of early ages on fecundity	Cauchy	Location: 0; scale: 0.1
α_0	alpha0	Base adult log hazard	Cauchy	Location: 0; scale:0.5
α_1	alpha1	Factor increasing mortality for younger ages (<10 years)	Cauchy	Location: 0; scale: 0.1
α_2	alpha2	Factor increasing mortality for older ages (>10 years)	Cauchy	Location: 0; scale: 0.1
δ	delta	Effect of environmental conditions (NCLI) on fecundity and YOY survival	Cauchy	Location: 0; scale: 0.1
$P(a,t)$	PA	Random assignment of pup allocations to pupping areas, for non-survey years	Dirichlet	θ: [0.17, 0.07, 0.76]* 30.15

Table 7. Parameter estimates distribution along with the number of effective samples used.

Parameter	Name	***Mean***	***SD***	***2.5%***	***50%***	***97.5%***	N_{eff}	$\hat{R}$
N_0	N0(millions)	2.048	0.116	1.838	2.044	2.291	3737	1.00
η	eta	12.907	3.316	7.838	12.467	20.767	4180	1.00
τ	tau	127.305	11.966	105.652	126.584	153.012	5343	1.00
ϕ_F	phi[1]	0.236	0.036	0.168	0.235	0.312	1484	1.01
ϕ_S	phi[2]	0.594	0.063	0.476	0.592	0.722	1315	1.01
ψ_{Gulf}	psi[1]	1.267	0.553	0.022	1.325	2.167	5038	1.01
ψ_{Front}	psi[2]	1.886	0.634	0.332	2.106	2.609	1414	1.01
ζ	Zeta	0.069	0.019	0.038	0.067	0.111	3830	1.00
$\pi *$	Pi	0.050	0.031	0.009	0.044	0.125	6578	1.00
υ	Upsilon	1.112	0.201	0.705	1.111	1.501	5595	1.00
σ_S	sigS	0.156	0.043	0.083	0.153	0.249	686	1.02
$\sigma_{H,1}$	sigH[1]	0.837	0.065	0.717	0.835	0.972	853	1.01
$\sigma_{H,2}$	sigH[2]	4.1469	0.337	3.566	4.144	4.890	135	1.10
$\sigma_{H,3}$	sigH[3]	1.915	0.122	1.697	1.907	2.175	255	1.06
$\sigma_{H,4}$	sigH[4]	0.528	0.041	0.454	0.527	0.616	652	1.02
σ_F	sigF	0.281	0.061	0.183	0.275	0.425	1651	1.01
β_1	beta1	1.234	0.130	0.969	1.236	1.489	2100	1.01
β_2	beta2	0.147	0.008	0.130	0.147	0.162	3192	1.00
α_0	alpha0	0.248	0.231	0.007	0.184	0.852	2467	1.01
α_1	alpha1	0.650	0.041	0.566	0.653	0.724	1951	1.01
α_2	alpha2	0.334	0.013	0.306	0.336	0.356	2526	1.04
δ	dlta	0.466	0.061	0.353	0.463	0.595	1702	1.01
$P(S\_Gulf)$*	PA[1]	0.169	0.058	0.074	0.163	0.299	7528	1.00
$P(N\_Gulf)$*	PA[2]	0.069	0.039	0.016	0.061	0.166	6538	1.00
$P(Front)$*	PA[3]	0.762	0.066	0.620	0.767	0.877	7556	1.00

*Average across years

Table 8. Parameters used to calculate harvest levels that would respect the management objectives under each management strategy. With the exception of $R_{max,theo}$, which is taken from the literature (Lang et al. In Press), all parameters were estimated directly from the IPM.

Management strategy	Parameter	Mean (millions)	Lower 95%CI	Upper 95%CI
ASMS	N_{max}	7.52	6.81	8.35
	N_{70}	5.26	4.77	5.84
R-ASMS	K	6.86	5.27	8.48
	N_{70}	4.80	3.69	5.94
PBR	N_{min}	4.06	-	-
	$R_{max,est}$	0.15	0.14	0.16
	$R_{max,theo}$	0.12	-	-

Table 9. Harvest levels compatible with the different management objectives and harvest control rules under the current and revised Atlantic Seal Management Strategy frameworks (ASMS and R-ASMS). Model projections were made assuming that ice conditions in the projection interval will either remain similar to past conditions, with a stronger weight given to ice conditions during the period 1995-2023 ("Future ice conditions reflecting recent variability") or follow a declining trend, as forecasted in Han et al. (2015)("Future ice conditions under RCP 8.5"). Three scenarios of harvest composition (proportions of young-of-the-year, YOY, vs adults) are presented: 1) 95% YOY/5% adults, 2) 90% YOY/10% adults, 3) 50% YOY/50% adults. Note that harvest levels are presented on an annual basis and pertain only to the Atlantic Canada harvest, other sources of removal were assumed constant (average over the last 10 years) over the projection interval. We also present an alternative management objective which would ensure a 95% probability of positive population growth. A dash ("-") signifies that the management objective cannot be met, even in the absence of harvest.

Harvest scenario	**ASMS**: Reach above N_{70} in 10 years, with 80% probability	**R-ASMS**: Reach above N_{70} in 1.5 generations with 80% probability	Positive growth, with 95% probability
Future ice conditions reflecting recent variability			
95% YOY	-	253,000	134,000
90% YOY	-	222,000	108,000
50% YOY	-	113,000	57,000
Future ice conditions under RCP 8.5			
95% YOY	-	208,000	87,000
90% YOY	-	181,000	79,000
50% YOY	-	90,000	40,000

FIGURES

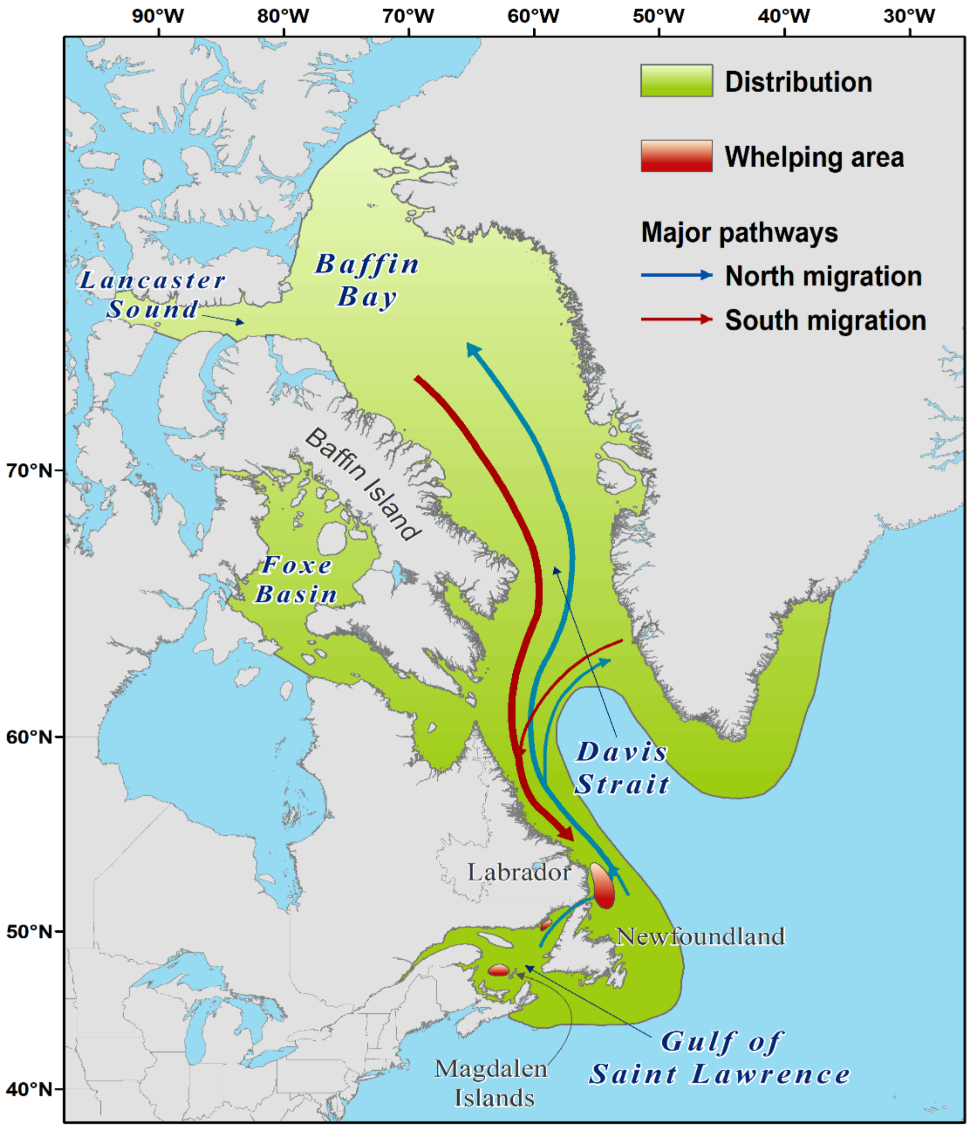

Figure 1. Distribution of the Northwest Atlantic harp seal population, along with main migratory pathways. Whelping patches are shown as red polygons.

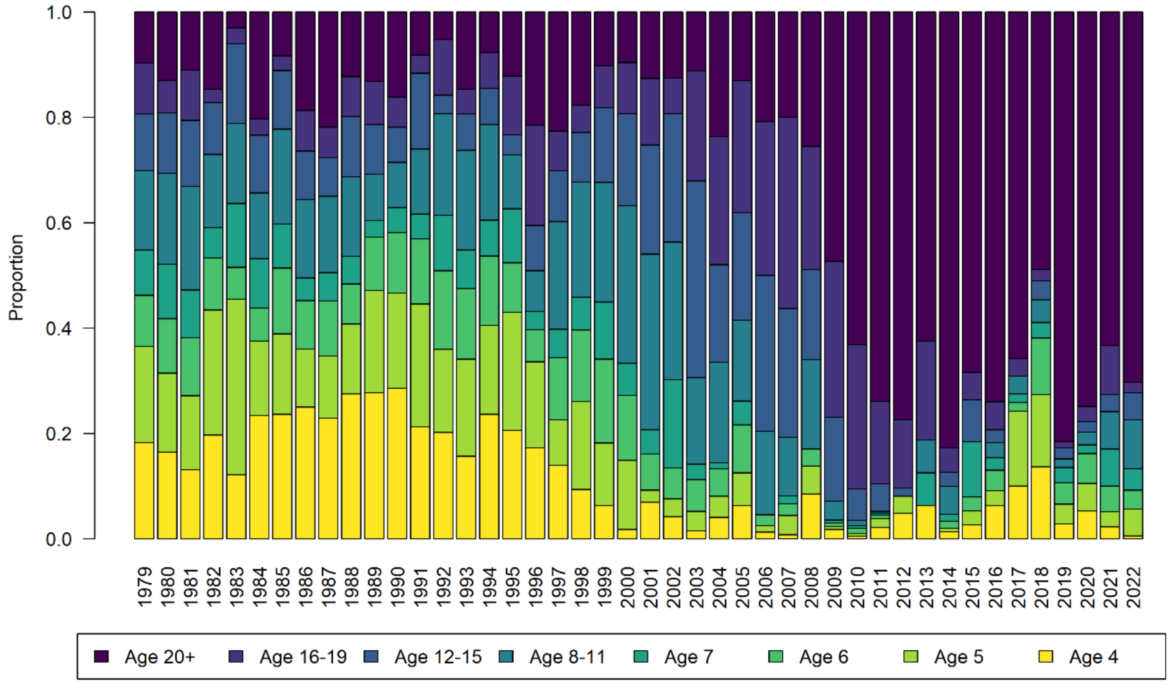

Figure 2. Proportion of samples comprised of different age classes (years) collected by year between 1979-2022. Only ages ≥ 5 are used in the integrated population model.

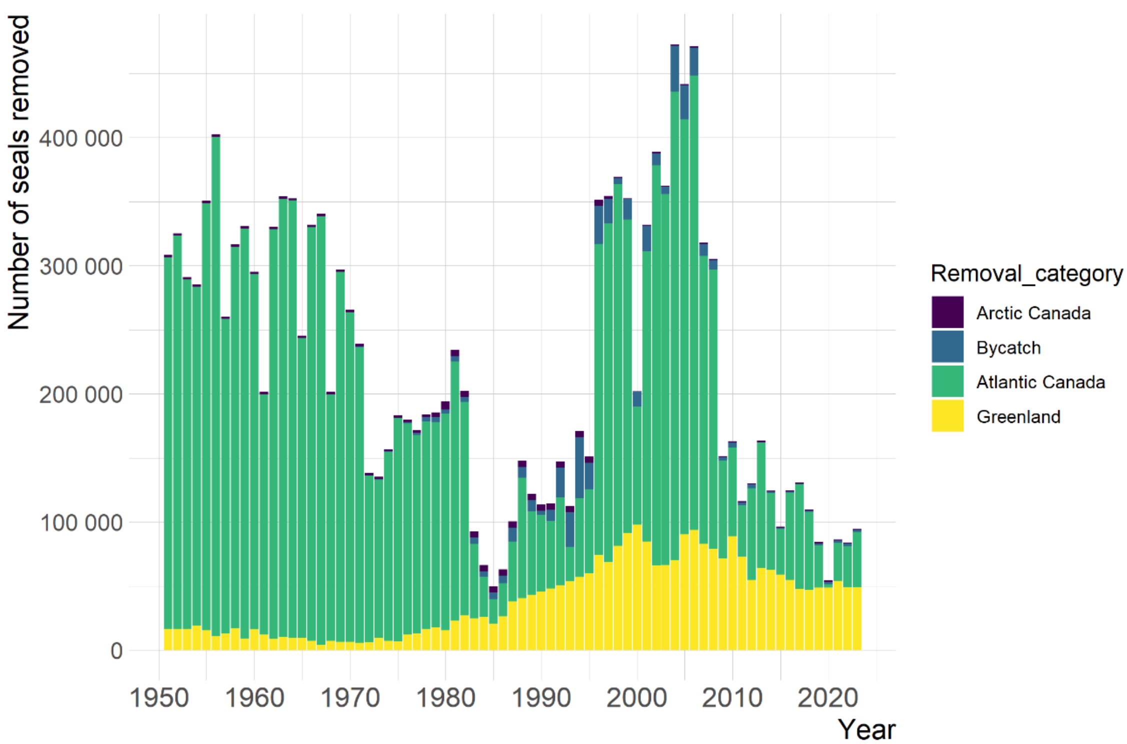

Figure 3. Total removals of NWA harp seals by source for 1952-2023.

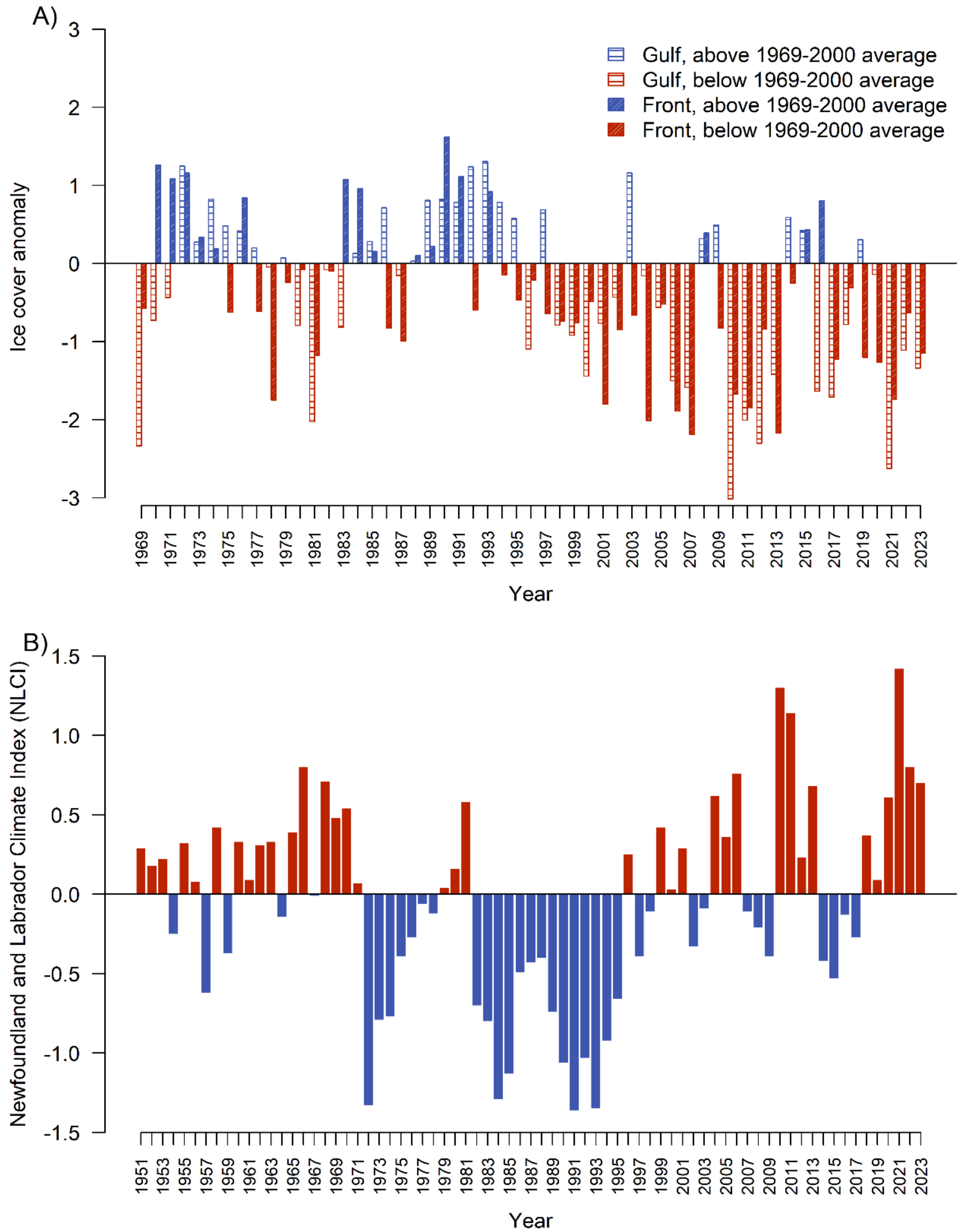

Figure 4. A) Ice anomalies using mean first-year ice cover during 1969-2000 as the baseline. Positive anomalies mean more ice cover, negative anomalies mean less ice cover. Data from the Canadian Ice Service of Environment and Climate Change Canada for the areas Gulf of St Lawrence and southern Labrador. B) Newfoundland Climate Index (NLCI) for 1951-2019 developed by Cyr and Galbraith (2021). Positive anomalies reflect warmer conditions, negative anomalies reflect cooler conditions.

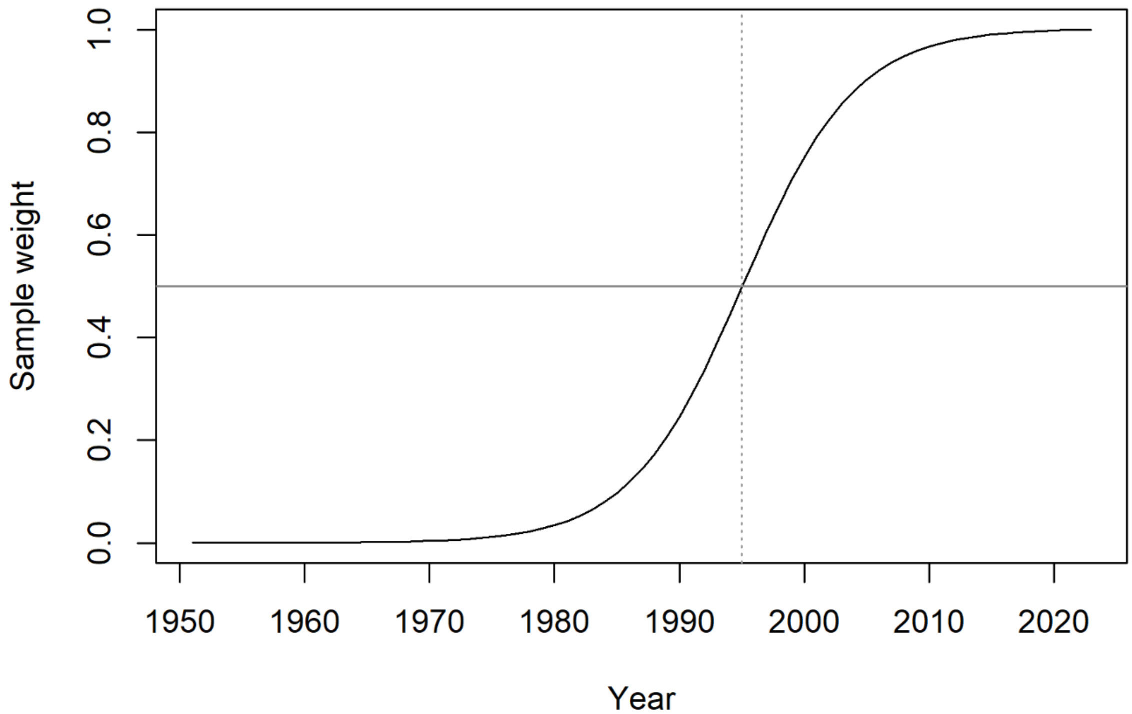

Figure 5. Weighting function used to draw future environmental conditions (NLCI, IC and environmental stochasticity) over the projection interval. Greater probabilities were given to environmental conditions prevailing during the post-1995 period in projections.

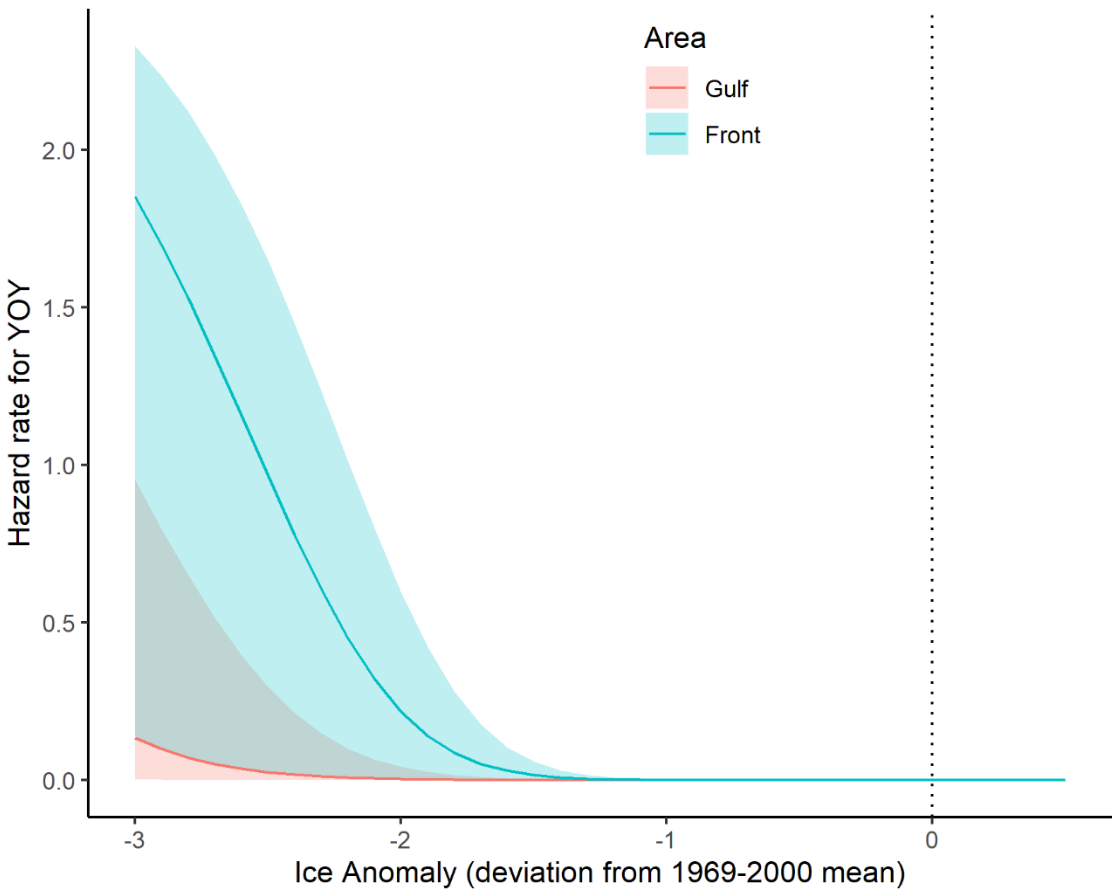

Figure 6. Model-based prediction (line: average prediction with bounds of the polygons representing the 20th and 80th percentiles of the posterior distributions) of the relationship between ice anomalies and hazard rate for YOY at the Gulf and Front whelping patches. An ice anomaly value of zero (dashed vertical line) means similar ice cover compared to the reference level, and a value below zero means less ice than the reference level.

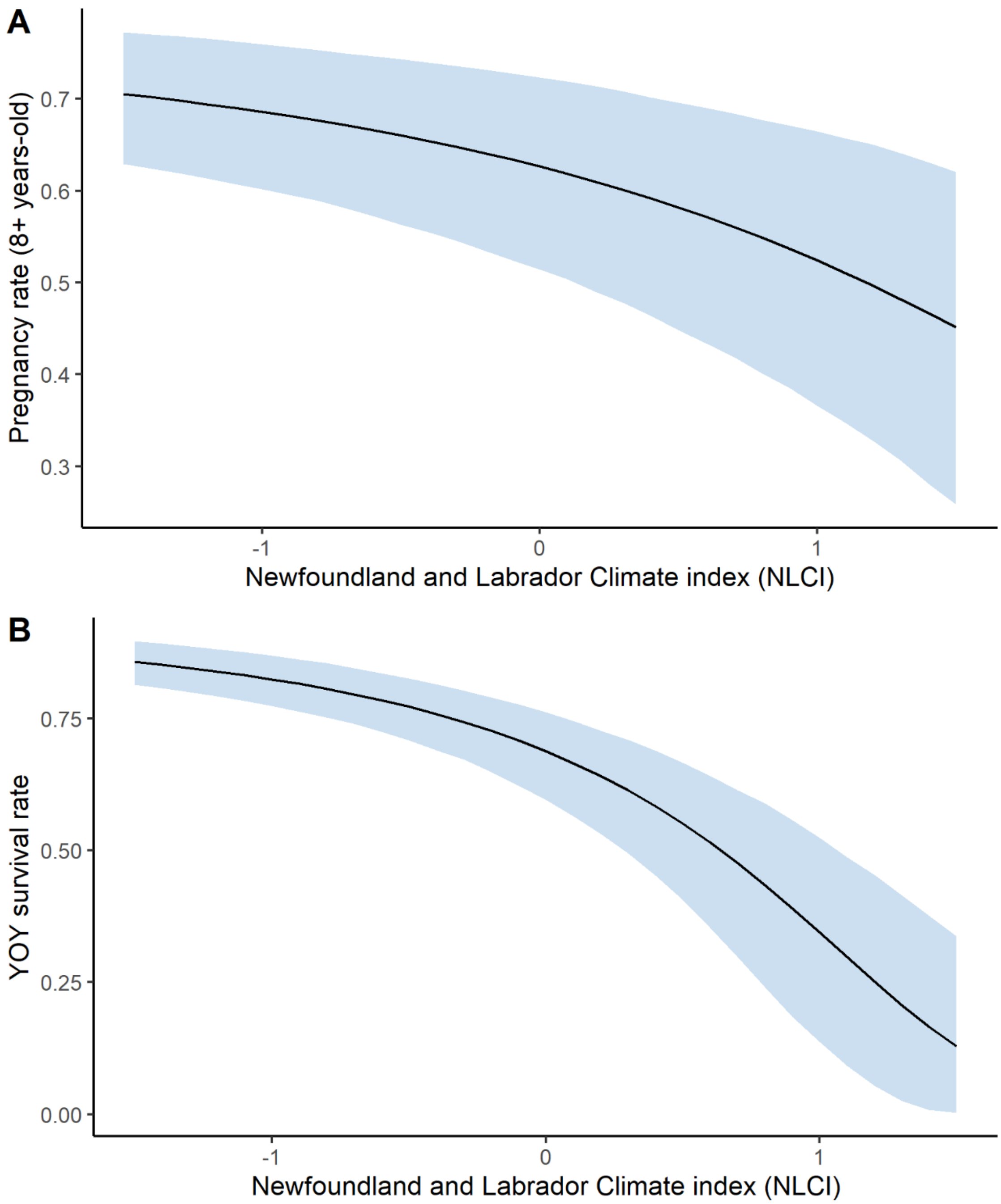

Figure 7. Model-based prediction (line: average prediction; polygon: 95% Credible Interval) of the impact of the Newfoundland and Labrador Climate Index (NLCI) on A) pregnancy rates (here the relationship is shown for adult females of age 8+ years old) and B) YOY survival.

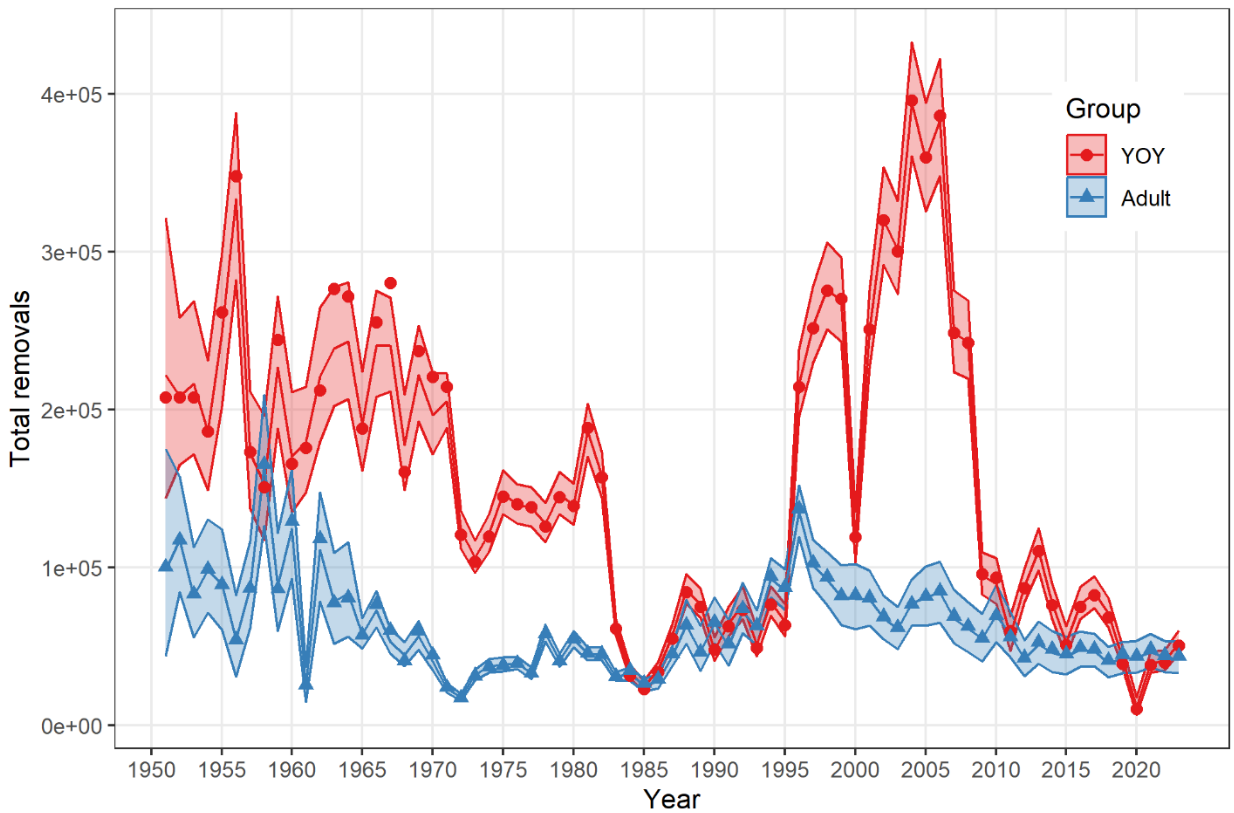

Figure 8. Model-based estimate of total removals of young-of-the-year (YOY; red) and adult (1+ year-olds; blue) NWA harp seals (line: average prediction; polygon: 95% Credible Interval). Observations are also presented (dots and triangles).

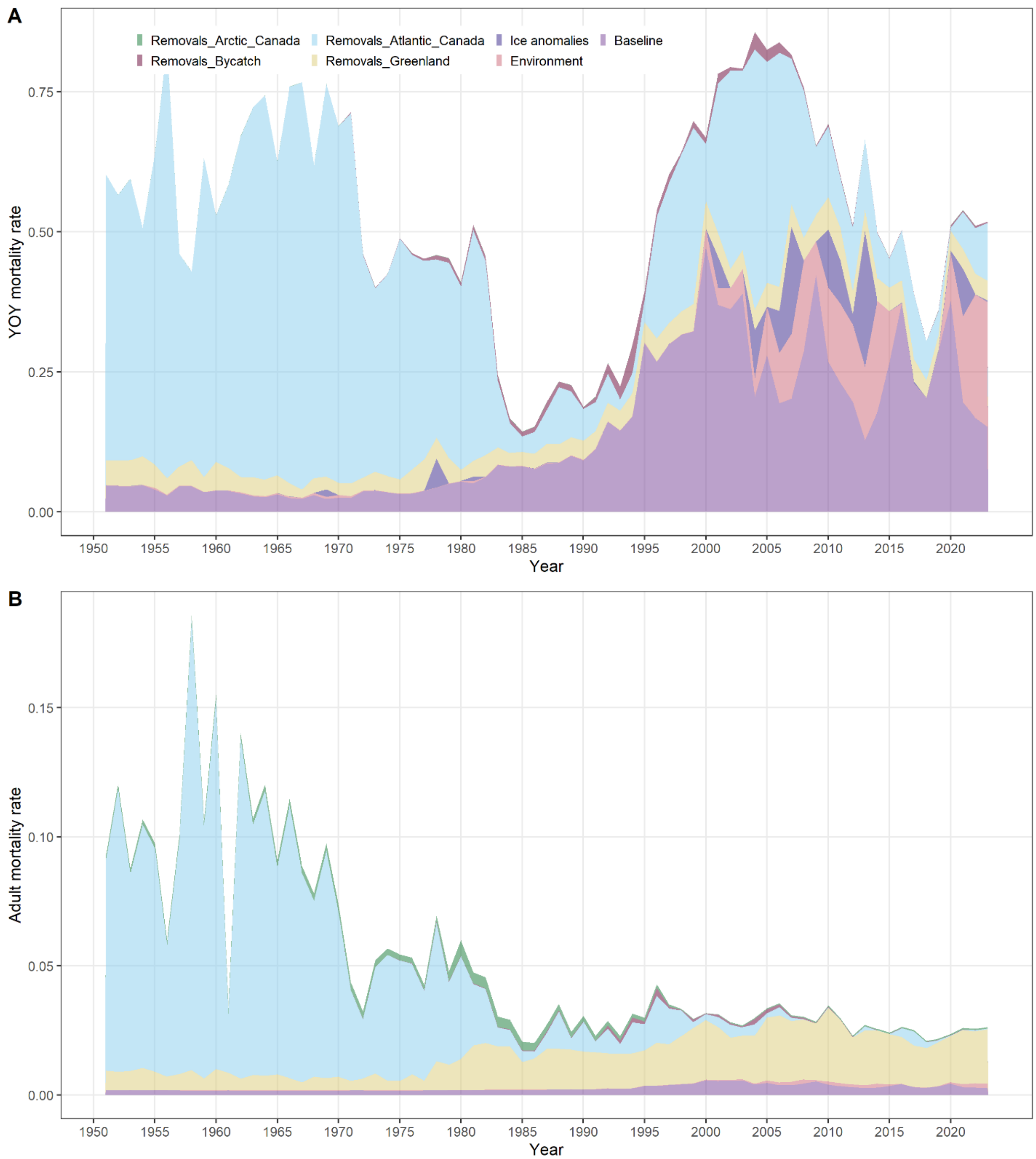

Figure 9. Model-based decomposition of the contribution of different sources of mortality to the total annual mortality rate of (A) young of the year (YOY) and (B) adult NWA harp seals. The different sources are: removals from Arctic Canada (turquoise), Atlantic Canada (blue), bycatch (dark pink), Greenland (beige), ice anomalies (dark purple), environmental effects (NCLI; pink) and baseline combined with density-dependence (purple).

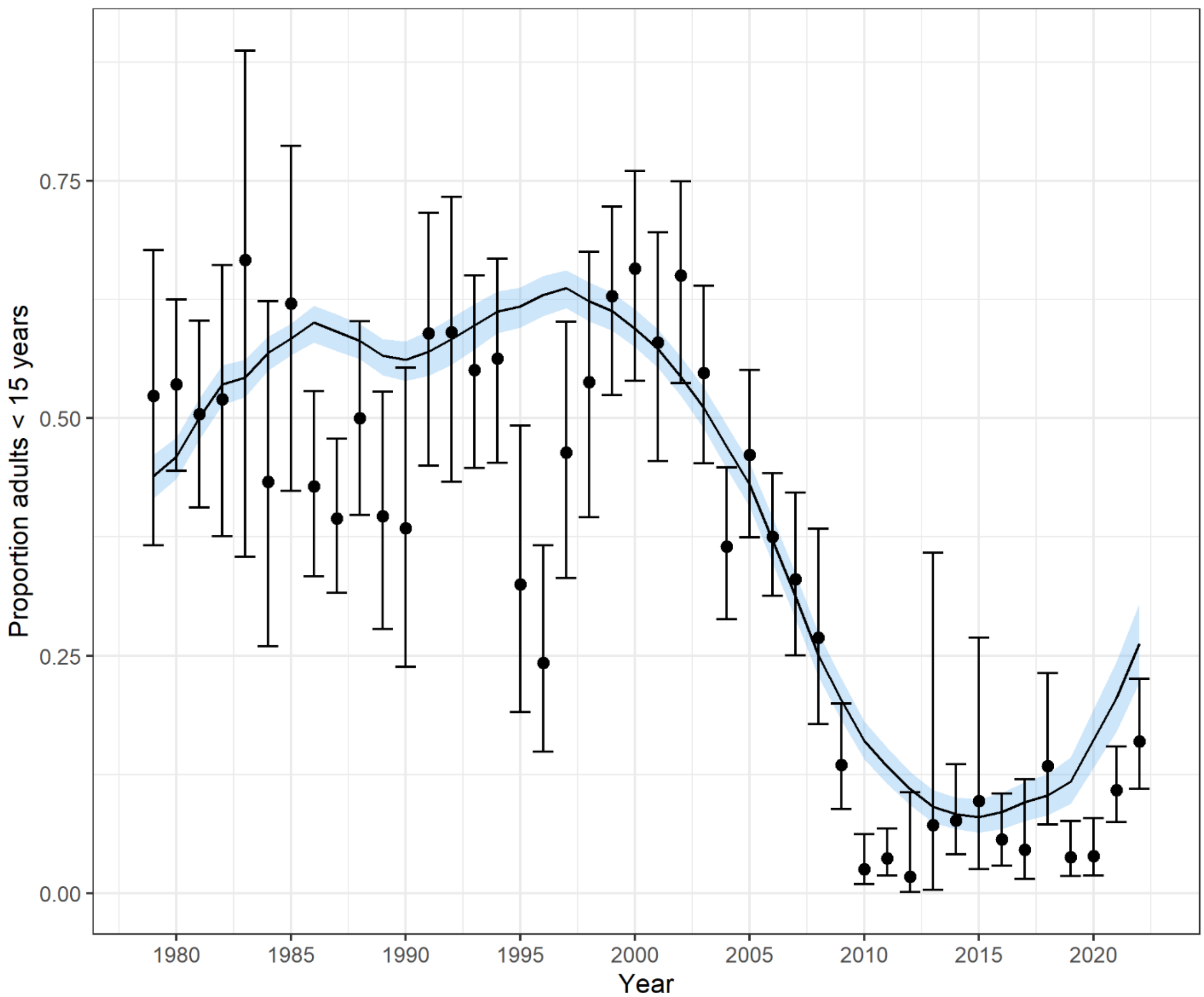

Figure 10. Model-based predictions (line: average prediction; polygon: 95% Credible Interval) of the proportion of adults aged between 5 and 15 years old ("young adults") across the time series. Observations with 95% Confidence intervals are also shown (dots and bars).

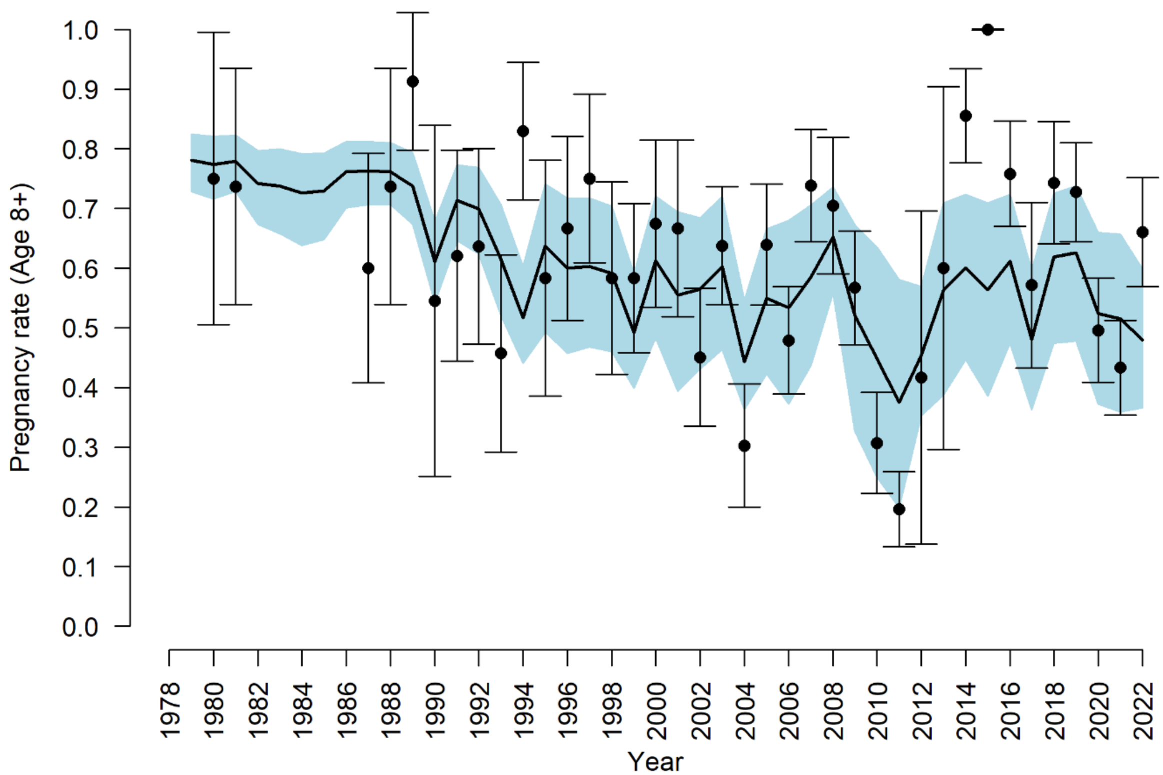

Figure 11. Model-based predictions of reproductive rates for females aged 8+ across the time series (line: average prediction; polygon: 95% Credible Interval). Observations with 95% Confidence intervals are also shown (dots and bars).

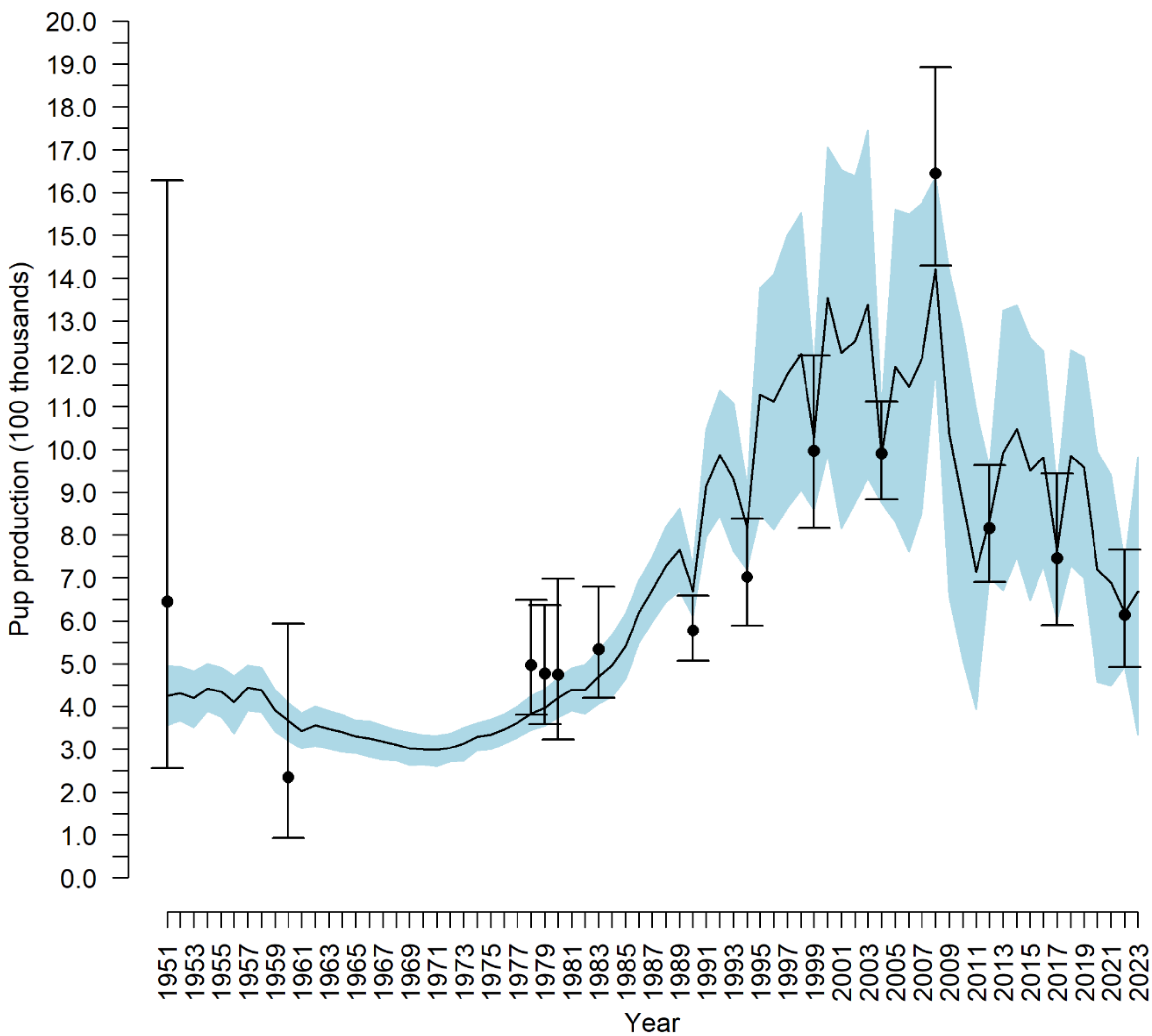

Figure 12. Model-based predictions (line: average prediction; polygon: 95% Credible Interval) of pup production across the time series. Observations with 95% Confidence intervals are also shown (dots and bars).

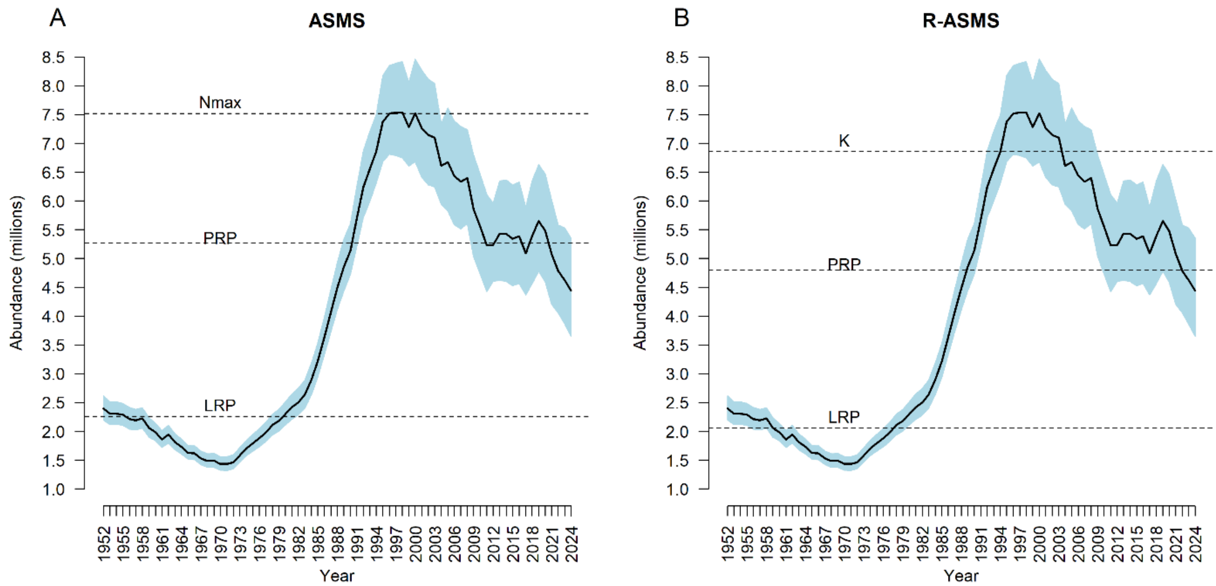

Figure 13. Model-based predictions (line: average prediction; polygon: 95% Credible Interval) of population abundance across the time series with the upper reference levels, the Precautionary Reference Point (PRP) and the Lower Reference Point (LRP) under the A) current Atlantic Seal Management Strategy (ASM) and B) Revised Atlantic Seal Management Strategy (R-ASMS).

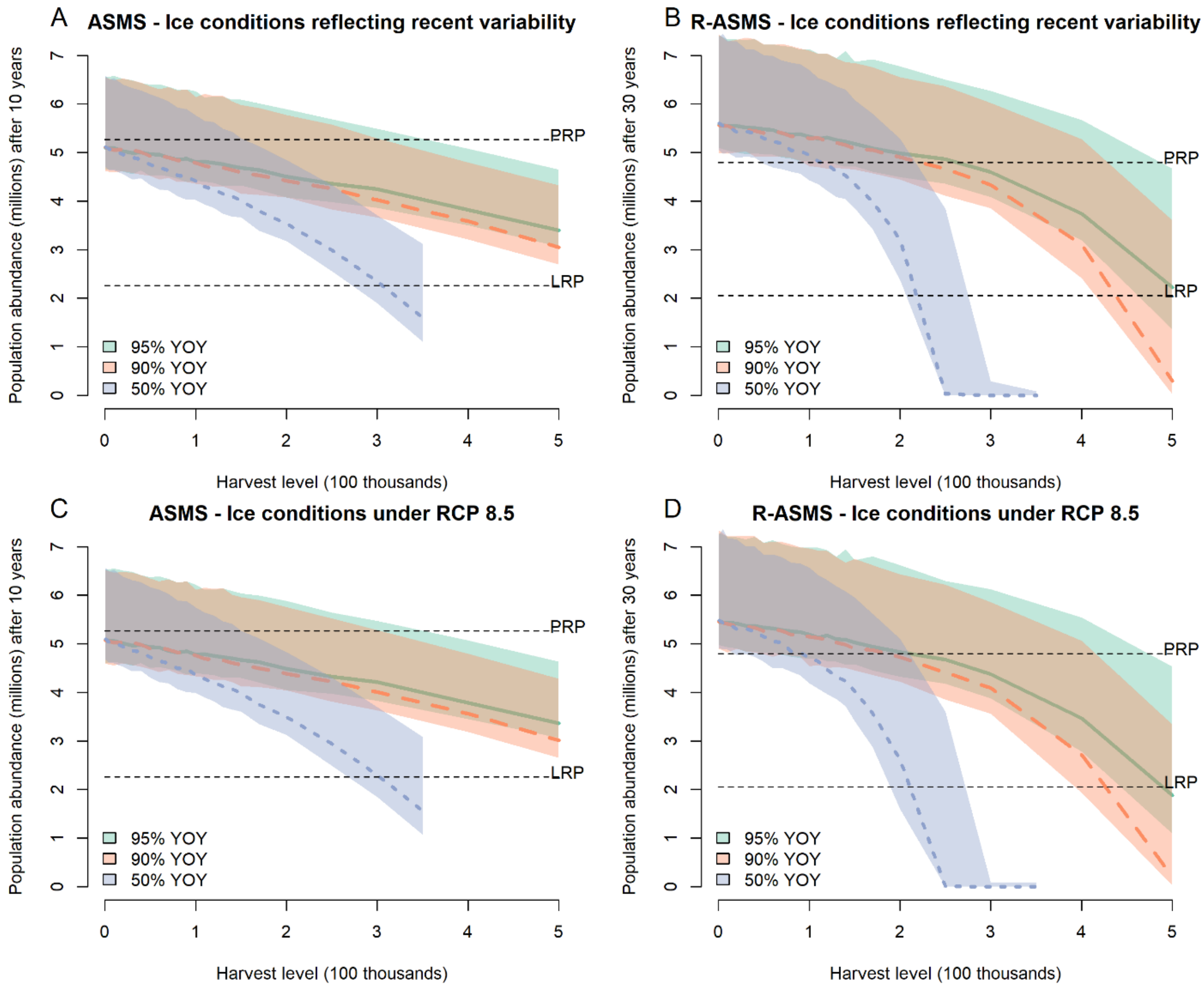

Figure 14. Projections of future NWA harp seal population abundance after 10 (panels A and C) or 30 (panels B and D) years under two scenarios of future ice conditions: 1) ice conditions in the future will reflect recent variability (panels A and B) or 2) ice conditions in the future will follow the declining trend projected under the RCP 8.5 greenhouse gas emission scenario (panels C and D). Projections are for various levels of simulated harvest in the future (x-axis) and the colors represent three potential age compositions of the harvest (blue = 50% adults/50% YOY, orange = 10% adults/90% YOY, and green = 5% adults/95% YOY). The colored lines represent the 20th percentile of the projected population abundance for each age composition category. The Precautionary Reference Point (PRP) and the Lower Reference Point (LRP), which are calculated as 70% and 30% of N_{max} under the Atlantic Seal Management Strategy (ASMS) and as 70% and 30% of K under the Revised Atlantic Seal Management Strategy (R-ASMS), respectively, are shown as dashed horizontal lines. Following the Harvest Control Rule (HCR) under the ASMS (panels A and C), the 20th percentile of the projected population abundance should reach above the PRP at the end of a 10 year projection period. Following the HCR under the R-ASMS (panels B and D), the 20th percentile of the projected population abundance should reach above the PRP at the end of a 30 year (or 1.5 generations) projection period.

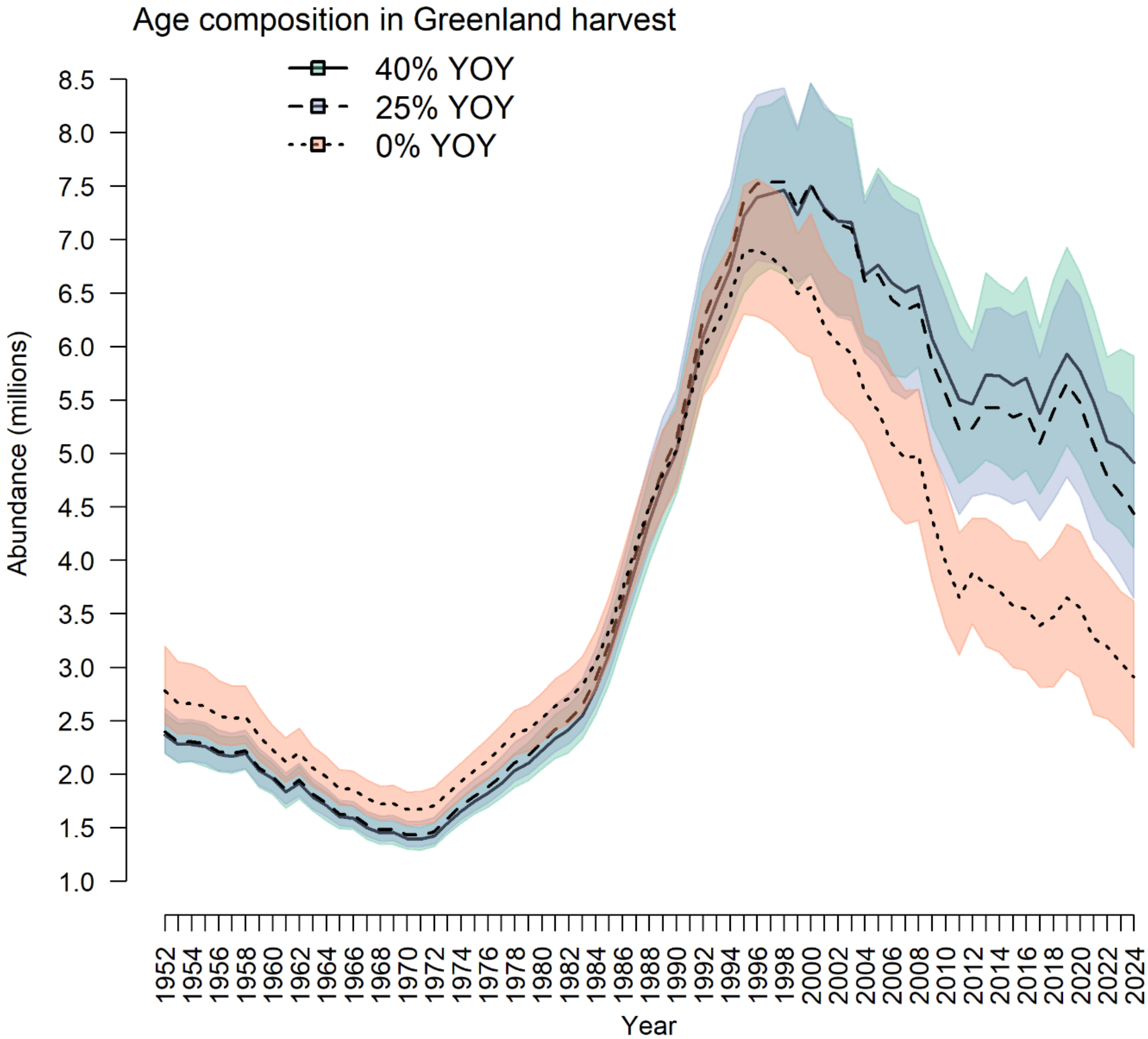

Figure 15. Sensitivity of Northwest Atlantic harp seal stock abundance estimate to the age composition of the Greenland harvest. Lines represent average predictions and polygons the 95% Credible Intervals.

APPENDIX 1

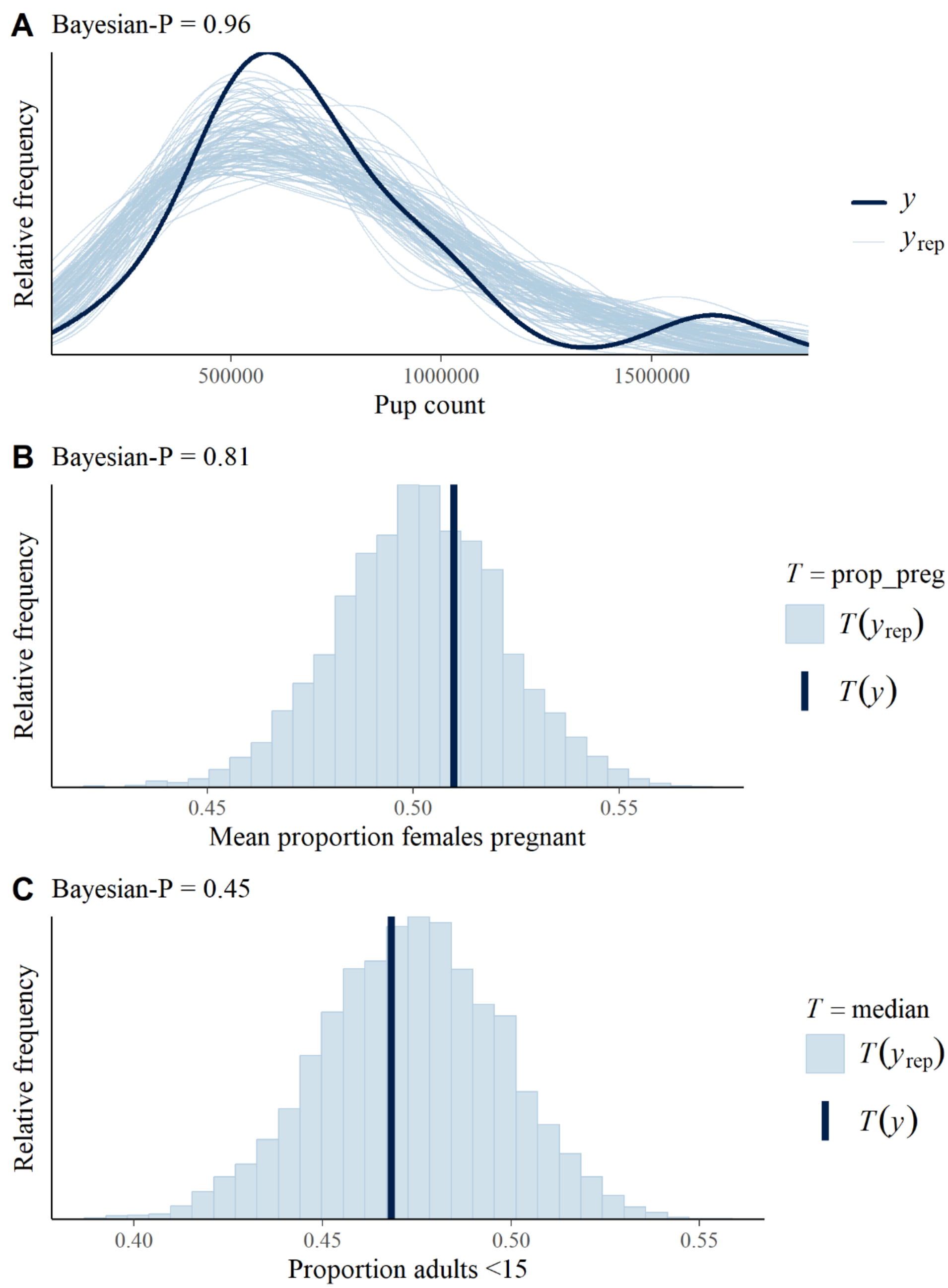

Figure A1. Comparison between observations and out-of-sample projections for A) pup counts, B) proportion of females pregnant and C) proportion of adults between age 5 and 15 years old in the samples. Bayesian P-values are also shown on top.

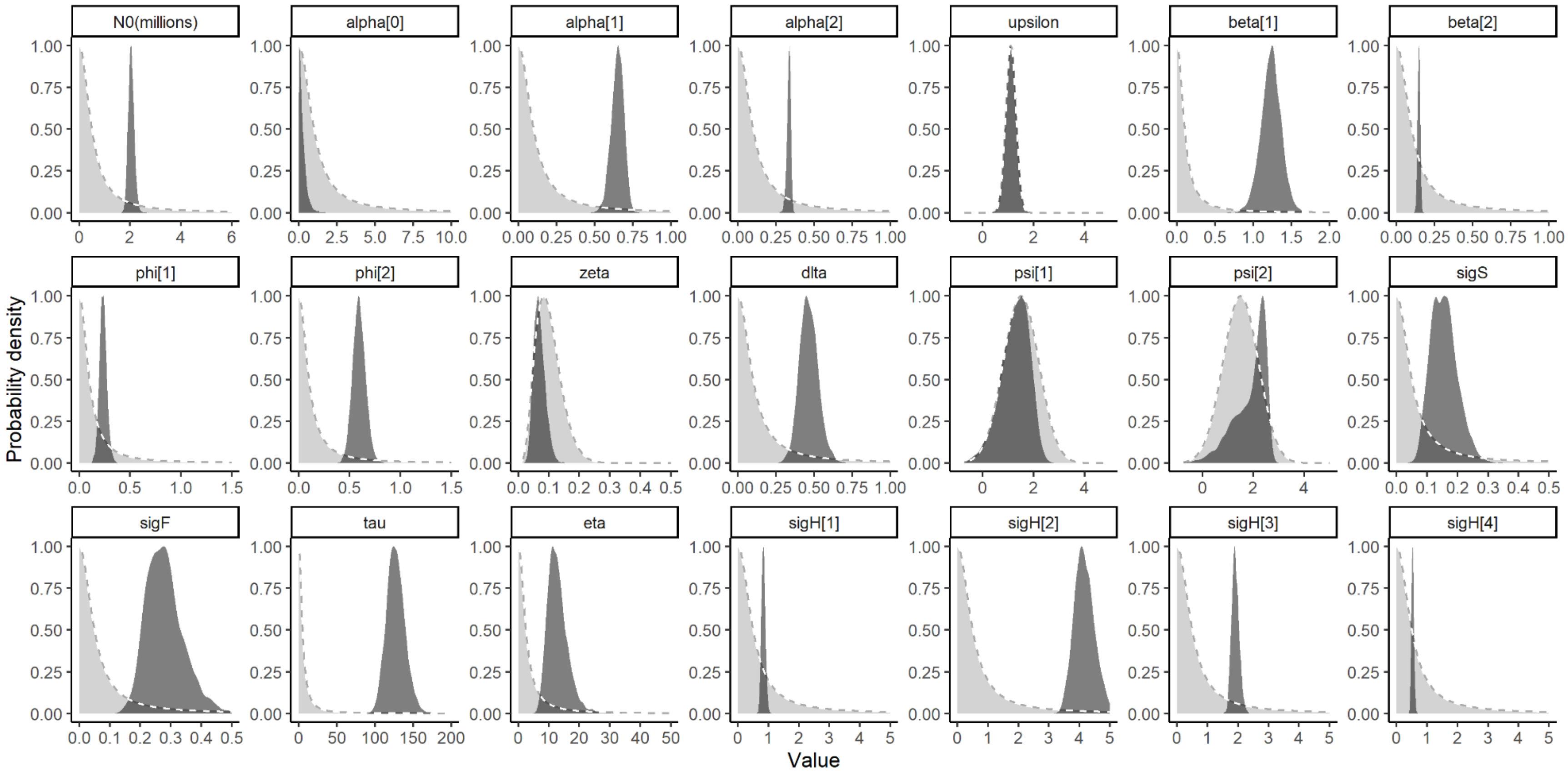

Figure A2. Prior (light grey) and posterior (dark grey) distribution of parameters.

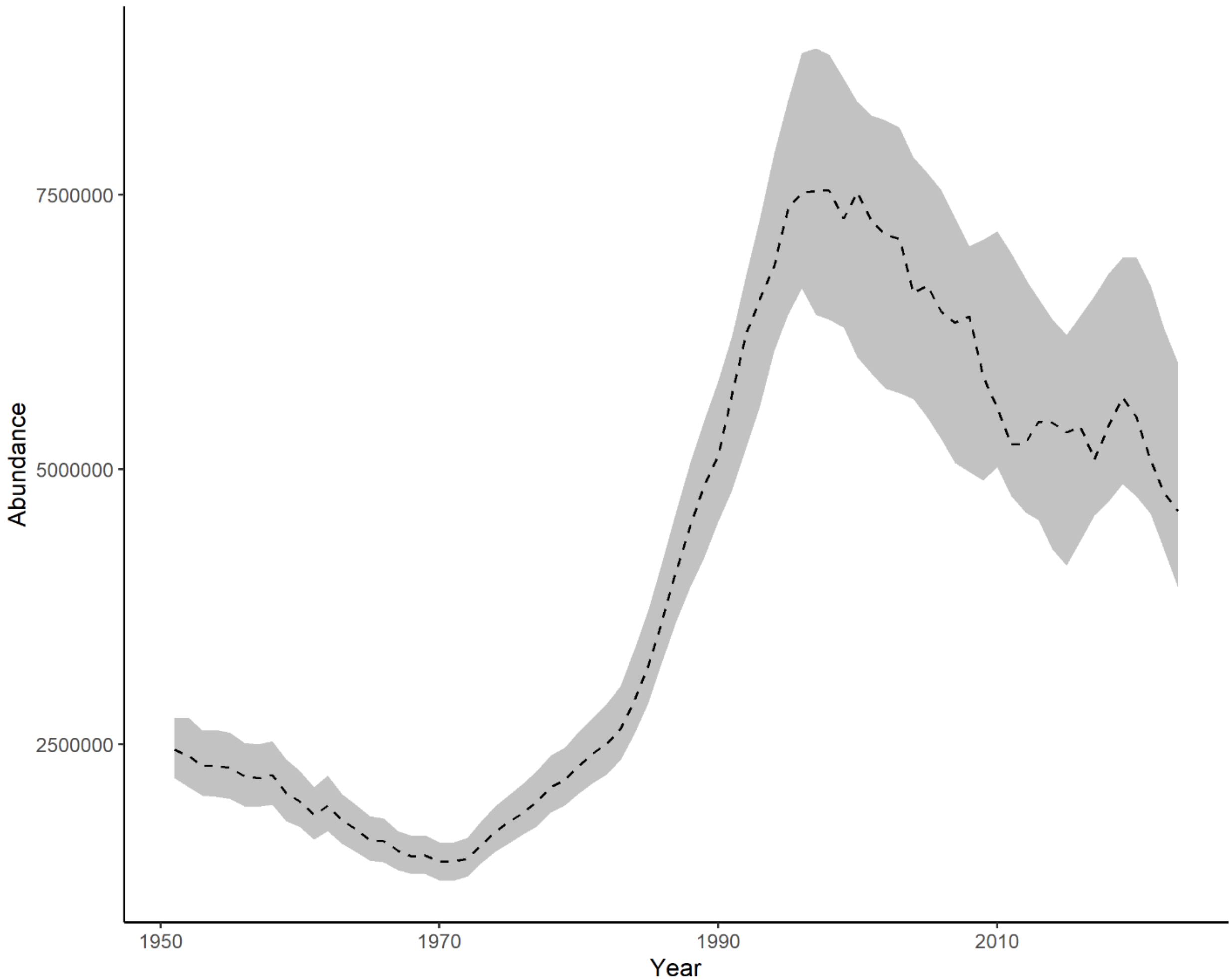

Figure A3. Hindcast posterior predictive simulations of population abundance (95% confidence interval in grey), with the model-estimated trend shown as a dashed black line.

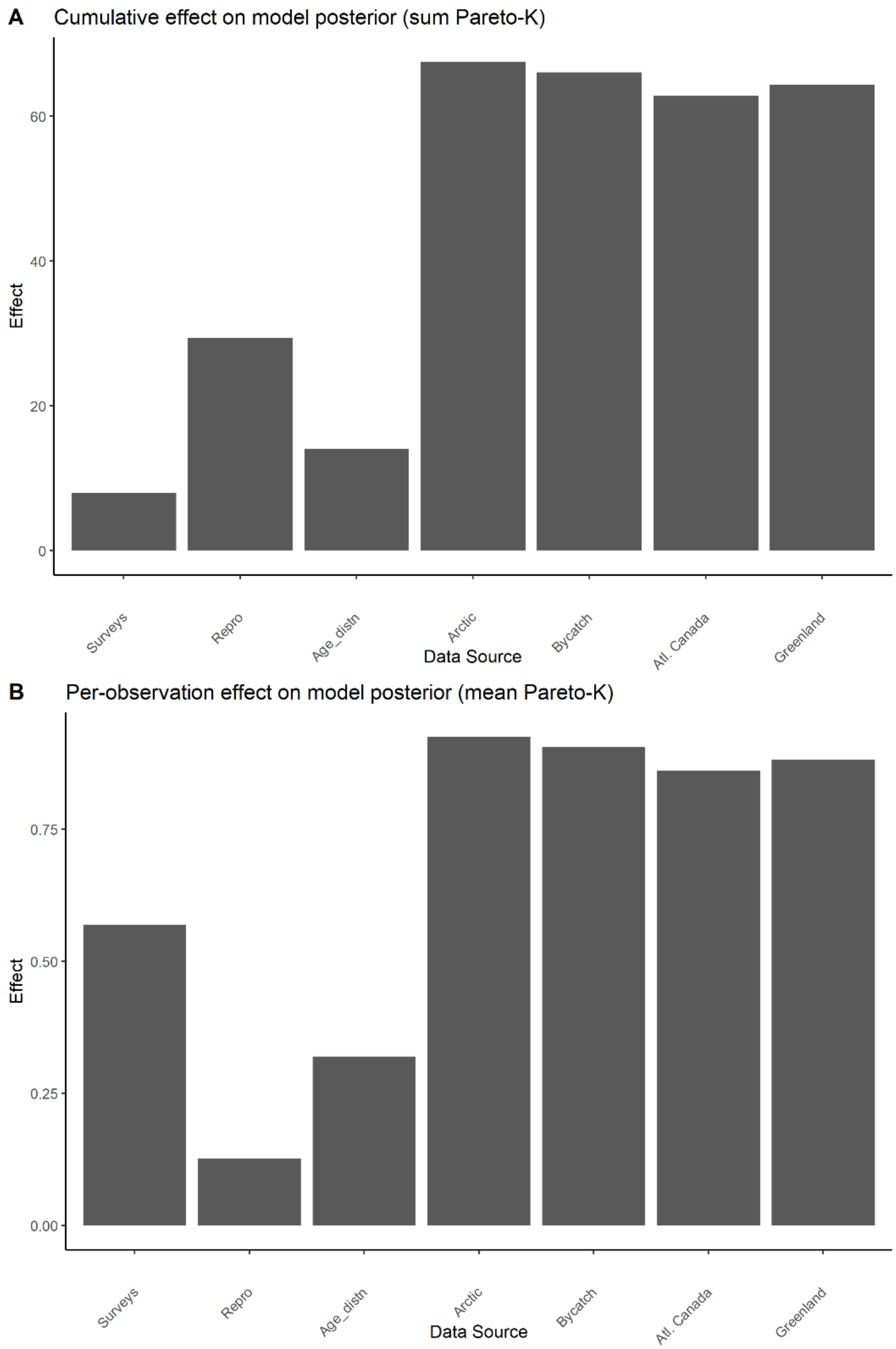

Figure A4. Relative contribution of different datasets to model predictions. Definitions: Surveys = pup counts during surveys, Repro = reproductive rates data, Age_distn = age composition data, Arctic = Arctic removals data, Bycatch = bycatch data, Atl. Canada = Atlantic Canada removals data, Greenland = Greenland removals data.

APPENDIX 2: SUPPLEMENTARY INFORMATION ON CATCH DATA

Northwest Atlantic harp seals are taken by commercial and subsistence hunters in the Atlantic Canada waters off southern Labrador and/or the Northeast coast of Newfoundland (‘the Front’-NAFO Divisions 2J and 3KL), in the Gulf of St. Lawrence (‘the Gulf’-NAFO Division 4RST), off western and southeastern Greenland (NAFO Division 1A-F; ICES Area XIVb), and in the eastern Canadian Arctic (primarily along the east coast of Baffin Island).

For each source of human removal, there are recognized uncertainties in the reported numbers of removals by year and, likewise, in the proportion of the reported removals composed of young of the year (YOY) versus seals 1 year of age and older (referred to as adults). In most cases the magnitude of these uncertainties has varied over the course of the time series. In the previous population modelling (Tinker et al. 2023), a single coefficient of variation (CV) of 0.1 was used to account for uncertainties in reporting for all sources of removals over all years. In the current assessment, we quantified the degree of uncertainty in total harvest numbers and age structure (proportion YOY) on an annual basis for each mortality source, based on previously published reports (Stenson 2010, Stenson and Upward 2020) and expert opinion.

For total removals and the proportion of YOY, we classified the level of certainty for each source of removals , as “high”, “moderate” or “low”. For total removals, we assumed that a high level of certainty corresponds to a CV of 0.05, a moderate level of certainty corresponds to a CV of 0.1 (i.e., the default value used for previous assessments), and a low level of certainty corresponds to a CV of 0.2. For the proportion of YOY, uncertainty around the reported proportion of the harvest consisting of YOY (*PYOY*) is described using a beta distribution with parameters $a = PYOY \times \tau$ and $b = (1 - PYOY) \times \tau$, where τ is a precision parameter (τ > 0, higher values of τ = reduced variance). As with total harvest numbers, we assigned one of three levels of certainty (“high”, “moderate” or “low”) to the *PYOY* values for each year and for each source or removals. Values of τ were set to 25, 100 or 2500 for low, medium or high certainty (respectively), corresponding to standard deviations of 0.1, 0.05 and 0.01 for *PYOY* = 0.5. These τ values were selected to correspond to the 95th quantiles of feasible values for reported *PYOY* values. Below we describe the sources of data for total removals and the proportion of YOY in each source of removal. This information, based on multiple sources (described below) and the expert opinion of coauthors G. B. Stenson and M. O. Hammill, served as the basis for the attribution of uncertainty levels for each source of removal (Table 5).

ARCTIC CANADA

Total removals

Annual removals for the period **1952-1982** were taken from Bowen (1982) and Roff and Bowen (1986). Removals for the period **1983-1996** were unknown and the estimated catch in 1982 was used for annual removals for this period. For the period **1997-2001**, data from a five year study of marine mammal harvest in Nunavut based upon interviews in each community (Anon. 2005) was used. No information is available for the period **2002-2023**. Hence, the average catch estimated during the five year study (715 per year) was rounded to 1,000 and assumed for this period.

Proportions of YOY

Roff and Bowen (1986) reported that approximately 3% of the harvest was comprised of YOY. As there is no information about how (and if) this proportion has changed over time, the 3% YOY in the harvest was assumed for **1952-2023**.

Level of uncertainty

There is very limited data on catch numbers and the proportion of YOY in the catches in the Canadian Arctic harvest (Stenson 2010). Because of this, we attributed a “high” level of uncertainty around catch numbers and proportion of YOY in the catches for **1952-2023**.

GREENLAND

Total removals

Catches for the period **1952-1953** were estimated by Bowen (1982). Reported catches were used for **1954-2017** from ICES (2019), except between 1988-1992 when no data were available. For this period, catches were estimated by linear interpolation between the available data following Stenson (2014). Data from **1993-2021** were updated from Stenson and Upward (2020) and ICES (2023) based on recent data obtained from the Greenland Institute of Natural Resources. For the period **2022-2023** the values are the average from the previous 5 years (2017-2021), following Stenson and Upward (2020).

Proportions of YOY

For the periods **1952-1962** and **1963-1969**, data was taken from Bowen (1982). For the period **1970-1983**, with the exception of 1981, data was taken from Kapel (1999). For year 1981, data from 1980 was used (Stenson et al. 1999). For 1984-1993, although samples were collected, sample sizes were small and not necessarily collected for the purpose of age composition evaluation. For **1984-2023**, an average from combined data collected in central and northwest Greenland over 1984-1991 and in southwest Greenland between 1986-1993 was used instead to estimate age composition. Greenland reports the proportion of young (1 to approximately 5 year-old) and older animals in the harvest. The proportion of young varies between 10-40% between years. As a result, the proportion of YOY cannot be higher that 40%.

Level of uncertainty

Removals in 1952-1953 were estimated and as such were considered of “moderate” uncertainty. There is little uncertainty in the total removals for 1954-1988 as reported catches were used. For 1998-1992, when no data were available, a high level of uncertainty was given. In 1993 the methods of collecting catch data changed from being centrally reported by an individual in each community to self reporting by individual hunters. We assumed this latter method would have greater uncertainty than catches from 1954-1988 and a “moderate” level of uncertainty was given for that period.

Because the proportion of YOY in the catches for the period 1952-1969 was based on some (albeit limited) data, this period was given a “moderate” uncertainty level. For the period 1970-1983, the level of uncertainty in the proportion of YOY was low because it was based on observed data obtained from larger sample sizes and over a wider distribution. We considered that the level of uncertainty was high from 1984 onward in the proportion of YOY in the sample because it represents an average of values observed during the period 1970-1983 and it is possible that this proportion has changed over time.

ATLANTIC CANADA

Total removals

Total catches at the Front and in the Gulf for the years **1952-1978** were compiled from values reported in the Statistical Bulletin of the International Commission for Northwest Atlantic

Fisheries (ICNAF 1970-1977). Total catches for the years **1979-1989** were compiled from values reported in the Statistical Bulletin of the Northwest Atlantic Fisheries Organization (NAFO 1984-94). Total catches at the Front and in the Gulf for the years **1990-2023** were provided by the DFO Statistics Branch.

Proportions of YOY

The catch statistics provided by ICNAF, NAFO and the DFO Statistical Branch are reported according to pelage type. Based upon these reports, Front and Gulf catches can be split into YOY and adults (age 1+). The age structures of catches during the **1952-1983** period were taken from Bowen (1982) and Roff and Bowen (1986). For the period **1984-2023**, the proportion of YOY seals taken in the harvest was taken from data provided by the Statistics Branch. This is the same as previously done (Bowen 1982, Roff and Bowen 1986, Sjare et al. 1996, Stenson et al. 1999, 2000, Stenson 2005, Stenson 2010). The only exceptions occurred in 1998 and 1999 when a portion of the catch was not identified according to pelage. The age of 7 % of the catch was not identified in 1998. It was assumed that the proportion of YOY in this catch was the same as for the remainder of the catch for which ages were available. In 1999, approximately 22 % of the catch did not have assigned ages. As these animals were all from the Gulf of St. Lawrence, the age structure of seals taken by the small boats in the Gulf (which were reported by age) was used.

Level of uncertainty

From 1952-1970, data on total removals was considered with moderate uncertainty since monitoring of the hunt was not extensive. From 1971-2023, which is a period when quotas were implemented, data on total removals were considered with low uncertainty because catches were better monitored during this period. For the proportion of YOY in the catches, the level of uncertainty was considered moderate for the period 1952-1964. In 1965 restrictions on hunting females were implemented and as a result of increased monitoring, we consider the uncertainty on the reported data to be low for the period 1965-2023.

BYCATCH

Total removals

Harp seals are taken as incidental bycatch in the spring Newfoundland lumpfish fishery and in the U.S. fisheries. Those sources of data are combined to yield a summed annual bycatch. There is no information on bycatch **prior to 1970**.

For the lumpfish fisheries, bycatch numbers for the period **1970-2003** were estimated by Sjare et al. (2005). A study using data from 1989 to 2003 estimated the rate of bycatch (number of seals bycaught per ton of roe)(Sjare et al. 2005). Bycatch from the beginning of the lumpfish fishery in 1970 until 1988 was estimated based upon mean bycatch levels from 1989-1991 (i.e., the initial period of the study). The average bycatch rate for the last five years of the study (1999-2003) were used to estimate bycatch numbers for **2004-2018** by Stenson and Upward (2020) and also for **2019-2023** based on lumpfish landings obtained from DFO Statistics Branch.

Data on incidental catches of harp seals in U.S. fisheries for the period **1970-2005** were summarized by Waring et al. (2005, 2007). For the period **2006-2011**, data was taken from Waring et al. (2013) and Waring et al. (2014). For the period **2012-2016**, data was taken from Hayes et al. (2019). For the period **2017-2019**, data was taken from the most recent assessments in the US for harp seals (Hayes et al. 2022). For **2020-2023**, the average of the previous 5 years (2015-2019) was used since harp seal status/bycatch was not reviewed or updated in the 2023 US assessment report.

Proportions of YOY

Sjare et al. (2005) estimated the proportion of YOY seals bycaught from **1989-2000** using age class records provided by fishers over that time period. As in Sjare et al. (2005), the average age classes from 1989 to 1991 were applied to the **1970-1988** period while averages for 1996 to 2000 were applied to **2000-2023** as in Stenson and Upward (2020).

Level of uncertainty

Since there is no bycatch data prior to 1970, but bycatch could still have happened during the period 1952-1970 in other fisheries, we considered our uncertainty towards that source of information as "moderate" for that period. Total removals from bycatch are, for the most part, extrapolations based on fishery yields and were thus considered with "moderate" uncertainty throughout, except in 1989-2003, where actual data were collected. The proportion of YOY in the bycatch is assumed to be known with low uncertainty throughout.

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