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Abundance Estimate and Harvest Impacts on Belcher Islands-Eastern Hudson Bay and James Bay Beluga: 2024 Update

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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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ABSTRACT

Stock assessment for Nunavik beluga is based on population models. A new population model was recently developed for the Belcher Islands-Eastern Hudson Bay (BEL-EHB) beluga stock. The new model is a Bayesian Integrated Population Model (IPM) informed by several sources of information (abundance estimates from aerial surveys, pregnancy rates, age, sex and reproductive state structure, harvest levels, as well as stock-specific genetic representation in the harvest). In 2024, a new aerial survey was flown to assess the abundance of the BEL-EHB and James Bay (JAM) beluga stocks. Here, we used the IPM fitted to the new 2024 survey estimate and updated data from all sources to assess the abundance, trend, and status of the BEL-EHB and JAM stocks. In addition, we present advice on potential harvest levels for the BEL-EHB beluga stock based on the current management objective and alternative management scenarios. Based on the IPM, abundance of the BEL-EHB stock in 2024 was 2,200 (95% CrI = [1,800; 2,500]) beluga and has been declining at a rate of 5.1% (95% CrI = [3.6; 7.2]) per year since 2021. Since 2021, an estimated average of 140 BEL-EHB beluga have been harvested annually. Under the DFO maximum sustainable yield framework, the Lower Reference Point (LRP) was estimated at 1,900 beluga and the Precautionary Reference Point (PRP) at 3,900 beluga for the BEL-EHB stock. No harvest level of BEL-EHB beluga would respect the current management plan of ensuring a 50% probability that the stock reaches or surpasses 3,400 animals in the next five to ten years, and no harvest levels would allow the stock to reach or surpass the PRP over a period of 5 to 10 years with > 50% probability. Simulations indicate that the stock would reach a state of quasi-extinction (i.e., less than 50 mature females) within the next 15 years should current harvest levels be perpetuated. Alternative management scenarios were also explored, and harvest levels allowing to meet the corresponding objectives are presented. Based on the 2024 model estimate, the annual PBR for BEL-EHB is 4 beluga. Based on the IPM, the abundance of the JAM stock in 2024 was estimated at 16,000 (95% CrI = [12,300; 20,600]) beluga, with apparent stability since 2021. An estimated average of 31 JAM beluga are being harvested annually since 2021. The PRP for the JAM stock is estimated at 8,800 and the LRP at 4,400. The annual PBR for JAM is 245 beluga.

INTRODUCTION

The beluga (*Delphinapterus leucas*) is widely distributed across Arctic and subarctic waters, with a substantial proportion of its global range distributed in Canadian waters (NAMMCO 2018; Hobbs et al. 2019). The division of beluga stocks is based on evidence of strong intra- and inter-annual site fidelity to summering grounds, coming from behavioural observations (Caron and Smith 1990), spatio-temporal patterns (Bailleul et al. 2012a), stable isotopes and contaminants differences (Rioux et al. 2012), as well as genetic distinctiveness (Brennin et al. 1997; Brown Gladden et al. 1997, 1999; de March et al. 2002, 2004; de March and Postma 2003; Postma et al. 2012; Turgeon et al. 2012; Colbeck et al. 2013; Parent et al. 2023). These characteristics make beluga more vulnerable to local extinction and may reduce their ability to adapt to local changes and re-colonize areas where they are extirpated (Wade et al. 2012; O'Corry-Crowe et al. 2018, 2020).

Four beluga stocks are recognized to inhabit or migrate along the Nunavik coasts: Ungava Bay (UNG), James Bay (JAM), western Hudson Bay (WHB) and Belcher Islands-eastern Hudson Bay (BEL-EHB) beluga. BEL-EHB beluga consist of a mixed stock composed of two genetically distinct populations (i.e., Belcher Islands [BEL] and Eastern Hudson Bay [EHB]; Parent et al. 2023) with overlapping summer distributions (Figure 1). Because the BEL and EHB genetic populations show strong overlap in summer distribution and cannot be distinguished during aerial surveys to produce separate abundance estimates of beluga in the area, they are managed together as a BEL-EHB stock (Hammill et al. 2023; Sauvé et al. 2024).

BEL-EHB beluga summer in the estuaries and offshore waters of the eastern Hudson Bay Arc (i.e., the curved segment of southeastern Hudson Bay, extending from Hopewell Islands to the junction with James Bay). Their distribution during summer can extend west of the Belcher Islands for up to 60 km (Figure 1; Bailleul et al. 2012b). Historically, the largest aggregations were observed in July and August in Lake Tasiujaq (formerly known as Richmond Gulf), Little and Great Whale rivers, and the Nastapoka River (Smith and Hammill 1986; Caron and Smith 1990). Commercial overharvesting decimated the beluga summering in Great Whale River in the 19th century, (Reeves and Mitchell 1987). While occasional sightings are still reported in the Nastapoka River estuary, no beluga have been observed there and in Tasiujaq Lake during aerial surveys since 2004 and 1993, respectively (Kingsley 2000; Gosselin et al. 2017; COSEWIC 2020; St-Pierre et al. 2024). Currently, the Little Whale River estuary appears to be the main coastal site for beluga aggregations in the eastern Hudson Bay Arc in the summer. In spring and fall, beluga from the eastern Hudson Bay area undertake a seasonal migration along the Nunavik coast and may sometimes travel in Ungava Bay to reach wintering areas in Hudson Strait and along the Labrador coast (Lewis et al. 2009; Bailleul et al. 2012a). There, they mix with other migratory beluga stocks during the winter (Bailleul et al. 2012b; Turgeon et al. 2012; Parent et al. 2023), although interbreeding among populations appears limited (Montana et al. 2024). A portion of BEL-EHB beluga also remains in the Belcher Islands area throughout the year (Parent et al. 2023).

Beluga in James Bay constitute a distinct breeding population and are distributed across the bay, up to Long Island to the north (COSEWIC 2020). Two areas of high concentrations have been consistently identified during aerial surveys: southeast of Akimiski Island and the northwest coast of the bay (Smith and Hammill 1986; Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024; Sauvé et al. 2025). Telemetry studies (Bailleul et al. 2012) and Inuit traditional knowledge, Qaujimajatuqangit (McDonald et al. 1997; Doidge et al. 2002; Lewis et al. 2009; Breton-Honeyman et al. 2013) suggest that JAM beluga undertake limited seasonal movements, mostly remaining in the James Bay and southern Hudson Bay areas (Bailleul et al. 2012a; Parent et al. 2023). Beluga are also found along the Ontario coast of Hudson Bay (Richard 2004), and there is uncertainty whether beluga observed in the northwest portion of James Bay during surveys may represent movement between the two areas.

BEL-EHB beluga are harvested by hunters in Nunavik both during summer and during the spring and fall migration periods, and are available to be harvested year-round by hunters in Sanikiluaq (Nunavut) (Figure 1). Management of beluga in Nunavik relies on summer abundance estimates, and on an understanding of stock composition of the harvest, which varies both seasonally and spatially. Beluga summer abundance in eastern Hudson Bay and in James Bay has been monitored since 1985 using a series of nine systematic aerial surveys covering the full extent of these stocks' distributions (Kingsley 2000; Gosselin et al. 2002, 2009, 2013, 2017; Gosselin 2005; St-Pierre et al. 2024; Sauvé et al. 2025). In addition, since the 1980s, harvesters across Nunavik and Nunavut have contributed skin samples from their catches, which have been used to estimate the relative proportion of the different beluga stocks found in the harvest (Brown Gladden et al. 1997; de March et al. 2002, 2004; de March and Postma 2003; Turgeon et al. 2009, 2012; Postma et al. 2012; Postma 2017; Parent et al. 2023).

Harvesting of BEL-EHB beluga by Nunavik communities is currently managed under a 5-year (2021-2026) management plan. The management objective is to ensure a 50% or greater probability that the stock will remain at or above 3,400 EHB beluga after five years. The 3,400 threshold in the management plan was established based on the best available science when the management plan was developed (DFO 2020). At that time, the stock was estimated to be slightly increasing or stable with an abundance of 3,400 individuals in 2016. This objective is to be met through a combination of harvest limits in the southeastern Hudson Bay coastal area (referred to as “the Arc”), as well as seasonal and regional closures in Northeast Hudson Bay, Hudson Strait and Ungava Bay.

Since the implementation of this management plan, an additional survey was flown in 2021, and new correction factors (availability and perception bias) for animals missed during surveys have been developed and retrospectively applied to surface abundance estimates from past surveys (St-Pierre et al. 2024). Furthermore, a re-analysis of genetic samples highlighted that beluga summering in the Eastern Hudson Bay Arc and censused during aerial surveys belonged to two rather than a single population (BEL and EHB rather than just EHB), thus representing a mixed stock (Parent et al. 2023). A population model incorporating this updated information estimated that the BEL-EHB stock has declined at a rate of 2.5 to 3.0% per year since 2015, to an estimated 2,900 individuals in 2021 (Hammill et al. 2023). As a consequence of those revisions, the 3,400 abundance reference level is no longer applicable.

The previous assessment for BEL-EHB and JAM was conducted in 2021 (Hammill et al. 2023) using a Bayesian Surplus Production model (SPM) incorporating information on catch levels, stock composition, and abundance estimates from aerial surveys (Hammill et al. 2021). In 2024, a new population model was developed for the BEL-EHB stock, which allows for incorporating additional sources of information, namely pregnancy rates, age, sex and reproductive state structure of the harvest (Van de Walle et al. In prep.). This model is a stochastic Bayesian Integrated Population Model (IPM) and was shown to provide many advantages over the SPM (Van de Walle et al. In prep.). In addition to better utilizing all available data to improve model fit, the new model yields more precise estimates of population size. Furthermore, in using a competing hazards formulation, the model fully de-couples harvest and natural mortality and thus allows for an estimate of the contribution of harvest to overall mortality.

Here, we used the new IPM fitted to the most recent time series of abundance estimates, including the 2024 survey (Sauvé et al. 2025), and updated stock structure, reproductive and genetics data to assess the abundance, trend, and status of the BEL-EHB beluga stock, and present advice on harvest levels aligned with different management objectives.

While the JAM stock has been surveyed since 1985, a model-derived abundance estimate was first produced in 2021 using the SPM developed for BEL-EHB (Hammill et al. 2023). There is currently insufficient information collected on the JAM beluga stock to inform the population model about population structure. The only data sources that can be used to estimate trends for the JAM beluga stock are survey data and harvest levels. Nonetheless, the fundamental demographic structure and life history characteristics described for the BEL-EHB beluga stock provide a useful framework for modelling population dynamics of the JAM beluga stock. Therefore, rather than relying on a non-structured SPM for estimating population trends of the JAM beluga stock, we instead modeled its dynamics using the same process model structure as the BEL-EHB beluga stock, but without providing observational data on population structure and reproductive rates to the model. Further, the JAM beluga stock is harvested mainly in Long Island and in relatively small proportions elsewhere along the Nunavik coast and in Sanikiluaq (Parent et al. 2023). In Hammill et al. (2023), only harvest in Long Island was considered as a source of harvest mortality for the JAM beluga stock. Here, we also have included harvest mortality from all management areas to produce a new estimate of abundance and trend for the JAM beluga stock.

Model results for the BEL-EHB and JAM beluga stocks are also used to estimate Reference Points to determine whether these stocks are in the Healthy, Cautious or Critical Zones as defined under the Precautionary Approach Framework (DFO 2006). In addition to providing information on abundance and trends and contribution of the various stocks to the harvest, the DFO Science Branch was tasked to provide the Potential Biological Removal (Wade 1998) for each stock based on updated abundance estimates, and to provide advice on the following:

1. Estimate the maximum number of BEL-EHB beluga that can be harvested to respect the current management plan of ensuring a 50% probability that the stock will reach or surpass 3,400 animals in a) the next five years, and b) the next ten years.
2. Provide harvest levels for BEL-EHB beluga that would result in a 50 to 95% probability of the stock a) remaining stable, b) reaching a 1% growth, c) reaching the Lower Reference Point (i.e., 24% of carrying capacity; LRP) and d) reaching the Precautionary Reference Point (48% of carrying capacity; PRP) over 5, 10 and 25 years.
3. Project the demographic trend of the BEL-EHB beluga stock over the next 3 generations (i.e., 86 years), using a) harvest levels recorded under the current management plan (2021-2024), or b) various percentages of these values as a baseline for future harvests.
4. Assess the impact of various management measures, such as seasonal and zonal closures, on the percentage of BEL-EHB beluga harvested by Nunavik communities and Sanikiluaq.

This assessment is intended to inform decisions on the management objectives for Nunavik beluga that are to be identified by co-management partners and in consultation with Nunavimmiut as part of the renewal process of the management plan.

MATERIALS AND METHODS

The methods section is divided into three subsections: we present the different sources of data that inform the model, a brief description of the model, and the different management objectives and alternative scenarios tested. The BEL-EHB beluga IPM has been described in length in Van de Walle et al. (In prep.) and is presented in Appendix 1. Here, we focus on presenting updates to data sources and methods used in the current stock assessment and in model projections for harvest advice.

DATA SOURCES

The IPM for BEL-EHB uses six sources of data: 1) abundance from aerial surveys, 2) harvest numbers, 3) genetic composition of the harvest, 4) pregnancy rates observed in the harvest, 5) harvest sex and age structure, and 6) proportion of females lactating in the harvest. The first three sources of data are specific to each stock. Those sources of data have been updated with recent information since Van de Walle et al. (In prep.) and Hammill et al. (2023) for BEL-EHB and JAM beluga, respectively. The additional three sources of data (4-6) are not specific to each stock as these data are collected on an individual basis from harvested animals. Accurate assignment of individuals to specific genetic populations is not possible at this time (Parent et al. 2024; DFO 2024). Therefore, we used data collected on all beluga harvested in Nunavik to inform the BEL-EHB model on age, sex, and reproductive state composition in the harvest. Genetic analyses indicate that the JAM stock, as opposed to the BEL-EHB stock, represents only a minor fraction of the harvest sampled (e.g., approximately 1% of the Hudson Strait harvest). Thus, the available data on harvest age distributions, pregnancy rates and lactation rates provided insufficient information for understanding the JAM stock dynamics. Consequently, only survey abundances, harvest numbers and genetic composition of the harvest were used to inform the JAM beluga stock model.

Abundance estimates from aerial surveys

Census data consist of nine visual systematic aerial surveys flown in 1985, 1993, 2001, 2004, 2008, 2011, 2015, 2021, and 2024 (Sauvé et al. 2025). All surveys were conducted following the same basic approach, despite some differences in survey altitude, type of aircraft used, and data collected. Details on survey methods and analyses are available in Sauvé et al. (2025). See Table 1 for survey estimates and associated uncertainties for the BEL-EHB and JAM beluga stocks.

Harvest numbers

The BEL-EHB and JAM beluga stocks are harvested in Nunavik and in Sanikiluaq, however the proportions of the harvest that BEL-EHB and JAM beluga stocks each represent varies both spatially and temporally. To account for this and to calculate the respective BEL-EHB and JAM beluga stock mortalities from harvest, we combined information on total harvest per management area and season with information about the corresponding genetic composition of the harvest (i.e., what proportion of the total harvest does each beluga stock represent). These two sources of information are used as input in the population model to generate an estimate of harvest mortalities for each stock (see Appendix 1 for details on model construction).

The number of beluga harvested is reported via a network of local wardens in Nunavik (1974-2024) and the Hunters and Trappers Association in Sanikiluaq (1977-2024). Harvest information is collected yearly from each community and then combined to yield harvest numbers for each management area (Table 2): Sanikiluaq (SAN), Eastern Hudson Bay Arc (ARC), Northeastern Hudson Bay (NEHB), Hudson Strait (HS), Ungava Bay (UB) and Long Island (James Bay; JB).

In the ARC, harvest occurs mostly during summer. In SAN, beluga can be harvested throughout the year and can be decomposed into summer, fall, winter and spring seasons. However, the community of Sanikiluaq approved a voluntary hunt closure between July 1st and September 30th in 2006 in consideration of concerns about the previously identified EHB beluga stock. The start of the closure was changed to July 15th in 2012. Therefore, there is still harvest in the summer (defined as July 1-August 31; Parent et al. 2023), but it is limited to early July. SAN harvest information is available on an annual basis, although weekly reports were available for years 2023 and 2024, allowing the direct classification of the harvest into the respective seasons. Prior to 2023, total annual SAN harvest numbers were broken down by season following the relative proportion of all genetic samples that were collected in each season. For NEHB, UB and HS, harvest is decomposed into spring and fall seasons, corresponding to the seasonal migration periods, and has been reported as such since 2009. Before 2009, the number of harvested beluga by management area was available on an annual basis. The NEHB management area did not exist before 2009 and in UB, all harvest prior to 2009 was assumed to be in the spring, which is when most (91%) of the harvest occurs (Hammill et al. 2023). Similarly, for HS, we back-calculated the proportion of the harvest taken during the spring and the fall seasons for 1974-2008 using the overall season-specific proportions from the 2009-2023 period. Harvest in JB is limited to summer months and is reported on an annual basis.

Genetic composition of the harvest

The SAN and ARC management areas combined correspond to the BEL-EHB beluga summering ground, therefore all beluga harvested in these areas during summer are defined as BEL-EHB beluga. Similarly, Long Island is within the summer range of JAM beluga. Based on genetics, the majority of beluga harvested in this area are from the JAM stock (Parent et al. 2023). As a result, we considered all harvest in Long Island to be from the JAM stock. In contrast, the NEHB, HS and UB management areas are located along the migratory path and/or wintering grounds of the BEL-EHB beluga stock, and occasionally some individuals from the JAM beluga stock are harvested in these areas as well. These areas are also shared with other beluga stocks during migration and winter. Harvests from these areas therefore represent a mix of beluga belonging to various stocks. Tissue samples from 1982-2023 were haplotyped for the mitochondrial DNA control region, following Parent et al. (2023), including 335 samples collected since 2021. Samples collected during summer (July and August) in SAN and ARC were used as the reference group for BEL-EHB beluga haplotype composition, whereas samples collected in Long Island and JB were used as the reference group for JAM. Then, a Genetic Mixture Analysis (GMA) was run to estimate the proportion of BEL-EHB and JAM beluga in other seasons and management areas (Table 3).

Sample size was insufficient (n < 10) to estimate the proportion of BEL-EHB and JAM from harvests carried out in NEHB during the spring and in UB during the fall. For those harvests, we calculated a proportional BEL-EHB contribution based on the fall and spring estimates from HS. Finally, Parent et al. (2023) showed that the proportion of BEL-EHB harvested in HS declines after the second week of November. To account for this and following Hammill et al. (2023), we separated the fall into "early fall" and "late fall" seasons for years 2018 onward, when weekly harvest reports were available (Table 2). Harvest mortality of BEL-EHB and JAM beluga was introduced in the model as mean estimates of proportional representation of BEL-EHB and JAM with their associated uncertainties (estimator variance).

Pregnancy rates

Annual pregnancy rates were estimated by quantifying progesterone levels in blubber samples collected from 232 mature female beluga harvested along the Nunavik coast between October and April of 2010-2024 (Van de Walle et al. In prep.). Females were considered mature if older than eight years of age, with age being determined from dental analyses (2010-2023) or assumed from skin coloration (2024) (Doidge 1990; Heide-Jørgensen and Teilmann 1994). Blubber progesterone extraction and quantification followed the methods described in Renaud et al. (2023). A progesterone level of 100 ng/g of tissue was used to determine presumed pregnancy (Renaud et al. 2023). Presumed pregnant and non-pregnant females were summed separately for each year. Sample sizes for annual reproductive rates ranged between 2 and 88 (mean = 15, CV = 1.43), depending on the year (Table 4).

Harvest sex and age structure

Information on sex and age were available for a proportion of beluga harvested and sampled in 1980-2023 (69%; 2,389 out of 3,468). Age was determined based on dental analysis as in Lesage et al. (2014) and was used to determine the age structure among harvested beluga (Figure A6). Sex was determined genetically for all years except 2024, since sex information from visual inspection of carcasses was often lacking from sample metadata (Parent et al. 2024). For the most recent 2024 data, genetic sex determination was not available and sex determined from visual inspection of the carcasses was used, when available. Information on age was not available in 2024.

Proportion of lactating females in the harvest

The Nunavik beluga management plan and Marine Mammal Regulations state that no person shall kill a beluga calf (dark in color and less than 2 m in length), or an adult beluga that is accompanied by a calf. Accordingly, a bias towards non-lactating females is expected in the harvest. The IPM accounts for the potential avoidance of lactating females; to inform the model on this avoidance factor, we used data on a subset of beluga females harvested in Quaqtaq in 2023 ($n = 21$) and 2024 ($n = 17$), and sampled by DFO personnel. Although samples come from only one location, beluga harvested in Quaqtaq represent a mixture of stocks, including BEL-EHB. For each harvested female, lactation was assessed by visual inspection of the mammary glands and detection of milk in the glands. In 2023 and 2024, 3 (proportion = 0.18) and 2 (proportion = 0.10) necropsied females were found to be lactating, respectively.

MODEL DESCRIPTION – A BRIEF OVERVIEW

We used a Bayesian multistate IPM that integrates multiple sources of data to estimate abundance and trend of the BEL-EHB stock (Van de Walle et al. In prep.). Here, we only present a brief overview of the model for BEL-EHB beluga stock. A more detailed description of the model is presented in Van de Walle et al. (In prep.) and in Appendix 1.

The IPM is comprised of three parts: 1) process model, 2) data model and 3) model fitting. The process model is a series of equations that describe demographic transitions and which, when solved, estimates dynamics in population abundance based on the values of the input parameters. The data model describes how the empirical datasets are linked to the predicted dynamics of the process model.

Briefly, the process model is an age x state projection matrix. It considers annual transitions from the time of the census at the end of the summer (survey time) at time t to the next census the following year at t+1. Annual transitions are between ages (60 age classes) and states (4 states: males (M), non-reproducing females (A), pregnant females (P) and females with a newborn calf (W)), determined by age and state-specific survival rates and probabilities of transiting between reproductive states for females. Production of new individuals is determined by fertilities (specifically, the probability of an adult female becoming pregnant and then giving birth to a calf that survives until the next census time).

Survival was calculated from instantaneous mortality rates. In this model, instantaneous mortality was treated as the sum of multiple competing hazards. We considered two sources of additive mortality: 1) natural or environmental mortality (hereafter referred to as baseline hazards) and 2) hunting mortality (hereafter referred to as hunting hazards). Hazards are calculated in log form as this allows for the inclusion of multiple predictor variables as simple additive linear functions.

Baseline hazards included age and sex effects (elevated risk for very young and very old animals, and for males), density-dependence and environmental stochasticity. Harvest hazards were allowed to vary with age (avoidance of younger animals), reproductive status (avoidance of lactating females), and to fluctuate over time through an annual stochasticity component. Survival rates are calculated by taking the exponential of the negative sum of baseline and harvest hazards. We also assumed that survival of calves in their first year of life was conditional on the survival of their mother.

Pregnancy rates were also expressed in terms of log hazards, for consistency with survival rate calculations. Pregnancy hazards considered the impact of density dependence and annual fluctuations through a stochasticity component. Pregnancy rates were assumed to be zero for females aged 7 years-old and below, and were also assumed to decline in older females to account for reproductive senescence.

The process model was fitted to the six different sources of data, i.e., abundance estimates, harvest levels along with their genetic composition and demographic composition (age and sex structure, as well as proportion of adult females lactating) through probabilistic relationships.

For JAM, we modeled population dynamics using the same process model structure described above for the BEL-EHB beluga stock (Equations A1 – A21). For the data model, we restricted comparisons of expected vs. observed values to the survey data (Equation A22) and harvest data (Equation A27), after accounting for the much smaller proportion of JAM animals to the overall harvest counts (Equation A26). This restriction of data sources required the use of strongly informed priors for those model parameters that could not be estimated based on survey and harvest data alone (i.e. baseline age- and sex-specific hazards, and reproductive rates). We therefore made use of the results of the fitted BEL-EHB model to set prior distributions for these parameters (see Prior section, below), while the parameters that could be estimated from survey and harvest data, i.e., strength of density-dependence (ϕ, which determines the value of K), environmental stochasticity (σ_e) and harvest hazards (γ_H and σ_e) – were set with non-informative priors. We initiated the population vector (age/sex structure) to correspond to the stationary stage distribution expected given estimated stochasticity and density-dependent effects (based on density relative to K) and average harvest mortality experienced by the JAM beluga stock at the start of the time series. This initial age-sex structure will thus differ from that of the BEL-EHB beluga stock. Therefore, our approach does not assume that any of the specific demographic trends in BEL-EHB apply to the JAM beluga stock, only that the basic life history structure is shared between stocks (e.g. the proportional magnitudes of baseline age/sex specific hazards and reproductive rates). Modifications to the BEL-EHB IPM to adapt it to the JAM beluga stock are presented in Appendix 1.

The models were coded and fitted through R version 4.4.0 (R Core Team 2024) and Stan version 2.35.0 (Carpenter et al. 2017). Parameters were estimated using Markov Chain Monte Carlo (MCMC) methods. For the BEL-EHB stock, we aimed for a posterior distribution of 5,000 samples, which was attained by using 10 chains with a thinning of 1 and a warm-up phase of 300 iterations and 500 sampling iterations per chain. For the JAM beluga stock, we aimed for a posterior distribution of 20,000 samples, which was attained by using 20 chains with a thinning of 1 and a warm-up phase of 300 iterations and 1,000 sampling iterations per chain. Model fit and validation was assessed by visual inspection of the mixing and convergence of the chains, inspection of the Gelman-Rubin convergence statistic ($\hat{R}$) and the number of effective samples (n_{eff}) for each parameter estimated (McElreath 2020). Further, we compared the posterior and prior distributions for all parameters and conducted posterior predictive checks, calculating Bayesian P-values to assess the goodness of model fit to the data.

MODEL ANALYSIS AND SCENARIOS

For BEL-EHB beluga, we used the results of the IPM to estimate the abundance in 2024 and recent trend of the stock. We also estimated the number of beluga harvested per year and the relative contribution of harvest to overall mortality. Then, we projected the model over a maximum of three generations (86 years, with generation time being 28.6 years in beluga; Lowry et al. 2017) under various harvest levels, to evaluate the impact of harvest on future population abundance and trends. We simulated harvest levels ranging from 0 to 100 BEL-EHB beluga per year. The simulated harvest levels represent only reported landings. Those harvest levels are then multiplied by the struck and lost factor to generate overall harvest mortalities in the simulations. Model projections assumed that future environmental stochasticity would be of similar magnitude to that experienced across the time series. We used the distribution of results over 1,000 iterated projections to compute the probability for the stock to reach different benchmarks over various time frames, as described below.

For JAM beluga, we also used the results of the IPM to estimate the abundance in 2024 and recent trend of the stock. We also estimated the number of JAM beluga harvested per year and the relative contribution of harvest to overall mortality. However, no management objective has yet been identified for the JAM beluga stock. Consequently, no harvest scenarios were tested for the JAM beluga stock.

CURRENT MANAGEMENT OBJECTIVE FOR THE BEL-EHB BELUGA STOCK

The current 5-year management plan (2021-2026) objective is to ensure a 50% or greater probability that the BEL-EHB beluga stock will remain at or above 3,400 beluga after five years, which corresponded with the 2016 abundance estimate at the time when the plan was established (DFO 2020). As indicated previously, the 2016 abundance was re-estimated in 2021 and in the current assessment. The 3,400 benchmark is no longer aligned with recent understandings of the BEL-EHB beluga stock dynamics (see Introduction). Nevertheless, to address this specific request, we estimated the maximum number of BEL-EHB beluga that would ensure a 50% or greater probability that the stock will remain at or above 3,400 beluga, as well as the newly estimated 2016 abundance from this assessment, after 5 years. We also estimated the BEL-EHB beluga harvest level that would allow the stock to reach 3,400 beluga (as well as the newly estimated 2016 abundance) in the next 5, 10, and 25 years.

DFO-Maximum Sustainable Yield (DFO-MSY)

Under the DFO-MSY framework, the LRP and PRP are calculated based on Maximum Sustainable Yield (MSY), where:

$$MSY = 0.6 \times K \tag{1}$$

Where K is the carrying capacity of the stock. MSY, LRP and PRP are linked as follows:

$$LRP = 0.4 \times MSY \tag{2}$$

$$PRP = 0.8 \times MSY \tag{3}$$

From these benchmarks, three zones of resource concern are defined (Figure 2; DFO 2006). The Critical Zone is below the LRP. The Healthy Zone is above the PRP, and the Cautious

Zone is situated below the PRP, but above the LRP. Within this framework, the objective is to manage exploitation of the resource so that it remains in the healthy zone. A stock is considered to be in the healthy zone if there is at least a 50% probability that its abundance lies above the PRP, whereas it is considered in the Critical Zone if there is a 50% probability that the stock abundance is below the LRP. Finally, a stock is considered to be in the Cautious Zone if its abundance lies between the LRP and PRP (Hammill et al. 2017). Under this framework, we assessed the status of the BEL-EHB and JAM beluga stocks relative to the LRP and PRP, and for BEL-EHB estimated the maximum harvest levels that would result in 50% to 95% probabilities of the stock reaching the LRP and PRP over 5, 10 and 25 years.

Alternative scenarios

We also explored two alternative management scenarios for the BEL-EHB beluga stock: 1) to ensure a stable abundance (i.e. an average growth rate of 0%), or 2) to ensure a positive annual growth rate of at least 1%. We provided the maximum harvest levels that would allow the stock to meet those objectives with 50% to 95% probabilities. Those scenarios were run for up to 25 years and since the results are independent of the projection period, we only present the maximum harvest level that would allow those objectives to be met after a 25 year projection period.

Finally, we projected the demographic trend of the BEL-EHB beluga stock over the next three generations (i.e., 86 years) assuming harvest levels recorded under the current management plan (2021-2024) persist in the future, or are reduced so they represent 10%, 25%, 50% or 75% of the current harvest level. We then calculated the expected stock abundance at the end of the projection period. Following the approach used for the St. Lawrence beluga in Tinker et al. (2024), we defined a quasi-extinction threshold as a stock with 50 or fewer adult females. The choice of three generations is based on guidelines from the International Union for the Conservation of Nature (IUCN) and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). It also represents the upper limit for recovery under the DFO Precautionary Approach framework.

POTENTIAL BIOLOGICAL REMOVAL (PBR)

The Potential Biological Removal (PBR) approach aims at identifying removal levels that have a 95% probability of the population being above the Maximum Net Productivity Level, which is defined as 50% of carrying capacity (K) over a period of 100 years. PBR is estimated as follows:

$$PBR = 0.5 \cdot R_{max} \cdot F_R \cdot N_{min} \tag{4}$$

where R_{max} is the maximum rate of population increase, F_R is a recovery factor (ranging 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). R_{max} is assumed to be 0.04 in cetaceans (Wade and Angliss 1997). Here, we used the IPM to estimate N_{min} as the 20th percentile of the posterior distribution of the population abundance estimate in 2024. We also used the model-based estimate of R_{max} to calculate the PBR (Lang et al. In prep.). The choice of F_R value depends on the status of the stock (Lang et al. In. prep.) and is thus determined based on results from the IPM. We used Table 1 in DFO (2025) to determine the value for F_R.

IMPACT OF THE GEOGRAPHICAL AND SEASONAL DISTRIBUTIONS OF HARVEST ON ALLOWABLE HARVEST LEVELS COMPATIBLE WITH MANAGEMENT OBJECTIVES

Over the last decades, beluga harvest activities in the Nunavik and Sanikiluaq areas have varied temporally and spatially. The current management plan intends to meet its objective through a combination of non-quota limitations (regional and seasonal closures) and quota limitations (i.e., a Total Allowable Take, TAT) in the Eastern Hudson Bay management zone. These management measures aim to divert the hunt towards the more abundant WHB and JAM stocks and away from the smaller BEL-EHB stock.

We assessed the impact of various seasonal and zonal distributions of the harvest on the number of BEL-EHB beluga harvested by Nunavik communities and Sanikiluaq. The impact of each scenario on the BEL-EHB stock is expressed as the total number of beluga that could be landed for each BEL-EHB beluga harvested given the observed area- and season-specific stock composition of the harvest (Table 3). These scenarios are examples only, and are not meant to be interpreted as management measures recommended by DFO Science. Additional scenarios could also be simulated using the same methods should interest be expressed by co-management partners.

Four scenarios were considered for the spatial distribution of the harvest:

1. The spatial distribution of harvest among management areas is proportional to that observed under the current management plan (i.e., average from 2021-2024 harvests);
2. Same as 1, except there is no harvest in the ARC area;
3. The distribution of harvest among management areas is proportional to the Inuit population inhabiting communities in each area; and
4. Harvest is concentrated in Hudson Strait.

Similarly, four scenarios were considered for the temporal distribution of the harvest:

A. The temporal distribution of beluga harvest is proportional to that observed under the current management plan (i.e., average from 2021-2024);

B. Harvest is concentrated in the spring (i.e., February 1 to August 31 in Nunavik, April 1 to June 30 in the Belchers Islands);

C. Harvest is concentred in the fall; with harvest in HS occurring in early fall only (i.e., September 1 to January 31 in NEHB and UB, September 1 to November 20 in HS, and September 1 to November 30); and

D. Same as C, except considering harvest in HS occurring in late fall only (i.e., September 1 to January 31 in NEHB and UB, November 21 to January 31 in HS, and September 1 to November 30).

RESULTS

BEL-EHB BELUGA STOCK STATUS AND HARVEST ADVICE

The IPM converged well, with trace plots of all estimated parameters showing good mixing of the 10 chains. $\hat{R}$ was below 1.1 and Neff was large for all parameters (Table A3). Priors were updated for all parameters, except for ρ where the posterior distribution was similar to the (informed) prior distribution (Figure A2). Out-of-sample predictions matched well with observations for harvest numbers (Figure A3), survey abundance (Figure A4), and pregnancy rates (Figure A5). The age and sex structure within harvested animals estimated by the model matched well with the observations (Figure A6). The combined Bayesian P-value was 0.62 (Figure A7), which indicated good fit to the data.

Population abundance and trends – BEL-EHB

The IPM estimated that BEL-EHB stock abundance in 2024 was 2,200 (95% Credible Interval, CrI = [1,800; 2,500]) beluga. Maximum rate of population increase (R_{max}) was estimated at 0.04 (95% CrI = [0.03; 0.05]) and carrying capacity, K, was 8,100 (95% CrI = [6,800; 10,300]) (Table 5). Over the time series, average annual rate of stock decline was 2.3% (95% CrI = [1.9; 2.7]), although a period of relative stability was observed between 2001-2014 (annual rate of increase <0.01). Since the implementation of the current management plan (2021), the annual rate of stock decline accelerated and averaged 5.1% (95% CrI = [3.6; 7.2]) (Figure 3).

The average number of BEL-EHB beluga harvested across Nunavik and in Sanikiluaq, excluding struck and lost, was the lowest in 2006 at 55 beluga and the highest in 1977 at 375 beluga (Figure 4A). Since 2021, the average number of BEL-EHB beluga harvested per year across Nunavik and in Sanikiluaq was estimated at 140 BEL-EHB beluga. In 2024, the estimated number of BEL-EHB beluga harvested was 183 (95% CrI = [167, 199]).

Nunavik harvest represents the most important source of harvest for BEL-EHB beluga, although there is an increasing trend in Sanikiluaq harvest of BEL-EHB beluga (Figure 4B). The maximum annual harvest of BEL-EHB beluga by Sanikiluaq was 84 beluga in 2015. Since 2021, an average of 24 BEL-EHB beluga were harvested in Sanikiluaq annually, whereas this number was 116 beluga in Nunavik. The estimated contribution of harvest (including struck and lost) from Nunavik and Sanikiluaq to overall mortality also increased since 2021 and reached 63% (95% CI = [51, 77]) in 2024 (Figure 5).

Harvest advice – BEL-EHB beluga stock

The model was projected over time under harvest levels (excluding struck and lost) ranging from 0 to 100 BEL-EHB beluga per year to assess future stock abundance under varying harvest pressure (Figure 6). The impact of harvest on stock abundance was sensitive to the projection period (Figure 7).

The current assessment estimates that the stock has been below 3,400 individuals (with a 95% probability) every year since 2015. If we retrospectively calculate abundance based on the new population model, the 2016 abundance is estimated at 3,000 (95% CrI: [2,700; 3,300]). Based on this, the BEL-EHB stock has been below the 2016 reference level since 2021 (with a 95% probability). As a result, no harvest level of BEL-EHB beluga would respect the current management plan of ensuring a 50% probability that the stock will reach or surpass the original management plan benchmark or the re-evaluated 2016 abundance in the next 5 to 10 years. If the period for recovery is increased to 25 years, then a maximum of 24 BEL-EHB beluga harvested per year would allow the stock to reach or surpass 3,400 beluga with an 50% probability (Table 6). In comparison, a total of 33 BEL-EHB beluga harvested per year would allow the stock to reach or surpass the re-evaluated 2016 abundance level (3,000 beluga) in 25 years with a 50% probability.

Under the DFO-MSY framework, the LRP was estimated at 1,900 beluga and the PRP at 3,900 beluga. Considering the estimated abundance of the stock in 2024, there is a 100% probability that the BEL-EHB stock is below the PRP and a 89% probability that it is above the LRP (Figure 3). Therefore, the BEL-EHB beluga stock is considered in the Cautious Zone. No harvest level would ensure a 80% or 95% probability that the stock reaches or surpasses the PRP (3,900 beluga) over a period of 5 to 10 years (Table 6). The only conditions under which an annual

BEL-EHB harvest would meet the objective of reaching above the PRP is when the projection period is set to 25 years and the probabilities of reaching above the PRP are set to 80% or less. In such cases, the maximum annual BEL-EHB harvest would be 3 and 13 beluga, to reach the PRP with probabilities of 80% and 50%, respectively.

Staying out of the Critical Zone with a 50% probability for the next 5,10 and 25 years would require annual harvest not to exceed 88, 66 and 55 BEL-EHB beluga, respectively (Table 6). Increasing to 95% the probability of remaining above the LRP would require further reduction of the annual harvest level to a maximum of 30-37 BEL-EHB beluga.

To have at least a 50% probability of maintaining the population at its current (2024) level or ensuring the stock grows at 1% per year, annual harvests could be 50 beluga (stability) or 38 beluga (1% growth). Increasing the probability of reaching these objectives to 95% would reduce the harvest to 35 beluga (stability) and 22 beluga (1% growth) (Table 6).

We projected the population forward in time for three generations (86 years) under the BEL-EHB harvest level observed in 2021-2024 (140 beluga), and percentages of this harvest, i.e., 75% (105 beluga), 50% (70 beluga), 25% (35 beluga) or 10% (14 beluga). Under harvest levels observed in recent years, the model estimates that the BEL-EHB stock would rapidly decline and reach 1,600 (95% CrI = [1,200; 2,000]) and 792 (95% CrI = [335, 1,249]) beluga in 5 and 10 years, respectively (Figure 8A). The model also predicts quasi-extinction (i.e., less than 50 adult females) by 2037 (50% probability) to 2039 (95% probability) (Figure 8B). With 75% and 50% of current harvest levels, quasi-extinction is also predicted to happen by 2044 and 2072, respectively, with a 50% probability. In contrast, with a reduction to 25% and 10% of the current harvest level, the population is projected to increase and reach 5,400 (95% CrI = [2,700; 7,200]) and 7,300 [95% CrI = [6,200; 8,600]) beluga in 86 years, respectively.

Potential Biological Removal – BEL-EHB beluga stock

Based on the model estimate of abundance, N_{min} was 2,000 beluga in 2024 (Table 5). Following criteria from Table 1 in DFO (2025), since the stock abundance (2,200 beluga) was less than 0.3 of K (8,100 beluga), F_R was set at 0.1. Using the model-based estimate value for R_{max} of 0.04 (Table 5), the Potential Biological Removal (PBR) for the BEL-EHB stock is 4 beluga.

JAMES BAY BELUGA STOCK STATUS

Trace plots of all estimated parameters showed good mixing of the 20 chains. $\hat{R}$ was below 1.1 for each parameter and Neff was large for all parameters (Table A3). Priors were updated for most parameters, except γ_1, γ_2, γ_3, $\nu_{AG,}$ ρ, ψ_1, and ξ (Figure A9). Out-of-sample predictions matched very well with observations for harvest numbers (Figure A10), and relatively well for survey abundance (Figure A11). Observations tended to show a wider distribution, probably because of the very large uncertainties around survey estimates. The combined Bayesian P-value was 0.54 (Figure A12), which indicated good fit to the data.

The IPM estimated that the JAM stock abundance has increased over the time series until 2014. The 2024 abundance was estimated at 16,000 (95% CrI = [12,300; 20,600]) beluga (Figure 9). Maximum rate of population increase (R_{max}) was estimated at 0.03 (95% CrI = [0.02; 0.05]) and carrying capacity, K, was 18,300 (95% CrI = [12,100; 30,300]) (Table 5). Over the time series, the average annual rate of population increase was 2.1% (95% CrI = [1.0; 3.1]). Since 2021 (beginning of the current management plan), abundance of the stock has been stable with an average rate of increase of -0.5% (95% CrI = [-7.2, 4.9]) (Figure 9).

Based on model results, the average yearly number of JAM beluga harvested varied between 4 in 1985 and 50 in 2016 (Figure 10). Since 2021, the average number of JAM beluga harvested per year was 31, with the 2024 estimate being 24 (95% CrI = [20, 29]). The contribution of harvest to overall mortality for the JAM stock was low and ranged between 1.6% (95% CrI = [0.2, 7.2]) in 2008 and 12.4% (95% CrI = [1.6, 39.9] in 2021 (Figure 11).

The PRP for the JAM stock estimated under the Maximum Sustainable Yield framework is 8,800, while the LRP is 4,400. Based on the 2024 estimate, the JAM stock is currently above the PRP with a 100% probability (Figure 9).

N_{min} was estimated at 14,200 in 2024. Based on the model estimates of K (18,300) and 2024 abundance (16,000), the stock abundance is above 0.70 of K, justifying the use of a F_R of 1 (DFO 2025). Using the model-based estimate value of R_{max} of 0.03, the Potential Biological Removal (PBR) for the JAM stock is 245 beluga.

IMPACT OF THE GEOGRAPHICAL AND SEASONAL DISTRIBUTIONS OF HARVEST ON ALLOWABLE HARVEST LEVELS COMPATIBLE WITH MANAGEMENT OBJECTIVES FOR BEL-EHB

Various scenarios distributing the Nunavik and Sanikiluaq beluga harvest over time and space were explored, using the ratio of total beluga harvest per BEL-EHB beluga landed as a metric (Table 7). For example, the 2021 – 2024 seasonal and geographic distribution of beluga harvest in Nunavik and Sanikiluaq would result in 3.8 beluga harvested for each BEL-EHB beluga landed. Alternatively, if all of the harvest was to occur in Hudson Strait in late fall, 20 beluga could be harvested for each BEL-EHB beluga landed.

DISCUSSION

Here, we present the first stock assessment using the recently developed integrated population model for BEL-EHB beluga (Van de Walle et al. In prep.). In previous stock assessments for Nunavik beluga, harvest advice was provided based on a Surplus Production Model (e.g., Hammill et al. 2023, Sauvé et al. 2024). It was estimated then that the BEL-EHB stock abundance was 2,900 (95% CrI = [1,700, 3,900]) in 2021 and that the stock had been declining at a rate of 3.0% per year since 2015 (Hammill et al. 2023). As for the JAM stock, its abundance was estimated at 16,700 (95% CrI = 11,6000-21,3000) beluga in 2021, and its demographic trend was deemed stable (Hammill et al. 2023). When compared using the same datasets for the BEL-EHB stock and over the same period of time, the SPM and the IPM performed similarly overall (Van de Walle et al. In prep.). However, the IPM yielded more precise estimates, and suggested a slower rate of decline in recent years due to the incorporation of additional sources of information in model formulation (Van de Walle et al. In prep.). Since then, a new 2024 aerial survey estimate has become available to inform the model. In addition, the entire time series of aerial survey abundance estimates has been fully revised (Sauvé et al. 2025). Although previous and new abundance estimates are highly correlated for both the BEL-EHB and JAM stocks (Sauvé et al. 2025), these changes nevertheless modified the abundance time series and its associated CV used as input for the IPM. Using the new IPM and updated data, the new estimate of BEL-EHB beluga abundance for 2024 is 2,200 (95% CrI = [1,800; 2,500]) and the annual rate of decline since 2021 is estimated at 5.1% (95% CrI = [3.6; 7.2]). The new estimate of JAM beluga abundance for 2024 is 16,000 (95% CrI = [12,300, 20,600]) and the stock trend is considered stable.

The last two aerial surveys (2021 and 2024) yielded the lowest and most precise estimates of BEL-EHB abundance in the time series, which dates back to 1985 (St-Pierre et al. 2024, Sauvé et al. 2025). These two most recent surveys thus had a leveraging effect on the BEL-EHB demographic trend and abundance estimated from the IPM. Consecutive survey estimates in the same direction are more likely to result in a high likelihood of representing a genuine trend in abundance. This, combined with the fact that these are the two most recent points in the time series, likely explain why model-based estimates indicate a greater rate of population decline at the end of the time series, compared to previous model runs in which the 2024 survey abundance estimate was not yet included (Sauvé et al. 2024; Van de Walle et al. In prep.).

Despite optimizing the use of available data to improve model fit, there remains uncertainties in the data sources that may affect the results from the IPM. Harvest numbers are a key source of information in the model for the BEL-EHB stock (Figure A8) that is greatly influencing model-based estimates. Since 2009, harvest statistics are available in a format that facilitates the decomposition of harvests into seasons and management areas. However, prior to that, only total annual harvests were readily available, thus we had to make some assumptions when splitting these among seasons. For instance, in the Hudson Strait, there remains uncertainties in the relative proportion of harvest occurring in the spring versus the fall for the period 1974-2008. A detailed and standardized compilation of past weekly harvest records would enable the refinement of the decomposition of reported Nunavik harvests by season and area and to assess how this has changed over time. However, challenging our assumption by adjusting up or down by 10% the percentage of the harvest that occurred in the spring versus the fall for the period 1974-2008 resulted in very limited impact (i.e. bias is small in comparison to the uncertainty) on the model-based estimation of initial population size and carrying capacity (K), and had virtually no impact on recent (2024) abundance estimates (Figure A13). Further, the genetic sample size for two combinations of management areas and seasons is insufficient to estimate the relative contribution of the different stocks of beluga landed. Again, assumptions were made based on neighboring management areas at similar times of the year. Promoting sampling in northeast Hudson Bay and Ungava Bay, particularly during spring, would allow for estimating the stock contribution of beluga harvested in nearby communities. Finally, as discussed in Van de Walle et al. (In prep.), there is currently very little data available to inform the model on the proportion of the harvest that is either non-recovered or non-reported (i.e., the sources of bias encompassing the struck and lost parameter) for both BEL-EHB and JAM beluga. Efforts should be made to improve estimates for this parameter for the Nunavik and Sanikiluaq beluga harvest as model-based estimates of population size and trends are sensitive to changes in this parameter (Van de Walle et al. In prep.).

The 3,400 threshold in the current management plan was established based on the most recent Science Advice available when the management plan was developed (DFO 2020). At that time, the EHB beluga stock was estimated to be slightly increasing or stable with an abundance of 3,400 in 2016. However, new correction factors (availability and perception bias) for surface abundance estimates of beluga from aerial surveys have been used in the most recent Science Advice (DFO 2022), which increased all abundance estimates in the time series. In addition, two aerial surveys yielded the lowest BEL-EHB abundance estimates since 1985 (Sauvé et al. 2025; St-Pierre et al. 2024), suggesting that rather than being stable, the BEL-EHB has been declining since 2015. Thus, the 3,400 beluga reference level is no longer valid. The management plan for beluga in Nunavik will be renewed. Here, we provided demographic projections for the stock under a large range of potential management objectives and time frames, that may inform the decision process.

We had sufficient data to construct a population model that yielded a good fit to the data and that quantitatively estimated reference levels that would trigger management measures under the Precautionary Approach (Lang et al. In prep.; Hammill et al. 2024). How these levels are determined vary among species and countries (reviewed in Hammill et al. 2024). Under the DFO-MSY framework, the LRP and PRP are calculated as 24% and 48% of K, i.e., carrying capacity, respectively. In a recent re-evaluation of the management framework for Atlantic seals, it was advised that when a population model can be constructed, it should be used to estimate *K*, and that *K* should be calculated over the longest period of time possible (Lang et al. In prep.). This is the approach used in the current assessment. While the JAM beluga stock would lie in the Healthy Zone using these criteria, i.e., above the PRP, the BEL-EHB beluga stock is approaching the LRP and the Critical Zone. Under the Precautionary Approach, if a stock falls below the LRP, it is considered to have suffered serious harm, and there is an obligation to implement a rebuilding plan for the stock (DFO 2006; Lang et al. In prep.). For a declining stock approaching the LRP, the requirement is to (1) implement management measures to promote stock growth and cease preventable declines and, (2) initiate the development of a rebuilding plan in advance of the stock declining to its LRP. Beluga in Nunavik are not managed under the Precautionary Approach and are thus not bound by these obligations. However, the Precautionary Approach may be useful to contextualize the status of Nunavik beluga stocks. It is also worth noting that environmental conditions which have prevailed and influenced beluga population dynamics in previous decades may not be representative of current and future conditions. Accordingly, *K*, reference points, and projections of population abundance for the JAM and BEL-EHB beluga stocks do not account for potential shifts in environmental conditions and may represent overestimates if adverse environmental conditions are observed in future decades.

The management of beluga in Nunavik is complex due to an interplay of factors. First, under the land claims agreements, hunting rights have to be balanced with the principles of conservation, which can result, at least in appearance, in a management paradox (Hammill et al. 2024). Second, there are a large number of communities involved, with different hunting practices carried out at different times of the year. Third, the beluga harvested along the Nunavik coast are comprised of a mixture of stocks that greatly vary in size and status, and which are shared by three jurisdictions. Efforts have so far been made to divert the hunt towards the more abundant WHB and JAM stocks and away from the smaller BEL-EHB stock, through several actions including seasonal closures and catch limitations. However, the number of BEL-EHB beluga harvested annually, as estimated by coupling information on total harvest with area- and season-specific genetic contribution of BEL-EHB to the harvest, has remained above recommended levels identified in the current management plan since its implementation in 2021. Current harvest levels are unsustainable. They have reached a level that, if maintained, will drive the stock to low and possibly unrecoverable levels (quasi-extinction) within the next 15 years. Beluga display intra- and interannual site fidelity to their summering grounds and therefore stocks are more vulnerable to local depletion than other species as they may have a reduced recolonization ability (Wade et al. 2012; O'Corry-Crowe et al. 2018, 2020). As a result, some communities, especially in the ARC, may eventually have reduced local access to this culturally and nutritionally significant resource and may have to shift to other areas to meet community needs.

We explored scenarios of season- and area-specific distribution of beluga harvests across Nunavik and the Belcher Islands. These alternative scenarios illustrate how regional and seasonal closures could minimize harvesting pressure on the BEL-EHB beluga stock while maintaining a high potential for beluga harvest by Nunavimmiut. In 2024, the eastern Hudson Bay Beluga Working Group (BWG), which brings together the main stakeholders involved in management, has resumed its activities. Bringing forward the results from these scenarios for discussion by the BWG, and simulating other season- and area-specific distributions of beluga harvests identified as of interest by co-management partners, could represent a step towards potential collaborative efforts aimed at identifying conservation measures that would contribute to stock recovery while maintaining subsistence hunting activities across Nunavik in the future, and which would align with some recent reflections on inclusive management approaches (e.g. Frid et al. 2023).

This stock assessment presents the second model-based estimate of abundance and trend for the JAM beluga stock, the previous having been reported by Hammill et al. (2023) using the SPM. In contrast to the BEL-EHB beluga stock, very few data are available on JAM beluga harvest composition (age, sex and reproductive status) to inform the population model. This is because harvest (and, therefore sampling) efforts directed at the JAM stock have been limited until very recently (since 2014), and currently remain low compared to BEL-EHB beluga. In addition, variance associated with JAM beluga aerial survey estimates is large, which may explain the limited contribution of the aerial surveys to model-based estimates. Therefore, results presented here should be interpreted with caution and should be seen as a first attempt towards a more integrated approach to the modelling of this stock. Nevertheless, the JAM stock is estimated to have stabilized in recent years and is close to carrying capacity. The stock is estimated to be well above the PRP and thus in the Healthy Zone.

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TABLES

Table 1. Survey estimates of BEL-EHB and JAM beluga stock abundance (mean, standard deviation, as well as lower and upper 95% Confidence Intervals).

Year	Mean abundance	Standard deviation	Lower 95% CI	Upper 95% CI
Belcher Islands - Eastern Hudson Bay (BEL-EHB)				
1985	4,497	1,168	2,725	7,420
1993	2,504	961	1,210	5,180
2001	2,634	1,166	1,149	6,035
2004	5,069	1,686	2,686	9,566
2008	4,326	938	2,843	6,584
2011	4,681	2,064	2,050	10,692
2015	8,506	4,341	3,312	21,842
2021	2,858	814	1,653	4,940
2024	1,491	366	928	2,396
James Bay (JAM)				
1985	4,788	1,525	2,604	8,805
1993	7,573	1,985	4,569	12,551
2001	17,958	4,477	11,098	29,059
2004	17,930	4,238	11,353	28,317
2008	25,686	18,174	7,369	89,535
2011	22,063	6,536	12,496	38,954
2015	22,847	7,557	12,149	42,964
2021	14,427	3,427	9,115	22,835
2024	11,455	2,650	7,322	17,921

Table 2. Reported harvest of beluga in four management areas in Nunavik and in Sanikiluaq (SAN, Nunavut) from 1974-2023. ARC represents the curved part of southeastern Hudson Bay and includes the Eastern Hudson Bay, Kuujjuarapik pilot project, and Northeastern Hudson Bay zone of voluntary closure management areas (Figure 1). HS represents the Hudson Strait management area, SAN represents the Sanikiluaq community, UB represents Ungava Bay and NEHB represents North East Hudson Bay. The letters FA stand for "Fall", whereas the letters SP stand for "Spring". For HS, starting in 2018, the fall season was further decomposed into an early (HS_{EF}) and late (HS_{LF}) phases (Hammill et al. 2023; Van de Walle et al. In prep.). Note that from 1974-2000, reports from HS also included catches in UB. The high value of harvest for SAN in 2015 is related to an ice entrapment where all individuals were harvested.

YEAR	ARC	HS	HS_{SP}	HS_{FA}	HS_{EF}	HS_{LF}	UB_{SP}	UB_{FA}	$NEHB_{SP}$	$NEHB_{FA}$	JAM	Total Nunavik	SAN
1974	184	421	NA	NA	NA	NA	0	0	0	0	0	605	0
1975	224	586	NA	NA	NA	NA	0	0	0	0	0	810	0
1976	216	463	NA	NA	NA	NA	0	0	0	0	0	679	0
1977	269	554	NA	NA	NA	NA	0	0	0	0	0	823	14
1978	164	243	NA	NA	NA	NA	0	0	0	0	0	407	6
1979	271	293	NA	NA	NA	NA	0	0	0	0	0	564	0
1980	280	281	NA	NA	NA	NA	0	0	0	0	0	561	0
1981	97	236	NA	NA	NA	NA	0	0	0	0	0	333	6
1982	114	271	NA	NA	NA	NA	0	0	0	0	0	385	30
1983	105	227	NA	NA	NA	NA	0	0	0	0	0	332	7
1984	131	189	NA	NA	NA	NA	0	0	0	0	0	320	28
1985	103	166	NA	NA	NA	NA	0	0	0	0	0	269	5
1986	43	126	NA	NA	NA	NA	0	0	0	0	0	169	25
1987	53	125	NA	NA	NA	NA	0	0	0	0	0	178	28
1988	52	117	NA	NA	NA	NA	0	0	0	0	0	169	20
1989	84	284	NA	NA	NA	NA	0	0	0	0	0	368	19
1990	53	109	NA	NA	NA	NA	0	0	0	0	0	162	20
1991	106	178	NA	NA	NA	NA	0	0	0	0	0	284	22
1992	78	96	NA	NA	NA	NA	0	0	0	0	0	174	20
1993	67	189	NA	NA	NA	NA	0	0	0	0	0	256	10
1994	82	207	NA	NA	NA	NA	0	0	0	0	0	289	50
1995	55	221	NA	NA	NA	NA	0	0	0	0	0	276	30
1996	56	211	NA	NA	NA	NA	0	0	0	0	0	267	30
1997	51	239	NA	NA	NA	NA	0	0	0	0	0	290	19
1998	50	252	NA	NA	NA	NA	0	0	0	0	0	302	54
1999	57	238	NA	NA	NA	NA	0	0	0	0	0	295	32
2000	62	208	NA	NA	NA	NA	0	0	0	0	0	270	23
2001	73	241	NA	NA	NA	NA	66	0	0	0	0	380	27
2002	5	161	NA	NA	NA	NA	13	0	0	0	0	179	15
2003	8	168	NA	NA	NA	NA	26	0	0	0	0	202	80
2004	3	144	NA	NA	NA	NA	4	0	0	0	0	151	94
2005	1	172	NA	NA	NA	NA	5	0	0	0	0	178	53
2006	0	147	NA	NA	NA	NA	2	0	0	0	0	149	22
2007	21	165	NA	NA	NA	NA	6	0	0	0	0	192	24
2008	23	92	NA	NA	NA	NA	5	0	0	0	0	120	33
2009	21	0	68	70	NA	NA	6	0	0	0	0	165	34
2010	16	0	138	61	NA	NA	8	7	0	0	0	230	47
2011	19	0	115	86	NA	NA	0	17	0	0	0	237	32
2012	13	0	208	56	NA	NA	10	2	0	0	0	289	61
2013	8	0	150	90	NA	NA	8	0	0	0	0	256	76
2014	22	0	208	37	NA	NA	11	0	1	14	5	298	26
2015	36	0	106	94	NA	NA	28	3	0	30	6	303	170
2016	17	0	121	19	NA	NA	24	3	0	3	38	225	43
2017	18	0	150	85	NA	NA	23	4	0	13	6	299	30
2018	14	0	146	0	91	0	100	2	2	17	6	378	50
2019	35	0	144	0	87	23	23	2	2	24	27	367	28
2020	39	0	189	0	71	7	90	1	0	5	28	430	46
2021	28	0	51	0	137	23	20	0	0	66	41	366	30
2022	19	0	161	0	33	90	24	0	25	22	10	384	51
2023	17	0	225	0	125	56	69	3	15	14	8	532	20
2024	43	0	289	0	98	97	114	12	0	24	4	681	48

Table 3. Proportion of beluga harvested in the different management areas and seasons originating from the BEL-EHB and JAM stocks used in the IPM. Some seasonal definitions change between regions. Sample size represents the total number of samples collected for genetic analyses. The 2.5 and 97.5% percentiles of the beta distribution used in the model for prior specification are also shown.

Management area	**Season**	**Sample size**	**Proportion BEL-EHB**	**Proportion JAM**
Nunavik				
East Hudson Bay (ARC)	All year	183	0.99[1] [0.95,1.00]	0.001 [0.00,0.01]
Hudson Strait	Spring (Feb. 1 – Aug. 31)	880	0.14 [0.12,0.17]	0.02 [0.01,0.03]
	Fall (Sept. 1 – Jan. 31)	739	0.33 [0.30,0.36]	0.004 [0.000,0.010]
	Early Fall (Sept. 1 – Nov. 20)	507	0.51 [0.47,0.56]	0.001 [0.000,0.005]
	Late Fall (Nov. 21 – Jan. 31)	232	0.05 [0.03,0.08]	0.05 [0.03,0.09]
Ungava Bay	Spring (Feb. 1 – Aug. 31)	168	0.02 [0.00,0.08]	0.02 [0.00,0.04]
	Fall (Sept. 1 – Jan. 31)	7	0.05[2] [0.00,0.32]	0.003 [0.00,0.015]
Northeast Hudson Bay	Spring (Feb. 1 – Aug. 31)	5	0.22[2] [0.05,0.70]	0.02 [0.00,0.18]
	Fall (Sept. 1 – Jan. 31)	48	0.52 [0.38,0.65]	0.10 [0.03,0.20]
Long Island (James Bay)	All year	75	0.00	0.99 [0.91,1.00]
Nunavut				
Sanikiluaq	Summer (Jul. 1 – Aug. 31)	66	0.99[1] [0.97,1.00]	0.001 [0.000,0.009]
	Fall (Sept. 1 – Nov. 30)	53	0.64 [0.51,0.76]	0.03 [0.00,0.09]
	Winter (Dec. 1 – Mar. 31)	59	0.57 [0.44,0.69]	0.08 [0.03,0.16]
	Spring (Apr. 1 – Jun. 30)	352	0.58 [0.52,0.63]	0.18 [0.14,0.22]

[1] All harvested beluga in those areas in the summer are deemed to be from BEL-EHB. A value of 0.99 was used in the model for ease of computation.

[2] Due to low sample sizes in those harvest categories, we calculated a proportional BEL-EHB contribution based on the fall and spring estimates from Hudson Strait.

Table 4. Pregnancy rates of beluga harvested along the Nunavik coast between October and May, 2009-2024, estimated from blubber progesterone levels.

Year	Sample size	Number of pregnant females	Proportion of pregnant females	Variance
2009	2	2	1.00	0.00
2010	2	1	0.50	0.25
2011	2	2	1.00	0.00
2012	4	2	0.50	0.25
2013	0	-	-	-
2014	2	0	0.00	0.00
2015	6	4	0.67	0.22
2016	2	0	0.00	0.00
2017	30	11	0.37	0.23
2018	14	4	0.29	0.20
2019	14	4	0.29	0.20
2020	7	0	0.00	0.00
2021	20	7	0.35	0.23
2022	13	5	0.39	0.24
2023	88	22	0.25	0.19
2024	26	12	0.46	0.25

Table 5. Reference points used to calculate beluga stock status, Potential Biological Removal, and probabilities to meet the management objectives presented in the document.

Parameter	BEL-EHB			JAM		
	Mean	Lower CrI	Upper CrI	Mean	Lower CrI	Upper CrI
N2024	2,200	1,800	2,500	16,000	12,300	20,600
K	8,100	6,800	10,300	18,300	12,100	30,300
PRP	3,900	-	-	8,800	-	-
LRP	1,900	-	-	4,400	-	-
R_{max}	0.04	0.03	0.05	0.03	0.02	0.05
N_{min}	2,000	-	-	14,200	-	-

Table 6. Harvest levels (number of BEL-EHB beluga harvested per year) compatible with various management objectives for the BEL-EHB beluga stock. Harvest levels presented exclude struck and lost. A dash indicates that the specified management objective is unachievable under zero-harvest conditions.

Management objective	Projection period	Probability of reaching the objective		
		50%	80%	95%
Current 2021-2026 management plan				
Reach or surpass 3,400 beluga	5 years	-	-	-
	10 years	-	-	-
	25 years	24	14	5
Reach or surpass 3,000 beluga	5 years	-	-	-
	10 years	-	-	-
	25 years	33	23	14
DFO Maximum Sustainable Yield				
Reach or surpass LRP	5 years	88	59	30
	10 years	66	50	36
	25 years	55	46	37
Reach or surpass PRP	5 years	-	-	-
	10 years	-	-	-
	25 years	13	3	-
Alternative management scenarios				
Stable population	25 years	50	43	35
Positive annual growth of 1%	25 years	38	30	22

Table 7. Total number of beluga that would be landed by Nunavik and Sanikiluaq hunters per BEL-EHB beluga harvested under alternative spatial and temporal distributions of harvest efforts, based on area- and season-specific stock composition of the harvest (see Table 3). The proportion of the harvest in each management area and each season for each scenario considered can be found in Tables A4 and A5.

Spatial distribution of harvest	Temporal distribution of harvest	Total no. beluga harvested per BEL-EHB landed
Scenario 1: Same as observed during 2021-2024	**Scenario A:** Same as observed during 2021-2024	3.8
	Scenario B: Spring only	4.7
	Scenario C: Fall only, with Early Fall only for HS	2.0
	Scenario D: Fall only, with Late Fall only for HS	5.4
Scenario 2: Same as Scenario 1, except no harvest in the ARC	**Scenario A:** Same as observed during 2021-2024	4.1
	Scenario B: Spring only	6.0
	Scenario C: Fall only, with Early Fall only for HS	2.2
	Scenario D: Fall only, with Late Fall only for HS	6.5
Scenario 3: Proportional to Inuit population distribution	**Scenario A:** Same as observed during 2021-2024	2.6
	Scenario B: Spring only	2.7
	Scenario C: Fall only, with Early Fall only for HS	3.1
	Scenario D: Fall only, with Late Fall only for HS	2.1
Scenario 4: Hudson Strait only	**Scenario A:** Same as observed during 2021-2024	4.7
	Scenario B: Spring only	7.1
	Scenario C: Fall only, with Early Fall only for HS	2.0
	Scenario D: Fall only, with Late Fall only for HS	20.0

FIGURES

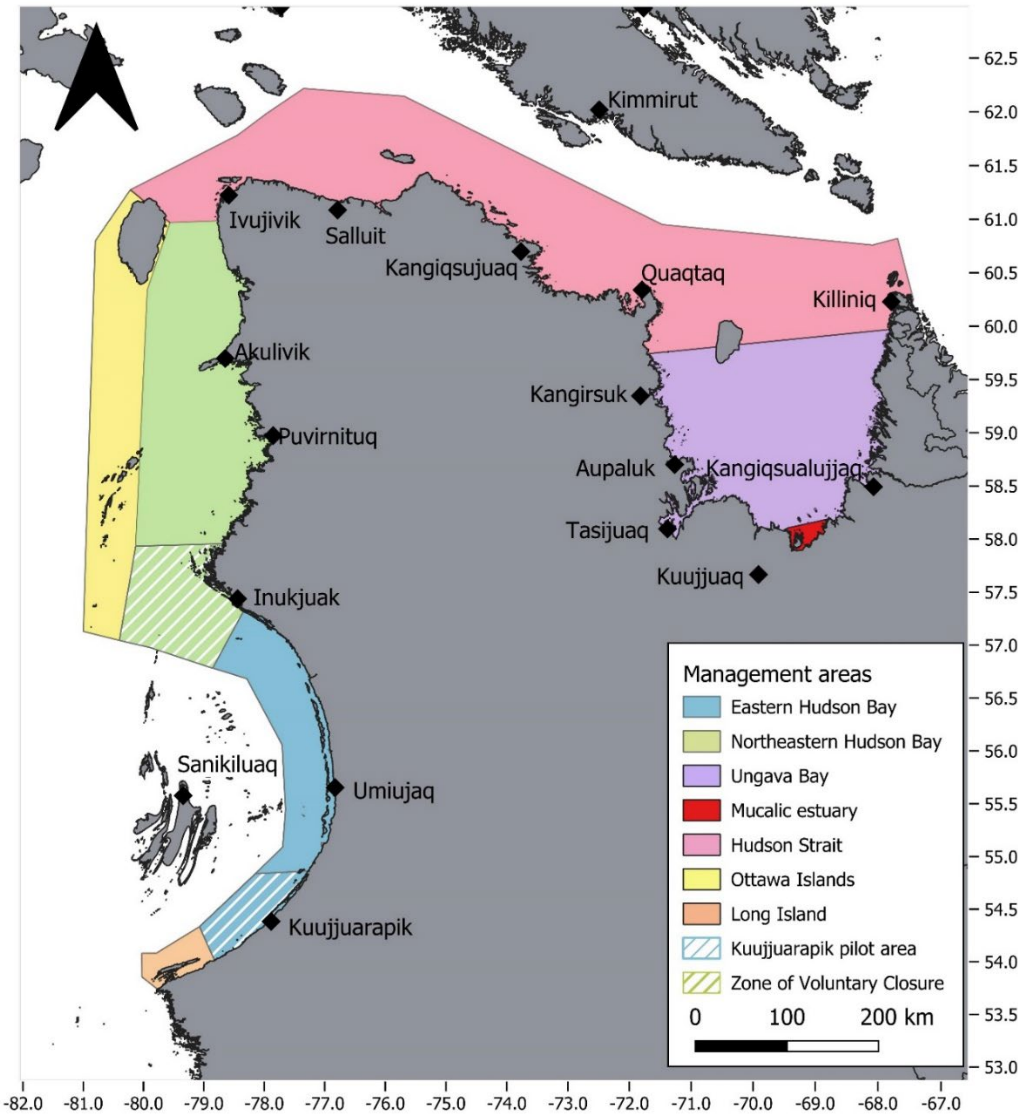

Figure 1. Map of communities (black) and management areas in Nunavik, Québec, Canada. We assigned reported harvest data to five management areas in Nunavik: 1) the "Arc", which comprises Eastern Hudson Bay including the Kuujjuarapik pilot area and the Zone of Voluntary Closure, 2) Northeastern Hudson Bay (except the Zone of voluntary closure), 3) Hudson Strait, 4) Ungava Bay and 5) James Bay (Long Island). No harvest were reported in Ottawa Islands. The IPM also accounts for harvests in Sanikiluaq, which is located on the Belcher Islands and is part of Nunavut. The Long Island, Belcher Islands and Arc areas are summering grounds for the James Bay (JAM), BEL and EHB beluga genetic populations, respectively. Therefore, all beluga harvested in Sanikiluaq and the Arc during summer (i.e., July and August) are considered taken from the BEL-EHB beluga stock. Similarly, all beluga harvested in Long Island during summer are deemed JAM beluga. In other seasons and management areas, the genetic composition of the harvest was used to calculate the BEL-EHB and JAM mortality associated with harvest.

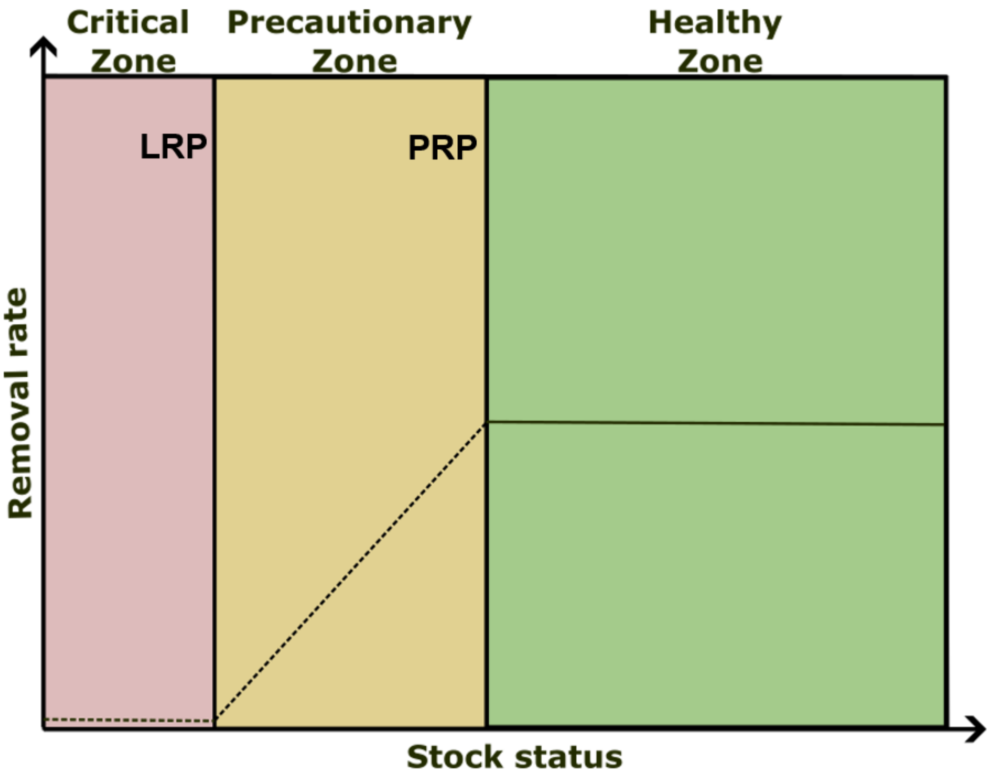

Figure 2. Removal rates compatible with the DFO Maximum Sustainable Yield Precautionary Approach (DFO 2006). Three zones of resource concern are defined and delimited by the Lower Reference Point (LRP) and the Precautionary Reference Point (PRP).

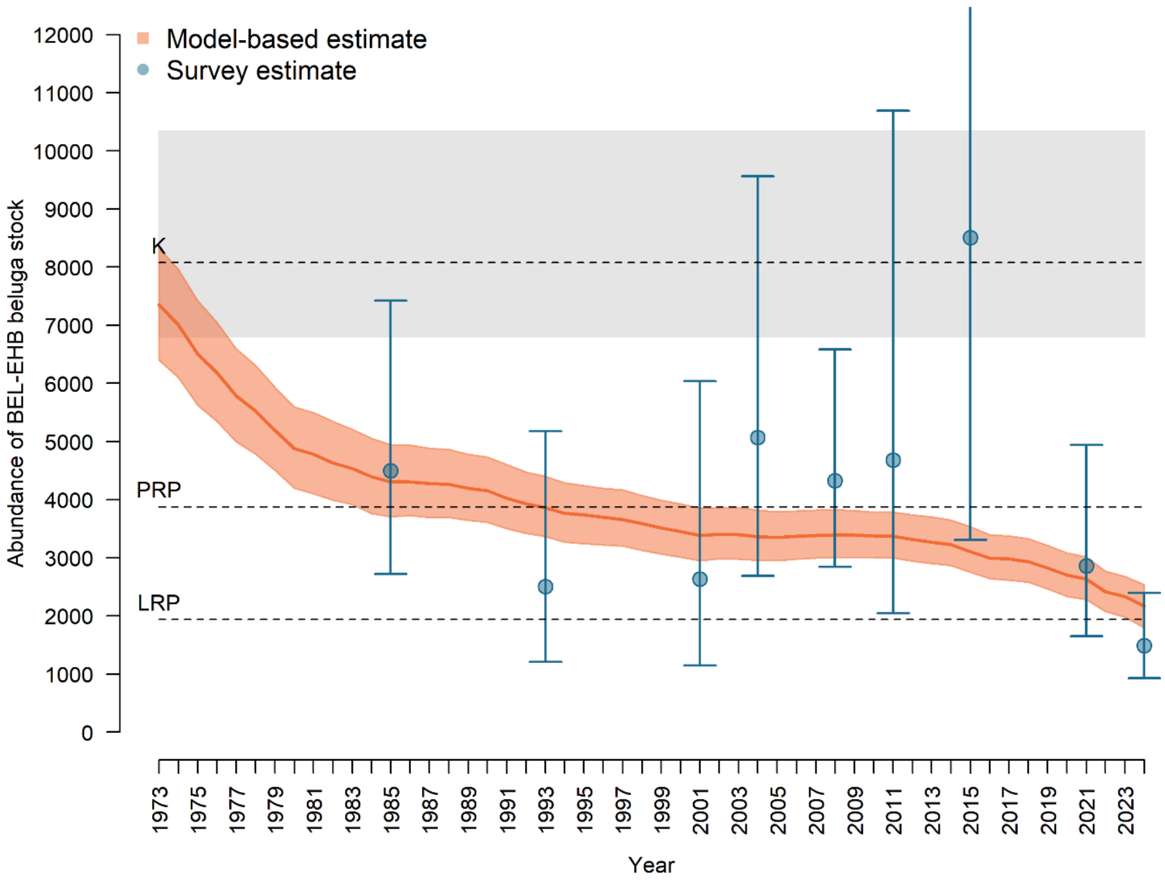

Figure 3. Demographic trend for the BEL-EHB beluga stock in Nunavik, Quebec, Canada. Abundance (mean: dark orange line, 95% Credible Interval: light orange polygon) is estimated from a multistate (age times state) Integrated Population Model. The benchmarks identified under the DFO-Maximum Sustainable Yield (MSY) management framework are identified, with MSY representing 60% of K, Precautionary Reference Point (PRP) representing 80% of MSY and 48% of K and the Lower Reference Point (LRP) representing 40% of MSY and 24% of K. Shading around the estimate of K represent the 95% CrI.

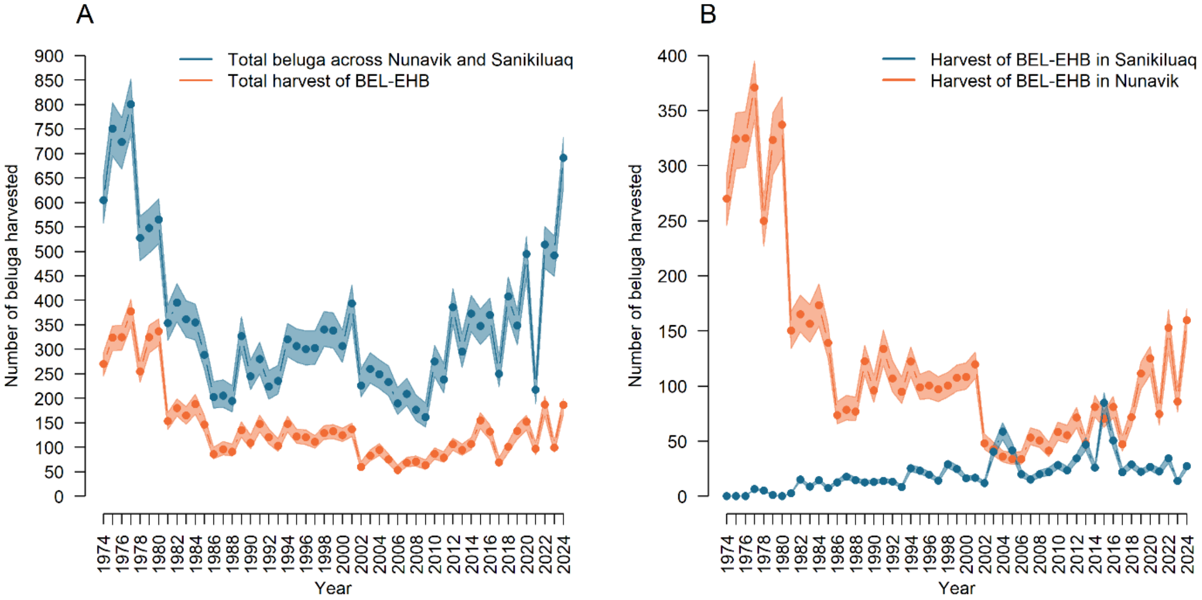

Figure 4. Temporal variation in the (A) the number of beluga landed across Nunavik and Sanikiluaq in total and specifically from the BEL-EHB stock, and (B) decomposition of the total annual BEL-EHB harvest between Nunavik (Quebec) and Sanikiluaq (Nunavut). In panel (A) circles represent reported harvests, while in panel (B), circles illustrate reported harvests multiplied by season- and region-specific stock composition of the harvest derived from genetic analyses. The shaded areas are the 95% Credible Interval of the posterior distributions from the multistate Integrated Population Model for BEL-EHB beluga.

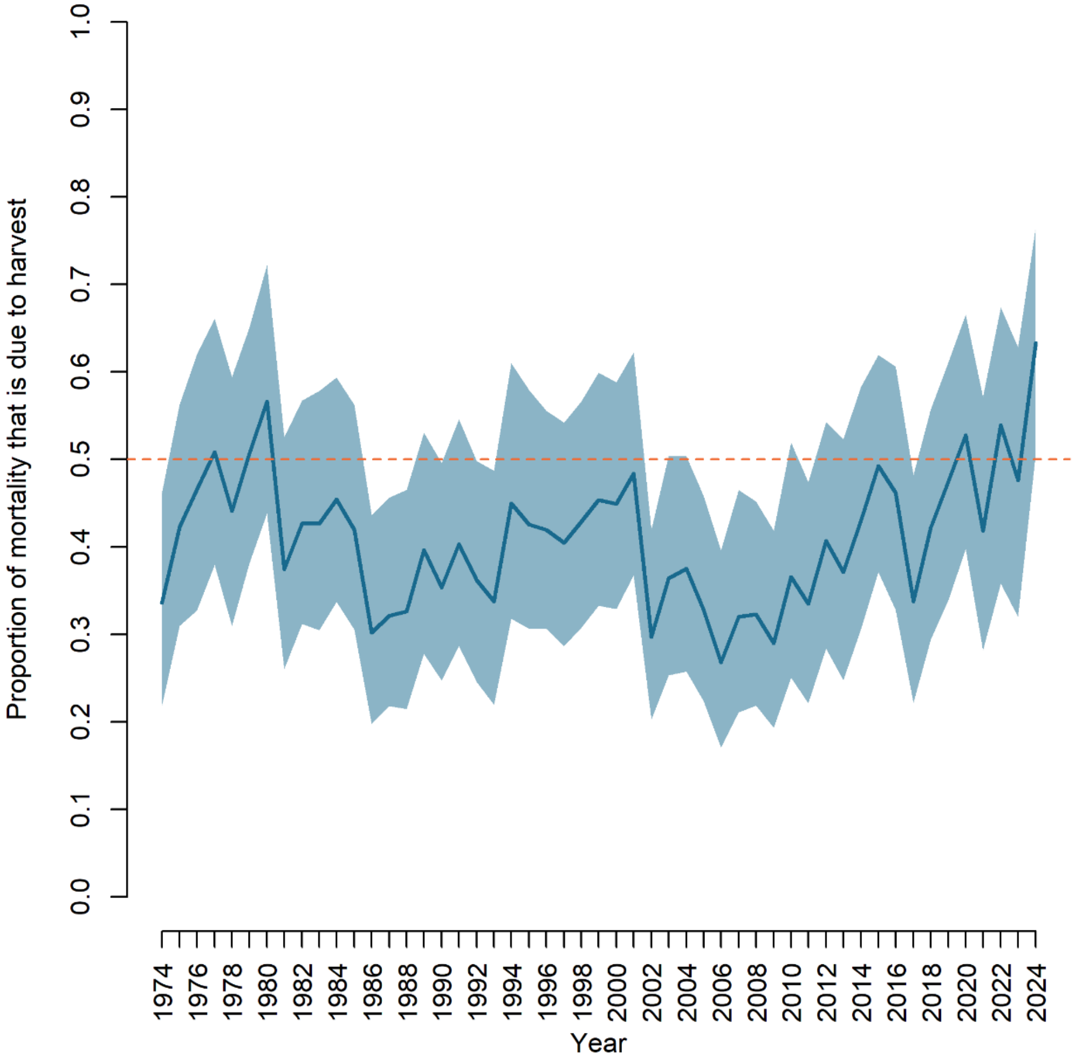

Figure 5. Temporal variation in the relative proportion of total mortality that is attributable to harvest, including animals that were landed and reported as well as those that were struck and lost (i.e., unrecovered or not reported), estimated by the multistate Integrated Population Model for BEL-EHB beluga. The horizontal dashed orange line represents a 50% harvest mortality. The solid blue line and the shaded area represent the mean and 95% Credible Interval from the posterior distribution, respectively.

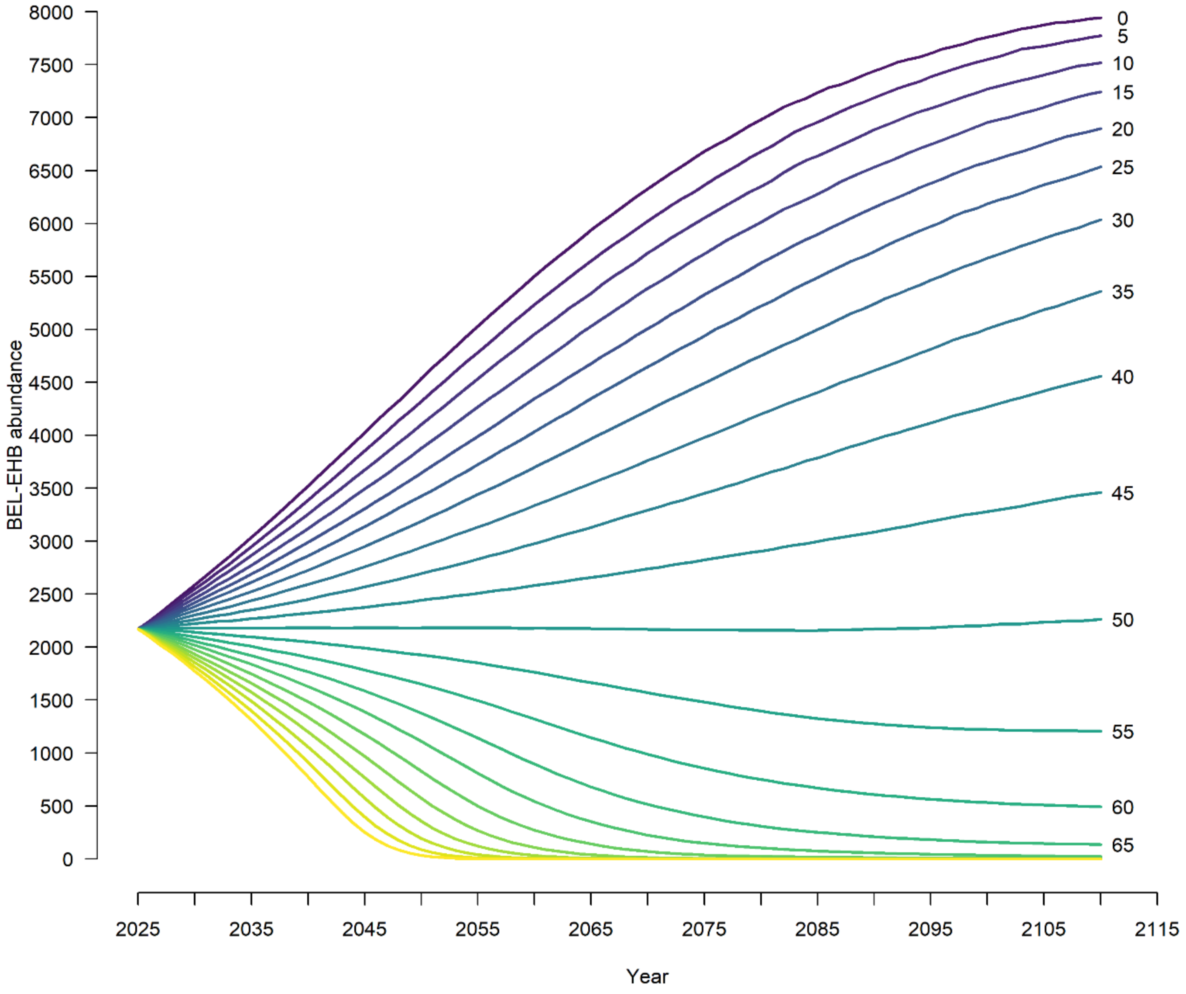

Figure 6. Projected demographic trend (over three generations) for the BEL-EHB stock considering scenarios of future harvest levels ranging from 0 to 100 BEL-EHB beluga per year (excluding struck and lost). Note that above 65 BEL-EHB beluga harvested per year, the population is predicted to go extinct within the next three generations.

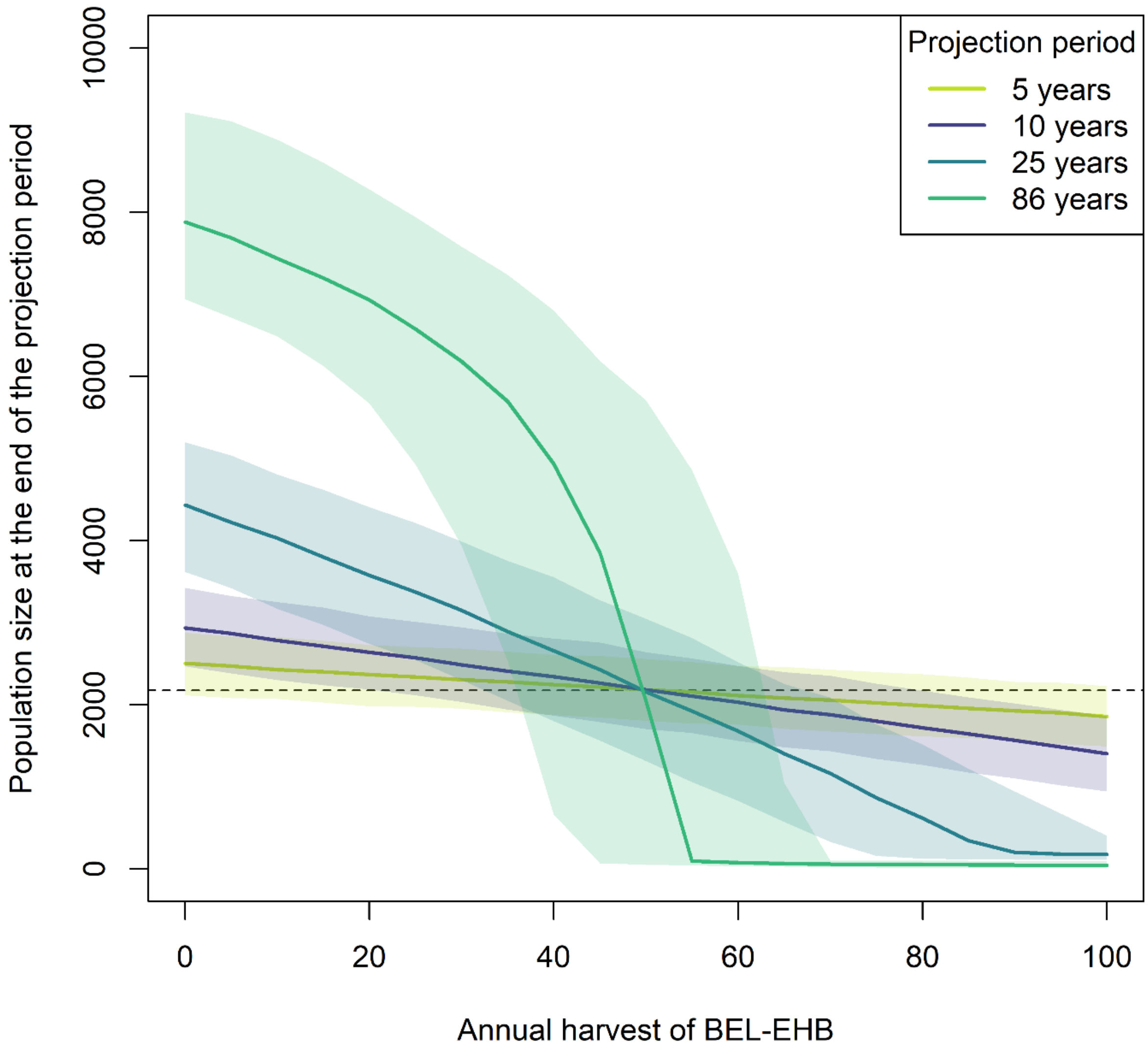

Figure 7. Population size at the end of the model projection period as a function of the annual number of BEL-EHB beluga harvested. Results are shown for four projection periods: 5 years (light green), 10 years (purple), 25 years (blue) and 3 generations (86 years, in dark green). The dotted line represents the 2024 estimate of abundance. Note that all of the lines cross at approximately 50 which is the long term harvest projected to result in a stable population (See table 6).

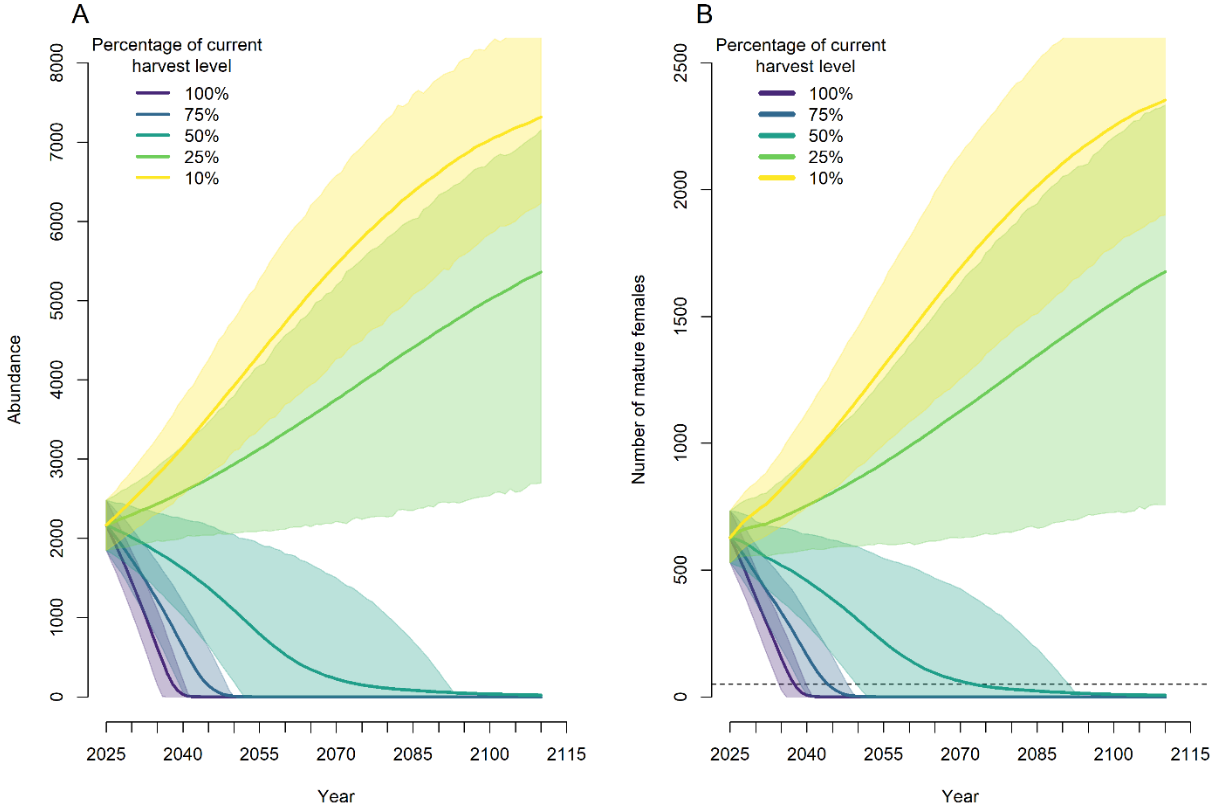

Figure 8. Projection of total abundance (A) and the number of mature females (B) for the BEL-EHB beluga stock over three generations (86 years) under various harvest levels. The current harvest level is 140 BEL-EHB beluga per year (i.e., the average over the 2021-2024 period), whereas 75%, 50%, 25% and 10% of this current level represent 105, 70, 35 and 14 BEL-EHB beluga per year. In (B), the dashed line represents 50 mature females, which is the quasi-extinction threshold.

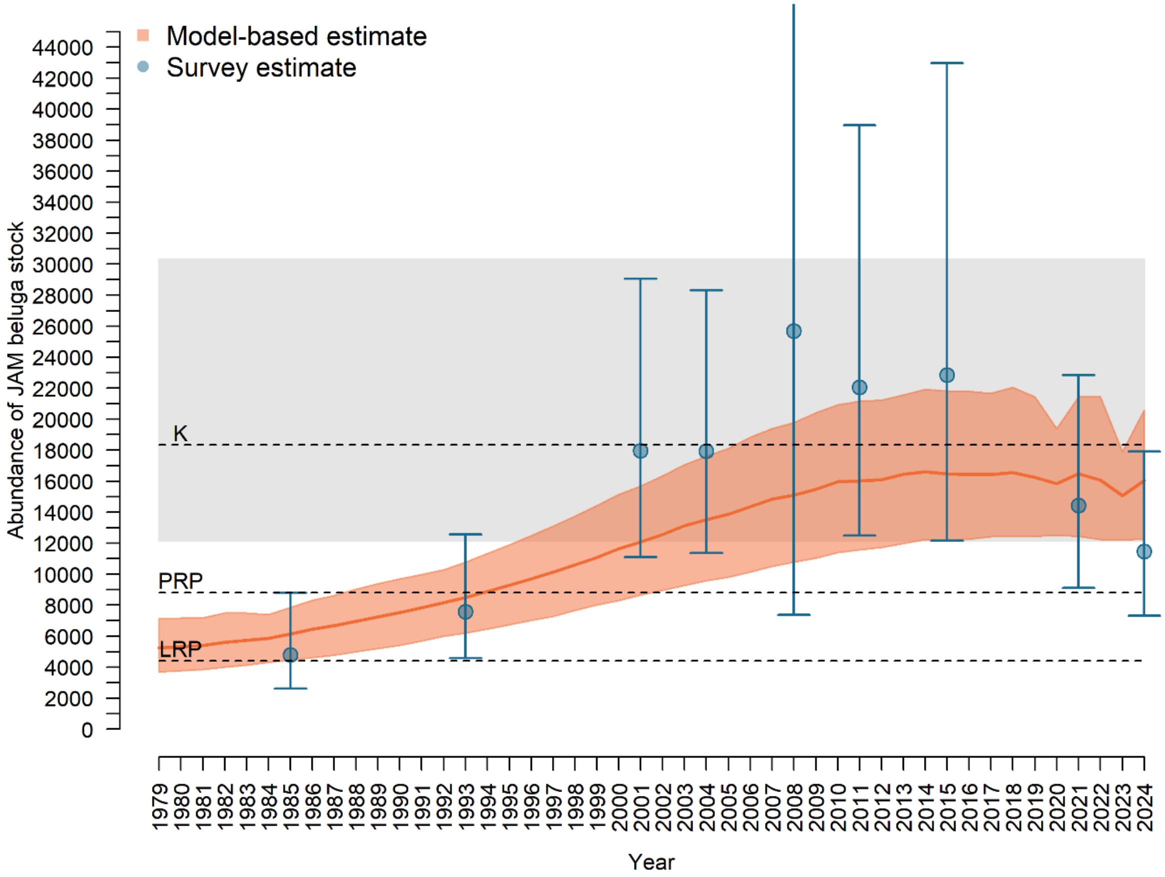

Figure 9. Demographic trend for the JAM beluga stock in Canada. Abundance (mean: dark orange line, 95% Credible Interval: light orange polygon) is estimated from a multistate (age times state) Integrated Population Model. The benchmarks identified under the DFO-Maximum Sustainable Yield (MSY) management framework are identified, with MSY representing 60% of K, the Precautionary Reference Point (PRP) representing 48% of MSY and the Lower Reference Point (LRP) representing 24% of MSY. Shading around the estimate of K represent its 95% CrI.

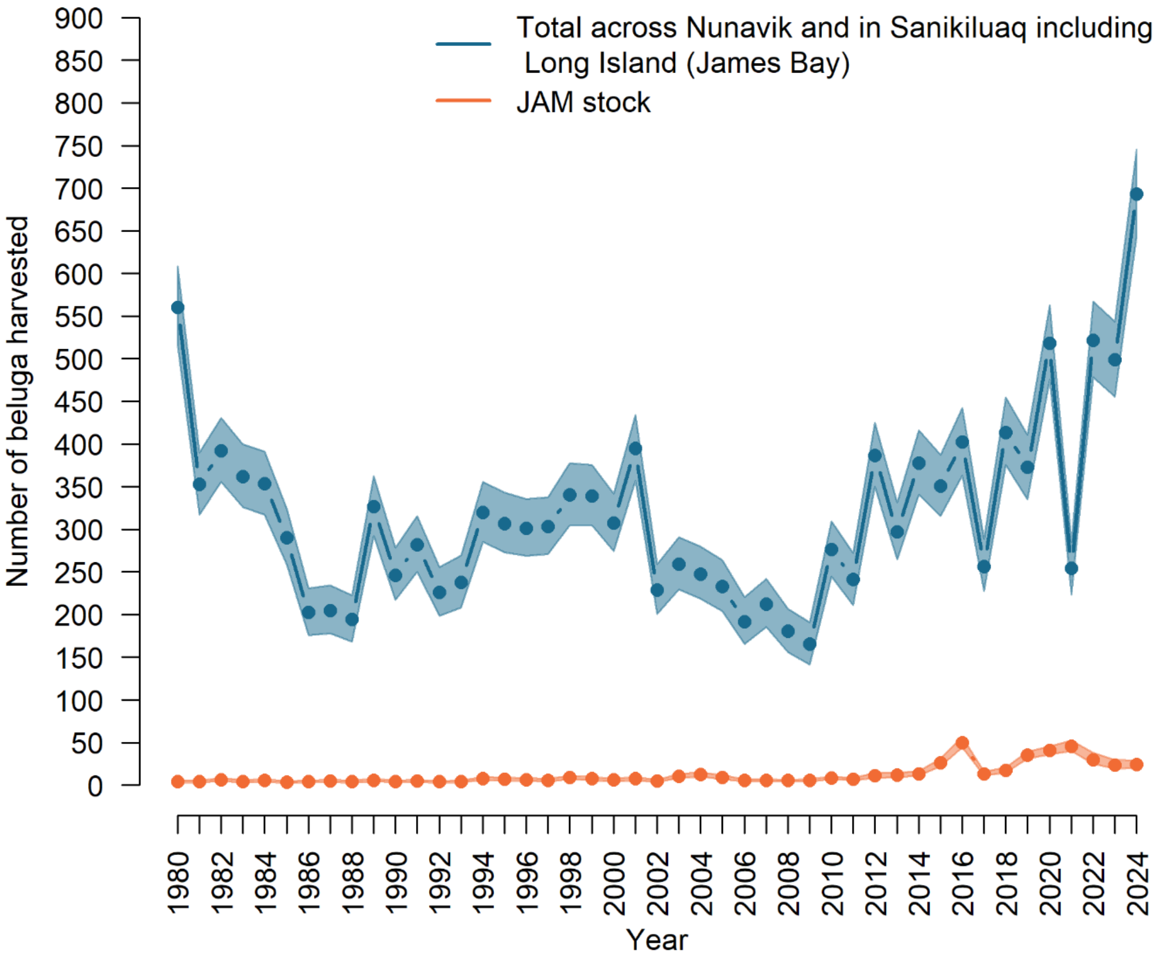

Figure 10. Temporal variation in the number of beluga landed across Nunavik and Long Island (James Bay) in total and specifically from the JAM stock, as estimated by the multistate Integrated Population Model. Solid lines represent the mean and the shaded areas are the 95% Credible Interval from the posterior distributions.

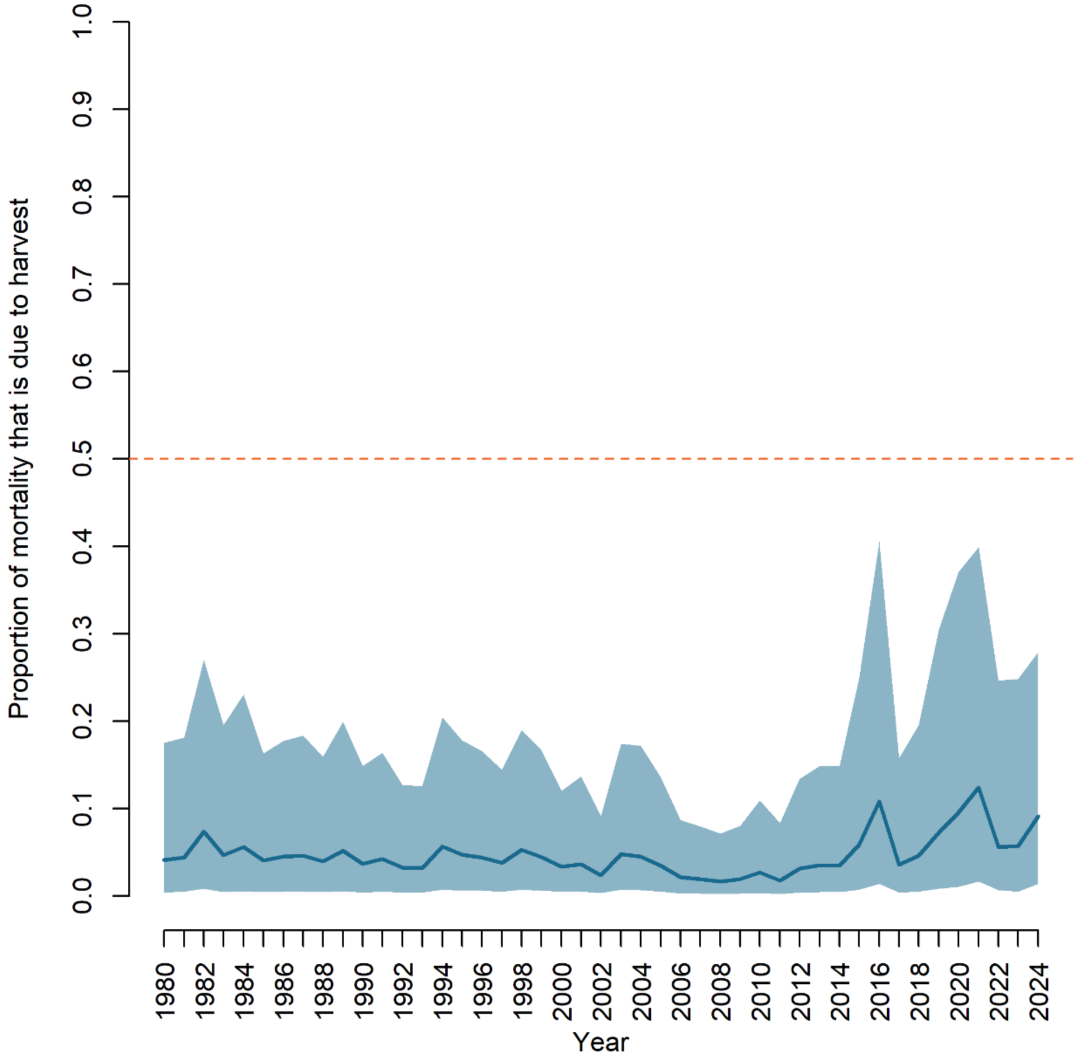

Figure 11. Temporal variation in the relative proportion of total mortality that is attributable to harvest, including animals that were landed and reported as well as those that were struck and lost (i.e., unrecovered or not reported), estimated by the multistate Integrated Population Model for JAM beluga. The horizontal dashed orange line shows the 50% line. The solid blue line represents the mean and the shaded area is the 95% Credible Interval from the posterior distribution.

APPENDIX 1

IPM FULL DESCRIPTION

Below is the full description of the IPM that is used for to model population abundance of the BEL-EHB stock (as described in Van de Walle et al. In prep.). In this document, the model structure was also used for JAM population, but with modifications to only consider survey abundance and harvest data for model fitting.

The IPM is comprised of three parts: 1) process model, 2) data model and 3) model fitting. The process model is a series of equations that describe demographic transitions and which, when solved, estimates dynamics in population abundance based on the values of the input parameters. The data model describes how the empirical datasets are linked to the predicted dynamics of the process model. The model fitting part describes how input parameters are estimated. Note that vectors and matrices are presented in bold characters, and $\odot$ represents the element-by-element vector multiplication.

Process model

We used a multi-state population model, as formulated by Caswell et al. (2018) and Roth and Caswell (2016). In this formulation, individuals are classified within two or more dimensions simultaneously. For beluga, we characterized individuals along two distinct dimensions: age class (*i*) and a combination of sex and reproductive state (hereafter referred to as “state”; *j*);

Dimension 1, $i, \in \{1, ..., w\}$

Dimension 2, $j, \in \{1, ..., b\}$

We considered 61 age classes ($w = 61$). Each age class was of length 1 year, except the last one which was left open-ended and included individuals of age ≥ 60 years old, age at which pregnancy is rare (Suydam 2009).

We considered four states ($b = 4$): 1) males (M), 2) non-reproducing females (A), 3) pregnant females (P) and 4) females with a calf (W; Figure A1). The model includes males in its formulation as a single and distinct state to account for sex-specific differences in survival. The model tracks male abundance over time, but males are not separated according to their reproductive state. In contrast, females are separated into three reproductive states, following Mosnier et al. (2015), to account for potential differential constraints acting on females at different reproductive stages of their life cycle. Non-reproducing females (A) include immature females and adult females that are either not pregnant or caring for a calf. Females can only reach the states P and W at the minimal ages of 8 and 9, respectively. Transitions between states occur during an annual time step, which is between the periods of census at times t and $t+1$. Census time is set at the time of aerial surveys, i.e. in late summer, hence the model considers a post-breeding census. Therefore, at the time of census, calves of the year are born and only early pregnancies are present. Transitions between states and fertilities (i.e., the production of new individuals) are presented in Figure A1.

The vector $\tilde{\boldsymbol{n}}$ contains the number of individuals within each combination of age class *i* and state *j*. The vector $\tilde{\boldsymbol{n}}$ is of length k, with $k = w \times b$.

$$\widetilde{\mathbf{n}} = \begin{pmatrix} n_{11} \\ \vdots \\ n_{w1} \\ - \\ n_{21} \\ \vdots \\ n_{w2} \\ - \\ \vdots \\ - \\ n_{1b} \\ \vdots \\ n_{wb} \end{pmatrix} \tag{A1}$$

The multistate matrix $\widetilde{\mathbf{A}}$ projects the population vector $\widetilde{\boldsymbol{n}}$ forward in time, from time t to time $t+1$ and has the same structure,

$$\widetilde{\mathbf{n}}(\mathrm{t}+1) = \widetilde{\mathbf{A}}(\mathrm{t})\widetilde{\mathbf{n}}(\mathrm{t}) \tag{A2}$$

The construction of the multistate projection matrix relies on the separation of processes (i.e., transitions of live individuals and production of offspring through reproduction) occurring in the different dimensions (i.e., age and state). The matrix $\widetilde{\mathbf{A}}$ can thus be decomposed into its constituents as follows:

$$\widetilde{\mathbf{A}} = \widetilde{\mathbf{U}} + \widetilde{\mathbf{F}} \tag{A3}$$

$\widetilde{\mathbf{A}}$, $\widetilde{\mathbf{U}}$, and $\tilde{\mathbf{F}}$ are all of dimension $wb \times wb$. The matrix $\widetilde{\mathbf{U}}$ contains transition probabilities for living individuals, and $\tilde{\mathbf{F}}$ contains the production of new individuals by mature individuals. Transitions within $\widetilde{\mathbf{U}}$ and $\tilde{\mathbf{F}}$ are further decomposed into distinct processes, each occurring in the distinct model dimensions (here two dimensions: age, and state). For instance, $\widetilde{\mathbf{U}}$ combines two distinct processes: 1) transitions between age classes included in the block-diagonal matrix $\mathbb{U}$, and 2) transition between states included in the block-diagonal matrix $\mathbb{B}$.

The hyperstate matrix $\widetilde{\mathbf{U}}$ is obtained by sequentially multiplying the two sub-processes:

$$\widetilde{\mathbf{U}} = \mathbf{K}^{T}\mathbb{B}\mathbf{K}\mathbb{U} \tag{A4}$$

Reading from right to left, individuals will move between dimensions at each time step following this specific sequence of transitions 1) age classes through $\mathbb{U}$ and 2) breeding state through $\mathbb{B}$. The vec-permutation matrix $\mathbf{K}$ rearranges the vector $\widetilde{\mathbf{n}}$ for the matrix multiplication in the next dimension. Note that $\mathbf{K}^{\mathbf{T}}$ is the transpose of the matrix $\mathbf{K}$.

The matrix $\mathbb{U}$ has matrices $\mathbf{U_j}$ arranged on its diagonal,

$$\mathbb{U} = \begin{pmatrix} \mathbf{U_1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{U_2} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{U_3} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{U_4} \end{pmatrix}, \tag{A5}$$

and is obtained using the following equation:

$$\mathbb{U} = \sum_{j=1}^{s/s_d} \mathbf{E_{jj}} \otimes \mathbf{U_j} \tag{A6}$$

where s is product of dimensions, i.e., $s = w \times b$ and s_d is the size of the dimension of interest, i.e., in the case of the $\mathbf{U}_{\boldsymbol{j}}$ matrices, $sd = w$. Note that block matrices $\mathbb{B}$, $\mathbb{R}$, and $\mathbb{F}$ (see below) are constructed in the same way.

The $\mathbf{U}_{\boldsymbol{j}}$ matrices are built for each state j at each time step t. They contain age- and state-specific survival probabilities (S) on the sub-diagonal.

$$\mathbf{U}_j(t) = \begin{pmatrix} 0 & \dots & 0 & 0 & 0 \\ S_{1,j}(t) \times SW & \dots & 0 & 0 & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & \dots & S_{w-2,j}(t) & 0 & 0 \\ 0 & \dots & 0 & S_{w-1,j}(t) & S_{w,j}(t) \end{pmatrix} \tag{A7}$$

Note that beluga reach sexual maturity at age 8 years old. Therefore, considering that age class 1 consists of 0 year-olds, females can only reach state P (pregnant female) once in age class 9 (corresponding to age 8 years-old). The state W (female with a calf) can then only be attained upon reaching age class 10. Therefore, the parameter S was set to 0 for P of age classes 1 through 8 and for W of age classes 1 through 9.

Beluga are weaned either after 1 or 2 years of lactation (Matthews and Ferguson 2015). While calves mostly rely on lactation during their first year, most beluga consume a mixture of milk and solid food during their second year of life and one third of calves are completely weaned after their first year. This suggests that beluga may be fully dependent on maternal provisioning during their first year of life, but may become independent in their second year. We thus assumed that the survival of calves (age 0 individuals, corresponding to age class 1) to the next year was conditional on the survival of their mother (SW). SW was estimated as the weighted average survival of W females, with weight corresponding to the estimated proportion of W females in each age class at the current year.

The matrix $\mathbb{B}$ has a similar structure to $\mathbb{U}$, but with matrices $\mathbf{B}_{\boldsymbol{i}}$ on the diagonal. The $\mathbf{B}_{\boldsymbol{i}}$ matrices contain the age- specific probabilities of transitioning between the four states, j (M, A, P and W), acknowledging this probability is zero for males. For females, those probabilities are conditional on pregnancy rates (Pr) and neonatal mortality (S_n), as pregnant females at time t may become pregnant again at time $t + 1$ if they lose their calf in the time interval.

$$\mathbf{B}_i(t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 - Pr_i(t) & 1 - S_n(t) & 1 \\ 0 & Pr_i(t) & 0 & 0 \\ 0 & 0 & S_n(t) & 0 \end{pmatrix} \tag{A8}$$

Note that for $i \; in \; 1 - 8$, Pr_i was set to zero.

The hyperstate matrix $\tilde{\mathbf{F}}$ combines 1) production of offspring included in the block-diagonal matrix $\mathbb{R}$ and 2) classification of offspring into the first breeding state included in the block-diagonal matrix $\mathbb{F}$**.** $\tilde{\mathbf{F}}$ is obtained by multiplying the two sub processes:

$$\tilde{\mathbf{F}} = \mathbf{K}^{\mathrm{T}} \mathbb{F} \mathbf{K} \mathbb{R} \tag{A9}$$

Reading from right to left, individuals will produce offspring at each time step following this specific sequence of transitions 1) production of individuals of age class 1 through $\mathbb{R}$ and 2) classification of age class 1 individuals within the male and non-reproducing female state through $\mathbb{F}$. The vec-permutation matrices $\mathbf{K}$ here again rearrange the dimensions of each of these matrices to respect matrix organization at each step of the multiplication.

The matrix $\mathbb{R}$ has matrices $\mathbf{R_j}$ arranged on the diagonal. The $\mathbf{R}_j$ matrices are built for each state j at each time step t. They contain the state-specific probabilities of producing individuals of the first age-class, i.e., calves. Only pregnant females (j = P) can produce calves, so $\mathbf{R}_j$ for $j \in$ (M, A, W) are zero matrices. In the $\mathbf{R}$ matrix for pregnant females, females at time t can give birth to a calf and reach the state W at time $t+1$ conditional on their survival (S) and that of their neonate (S_n) until population census.

$$\mathbf{R}_j(t) = \begin{pmatrix} S_{1,3}(t) \times S_n(t) & S_{2,3}(t) \times S_n(t) & \cdots & S_{w,3}(t) \times S_n(t) \\ 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix} \tag{A10}$$

As a result of this process, all newly produced offspring are classified within the age class 1, but they remain classified within the breeding state category of their mother ($j = 3$). Reclassification of the newly produced offspring within the male (M) or non-reproducing female (F) states is achieved using the matrix $\mathbb{F}$. The matrix $\mathbb{F}$ contains the $\mathbf{F_i}$ matrices on its diagonal. Matrices $\mathbf{F_i}$ are of dimension $b \times b$ and put back within the male (M) or non-reproducing female (F) state the offspring coming from pregnant females.

$$\mathbf{F}_i = \begin{pmatrix} 0 & 0 & \tau & 0 \\ 0 & 0 & 1-\tau & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \tag{A11}$$

with τ being the probability that newly produced offspring are males. We assumed an equal sex ratio at birth, so τ was fixed at 0.5.

Survival as competing hazards

Survival was computed in terms of instantaneous hazards, following Tinker et al. (2024). In this framework, mortality is the result of multiple competing hazards (Λ). Each hazard represents one distinct additive source of instantaneous mortality. We considered two sources of additive mortality: 1) natural or environmental mortality (hereafter referred to as baseline hazards; Λ_B), and 2) hunting mortality (hereafter referred to as hunting hazards; Λ_H). Hazards are given in their log form as this allowed the inclusion of predictor variables as simple additive linear functions. Survival rates are then given by the exponential of the negative sum of all instantaneous hazards. Each source of hazard is described in more detail below.

Baseline hazards

Age-specific baseline hazards ($\mathbf{\Lambda_B}$) are calculated for each state (j) at each time step (t) as follows:

$$\log\left(\mathbf{\Lambda_{B,j}}(\mathrm{t})\right) = \zeta + \gamma_0 + \gamma_1 \cdot \mathbf{\Delta_j} + \gamma_2 \cdot \mathbf{\Omega_j} + \gamma_3 \cdot \mathbf{\Gamma_j} + \mathbf{\Delta_j} \cdot \left[\phi \cdot \left(\frac{\mathrm{N(t)}}{1000}\right) + \sigma_e \cdot \epsilon_e(\mathrm{t})\right] \tag{A12}$$

The parameter ζ is a minimum log hazard rate set to an arbitrarily low value (here $\zeta = -10$, which corresponds to an annual survival rate > 0.9999). The inclusion of this parameter allows all remaining terms to be interpreted as log hazard ratios with respect to this minimum. The parameter γ_0 corresponds to the baseline adult mortality. Differential hazards in early and late life are captured by the terms $\gamma_1 \cdot \boldsymbol{\Delta_j}$ and $\gamma_2 \cdot \boldsymbol{\Omega_j}$, respectively. The parameters γ_1 and γ_2 correspond to the effects of early and late hazards, respectively, while $\boldsymbol{\Delta_j}$ and $\boldsymbol{\Omega_j}$ are age-modifying vectors of length w. Age-modifying vectors are the same across all values of j and are further described below in equations A13-15.

We accounted for potential sex-specific differences in adult survival rates (Tinker et al. 2024) by including the parameter γ_3, which corresponds to the log hazard ratio for adult males relative to adult females. The parameter γ_3 only applies to adult males, which is ensured by the vector $\boldsymbol{\Gamma}_j$ which for $j \in$ {A, P, W} has zeros in all entries and for $j = M$ has ones in entries corresponding to adults and zeros elsewhere.

We estimated the magnitude of density-dependent effects on mortality via parameter ϕ, which was multiplied by population size in thousands, $N(t)/1000$. We accounted for environmental stochasticity by including random effect $\sigma_e \cdot \epsilon_e(t)$, where σ_e represents the magnitude of environmental stochasticity and $\epsilon_e(t)$ is a normal random variate with unit variance. Density-dependent effects and environmental stochasticity are more likely to impact the survival of younger age classes (Eberhardt 2002; Lair et al. 2015). Therefore, we scaled these effects to age by multiplication with age-modifying vector $\boldsymbol{\Delta_j}$, which increases hazards for younger individuals:

$$\boldsymbol{\Delta_j} = \frac{\widehat{\boldsymbol{\Delta_J}} - min\left(\widehat{\boldsymbol{\Delta_J}}\right)}{max\left(\widehat{\boldsymbol{\Delta_J}}\right) - min\left(\widehat{\boldsymbol{\Delta_J}}\right)} \tag{A13}$$

$$\text{and} \quad \widehat{\boldsymbol{\Delta_J}} = e^{\delta \cdot \log\left(\frac{1}{\boldsymbol{v_j}}\right)} \tag{A14}$$

The age-modifying vector $\boldsymbol{\Omega_j}$, which increases hazards for older individuals, was calculated as:

$$\boldsymbol{\Omega_j} = \frac{\boldsymbol{v}_j^{\omega+1}}{max\left(\boldsymbol{v_j}\right)^{\omega+1}} \tag{A15}$$

In Equations A14 and A15, the vector $\boldsymbol{v_j}$ is the vector of age classes of length *w*, while the parameters δ and ω determine the degree of non-linearity in the functional forms of $\boldsymbol{\Delta_j}$ and $\boldsymbol{\Omega_j}$.

Harvest hazards

Harvest mortality was included as a separate hazard, $\boldsymbol{\Lambda_H}$, for each state j, and each year t, as follows:

$$log\left(\boldsymbol{\Lambda_{H,j}(t)}\right) = \zeta + \gamma_H + \sigma_H \cdot \epsilon_H(t) + log\left(\boldsymbol{\Theta_j}\right) \tag{A16}$$

In equation A16, ζ corresponds to the minimum log hazard, as defined in equation A12. The parameter γ_H is the mean log hazard ratio associated with harvest mortality. Parameter σ_H is the magnitude of variation in harvest hazards and $\epsilon_H(t)$ is a random effect (normally distributed with unit variance) accounting for annual fluctuations in harvest hazards.

The age distribution of harvested and sampled individuals presents a noticeable under representation of younger age classes (Figure A6). This may be attributed to hunters actively avoiding calves and juveniles, as outlined in the Marine Mammal Regulations (SOR/93-56) and in the Nunavik beluga management plan, and because larger animals provide more food (Regional Anguvigaq and Anguvigarait, *pers. comm.*). We accounted for this age bias in harvesting by multiplying the harvest hazard function with the age-modifying vector $\boldsymbol{\Theta}$, which increases the strength of the harvest mortality hazard as individuals age. The parameter $\boldsymbol{\Theta}$ is of length *w*, ranges from 0 to 1 and was calculated as follows:

$$\boldsymbol{\Theta_j} = \frac{1}{1 + e^{-(-10 + \psi_1 + \psi_2 \cdot \boldsymbol{v_j})}} \tag{A17}$$

where ψ_1 and ψ_2 are parameters to be estimated by the model and characterize the functional relationship between age and harvest hazards.

Survival rates

For males, non-reproducing females and pregnant females (i.e., $j \epsilon \{M, A, P\}$), hazards were back-transformed to an age varying vector of survival rates at each time step t as follows:

$$\boldsymbol{S_j(t)} = e^{-\left(\boldsymbol{\Lambda_{B,j}(t)} + \boldsymbol{\Lambda_{H,j}(t)}\right)} \tag{A18.1}$$

We note that the survival rate for first year calves was further modified to account for the mothers survival rate, as shown in equation A7. To account for the potential avoidance of females with calves by hunters, harvest hazards were multiplied by a bias factor, ξ, which represents the proportional reduction in harvest-related hazard for state W relative to other states, as follows:

$$\boldsymbol{S_W(t)} = e^{-\left(\boldsymbol{\Lambda_{B,W}(t)} + \boldsymbol{\Lambda_{H,W}(t)} \cdot \xi\right)} \tag{A18.2}$$

Pregnant females at time t will give birth over the summer, while censuses occur at the end of the summer. If a female loses her calf in the time interval between birth and census, the female could be in state A at census time. Therefore, we also calculated neonate survival S_n as a fraction of survival rate of yearling males at every year t:

$$Sn(t) = S_{1,1}(t)^{0.1} \tag{A19}$$

Pregnancy rates

Non-reproducing females ($j = A$) can become pregnant between year t and year $t + 1$, conditional on their survival and pregnancy probability, Pr. We used the same approach as for hazards to model the probability of becoming pregnant, only here "hazards" ($\boldsymbol{\Lambda}_{Pr}$) correspond to the instantaneous probability of *not* becoming pregnant. $\boldsymbol{\Lambda}_{Pr}$ was calculated as follows:

$$log\left(\boldsymbol{\Lambda_{Pr}(t)}\right) = \eta + \rho \cdot \phi \cdot \left(\frac{N(t)}{1000} + \sigma_e \cdot \epsilon_e(t)\right) \tag{A20}$$

and

$$Pr(t) = e^{-\boldsymbol{\Lambda}_{Pr}(t)} \cdot \boldsymbol{\Upsilon} \tag{A21}$$

where $\boldsymbol{\Upsilon}$ is an age-modifying vector of length *w* accounting for age variation factors in pregnancy rates such as an absence of reproductive activity before age 8 years-old ($\boldsymbol{\Upsilon}_{1-7} = 0$) and a decline in pregnancy rates with age (i.e., senescence). Equation A20 includes baseline pregnancy hazards (h) and the effects of density dependence and environmental stochasticity, assumed to be proportional to the density-dependent and stochastic effects described for juvenile survival (equation A12) but scaled by parameter r.

DATA MODEL

The process model was fitted to the different sources of data, i.e., abundance estimates, harvest levels along with their genetic composition, demographic composition (age and sex structure, as well as proportion of adult females lactating). We defined probabilistic relationships between each data set and the corresponding predictions generated by the process model.

The uncertainty distributions associated with survey estimates followed a lognormal distribution, thus we related the observed point estimates from aerial surveys ($ObsS(t)$) to the model-estimated abundance values ($N\ (t)$) using a lognormal distribution:

$$ObsS(t) \sim lognormal\left(\mu = log\left(\frac{N(t)^2}{\sqrt{N(t)^2 + SE(t)^2}}\right), \sigma = \left(\sqrt{log\left(1 + \frac{SE(t)^2}{N(t)^2}\right)}\right)\right) \qquad \text{(A22)}$$

where $SE(t)$ represents the standard error estimate computed separately for each aerial survey (St-Pierre et al. 2024).

The observed proportion of females pregnant in the harvest sample at time t ($NPr(t)$) was related to the expected proportion of harvested females that are pregnant ($PPr(t)$) using a beta-binomial distribution:

$$NPr(t) \sim betabinomial(NAF(t), \alpha, \beta), \qquad \text{(A23)}$$

where

$$\alpha = \nu_{Pr} \cdot Prop_{BE/JAM}(t)^2 \cdot PPr(t) \qquad \text{(A24)}$$

and

$$\beta = \nu_{Pr} \cdot Prop_{BE/JAM}(t)^2 \cdot \left(1 - PPr(t)\right) \qquad \text{(A25)}$$

where $NAF(t)$ is the observed number of adult females sampled, ν_{Pr} is the precision of pregnancy rates proportions, and $Prop_{BE/JAM}(t)$ is the estimated proportion of the sample from the BEL-EHB (or JAM) stock. The realized precision of equation A23 is thus assumed to depend on the proportion of the sample comprised of BEL-EHB (or JAM) animals: the higher this fraction, the more we expect the observed pregnancy rates to reflect the model-estimated pregnancy rates for the BEL-EHB (or JAM) stock. $Prop_{BE/JAM}(t)$ is calculated as follows:

$$Prop_{BE/JAM}(t) = \sum \left(P_H(t) \odot P_{BE/JAM}(t)\right) \qquad \text{(A26)}$$

where $P_H(t)$ is the yearly proportion of total hunt by area/season and $P_{BE/JAM}(t)$ is the genetically-determined proportion of individuals attributed to the BEL-EHB (or JAM) stock by area/season for each year. To account for uncertainty in genetic-based composition estimates, $P_{BE/JAM}(t)$ is itself treated as an estimated parameter drawn from a beta distribution with mean and variance corresponding to the mean values and estimator variances reported in Table 3.

The total reported number of animals harvested at each year t, $HarvO(t)$, is assumed to follow a Poisson distribution with an expected mean corresponding to the model-based estimate of total number of beluga harvested each year ($HarvE(t)$):

$$HarvO(t) \sim Poisson\big(HarvE(t)\big) \tag{A27}$$

with

$$HarvE(t) = \sum\left(\tilde{\mathbf{d}}(\mathrm{t}) \odot \left(\frac{\mathbf{\Lambda}_H(t)}{\mathbf{\Lambda}_H(t) + \mathbf{\Lambda}_B(t)}\right)\right) \cdot \frac{Q}{Prop_{BE/JAM}(t)} \tag{A28}$$

and

$$\tilde{\mathbf{d}}(\mathrm{t}) = \widetilde{\mathbf{M}}(\mathrm{t}) \cdot \tilde{\mathbf{n}}(\mathrm{t}-1) \tag{A29}$$

Specifically, we multiplied the population vector at year $t - 1$, $\tilde{\mathbf{n}}(\mathrm{t} - 1)$, with a mortality matrix, $\widetilde{\mathbf{M}}(\mathrm{t})$, of the same dimension as the $\widetilde{\mathbf{A}}$ matrix ($w \times b$ by $w \times b$). The $\widetilde{\mathbf{M}}(\mathrm{t})$ matrix only contains mortality probabilities at year t from all hazards combined on the diagonal, so that its multiplication with the vector $\tilde{\mathbf{n}}(\mathrm{t} - 1)$ gives the vector of beluga that died at year t, $\widetilde{\boldsymbol{d}}(\boldsymbol{t})$. To obtain the harvest-related number of deaths ($HarvE(t)$), we multiplied this vector by the proportion of hazards associated with harvest over all sources of hazard. Here, the vectors $\mathbf{\Lambda}_B$ and $\mathbf{\Lambda}_{\boldsymbol{H}}$ contain the baseline and harvest hazards arranged for states M, A, P and W, so that their respective lengths are $w \times b = 240$. This gives the total mortality that is attributed to harvest. This is then multiplied by Q, which is the inverse of the proportion of beluga struck and lost (SnL) to provide the number of BEL-EHB (or JAM) beluga that were landed and reported. SnL is the proportion of animals killed or wounded but lost or killed and not reported. Then, to link this number to the overall number of beluga harvested across management areas, we divided it by the estimated proportion of BEL-EHB (or JAM) ($Prop_{BE/JAM}(t)$) in the harvest (equation A26).

The age distribution observed in the sample of harvested animals ($\boldsymbol{AgeO}(t)$) was linked to the vector of ages among dead animals ($\boldsymbol{AgeE}(t)$) using a Dirichlet-Multinomial function:

$$\boldsymbol{AgeO}(t) \sim Dirichlet.multinomial\left(\alpha = \nu_{Ag} \cdot Prop_{BE}(t)^2 \cdot \boldsymbol{AgeE}(t)\right) \tag{A30}$$

We note that the precision parameter ν_{Ag} is scaled by the estimated proportion of BEL-EHB in the harvest ($Prop_{BE}(t)$), following the same rationale as described for pregnancy rates. Vector $\boldsymbol{AgeE}(t)$ was calculated as:

$$\boldsymbol{AgeE}(t) = \widetilde{\boldsymbol{d}}(t) / \sum \widetilde{\boldsymbol{d}}(t) \tag{A31}$$

The proportion of females lactating in the sample of harvested beluga at time t ($N\_lac(t)$) was linked to the proportion of females in the harvest expected to be lactating at time t ($P\_lac(t)$), as follows:

$$N\_lac(t) \sim betabinomial(N\_AFL(t), \alpha, \beta\ ) \tag{A32}$$

with

$$\alpha = \nu_{Pr} \cdot Prop_{BE}(t)^2 \cdot P\_lac(t) \quad \text{(A33)}$$

and

$$\beta = \nu_{Pr} \cdot Prop_{BE}(t)^2 \cdot (1 - P\_lac(t)) \quad \text{(A34)}$$

where $NAFL(t)$ is the observed number of adult females examined for evidence of lactation at time t, ν_{Pr} is the precision of pregnancy rates proportions, and $Prop_{BE}(t)$ is the estimated proportion of the sample from the BEL-EHB stock at time t. We note that $P\_lac(t)$ accounts for harvested females with calves aged from 0 to 1 year (since 1-year-old dependent calves are still expected to be nursing). We thus calculated $P\_lac(t)$ as the number of harvested females with newborn calves (*W*) at year *t*, plus the number of harvested available females (*A*) that had been W females at year *t*-1 (conditioned upon the joint probability of female survival and calf survival), divided by the total number of adult females in the harvest.

PRIORS

For fitting the BEL-EHB model, we used uninformative priors for most parameters, except for η, ρ and SnL (Table A1). For η and ρ, which describes baseline reproductive rate and the relative effects of density dependence on pregnancy, respectively, we used an informative prior based on the St. Lawrence beluga population (Tinker et al. 2024). The correction factors for struck and lost in Nunavik hunts are unknown, but studies from Alaska, Nunavut, and Greenland suggest these factors range from 1.10 to 1.41 and vary spatio-temporally, depending on hunting practices, landscape and season. For instance, Innes and Stewart (2002) reported a correction factor of 1.41 from Canada and Greenland, whereas Heide-Jørgensen and Rosing-Asvid (2002) reported 1.10 and 1.30 for Greenland before 1995 and after 1995, respectively. A recent population modelling study used an average correction factor of 1.27 (Biddlecombe et al. 2024), which we adopted here. Using this correction factor (Snl_corr), the proportions of beluga recovered and reported (*Q* = *1/*Snl_corr) is 0.79, and struck and lost (*SnL* = 1 - *Q*) is 0.21. We assumed that SnL follows a beta distribution with a mean of 0.21 and a standard error of 0.05 (alpha = 14.0, beta = 51.9). We also explored alternative scenarios where SnL_corr was either reduced or augmented by 10% (1.17 and 1.37) to quantify the impact of this correction factor on model-based estimates.

For fitting the JAM model, we relied on the results of the BEL-EHB model to inform priors for several model parameters. We used the estimated posterior distributions for key parameters from the BEL-EHB model as priors for the equivalent parameters in the JAM model, while maintaining vague (uninformative) priors for those parameters that could be estimated by the model using the JAM-specific datasets (Table A2). Specifically, we set informative priors on the process model parameters $\eta, \rho, \gamma_0, \gamma_1, \gamma_2, \Delta_j, \Omega_j$, ψ_1, ψ_2 and ξ, which control (respectively) baseline reproductive rates and scaling of density dependence relative to survival, baseline natural hazards (excluding effects of density-dependence and environmental stochasticity), age-effects for natural hazards, age-biases in harvest mortality, and reduction in harvest probability for lactating females. All remaining process model parameters (including effects of density dependence, environmental stochasticity, and time-varying harvest mortality) had the same uninformative prior distributions as described for the BEL-EHB model.

For both models, we also applied constraints on some derived parameters to facilitate convergence and ensure that the model predicted realistic outcomes. For instance, while calculating carrying capacity (K), we applied the logical constraint that at K, asymptotic population growth rate, λ, should be 1 (stable population). We used a prior for the maximum value for λ ($\lambda_{max} = exp(R_{max})$) with a log-normal distribution centered at a mean of 1.04 (*exp*(default R_{max} for cetaceans)) and a SD of 0.008. As a result, 95% of the prior distribution of λ_{max} fell between approximately 1.01 and 1.07, corresponding to 1% and 7% annual growth, respectively.

MODEL ANALYSIS

Model Fitting and validation

Model was coded and fitted through R version 4.4.0 (R Core Team 2024) and Stan version 2.35.0 (Carpenter et al. 2017). Parameters were estimated using Markov Chain Monte Carlo (MCMC) methods. We aimed for a posterior distribution of 10,000 samples, which was attained by using 20 chains with a thinning of 1 and a warm-up phase of 300 iterations and 500 sampling iterations per chain. We relied on a suite of methods to assess model fit and to perform model validation. First, we visually inspected the trace plots to assess the level of mixing of the chains and convergence. Then, we verified the Gelman-Rubin convergence statistic ($\hat{R}$), where $\hat{R}$ below 1.1 indicated good chain mixing. We also verified that the effective number of samples (n_{eff}) was not well below the actual number of iterations (minus warm-up), which would indicate poor MCMC sampling efficiency (McElreath 2020). Further, we compared the posterior and prior distributions for all parameters to assess whether and to what extent the parameters were updated. We conducted posterior predictive checks as an evaluation of model goodness of fit. Specifically, we derived out-of-sample predictions of harvest numbers, survey abundance, and pregnancy rates. Then, we visually checked how predicted values matched with observed values for each source of data. Bayesian P-values were computed as the discrepancy between the sum of squared Pearson residuals for predicted and observed values, with $0.05 < P < 0.95$ indicating good fit to the data.

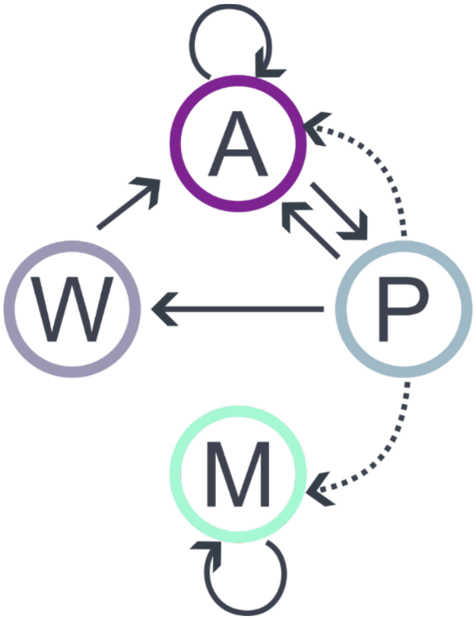

Figure A1. Life cycle graph of the beluga, showing annual state transitions (solid lines) and production of new individuals (dashed lines) Definitions: M: males, A: non-reproducing females, P: pregnant females, W: females with a calf.

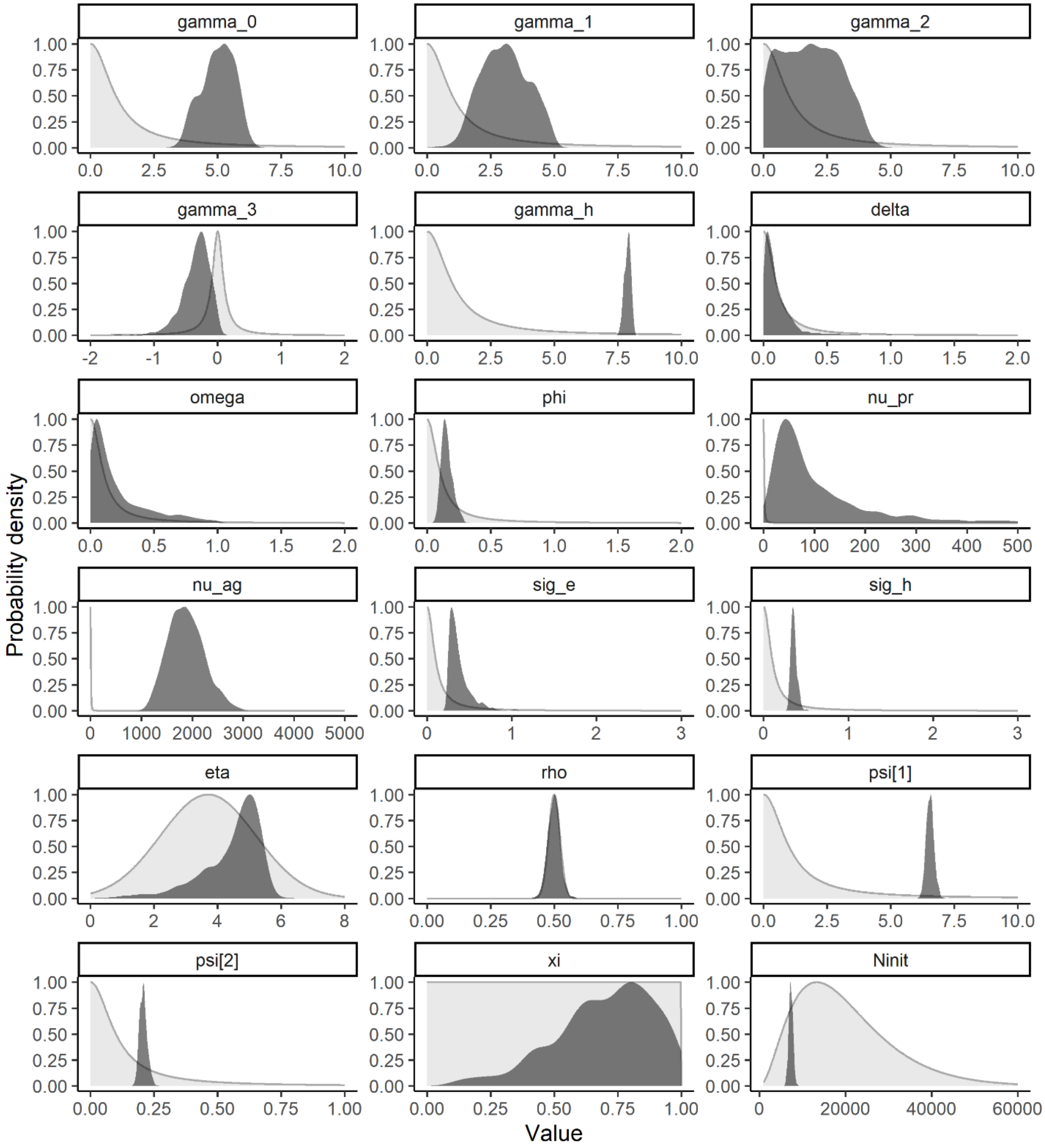

Figure A2. Prior (light grey) and posterior (dark grey) distribution of IPM parameters for BEL-EHB beluga stock.

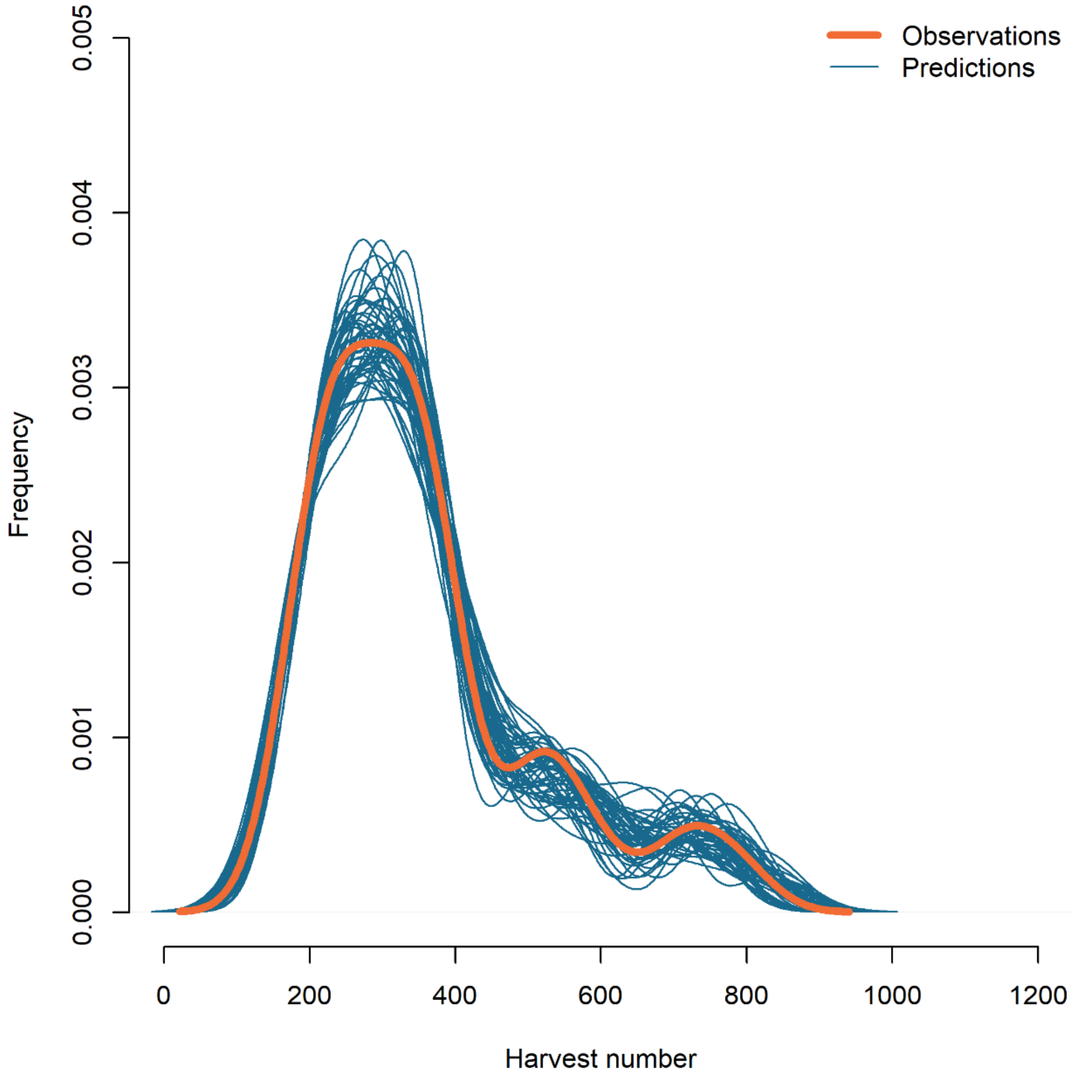

Figure A3. Comparison between the observed number of beluga harvested annually and the out-of-sample predictions for BEL-EHB beluga stock. For ease of visualization, only 50 randomly chosen predictions are presented.

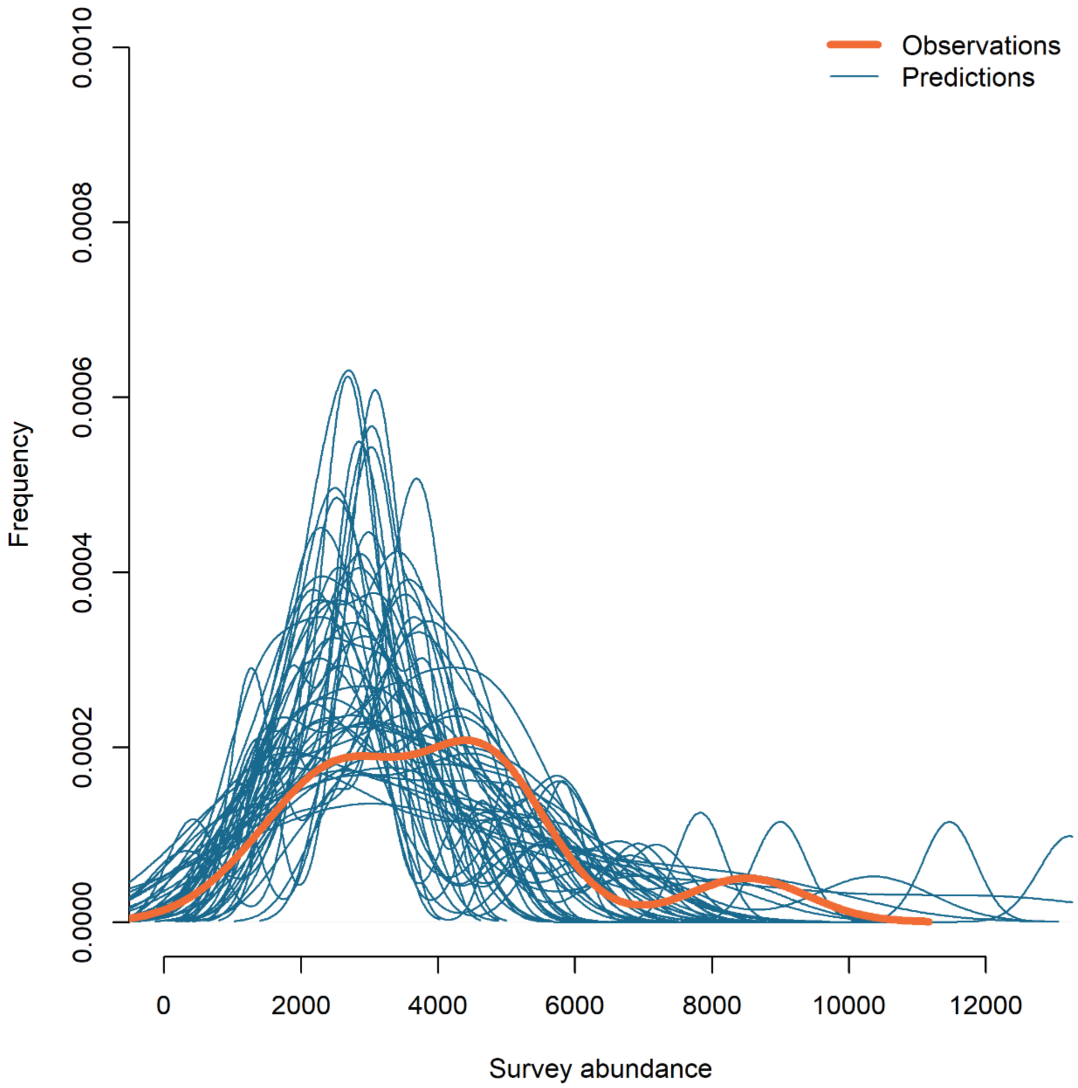

Figure A4. Comparison between the observed abundance of beluga (aerial surveys) annually and the out-of-sample predictions for BEL-EHB beluga stock. For ease of visualization, only 50 randomly chosen predictions are presented.

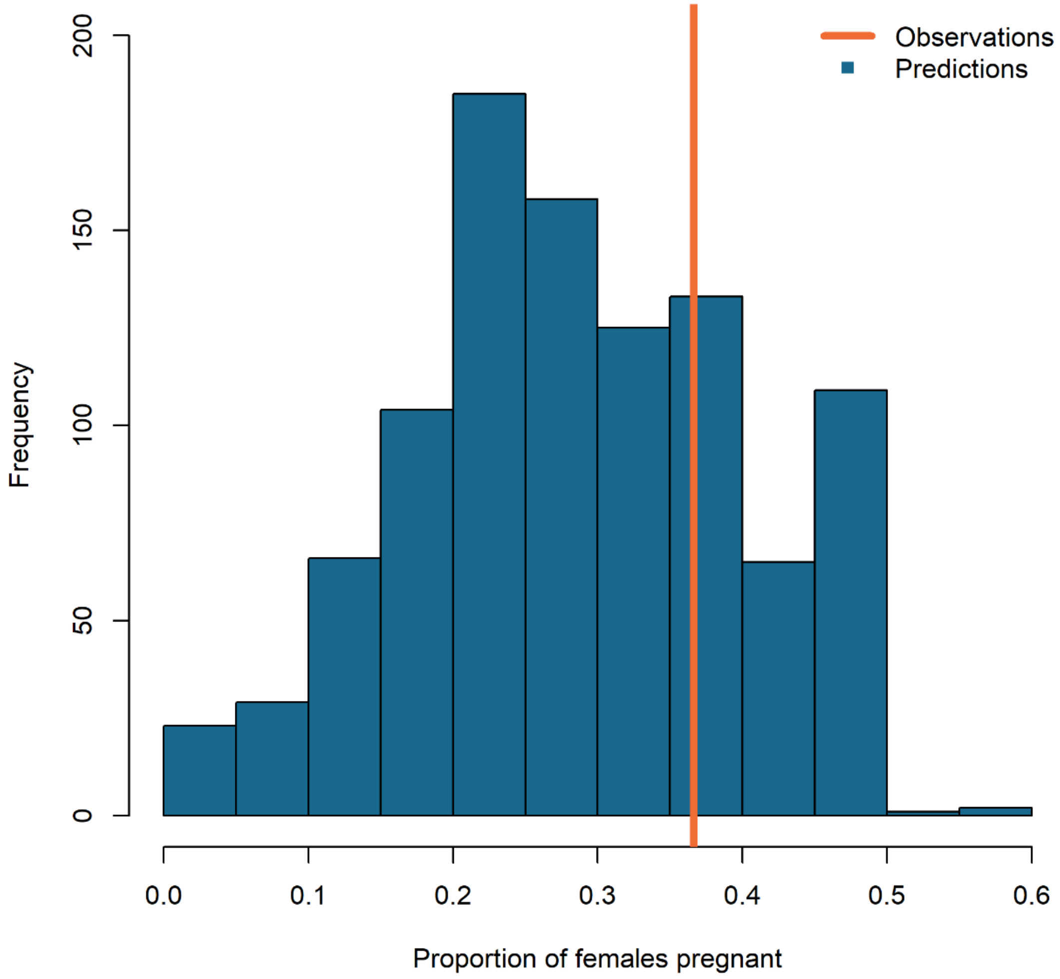

Figure A5. Comparison between the observed proportion of pregnant females and the out-of-sample predictions for BEL-EHB beluga stock. Medians across years are shown.

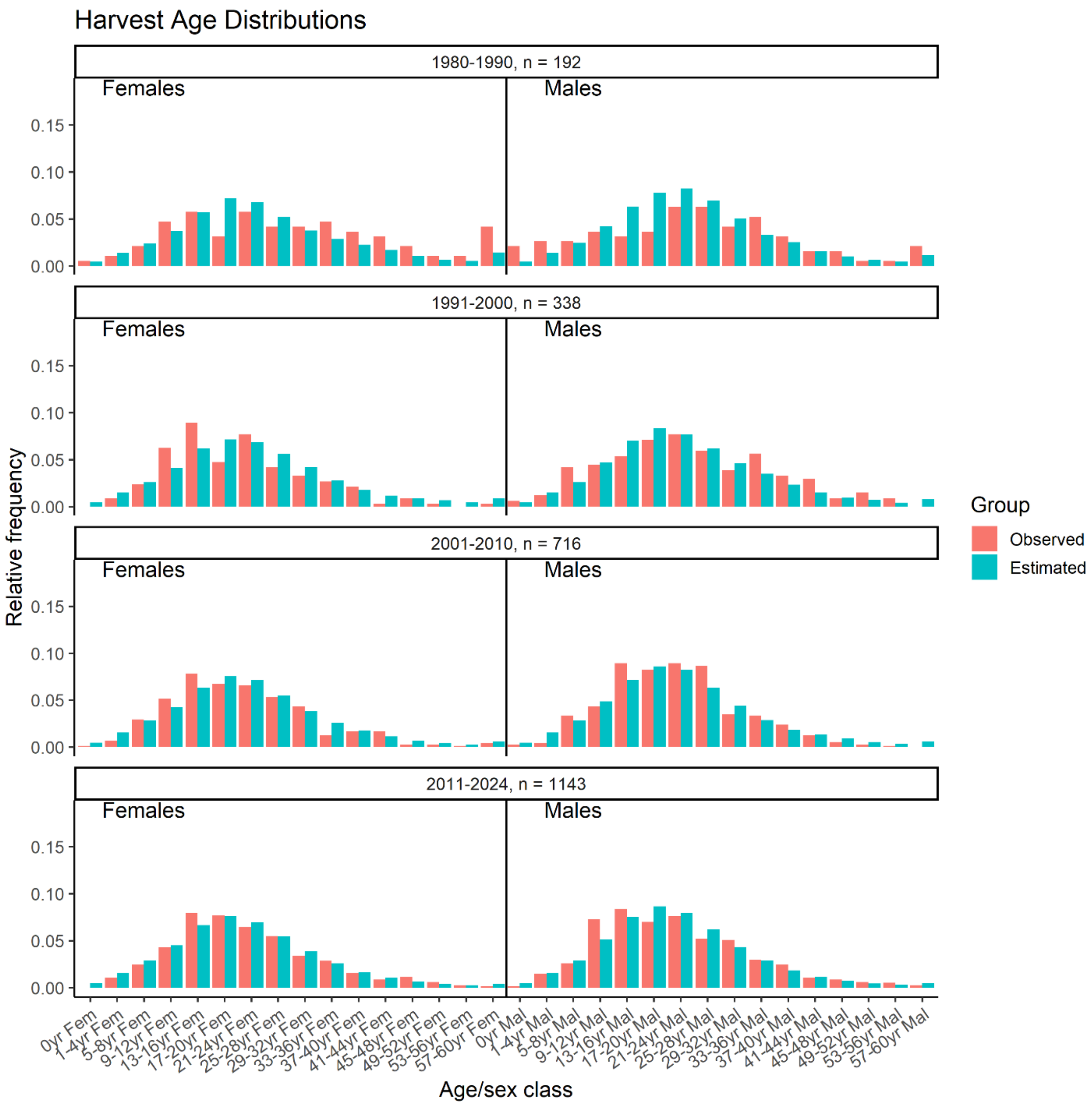

Figure A6. Observed (orange) and estimated by the IPM (blue) age and sex distributions for four time periods (1980-1990, 1991-2000, 2001-2010 and 2011-2023) for BEL-EHB beluga stock.

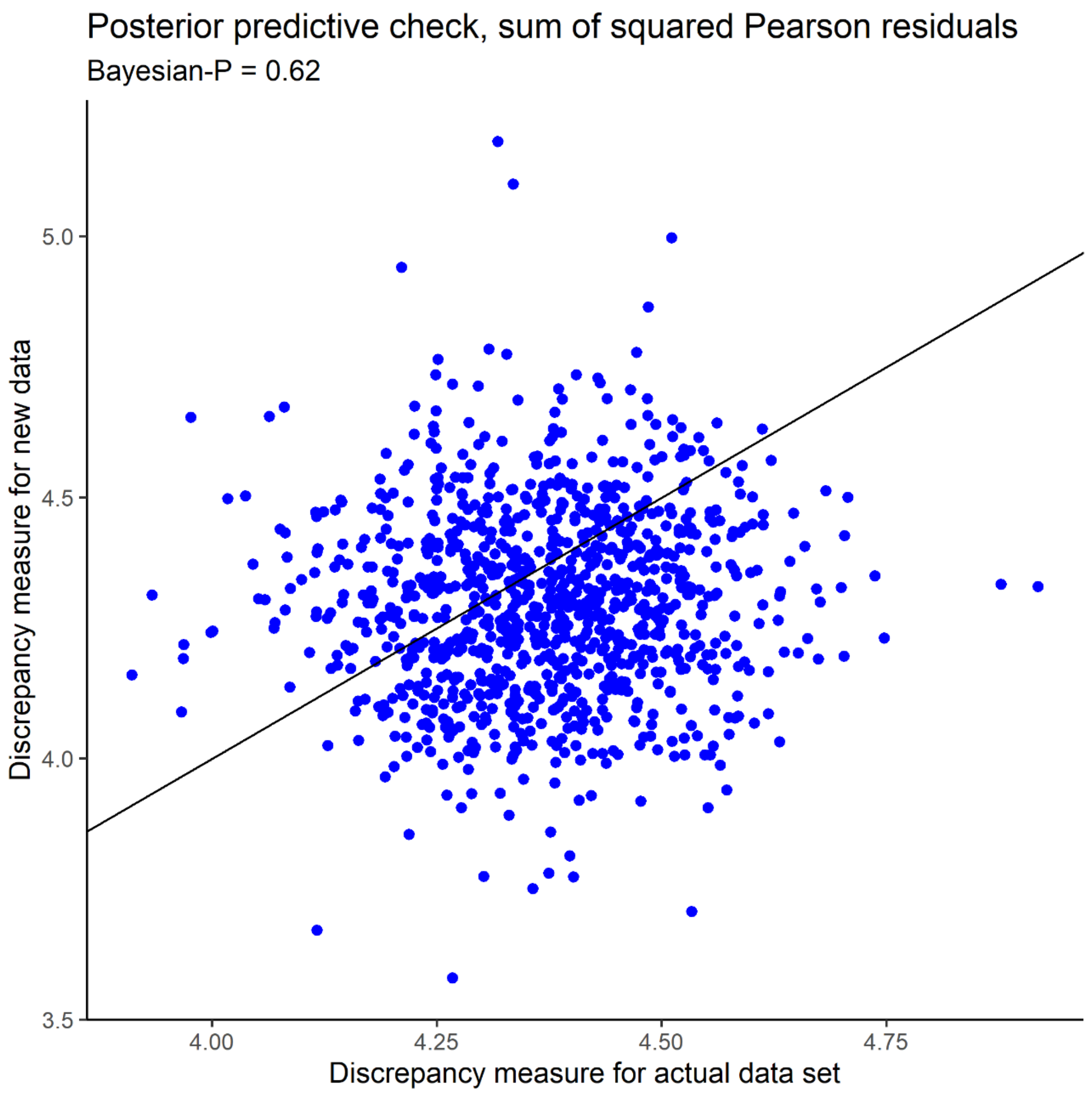

Figure A7. Correlation between sum of squared residuals between observations and model-based predictions for the IPM for the BEL-EHB beluga stock.

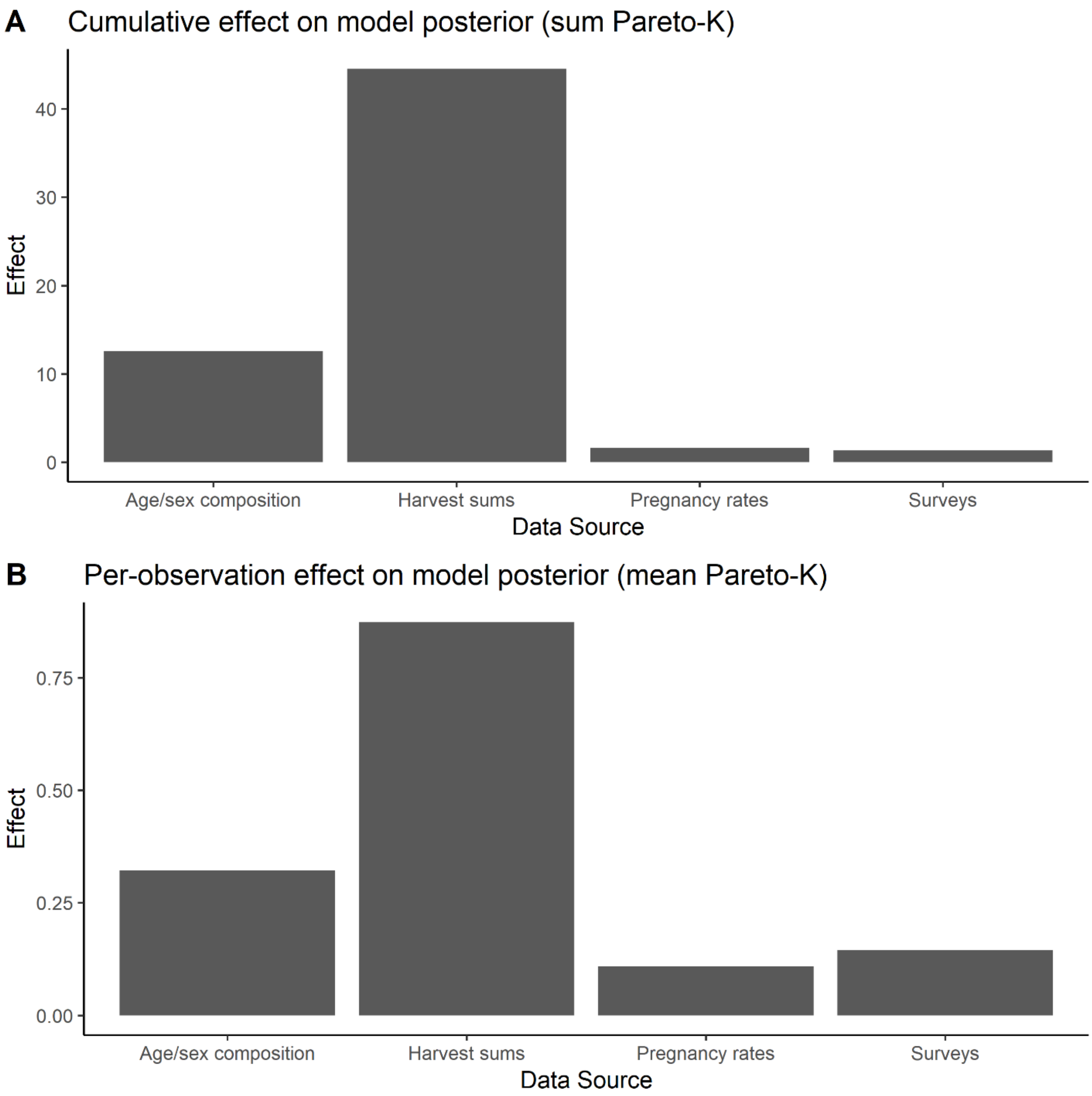

Figure A8. Relative cumulative (A) and per-observation (B) contribution of the four main data sources to IPM estimates for BEL-EHB beluga stock.

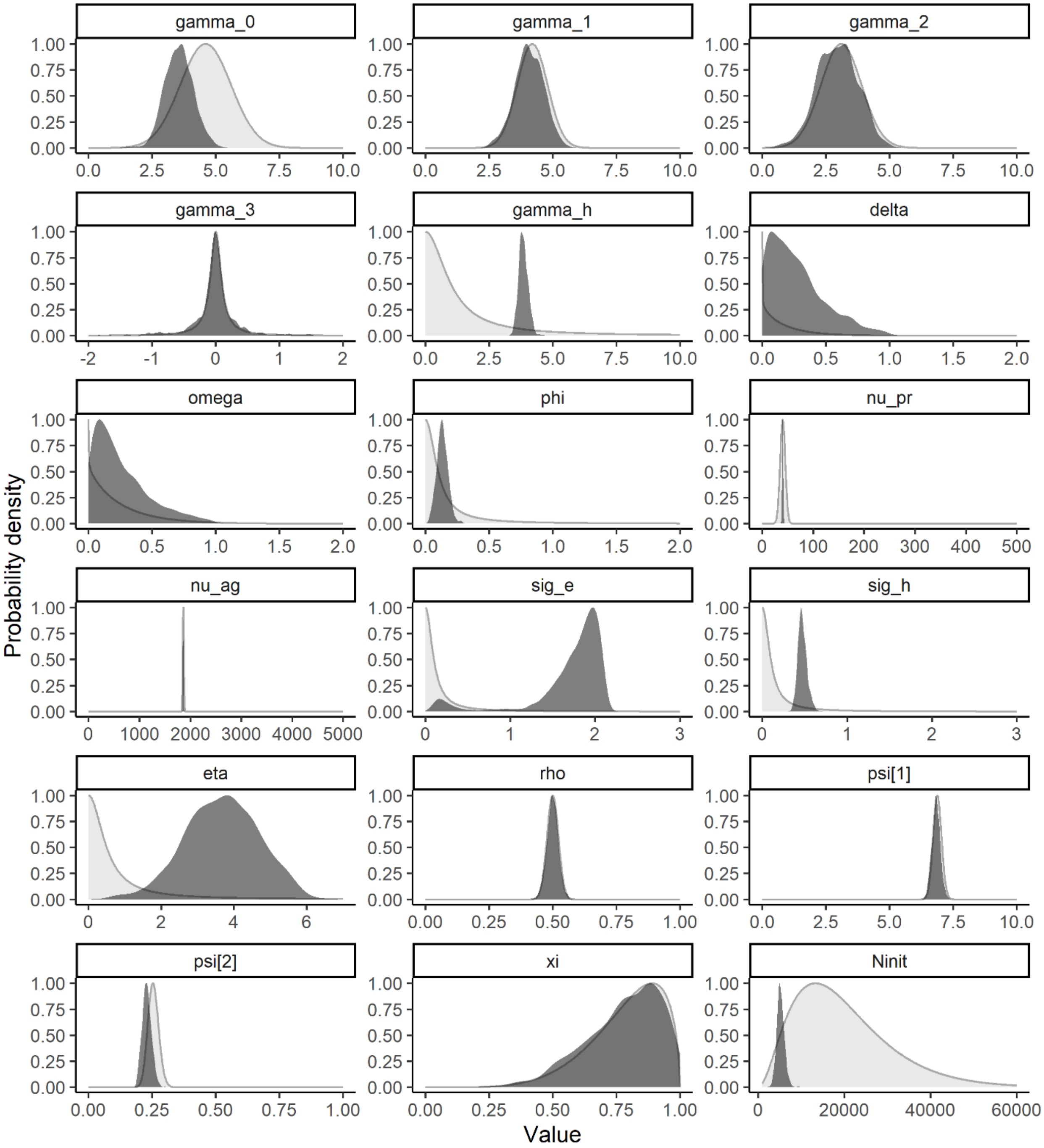

Figure A9. Prior (light grey) and posterior (dark grey) distribution of IPM parameters for JAM beluga stock.

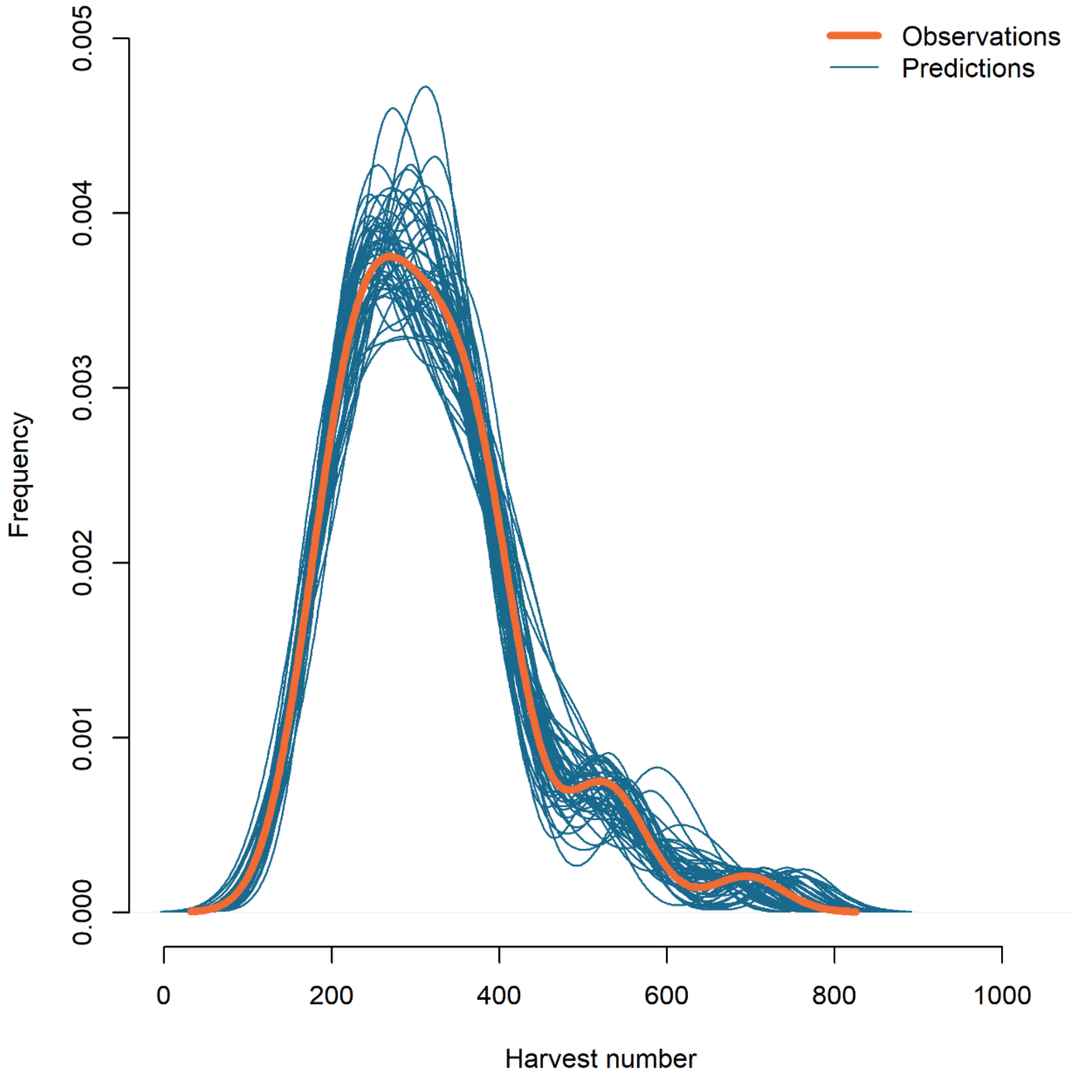

Figure A10. Comparison between the observed number of beluga harvested annually and the out-of-sample predictions for JAM beluga stock. For ease of visualization, only 50 randomly chosen predictions are presented.

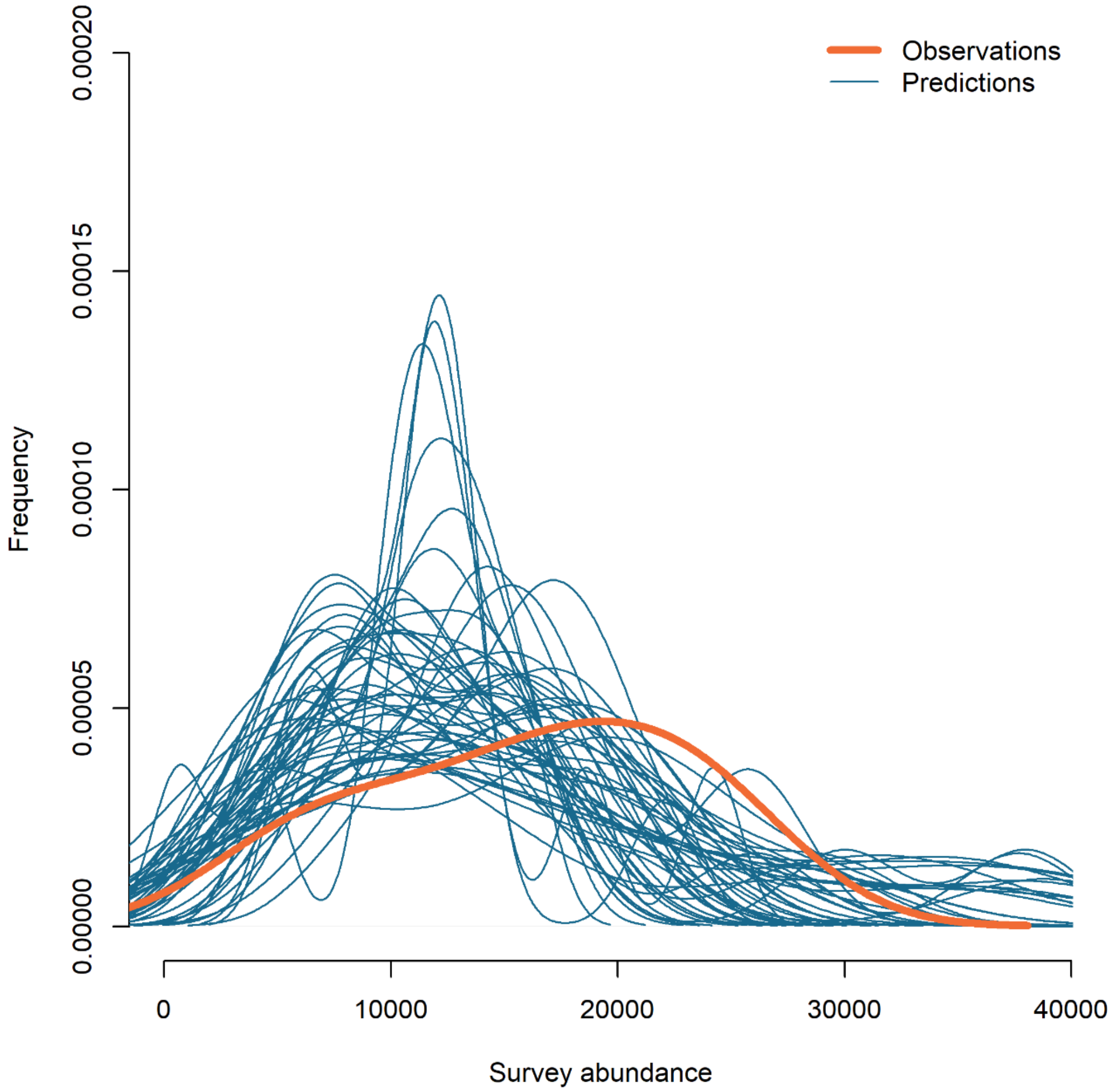

Figure A11. Comparison between the observed abundance of beluga (aerial surveys) annually and the out-of-sample predictions for JAM beluga stock. For ease of visualization, only 50 randomly chosen predictions are presented.

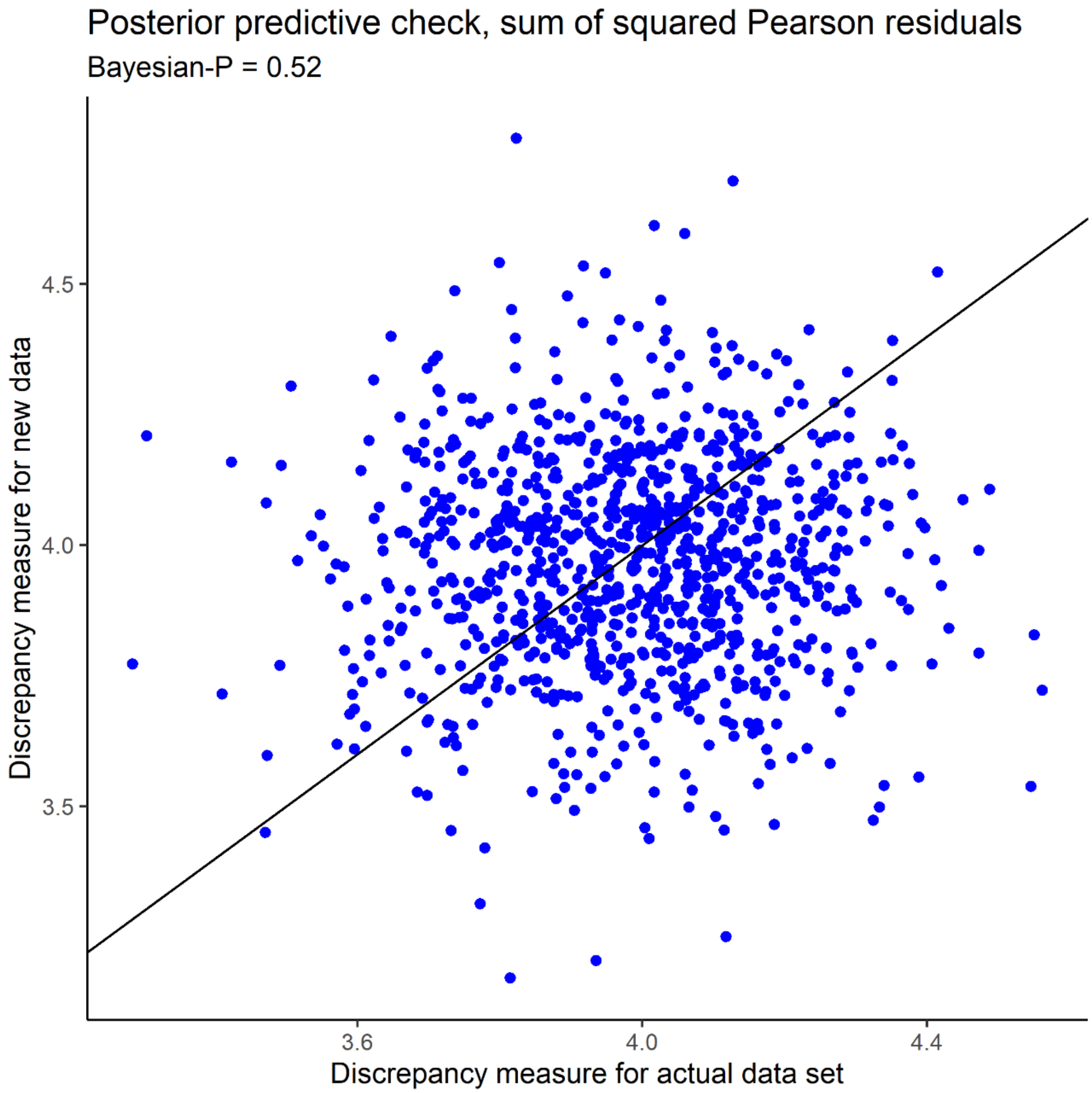

Figure A12. Correlation between sum of squared residuals between observations and model-based predictions for the IPM for the JAM beluga stock.

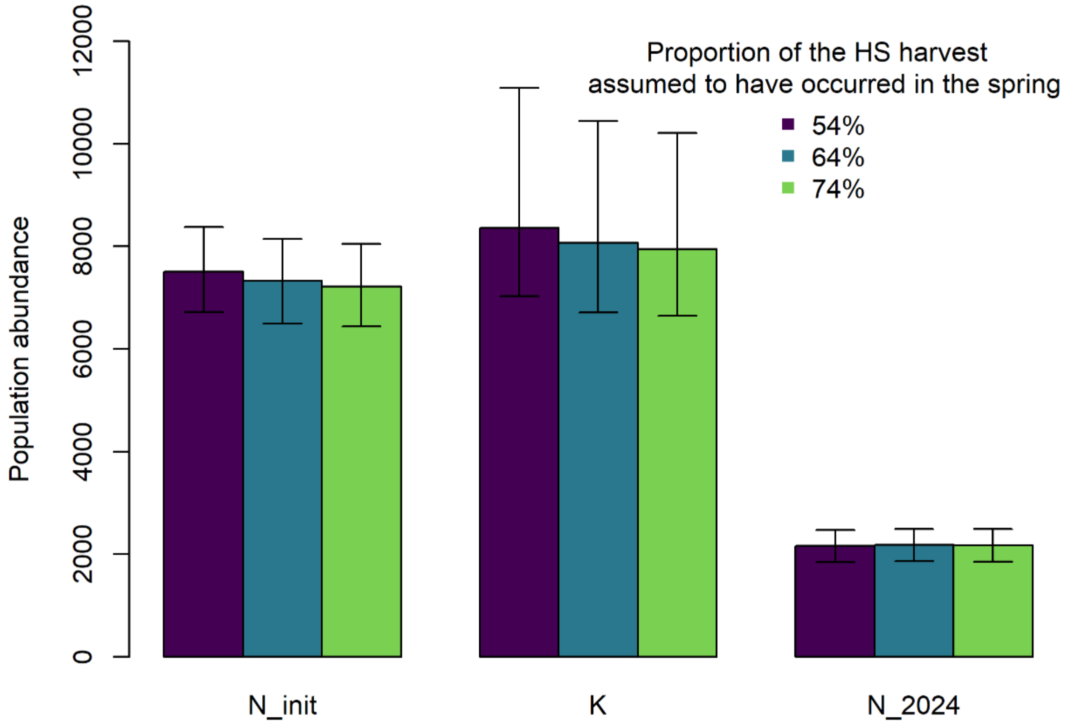

Figure A13. Effect of changing the proportion of the Hudson Strait harvest assumed to have occurred in the Spring (versus the Fall) for years 1974-2008 on model-based estimates of initial population size (N_init), carrying capacity (K) and stock abundance in 2024 (N_2024). Error bars represent the upper and lower limits of the Credible Interval, CrI.

Table A1. Description of model parameters and prior distributions for the BEL-EHB beluga stock.

Parameter	Name	Description	Prior distribution	Value	Lower bound	Upper bound
N_{init}	-	Initial population size	Gamma	α (shape): 3; β (rate): 0.00015	1000	60000
ρ	rho	Scaling factor for density dependence on pregnancy rates relative to juvenile survival	Beta	α: 250; β: 250	0	1
η	eta	Base parameter for pregnancy rate	Normal	mean: 3.7; sd: 1.5	0	8
γ_0	gamma_0	Baseline log hazard ratio	Half-Cauchy	location: 0; scale: 1	0	10
γ_1	gamma_1	Log hazard ratio for younger ages (early hazards)	Half-Cauchy	location: 0; scale: 1	0	10
γ_2	gamma_2	Log hazard ratio for older ages (late hazards)	Half-Cauchy	location: 0; scale: 1	0	10
γ_3	gamma_3	Log hazard ratio, adult males *vs* females	Half-Cauchy	location: 0; scale: 0.1	-2	2
γ_h	gamma_h	Mean harvest log hazard	Half-Cauchy	location: 0; scale: 1	0	10
δ	delta	Parameter determining functional form for early hazards	Half-Cauchy	location: 0; scale: 0.1	0	2
ω	omega	Parameter determining functional form for late hazards	Half-Cauchy	location: 0; scale: 0.1	0	2
ψ_1	psi[1]	Age-modifying harvest probability function parameter	Half-Cauchy	location: 0; scale: 1	0	10
ψ_2	psi[2]	Age-modifying harvest probability function parameter	Half-Cauchy	location: 0; scale: 0.1	0	1
ϕ	phi	Density-dependent log hazard ratio	Half-Cauchy	location: 0; scale: 0.1	0	2
υ_{Pr}	nu_pr	Precision of pregnancy rate proportions	Half-Cauchy	location: 0; scale: 1	0	500
υ_{Ag}	nu_ag	Precision of counts by sex and age	Half-Cauchy	location: 0; scale: 5	0	5000
σ_h	sigma_h	Magnitude of variation in hunting hazards	Half-Cauchy	location: 0; scale: 0.1	0	3
σ_e	sigma_e	Magnitude of environmental stochasticity	Half-Cauchy	location: 0; scale: 0.1	0	3
SnL	-	Struck and loss factor	Beta	α: 21.0; β: 56.8	0	1
ξ	xi	Adjustment factor for avoidance by hunters of females with dependent calves	Beta	α: 1; β: 1	0	1

Table A2. Description of model parameters and prior distributions for the JAM beluga stock. Note that for some priors, values were chosen based on posterior distributions of parameters from the BEL-EHB beluga model (see text for more details).

Parameter	Name	Description	Prior distribution	Value	Lower bound	Upper bound
N_{init}	-	Initial population size	Gamma	α (shape): 3; β (rate): 0.00015	1000	60000
ρ	rho	Scaling factor for density dependence on pregnancy rates relative to juvenile survival	Beta	α: 250; β: 250	0	1
η	eta	Base parameter for pregnancy rate	Half-Cauchy	mean: 0; sd: 0.5	0	7
γ_0	gamma_0	Baseline log hazard ratio	Normal	mean: 4.6; sd: 1	0	10
γ_1	gamma_1	Log hazard ratio for younger ages (early hazards)	Normal	mean: 4.2; sd: 1	0	10
γ_2	gamma_2	Log hazard ratio for older ages (late hazards)	Normal	mean: 3.1; sd: 1	0	10
γ_3	gamma_3	Log hazard ratio, adult males *vs* females	Half-Cauchy	location: 0; scale: 0.1	-2	2
γ_h	gamma_h	Mean harvest log hazard	Half-Cauchy	location: 0; scale: 1	0	10
δ	delta	Parameter determining functional form for early hazards	Gamma	α: 0.9; β: 4.77	0	2
ω	omega	Parameter determining functional form for late hazards	Gamma	α: 0.95; β: 3.68	0	2
ψ_1	psi[1]	Age-modifying harvest probability function parameter	Gamma	α: 1712; β: 249	0	10
ψ_2	psi[2]	Age-modifying harvest probability function parameter	Gamma	α: 147; β: 578	0	1
ϕ	phi	Density-dependent log hazard ratio	Half-Cauchy	location: 0; scale: 0.1	0	2
υ_{Pr}	nu_pr	Precision of pregnancy rate proportions	Normal	mean: 40; sd: 5	0	500
υ_{Ag}	nu_ag	Precision of counts by sex and age	Normal	mean: 1860; sd: 10	0	5000
σ_h	sigma_h	Magnitude of variation in hunting hazards	Half-Cauchy	location: 0; scale: 0.1	0	3
σ_e	sigma_e	Magnitude of environmental stochasticity	Half-Cauchy	location: 0; scale: 0.1	0	3
SnL	-	Struck and loss factor	Beta	α: 21.0; β: 56.8	0	1
ξ	xi	Adjustment factor for avoidance by hunters of females with dependent calves	Beta	α: 5.9; β: 1.6	0	1

Table A3. Parameter estimate posterior distributions, number of effective samples used, $\boldsymbol{N_{eff}}$ *and the* $\boldsymbol{\hat{R}}$ *statistics, from the IPM for BEL-EHB and JAM beluga stocks.*

Parameter	***Mean***	***SD***	***2.5%***	***50%***	***97.5%***	$\boldsymbol{N_{eff}}$	$\boldsymbol{\hat{R}}$
Belcher-Islands - Eastern Hudson Bay (BEL-EHB)							
N_{init}	7354	486	6396	7345	8327	326	1.03
ρ	0.50	0.02	0.45	0.50	0.55	1020	1.00
η	4.47	0.90	2.03	4.73	5.56	212	1.06
γ_0	5.06	0.64	3.80	5.11	6.12	117	1.07
γ_1	3.01	0.91	1.41	3.00	4.73	109	1.08
γ_2	1.78	1.11	0.04	1.74	3.82	81	1.08
γ_3	-0.35	0.22	-0.89	-0.32	-0.01	496	1.02
γ_h	7.89	0.12	7.63	7.90	8.11	87	1.08
δ	0.11	0.12	0.00	0.07	0.43	654	1.01
ω	0.21	0.23	0.00	0.12	0.84	794	1.01
ψ_1	6.54	0.15	6.25	6.54	6.85	352	1.02
ψ_2	0.21	0.01	0.18	0.21	0.24	419	1.03
ϕ	0.16	0.05	0.08	0.15	0.26	303	1.03
υ_{Pr}	105.15	96.65	17.01	69.14	392.96	620	1.03
υ_{Ag}	1883.79	349.97	1287.31	1852.11	2643.62	826	1.01
σ_h	0.36	0.04	0.30	0.35	0.44	78	1.09
σ_e	0.37	0.12	0.25	0.34	0.70	500	1.02
ξ	0.70	0.19	0.24	0.73	0.98	494	1.03
James Bay (JAM)							
N_{init}	5249	878	3680	5185	7148	983	1.02
ρ	0.50	0.02	0.46	0.50	0.54	4990	1.00
η	3.67	0.97	1.71	3.70	5.46	2966	1.01
γ_0	3.58	0.55	2.47	3.58	4.65	978	1.02
γ_1	4.07	0.54	2.98	4.07	5.15	3294	1.00
γ_2	2.99	0.80	1.41	3.00	4.55	3416	1.01
γ_3	-0.02	0.35	-0.83	-0.01	0.75	333	1.04
γ_h	3.85	0.18	3.52	3.84	4.23	754	1.02
δ	0.27	0.22	0.01	0.21	0.83	2008	1.01
ω	0.26	0.22	0.01	0.20	0.80	3627	1.00
ψ_1	6.83	0.16	6.52	6.83	7.17	4217	1.00
ψ_2	0.23	0.02	0.20	0.23	0.27	4225	1.00
ϕ	0.13	0.04	0.05	0.13	0.22	657	1.03
υ_{Pr}	40.00	1.00	38.07	40.00	41.99	4089	1.01
υ_{Ag}	1860.07	5.02	1850.27	1860.08	1870.01	7659	1.00
σ_h	0.48	0.05	0.38	0.47	0.60	808	1.01
σ_e	1.70	0.46	0.17	1.84	2.09	502	1.04
ξ	0.78	0.14	0.45	0.81	0.98	3176	1.00

Table A4. Distribution of the overall beluga harvest among the five management areas in Nunavik and Sanikiluaq associated with in the four scenarios of spatial distribution of the harvest considered.

Scenario considered	Management area				
	ARC	NEHB	HS	UB	SAN
Scenario 1: Same as observed during 2021-2024	0.055	0.085	0.665	0.119	0.076
Scenario 2: Same as Scenario 1, except no harvest in the ARC	0.000	0.090	0.703	0.126	0.081
Scenario 3: Proportional to Inuit distribution	0.209	0.184	0.218	0.321	0.067
Scenario 4: Hudson Strait only	0.000	0.000	1.000	0.000	0.000

Table A5. Seasonal distribution of the overall beluga harvest within each management area associated with in the four scenarios of seasonal distribution of the harvest considered: A) the temporal distribution of beluga harvest is proportional to that observed under the current management plan (i.e., average from 2021-2024), B) harvest is concentrated in the spring (i.e., February 1 to August 31 in Nunavik, April 1 to June 30 in the Belchers Islands). C) harvest is concentred in the fall; with harvest in HS occurring in early fall only (i.e., September 1 to January 31 in NEHB and UB, September 1 to November 20 in HS, and September 1 to November 30), and D) same as C, except considering harvest in HS occurring in late fall only (i.e., September 1 to January 31 in NEHB and UB, November 21 to January 31 in HS, and September 1 to November 30).

Scenario considered	ARC	NEHB		HS			UB		SAN			
	Year-round	Spring	Fall	Spring	Early Fall	Late Fall	Spring	Fall	Spring	Fall	Summer	Winter
Scenario A	1.00	0.24	0.76	0.56	0.26	0.18	0.94	0.06	0.76	0.11	0.00	0.13
Scenario B	1.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00
Scenario C	1.00	0.00	1.00	0.00	1.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00
Scenario D	1.00	0.00	1.00	0.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00