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Management Approaches, Abundance Indices and Total Allowable Harvest levels of Belugas in Hudson Bay

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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

A surplus production model that incorporated information on harvests and stock composition of the harvest was fitted to aerial survey data from eastern and western Hudson Bay belugas using Bayesian methods. For eastern Hudson Bay, the model produced an abundance estimate of 3400 animals and indicated that the population is stable. For eastern Hudson Bay, the sustainable yield, which maintains a stable population, was 68 belugas. Two Precautionary Approach frameworks were developed and allowed for harvests of 17-61 animals depending on the probability of achieving recovery to healthy levels within 50 years. For western Hudson Bay, the model indicated that the population could be stable or increasing depending on model assumptions related to environmental carrying capacity. It was concluded that the best estimate of abundance for this stock was from the aerial survey flown in 2015 (N=54,500). The Potential Biological Removal method was used to estimate allowable removal levels from the western Hudson Bay stock. Depending on recovery factors applied, PBR estimates varied from 251 to 1,004 for recovery factors of 0.1 to 1. The most recent harvest data of Western Hudson Bay whales was 584 animals in 2015.

Approche de gestion, indices d’abondance et niveau de capture totale admissible pour le beluga de la baie d’Hudson

RÉSUMÉ

Un modèle de production excédentaire incorporant des informations sur les récoltes et la composition des stocks de la récolte a été adapté aux données de relevés aériens des bélugas de l'est et de l'ouest de la baie d'Hudson en utilisant des méthodes bayésiennes. Pour l'est de la baie d'Hudson, le modèle a produit une estimation de l'abondance de 3400 animaux et indique que la population était stable. Pour l'est de la baie d'Hudson, le rendement durable, qui maintient une population stable, était de 68 bélugas. Deux cadres d'approche de précaution ont été développés et ont permis des récoltes variant de 17 à 61 animaux en fonction de la probabilité d'un rétablissement dans la zone saine dans une période de 50 ans. Pour l'ouest de la baie d'Hudson, le modèle indiquait que la population pourrait être stable ou en augmentation en fonction des hypothèses du modèle liées à la capacité de support environnementale. On a conclu que la meilleure estimation de l'abondance pour ce stock provenait du relevé aérien effectuée en 2015 (N = 54 500). Le modèle de retrait biologique potentiel (PBR) a été utilisé pour estimer les niveaux de retrait admissibles du stock de l'ouest de la baie d'Hudson. En fonction des facteurs de rétablissement appliqués, les estimations du PBR ont varié de 251 à 1 400 pour les facteurs de rétablissement de 0,1 à 1. Les données de récolte les plus récentes des baleines de l’ouest de la baie d’Hudson étaient de 584 animaux en 2015.

INTRODUCTION

The beluga (*Delphinapterus leucas*) is a toothed whale with pan-Arctic distribution extending into the Hudson Bay complex in sub-arctic eastern Canada (Richard and Pike 1993). Inuit subsistence hunting of beluga in Hudson Bay and adjoining waters is directed towards a migratory population that summers in Hudson Bay but largely leaves this area to overwinter in Hudson Strait and the Labrador Sea. Photo-identification, satellite telemetry and genetic studies have shown that beluga exhibit strong seasonal site fidelity to specific congregation areas during summer (Caron and Smith 1990; de March and Postma 2003, Lewis et al. 2009). Despite interbreeding on wintering grounds (Turgeon et al. 2012), cultural conservatism of maternally-transmitted migration routes seems to prevent substantial exchange between these summering aggregations (Colbeck et al. 2012), thus making beluga vulnerable to local extirpation (COSEWIC 2004).This cumulative evidence has led to the current use of discrete summering stocks as management units (e.g., Smith and Hammill 1986, Richard et al. 1990; Richard 2010).

The Eastern Hudson Bay (EHB) stock is centered in the eastern Hudson Bay arc. Historically, this stock may have numbered approximately 8,000-11,600 (Doniol-Valcroze et al. 2012a), but was depleted by intensive commercial hunting in the nineteenth century (Reeves and Mitchell 1987). They were designated by COSEWIC as Threatened in April 1988; and revised to Endangered in May 2004.

Belugas are also found during the summer along the western coast of Hudson Bay, extending from roughly the Winisk River, in Ontario, northwards to Lyon Inlet, Nunavut, with the main concentration centered near the Seal, Churchill and Nelson river estuaries in Manitoba (Figure 1) (Richard 2010). WHB belugas were designated by COSEWIC as Special Concern in May 2004.

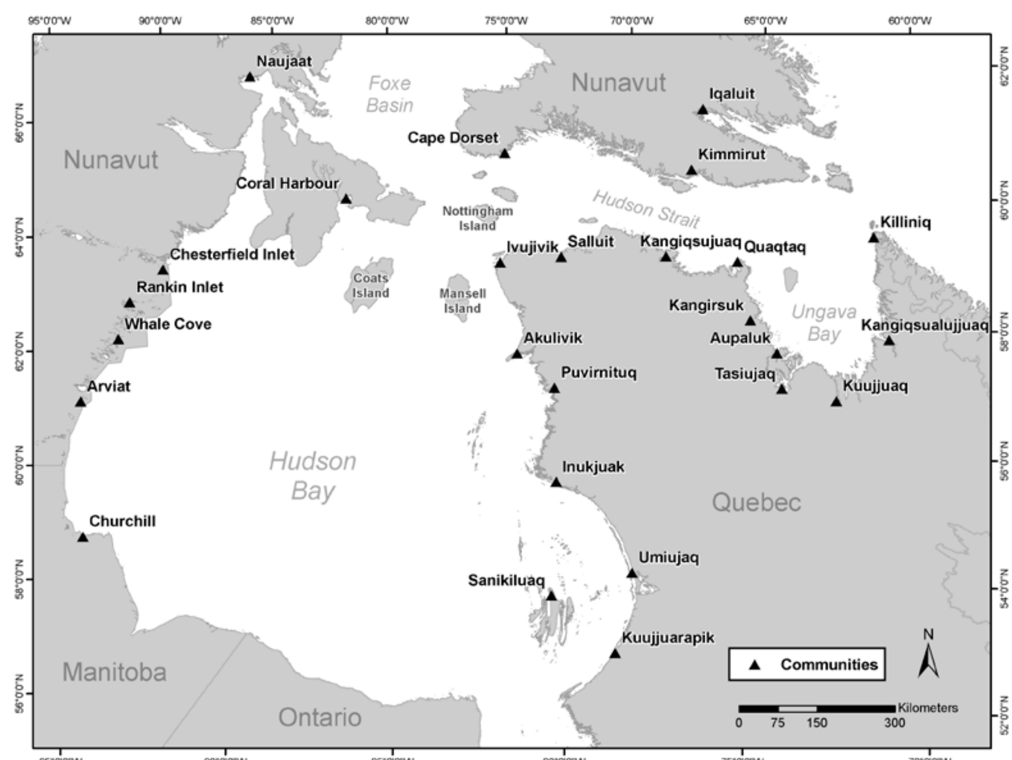

Figure 1. Map of Hudson and James Bays Hudson Strait, Foxe Basin.

Harvesting of EHB beluga is limited by a management plan that ends in January 2017. Harvesting of beluga from the WHB stock is not limited, but WHB whales comprise an important component of the winter beluga harvest in Hudson Strait, by hunters living in northern Quebec (Nunavik). An aerial survey was flown during the summer of 2015 to evaluate the abundance of both EHB and WHB belugas (Gosselin et al. 2017; Matthews et al. 2017). Here, a population model incorporating information on harvests is fitted to aerial survey estimates of abundance to provide estimates of allowable harvest levels that will be used in the setting of the Total Allowable Take (TAT) in the next management cycle (EHB stock only).

Ecosystems Fisheries Management has requested harvest advice to determine the maximum number of belugas that can be harvested from the EHB population while maintaining a 25, 50 and 75% chance of a population increase over the next 10 years. EFM also requested that a precautionary approach (PA) framework be developed that could be used in the management of EHB beluga, examine the impact of current harvests within this framework, recommend a recovery population target under this framework and provide scenarios which include the maximum number of EHB belugas that can be hunted and still provide for recovery within 25 and 50 years.

MATERIALS AND METHODS

A population model that included information on removals and the stock composition of the catch was fitted to aerial survey estimates of abundance from the Eastern Hudson Bay (N=7 surveys) and Western Hudson Bay (N=3 surveys) stocks (Gosselin et al. 2017; Matthews et al 2017 (Table 1). The survey estimates have been corrected for availability bias. Each stock was modelled separately.

Table 1. Abundance estimates for the EHB and WHB beluga whale stocks. Indices have been corrected for availability bias. Data are from Gosselin et al. 2017, Matthews et al. 2017; Richard et al. 1990; Richard 2005).

Year	EHB estimate (SE)	WHB estimate (SE)
1985	4282 (557)	-
1993	2729 (1092)	-
1987	-	31,124 (6967)
2001	2924 (1404)	-
2004	4274 (1581)	51,761 (15,875)
2008	2646 (1244)	-
2011	3351 (1642)	-
2015	3819 (1642)	54,473 (5,329)

Reported harvest information was available from Nunavik and Sanikilluaq (1974-2016) (Lesage et al. 2009; Doniol-Valcroze et al. 2012b). All beluga harvested directly in the eastern Hudson Bay arc during the summer are assumed to belong to the EHB summer stock. Animals harvested in the Long Island area are assumed to not belong to the EHB stock and are excluded here. Harvests in other areas and during spring and fall, however, are directed towards migrating whales from a mixture of stocks (Turgeon et al. 2012; Mosnier et al. 2017). The community of Sanikilluaq in Nunavut also harvests from a mixture of stocks involving animals classified as EHB and NOT_ EHB animals and the proportion of EHB whales in harvests from this community are included in the harvesting of EHB animals. We assumed that 86% of the harvest occurred during the extended Spring (May-15 July). Beluga are also harvested by communities around the western Hudson Bay coast, northwestern Hudson Bay, Foxe Basin, Hudson Strait and Iqaluit (1977-2015)(Figure 2, Appendix 1, Tables 2,3).

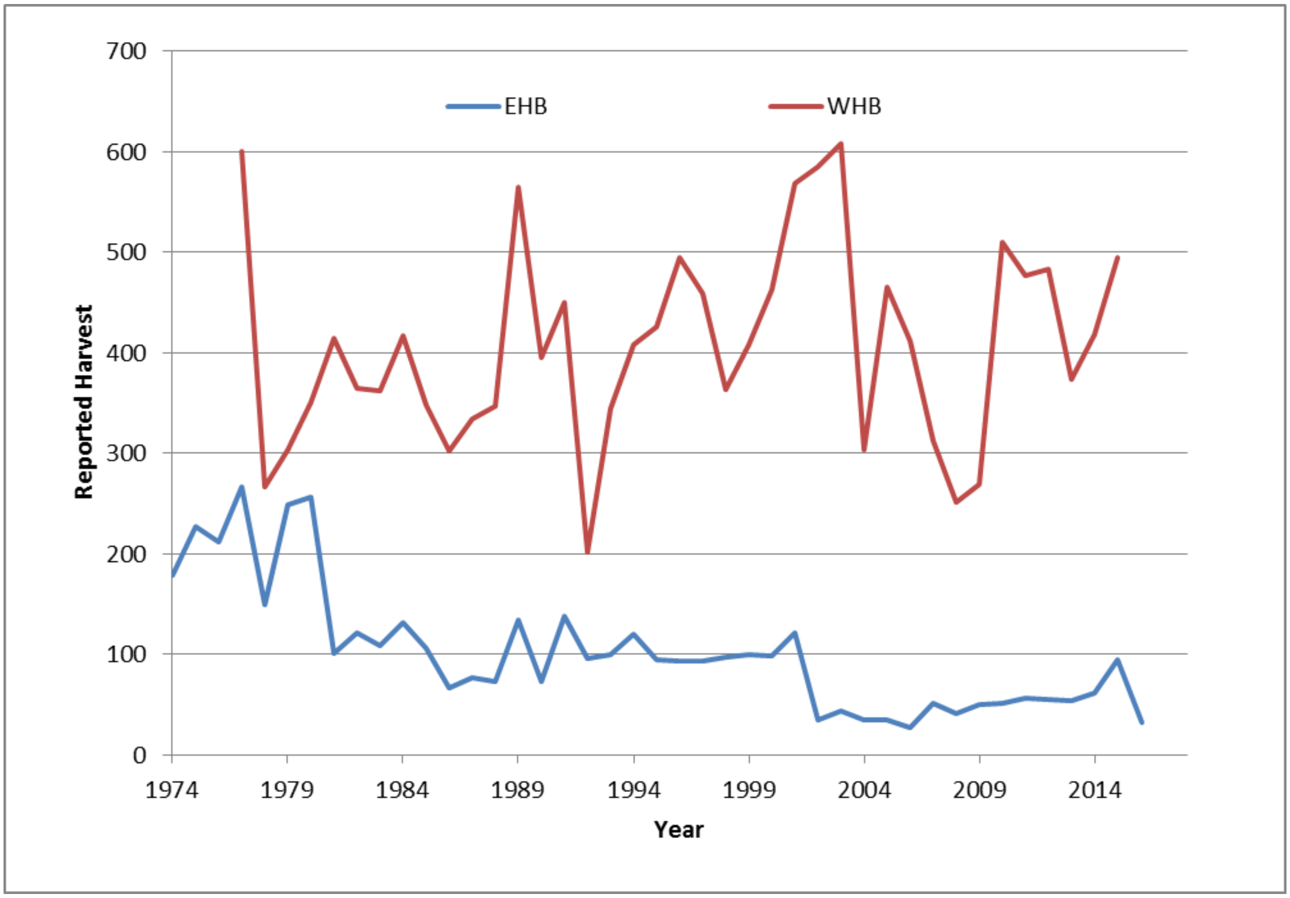

Figure 2. Total reported harvest of Western Hudson Bay (WHB) belugas by communities in Nunavut and Nunavikand total reported harvest of Eastern Hudson Bay (EHB) belugas by hunters from Nunavut and Nunavik.

MODEL SPECIFICATION

A stochastic stock-production model was fitted by Bayesian methods (Doniol-Valcroze et al. 2012a,b; Hammill et al. 2016; Marcoux and Hammill 2016). We sought to separate the observation error (associated with data collection and abundance estimation) from the process error (arising from natural variability in population dynamics). To this end, we developed a hierarchical state-space model that considers survey data to be the outcome of two distinct stochastic processes: a state process and an observation process (de Valpine and Hastings 2002).

The state process describes the underlying population dynamics and the evolution of the true stock size over time. Previous assessments of the EHB stock have assumed exponential growth of the population. We present the exponential growth model and also model changes assuming that density-dependent factors are affecting the dynamics of this population.

Exponential growth model

Population size (N_t) was estimated using:

$$N_t = N_{t-1} \cdot \exp(\lambda_{\max} - 1) \cdot \varepsilon_{p_t} - R_t \text{, with } \varepsilon_{p_t} \sim \log N(0, \tau_p)$$

where $\lambda_{\max}$ is the maximum growth rate, R_t is removals of EHB belugas from the population by harvesting and ε_{p_t} is a stochastic term for the process error, which is the variability in reproduction and survival with mean of 1 and variability of τ_p (Table 1).

Density-dependent growth model

Density-dependent growth was modelled using a discrete theta-logistic model (Pella and Tomlinson 1969; Innes and Stewart 2002):

$$N_t = N_{t-1} + N_{t-1} \cdot (\lambda_{\max} - 1) \cdot \left[1 - (N_{t-1}/K)^{\theta}\right] \cdot \varepsilon_{p_t} - R_t \text{, with } \varepsilon_{p_t} \sim \log N(0, \tau_p)$$

where K is environmental carrying capacity and theta (θ) defines the shape of the density-dependent function,

In both models, removals were calculated as

$$R_t = C_t \cdot (1 + SL)$$

Where reported catches Ct = Reported catch * proportion of EHB animals in the catch and SL is the estimated struck and loss, i.e., the proportion of animals that were wounded or killed but not recovered.

The observation process describes the relationship between true population size and observed data. In our model, survey estimates S_t are linked to population size N_t by a multiplicative error term ε_{s_t}:

$$S_t = N_t \cdot \varepsilon_{s_t} \text{, with } \varepsilon_{s_t} \sim \log N(0, \tau_s)$$

PRIORS

Existing information, traditional knowledge and expert opinions were used to formulate prior distributions for the random variables included in the model (Appendix 1, Table 3). Beginning with the EHB stock, the initial population size was given a uniform prior between 2000 and 15,000 individuals. The lower bound reflects observations of at least a few hundred belugas in the EHB estuaries, but recognizes that the population had been reduced considerably from pristine sizes (Smith and Hammill 1986; Reeves and Mitchell 1987). Doniol-Valcroze et al. (2012b), estimated a pristine population of around 8,000 (95% CI 7,200-8,700) assuming no losses during the commercial hunt. This estimate does not take into account the subsistence hunt, although compared to the commercial harvest its impact was likely to have been relatively small. For K, a range of 2,000 to 20,000 was used. The upper bound encompassed the possible range of estimates of pristine population size, including if loss rates were as high as 2 and would likely account for subsistence harvests at the time as well (Doniol-Valcroze et al. 2012a,b; Hammill et al. 2005). The maximum rate of population increase is not known. Based on aerial surveys, Lowry et al (2008) estimated a rate of increase of 0.048 (95% CI 0.021-0.075) for belugas in Bristol Bay in Alaska. For the St Lawrence estuary beluga, Beland et al. (1988) using the age distribution of stranded carcasses, estimated a mean rate of increase of 0.049 (95% CL=0.038 to 0.061). Other studies have used maximum rates of increase of 6% (Hobbs et al. 2006), 8% (Alvarez-Flores and Heide-Jørgensen 2004; Doniol-Valcroze et al. 2012a, b) and 10% (Innes and Stewart 2002). We used a prior with uniform distribution with a range of 0.0001 to 0.06. The lower bound allows for essentially zero growth at K, while the upper bound of 0.06 assumes an adult survival rate of 0.97 (Hobbs et al. 2006). For the density-dependent model, the point at which a population attains Maximum Sustainable Yield is also uncertain. Marine mammals are generally considered to attain MSY levels at around 60% of K (Taylor and DeMaster 1993; Butterworth et al. 2002; Hobbs et al. 2006). Therefore, theta (θ) was set to 2.39 which results in maximum productivity at 60% of K (Hobbs et al. 2006).

Reported harvests underestimate the number of beluga killed because of animals wounded or killed but not recovered, as well as under-reporting. The struck and loss (SL) rates in Canadian hunts are not known exactly but are believed to range from around 20% for shallow water hunts up to 60% for deep-water hunting, e.g. along ice edges (Seaman and Burns 1981). Heide-Jørgensen and Rosing-Asvid (2002) calculated a SL factor of 0.29 for Greenland, not including unreported catches. Innes and Stewart (2002) estimated a correction factor that accounted for SL and whales not reported in Baffin Bay at 0.41 whales per whale landed. In Cooke Inlet, SL has varied from 33-66% (Hobbs et al. 2006). Richard (2008) estimated SL rates of 18% (CV=13%, range 10-30%). We used a moderately informative prior following a Beta (3, 4) distribution, with a median of 0.42 and quartile points at 0.29 and 0.55, which was used in the previous assessment (Doniol-Valcroze et al. 2012a). These priors result in lower SL estimates than used in earlier assessments where the struck and lost was given a log-normal prior with a median of 0.61 and quartile points at 0.43 and 0.85 (Doniol-Valcroze et al. 2012a,b).

The stochastic process error terms ε_{pt} were given a log-normal distribution with a zero location parameter. The precision parameter for this lognormal distribution was assigned a moderately informative prior following a bounded gamma (1.5, 0.001) distribution. These parameters were chosen so that the resulting coefficients of variation (CV) would have quartiles of 5.5% and 8.7%, reflecting our belief that beluga stock dynamics are not highly variable.

Although estimates of uncertainty were available for each survey estimate, they were incorporated into the fitting process only by guiding the formulation of the prior distribution of the survey error. The survey error term ε_{st} followed a log-normal distribution with a zero location parameter. Its precision parameter was given a moderately informative prior following a gamma (2.5, 0.4) distribution. These parameters were chosen so that the resulting CV on the survey estimates would have quartiles of 35% and 55%, which are approximately equivalent to the range of actual CV for the survey abundance estimates.

The proportions of EHB beluga harvested in each zone are incorporated into the model as probabilities. The genetic priors assumed a Beta distribution, with known mean and standard error, but for which the α and β parameters are not available. We solved the system of equations for the mean and variance of a Beta distribution to determine the values of α and β that describe the observed distributions. These Beta distributions were then used as priors for the proportions of EHB animals in the hunt at Sanikiluaq, Hudson Strait (HS) for all season (hunt prior to 2009) and HS for spring and fall (2009–2012), Ungava Bay, and northeastern Hudson Bay spring and fall (Appendix 1,Table 3)(Mosnier et al. 2017). The regions are shown in Figure 3.

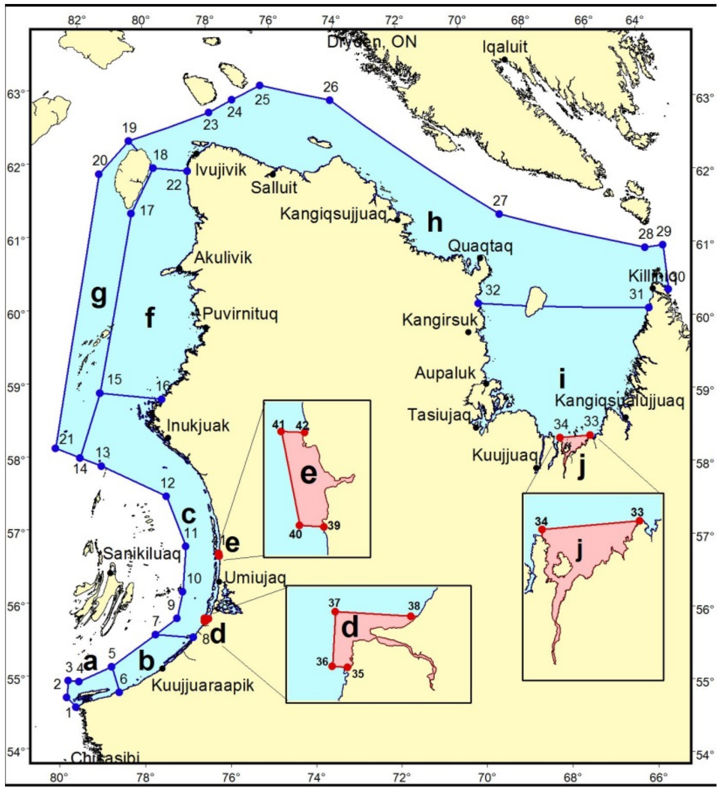

Figure 3. The regions in eastern Hudson Bay that are considered as different hunting areas in the management plan, with different probabilities of EHB whales taken in each area.

For the western Hudson Bay population we used the same initial priors, except as outlined below. We assumed that communities with mixed stock harvests, the proportion of WHB animals in the harvest was estimated as: Proportion WHB=1-proportion (EHB). There has been a long history of whaling in the Churchill area, but historical catch data have not been compiled. Non-informative priors for the starting population in 1977 and K assumed a Uniform distribution, with values ranging from 10,000 to 100,000. In a second series of runs, the range of priors for K was increased to have limits of 10,000 to 200,000. To model SL, the priors from the EHB model (SL~beta (3,4)) were used, which had a median at 0.42 with quartiles values of 0.29 and 0.54. Richard (2008) estimated a much lower SL of 18% (range 10-20%) for Nunavut. Runs were repeated assuming the priors could be described using a beta distribution (SL~beta (3,19)), with a median at 0.12, quartiles at 0.08 and 0.18 and 95% C.I. of 0.03 to 0.31. Harvest data were not available for 2016 for the WHB stock; for running the model and estimating stock abundance in 2016, we assumed a reported harvest equal to the average reported harvest from the last 20 years (N=435, SE=23).

PARAMETER ESTIMATION AND MODEL DIAGNOSTICS

We obtained posterior estimates of all the parameters using a Gibbs sampler algorithm implemented in JAGS (Plummer 2003). Results were examined using packages R^2 jags and coda developed in the R programming language (R Core Team 2013). With any MCMC simulation, it is important to check convergence of the sampled values to their stationary distribution (Brooks et al. 2004; King et al. 2010). Initial runs of the code were made to investigate convergence and mixing (i.e., the extent and spread with which the parameter space was explored by the chain), as well as autocorrelation. Following these initial runs, we kept one sample every 40 iterations from 5 chains of 10,000 iterations, after a burn-in of 10,000 samples.

Mixing of the chains was tested using Geweke's test of similarity between different parts of each chain (Geweke 1996), and for convergence between chains using the Brooks-Gelman-Rubin (BRG) diagnostic, which compares the width of 80% Credible Interval (CI) of pooled chains with the mean of widths of the 80% CI of individual chains (Brooks and Gelman 1998).

MANAGEMENT FRAMEWORKS

Sustainable Yield (SY)

The management objective of SY is to maintain a constant population over a period of 10 years or more. In the past, harvests have been set assuming that the probability of decline does not exceed 50%.

DFO-Maximum Sustainable Yield (DFO-MSY)

The general DFO-MSY framework identifies a lower reference level (LRL) and a precautionary reference level (PRL), which establishes three management zones (Figure 4) (DFO 2013). A population is considered healthy if there is at least a 50% probability that it is above the PRL. A population is considered to be critical if there is a 50% probability that it lies below the LRL. A stock is considered to be in a cautious zone, if its numbers lie between the LRL and PRL (Hammill et al. 2016).This framework is based on the concept of maximum sustainable yield (MSY), where the objective is to maintain the population at levels of 80% of MSY, which here lies at 60% of K (Figure 4).

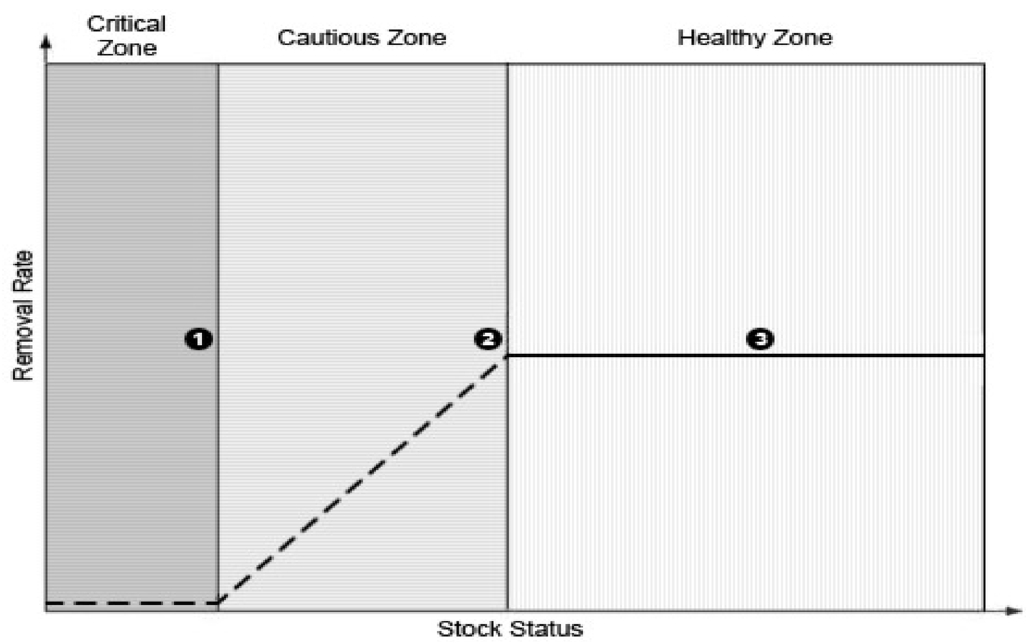

Figure 4. Suggested PA framework for fisheries in Canada. 1. The Lower reference level (LRL). 2. The precautionary reference level (PRL). 3. A removal rate identified to maintain the resource within the Healthy zone (DFO 2006).

DFO ATLANTIC SEAL MANAGEMENT (DFO-ASM)

The DFO-ASM framework is similar to the MSY framework, with PRL, and LRL and three zones of resource concern (Critical, cautious and Healthy). However, in the DFO-ASM framework, the PRL is set at 70% of the highest population observed (N_{max}) from a survey or model estimate. The LRL is set at 30% of $N_{max.}$ In this study N_{max} was set at the highest population observed. The management objective is to maintain a 95% probability that the population is above the LRL and 80% probability that the population is above the PRL (Hammill and Stenson 2003, 2007, 2009, 2013; Stenson et al. 2012).

Under both the DFO MSY and ASM frameworks if populations are in the critical or cautious zones, then stock rebuilding is to occur within 1.5 to 2 generations (39-52) years for beluga assuming 1 growth layer group per year (Stewart et al. 2006).

Recovery target

COSEWIC identified EHB beluga as 'Endangered', but they have not been listed by the Government of Canada. A recovery target population of 70% of the estimated pristine population size of 12,500, i.e. 8,750 has been proposed for this stock (DFO 2005). It has been suggested that this figure may have overestimated losses during harvesting. A second estimate of pristine population size of 8,000 has been proposed. This results in a recovery target of 5,600 animals, if the recovery target is set at 70% of the estimated pristine population (Doniol-Valcroze et al. 2012a) There have been no discussions with stakeholders with respect to this target. The time to recover above this target was estimated as 100 years (DFO 2005).

PBR

Total allowable removals were calculated using the Potential Biological Removal (PBR), which is calculated from:

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

where R_{max} is the maximum rate of population increase, F_R is a recovery factor (between 0.1 and 1), and N_{min} is the estimated population size using the 20-percentile of the lognormal distribution (Wade 1998). The default R_{max} is 1.04 for cetaceans, but if reliable estimates are available, then these can be used instead.

$N_{min,t} = Nt / [\exp(z20 \bullet \mathrm{sqrt}[\ln(1+CV2)])]$,

with z20 = 0.842 (standard normal variate for 20th percentile) and CV is the coefficient of variation (Wade 1998).

COMPLEMENTARY ANALYSIS

As a complement to the description of the population trends with the population dynamic model, we used additional information provided by several sampling programs involving Nunavik and Nunavut hunters during the harvest season (see details in Mosnier et al. 2017) to describe the evolution of the sex ratio and the mean age of the hunted beluga from 1984 to 2015. This dataset included genetic information used in the mixture analysis to estimate the proportion of the different source stocks (EHB or WHB) occurring in the harvest of migrating whales (Mosnier et al. 2017). However, this analysis does not allow classification of individual sample as EHB or WHB. Using information on haplotype genetic distance, sequence evolution and phylogenetic patterns (Postma et al. 2012) and other information such as frequency occurrence at different hunting locations, samples were identified as EHB_{type} or NOT_EHB_{type}. The sex of the animal was determined by the hunter and confirmed by the genetic analysis and its age was estimated by counting dentinal growth layers groups (GLG) in tooth sections, considering 1 growth layers group per year (Stewart et al. 2006). Trends in sex ratio and mean age was tested with linear regressions separating the EHB_{type} from the NOT_EHB_{type} samples.

RESULTS

SEX RATIO AND MEAN AGE IN THE NUNAVIK HUNT

The dataset provides information about the sex ratio and the age of hunted belugas in 1984 and 1985 and then regularly between 1993 and 2015 (Figures 5, 6). As expected the EHB_{type} sample size is generally smaller than the NOT_EHB_{type} one.

Overall results suggest a slight overrepresentation of male vs female beluga in the harvest from both EHB_{type} and NOT_EHB_{type} (Figure 5AB). The evolution of the sex ratio between 1984 and 2015 evaluated by linear regression shows non-significant decreasing trends ($p = 0.81$ and $p = 0.31$ for EHB_{type} and NOT_EHB_{type} respectively).

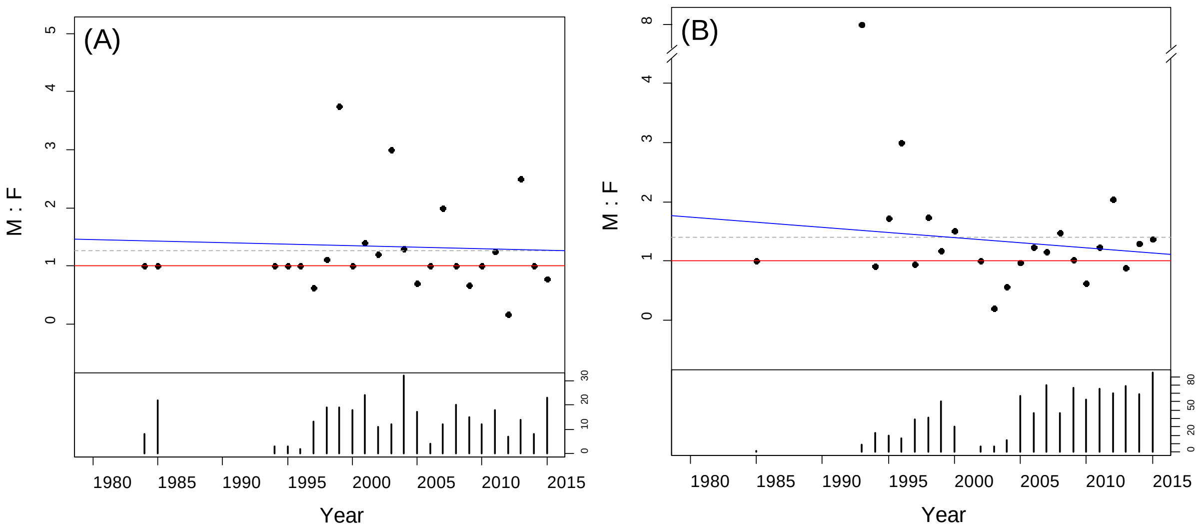

Figure 5. Changes in the sex ratio (M:F) of samples provided by Nunavik hunters from their harvests. (A) shows EHB_{class} and (B) NOT_EHB_{class} belugas from 1984 to 2015. The red line is the 1:1 sex ratio. The blue line is the weighted linear regression (weighted by the sample size in each year) and the dotted line shows the mean value of the sex ratio for the whole period. The lower graph indicates the sample size for each year.

The mean age of hunted beluga over the entire period is 18.5 and 23.6 years old for EHB_{type} and NOT_EHB_{type} respectively. There is a significant increase in the mean age of hunted EHB_{type} beluga from 1984 to 2015 (0.21 year/year; $p = 0.011$; Figure 6A). However, while the trend remains positive (0.18 year/year), it becomes non-significant ($p=0.11$) when extreme values observed in 1984-1985 (mean age respectively 7 and 9 years old) and 1994-1995 (42 and 47 years old) are removed. No significant trend exists in the mean age of hunted NOT_EHB_{type} beluga (Figure 6B).

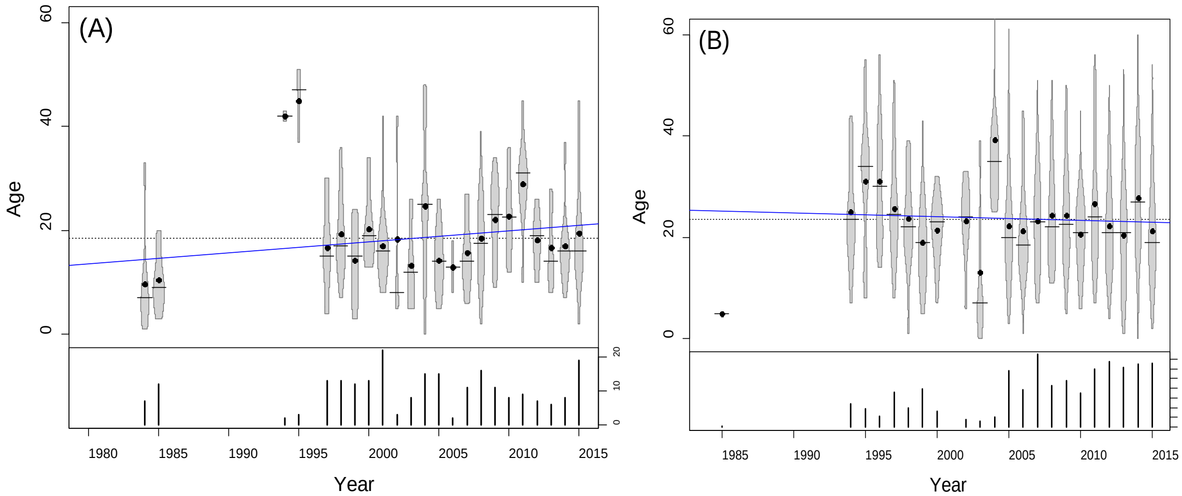

Figure 6. Changes in the age distribution in (A) EHB_{class} and (B) NOT_EHB_{class} belugas from 1984 to 2015 as a violin plot. Black dots indicate the mean and small horizontal lines the median of the age of sampled individuals for each year. The dotted line shows the mean age for the whole period. The blue line is the linear regression. The lower graph indicates the sample size for each year.

EASTERN HUDSON BAY BELUGA

Population Models

The impacts of using different start dates (1974 vs 1985) and model types (exponential vs density-dependent) were examined. Both models (exponential and density-dependent) with a 1985 start date converged quickly, with little sign of autocorrelation (Appendix 2). For the exponential model, cross correlation was observed between lambda and the starting population size (-ve) and between lambda and the current population size (Appendix 2, Figure 1). For the density dependent model, cross-correlation was observed between lambda and the starting population (-ve) and lambda and the current estimate of population size (+ve) (Appendix 2, Figure 2). Model fit was similar for both the exponential and density dependent model approaches (Figure 7). The density dependent model estimated a starting population of 3,953 in 1985 (vs 3,882 for exponential model) and a 2016 estimate of 3,443 (vs 3,447 for exponential model).

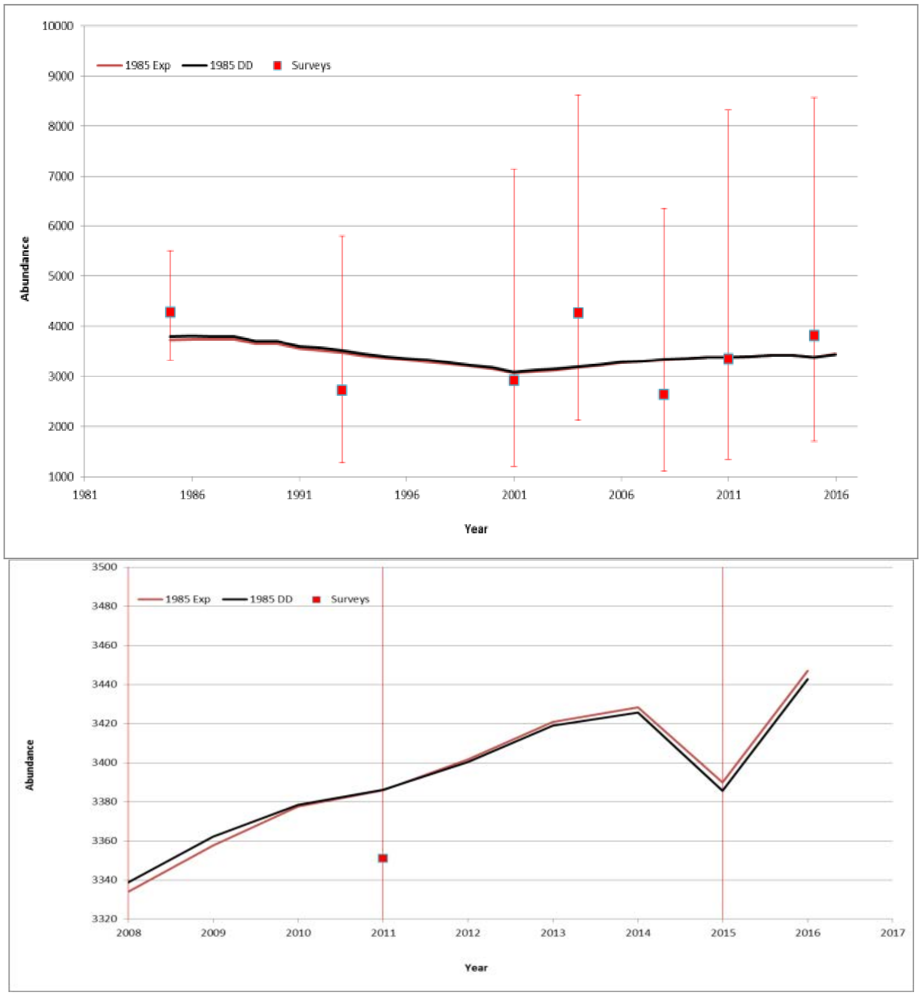

Figure 7. Median trends (1985-2016) for EHB beluga stock obtained from fitting an exponential model (1985 start) (upper panel) and a density-dependent model (1985 start) to aerial survey data (±95% confidence intervals).The lower panel shows model trends for the period 2008-2016.

Significant updates of the priors occurred for the parameters in both models (Appendix 2, Tables 1, 2): starting population, lambda and K. The posterior for Lambda in the exponential model was 0.028 (95% CI=0.01-0.05), while for the density-dependent model it was 0.033 (95% CI=-.01-0.08). Lambda is a constant value in the exponential model, while in the density-dependent model, the effective lambda varies with population size (Figure 8) (Appendix 2, Tables 1, 2).

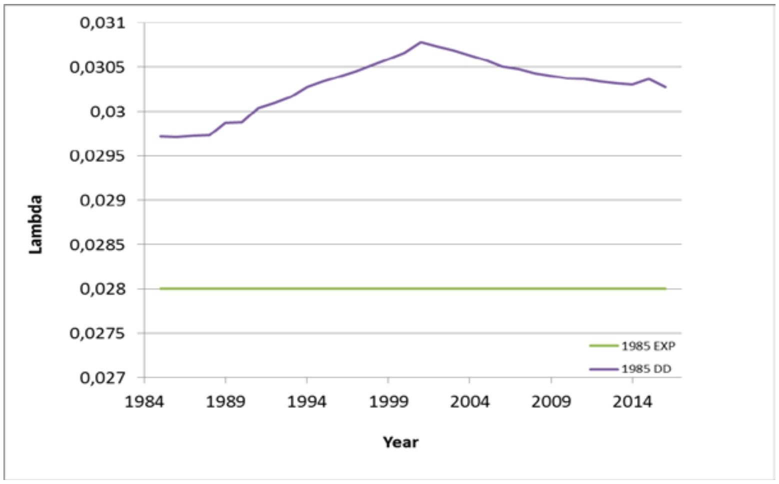

Figure 8. Estimated change of EHB beluga stock in the effective lambda between 1985 and 2016 assuming exponential growth or density-dependent growth to describe the dynamics of the population.

When the models were initiated in 1974, the density dependent model estimated a starting population of 6,600 (vs 4100 for the exponential model) and it suggested a steeper decline in the population from 1974 to 1985 than the exponential model (Appendix 2, Figures 3, 4). The density dependent model estimated a population of 3,758 animals in 1985 vs 3,814 (exponential model). The 1985 aerial survey estimate was 4,282 animals. The estimated 2016 population was 3,408 from the density dependent model compared to 3,400 (exponential model) and a 2015 aerial survey estimate of 3,819 (Appendix 2, Tables 3, 4).

Previous assessments have used a 1985 start date and an exponential model to describe the dynamics of the EHB stock. However, harvest data are available since 1974 and we could not see any problems with these data, nor could we justify not including them in the stock assessment. Therefore, in this assessment we started the analysis in 1974. In earlier assessments, the dynamics of the EHB stock were described using an exponential growth model because of limited survey information, which also limited our ability to estimate K and because over short periods of time, growth could be assumed to be constant. With the 2015 survey, we now have seven surveys that extend back to 1985, and with the additional harvest data, the assessment now covers a period extending over 42 years (1974-2016). With an assessment now covering nearly half a century it is less appropriate to assume that growth is constant. Instead, it is more appropriate to assume that there may have been some changes in the stock dynamics owing to changes in ecosystem conditions/variability and or changes in abundance, which will be better described assuming density-dependent dynamics. Therefore, the density dependent model with a 1974 start date was used to provide the advice for the EHB beluga stock.

The density dependent model estimates K=8,300 (95% CI=5,400-19,300), and a starting population of 6,600 (95% CI=4,800-9,300) in 1974. The model indicates that the population declined from 1974 reaching a minimum of 3,100 in 2001 and since then has increased to a current population estimate of 3,400 (95% CI=2,200-5,000, all rounded to nearest 100)(Figure 9)(Appendix 2, Table 4).

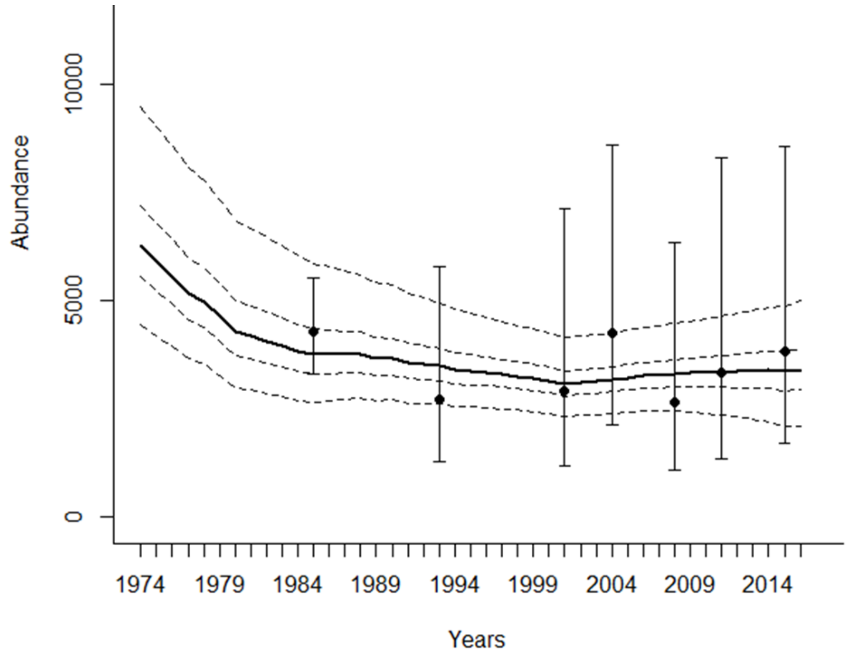

Figure 9. Estimated trajectory of EHB beluga stock obtained by fitting a density dependent model to seven aerial surveys (1985-2015), taking into account harvest data (1974-2016). Surveys (±95%CL), median (solid), 25th, 75th quantile (inner dotted lines) and 95% CI (outer dotted lines).

Management frameworks

Ecosystem and Fisheries Management requested advice following the Sustainable Yield (SY) approach as has been used in the past, the development of a PA framework and time to recovery. The PA management frameworks described in this document have been developed internally (Hammill et al. 2017). The setting of management objectives and risk tolerance are guided by processes that include discussions and consultations among management authorities, co-management partners and aboriginal rights holders. These discussions have not yet taken place.

Sustainable Yield (SY)

Using SY, an annual harvest of 68 EHB belugas would have a 50% probability of the population declining over a 10 year period (Figure 10).

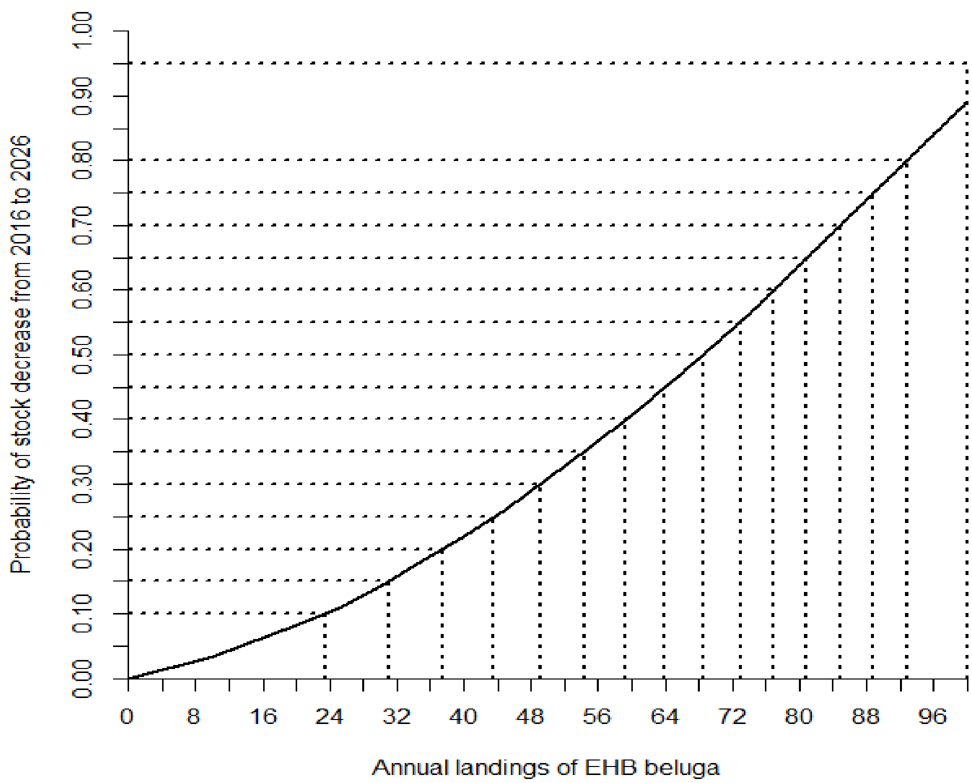

Figure 10. Probability of a population decline from current levels over 10 years at different levels of landings of EHB belugas.

DFO-MSY

For the DFO Maximum Sustainable Yield (MSY) framework, the model estimated K=8,300. This results in a PRL of 4000 and a LRL 2,800. At a current population of 3,400 animals, EHB belugas are in the cautious zone. The management objective is to set harvest levels that will allow the population to move into the Healthy zone with a high probability within 1.5 to 2 generations (39-52 years in the case of beluga).

If we identify a time frame of 50 years, then to have a 0.7 probability of the population being above the PRL, annual reported harvests of EHB belugas should not exceed 40 animals (Figure 11). Assuming a 0.50 probability results in an allowable annual reported harvest of 61 animals (Table 2).

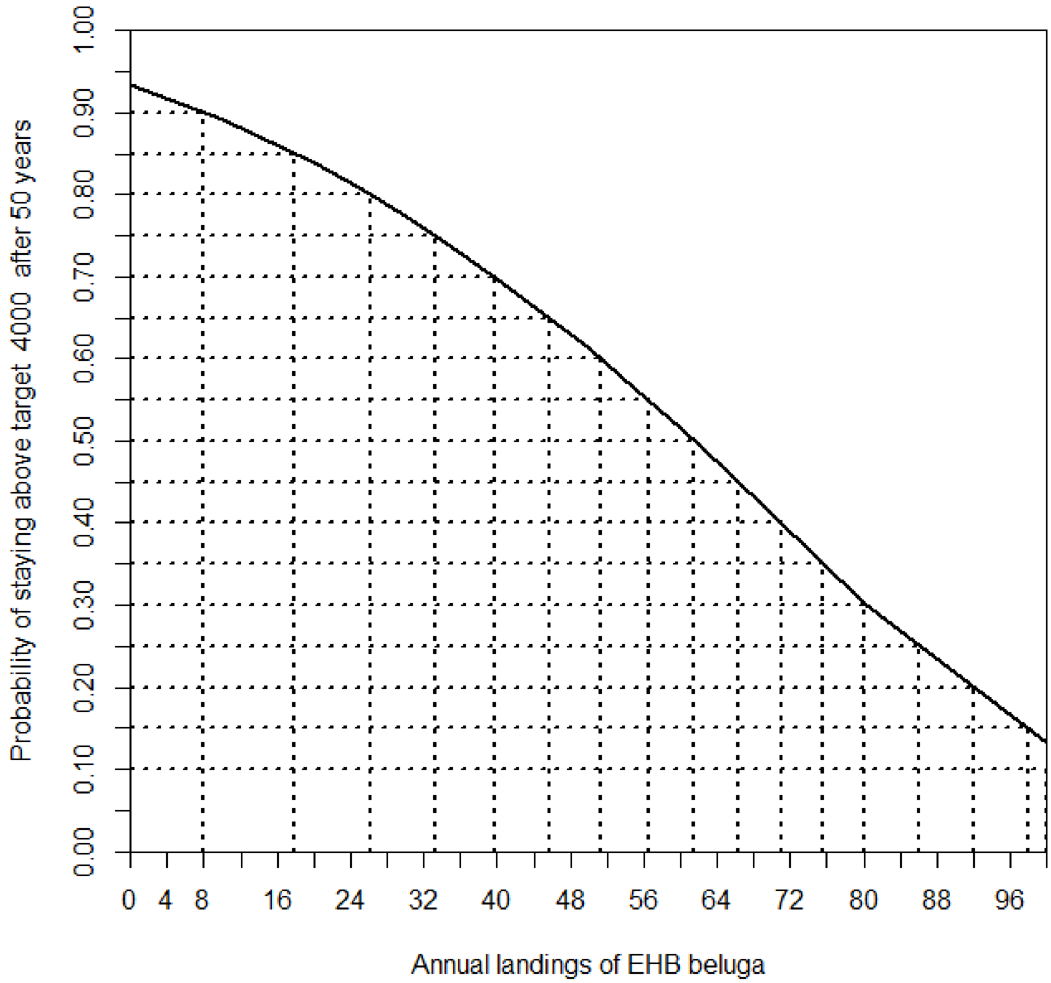

Figure 11. MSY framework. The probability that the population will be above the PRL of 4,000 animals in 50 years for different levels of harvest of EHB beluga.

DFO Atlantic Seal Management (DFO ASM)

For the ASM Framework N_{MAX} is set at the largest population seen or estimated. From the model, the largest population is the starting population in 1974 of 6,600. The PRL and LRL are established as proportions of N_{MAX}. The PRL and LRL would be 4,600 and 2,000 respectively. The management objective is to set harvest levels that will allow the population to move into the Healthy zone with a high probability within 1.5 to 2 generations (39-52 years in the case of beluga).

If we identify a time frame of 50 years, then to have a 0.7 probability of the population being above the PRL, annual reported harvests of EHB belugas should not exceed 31 animals (Figure 12). Assuming a 50% probability results in an allowable annual reported harvest of 50 animals (Table 2).

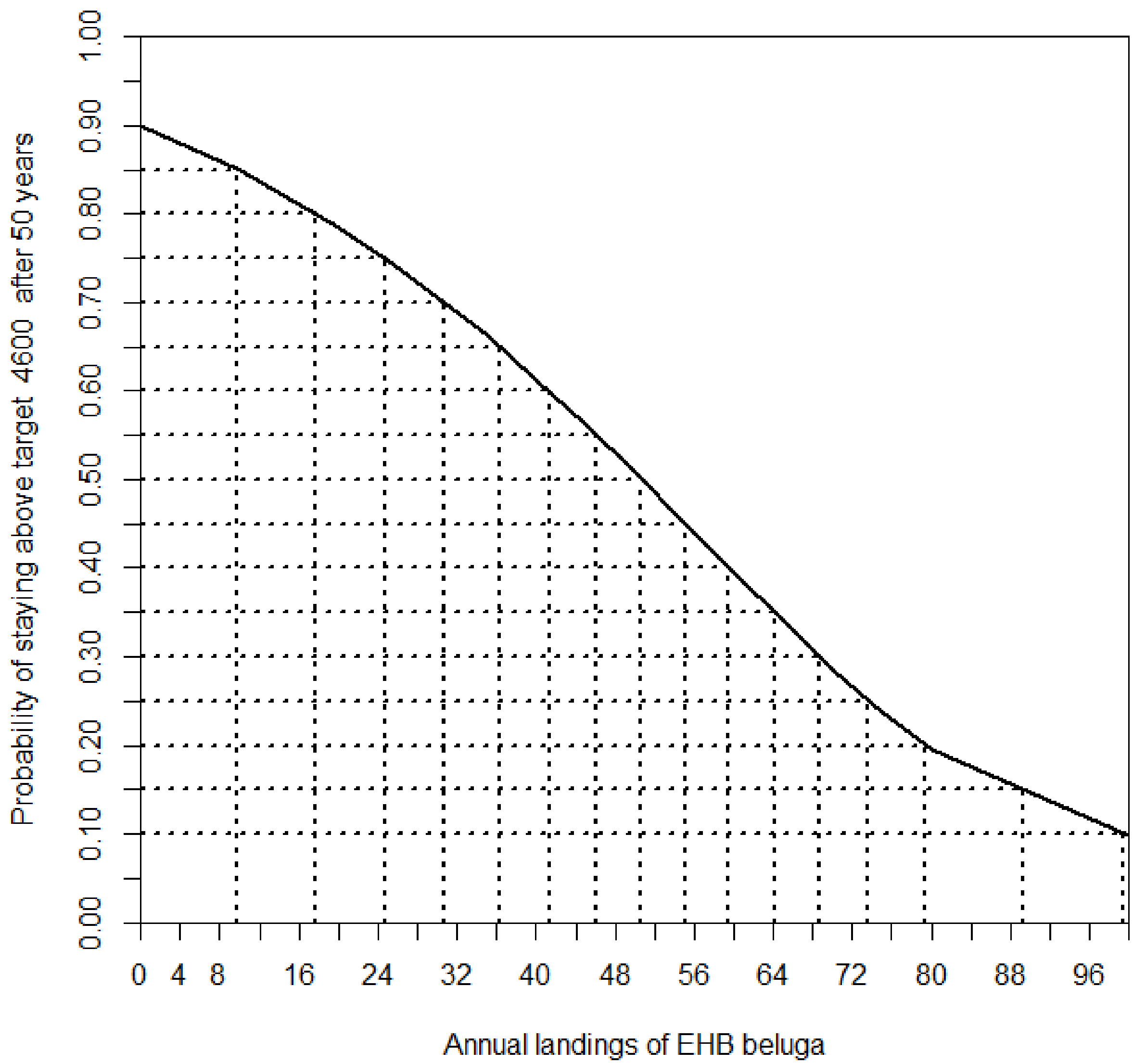

Figure 12. ASM framework. The probability that the population will be above the PRL of 4,700 animals) after 10 years for different levels of harvest of EHB beluga.

SARA recovery target

If the recovery target is set at 8,750 beluga, the probability of reaching this target is 0.45, if there is no harvesting and only 0.25 if approximately 50 animals are removed annually over the next 100 years. If the target is 5,600 whales, then there is a 0.79 probability of the population recovering within 100 years if there are no harvests. This declines to 0.4 for an annual harvest of 50 beluga (Figure 13).

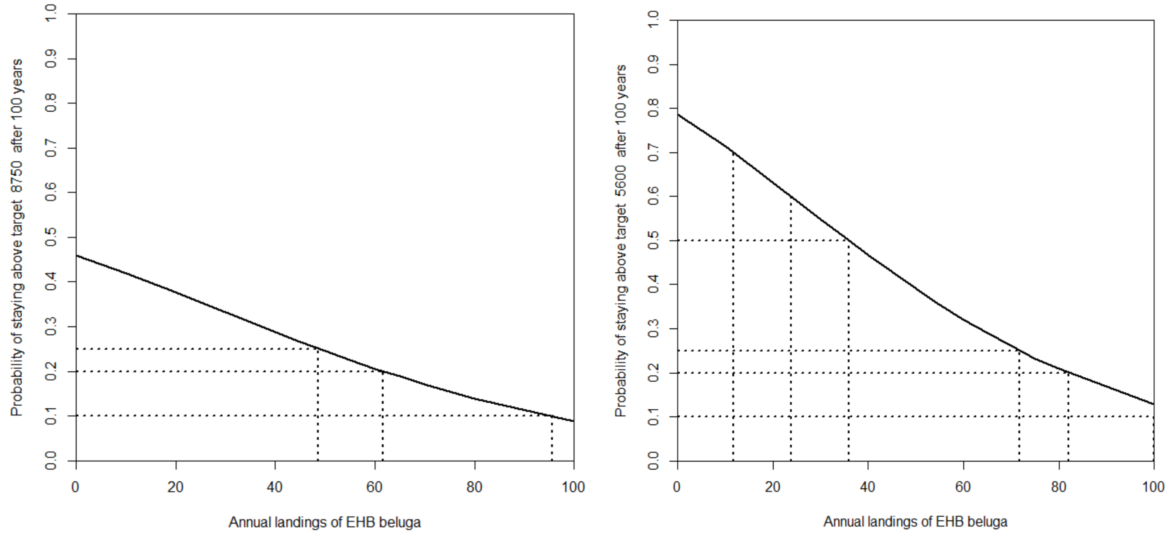

Figure 13. Probability of the population subject to different levels of harvest of EHB animals, recovering to 70% of estimated pristine levels of 8,750 (left) or 5,600 (right) within 100 years.

PBR

The PBR approach provides an estimate of overall allowable mortality. Thus the Total Allowable Take (TAT) must be adjusted to take into account, other human related mortality. Therefore, the TAT = PBR-(Struck and Lost +other human related mortality). Using a median abundance estimate of 3,400, (cv=0.21) and Struck and Lost rate of 0.39 from the model, the PBR would vary from 3 to 35 depending on the FR and whether the model or survey estimate of abundance is used in the calculation (Table 2).

Table 2. Comparison of harvest levels among the different management frameworks. Stocks between the Precautionary Reference Level (PRL) and the Limit Reference Level (LRL) are in the cautious zone. Harvest levels are based on the probability that a stock will increase above the PRL within 50 years. All harvest levels take into account Struck and Loss. To make PBR comparable, Struck and Loss must be considered. We used median posterior SL value of 0.39 from the model (adjusted reported harvest)

MSY/ Abundance	K	PRL =0.48*K	LRL =0.24*K	Prob > LRL	Prob > PRL	Harvest p>0.8 50 y	Harvest p>0.7 50 y	Harvest p>0.6 50 y	Harvest p>0.5 50 y
3400`	8,263	4,000	2000	1	0.1	26	40	51	61

ASM	N_{MAX}	=0.7*Max	=0.3*Max	-	-	Harvest p>0.8 in 50 y	Harvest p>0.7 in 50 y	Harvest p>0.6 In 50 y	Harvest p>0.5 In 50 y
3400	6594	4,600	2,000	1	0.05	17	31	41	50
PBR	N_{min}	-	-	-	-	F_R=1	F_R=.75	F_R=.5	F_R=.1
3400	2848	-	-	-	-	57 (35)	43 (26)	28 (17)	6 (3)

WESTERN HUDSON BAY

Two model scenarios were examined to describe the dynamics of this stock. The first scenario examined the impact of changing the SL parameter from a median value of 0.42 to 0.13, while the second scenario examined the impact of changing the upper limits for K.prior from 100,000 to 200,000. The model was fitted to three aerial survey estimates of abundance along the WHB coast (Table 1) and included harvest data from both the Nunavik communities and several Nunavut communities (Appendix 1, Tables 1, 2). In both cases for the SL.prior, whether the median value was 0.42 or 0.13, there was not enough information to update the SL model priors. In model runs using an upper limit for K.prior of 100,000, changing the priors used for SL from a median of 0.42 to 0.13 had little impact on K (posterior median went from 65,200 to 63,400), the starting population size (46,400 to 44,800) and estimated population size in 2016 (from 47,900 to 48,500). However, the maximum rate of increase declined from 0.039 to 0.037 (Appendix 3, Table 1). Both runs, with SL.prior median =0.42 or SL.prior median=0.13, indicated that the population is stable, and model estimates were above the 1987 aerial survey estimate, but below the 2004 and 2015 aerial survey estimates (Table 1, Figure 14).

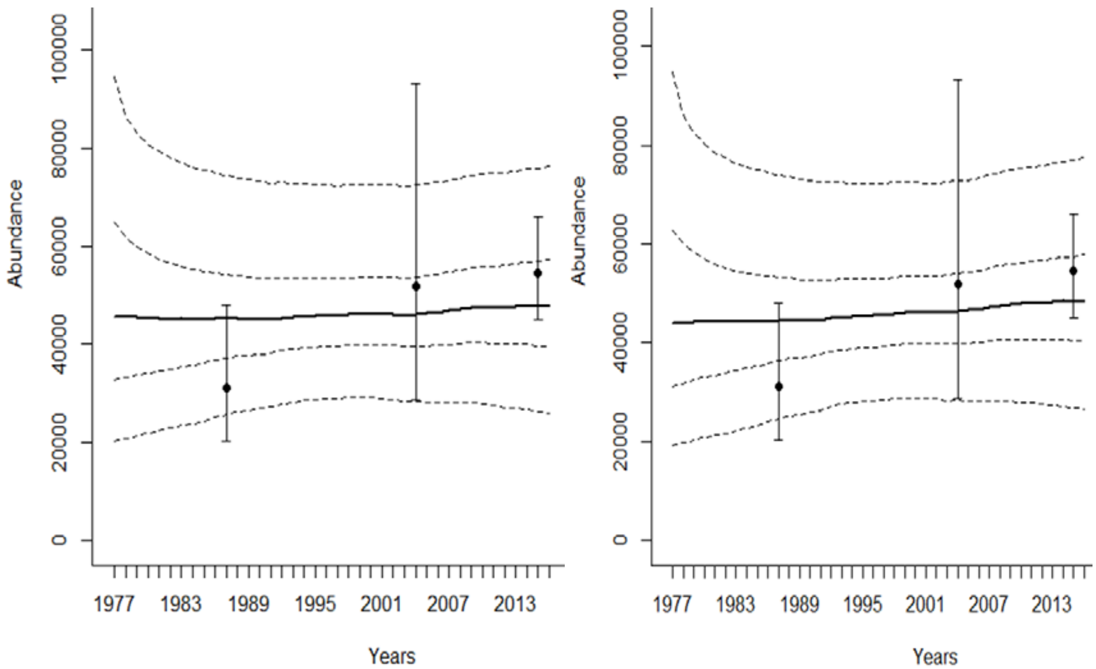

Figure 14. Trajectory of WHB belugas estimated by fitting a population model to the aerial survey estimates and incorporating harvest data (1977-2016). Runs with maximum prior for carrying capacity (K) =100,000 , and median Struck and Lost (SL), SL. prior=0.42 (left) and using median SL .prior=0.13 (right).

The posteriors for lambda and for K from the first runs of the WHB model were pushing the upper limits of the priors for these variables (Appendix 3, Table 1, Figure 1). Model runs were repeated increasing the upper limit for K from 100,000 to 200,000. Changing the upper limits on the prior for K had a significant impact on some model outputs, but little difference was observed when the median for the SL prior was adjusted from 0.42 to 0.13. Increasing the upper limit for K from 100,000 to 200,000 resulted in an increase in the median value for K from 65,200 to 95,200 (when median SL.prior=0.42); the starting population decreased slightly from 46,400 to 40,200, the estimated population in 2016 increased from 47,900 to 52,200 and the median rate of increase declined from 0.039 to 0.035 (Appendix 3, Tables 1, 2). More importantly, our understanding of the population trajectory changed from one where the population was stable, to one where the population was increasing (Figure 15).

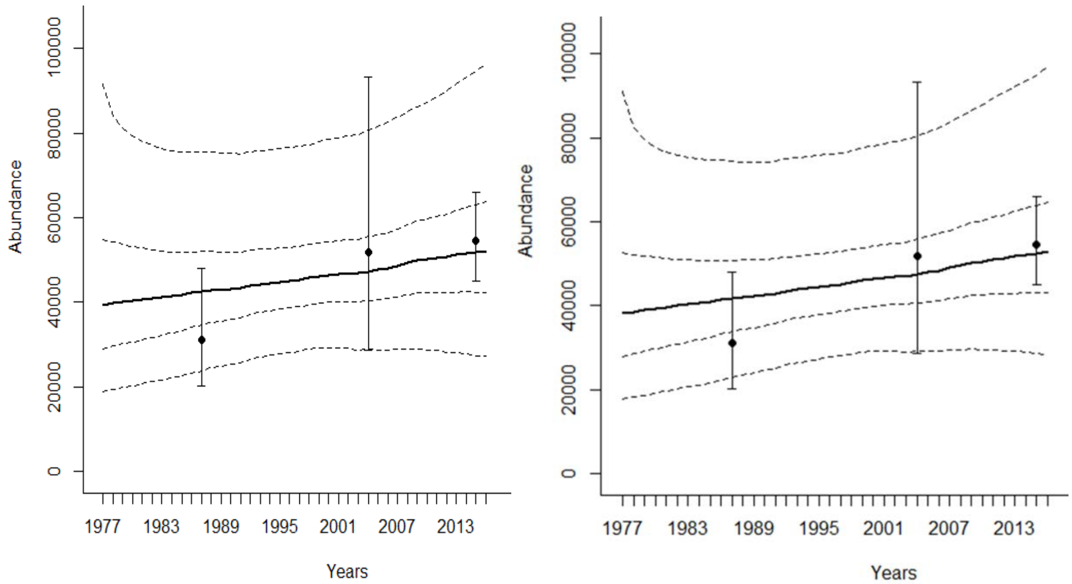

Figure 15. Trajectory of WHB belugas estimated by fitting a population model to the aerial survey estimates and incorporating harvest data (1977-2016). Runs with maximum prior for carrying capacity (K) =200,000 , and median Struck and Lost (SL), SL.prior=0.42 (left) and using median SL.prior=0.13 (right).

WHB PBR

For the WHB stock, the model could only be fitted to three aerial survey estimates and it could not be determined which form of the model was most appropriate (model with the upper prior for K limited to 100,000 or limited to 200,000). Therefore, the model was not used to provide inputs for estimating PBR. Instead, PBR was estimated using the aerial survey estimates (Hammill et al. 2017). For a 2015 survey estimate of 54,473 (CV=0.098), N_{min} was 50,168, PBR=1,004, 753, 502 and 251, for recovery factors of 1, 0.75, 0.5 and 0.25 respectively.

DISCUSSION

EHB BELUGA

The EHB beluga stock is one of three relatively small beluga stocks in Canada. Numbering around 3,400 animals it is approximately three times the size of the other two small stocks, the Cumberland Sound beluga and St Lawrence Estuary beluga stocks which number around 1,000 animals each (Marcoux and Hammill 2016; Mosnier et al 2015). The population model trajectory shows that the EHB stock continued to decline even after quotas were introduced in the mid-1980s, because catches of EHB animals remained high throughout this period. Since the early 2000s, there has been an effort to focus harvesting in Hudson Strait, which has reduced the removal of EHB belugas and has resulted in stabilization of the stock (Figure 16).

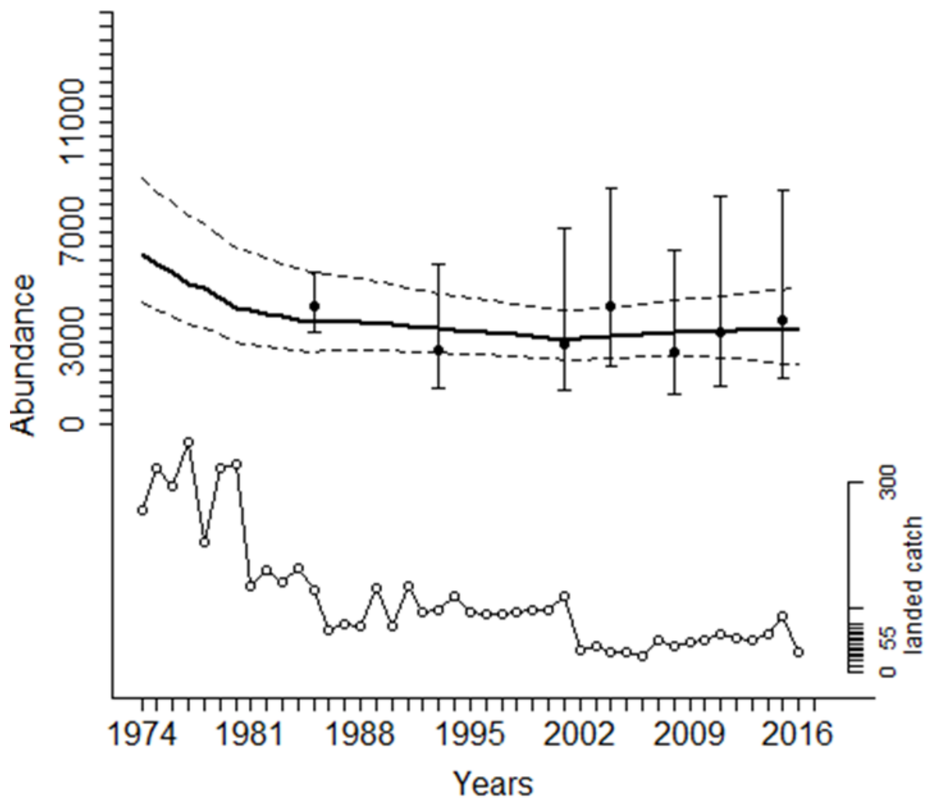

Figure 16. Estimated trajectory of the EHB stock obtained by fitting a density dependent model to seven aerial surveys (1985-2015), taking into account harvest data (1974-2016). Surveys (±95%CL), median (solid), 25th, 75th quantile (inner dotted lines) and 95% CI (outer dotted lines)(top). Reported harvests of EHB belugas estimated using prior distributions identified in Appendix 1, Table 3 (Bottom).

This stabilization is due to the efforts of hunters and managers to find ways to reduce the harvest of EHB whales. Monitoring is extensive, with weekly harvest reporting by the community wardens. Hunters provide a skin and tooth sample for DNA analyses and ageing to determine stock composition, age and sex structure of the harvest. If the harvest samples are indicative of the harvest overall, then hunters tend to harvest more males. Unless there have been major changes in hunter selectivity, lack of trend in mean age of animals taken in the harvest suggests that the population is stable, which is in agreement with the population trajectory from the model.

Modelling of the EHB stock is based on seven aerial survey estimates, all of them associated with considerable uncertainty. Additional uncertainty is associated with the estimated rate of increase of the stock, estimates of struck-and-loss, and the proportions of EHB whales in each regional harvest. Using Bayesian methods allowed us to explicitly incorporate uncertainty around these parameters (Wade 2000), which are represented in the model by statistical distributions instead of single values. Bayesian fitting also ensured that uncertainty was propagated throughout the analysis, and that the correlations among parameters were preserved (Hoyle and Maunder 2004). The resulting stock trajectory is based on realistic population dynamics and offers more information than a simple trend analysis.

However, there is additional uncertainty in the stock composition of animals that are being counted in the EHB survey area that requires further examination. The EHB stock has been identified based on the concept that beluga return to the same summering areas and has been determined to be genetically distinct. This stock occupies an area bounded by the northern part of the EHB arc, just to the north of the village of Inukjuak, and in the south by an east-west line running approximately midway between the village of Kuujjuarapik and the top of Long Island at the entrance to James Bay (55 °, 11’ N) (Gosselin et al. 2017). In an east-west direction, the EHB stock range extends over an area running from the EHB coast westwards to 60 km west of the Belcher Islands (81° W longitude)(Figure 1). Thus, the area around the Belcher Islands is completely embedded within the summer range of the EHB stock.

The genetic evidence that confirms EHB stock discreteness from beluga in James Bay and western Hudson Bay has been based on samples obtained from hunters along the EHB coast, primarily near the Little Whale and Nastapoka Rivers. Satellite transmitters deployed on animals at the Little Whale and Nastapoka River estuaries have provided information on summer movements. These tagged animals remained within the EHB stock area during summer, undertaking regular movements between the coast and the offshore area of the Belcher Islands , then migrating in fall to overwinter in Hudson Strait (Bailleul et al. 2012). Satellite transmitters deployed on beluga in James Bay suggest that these animals remain there well into the fall. Transmitters deployed on beluga in western Hudson Bay have shown that these animals remain there until the end of the summer before migrating out of Hudson Bay for the winter. Some of these tracked WHB animals have migrated past the Belcher Islands in the fall.

It has been assumed that animals seen during the summer surveys of the offshore EHB areas had the same genetic composition as animals sampled from the two coastal EHB rivers (i.e. the Little whale and Nastapoka Rivers). However, in recent years, some samples from animals harvested around the Belcher Islands have had different haplotypes frequencies, not seen elsewhere. If the genetic composition of animals seen in these offshore areas is more complex than characterized by the typical ‘EHB type’, then we may be underestimating the impact of the harvest on the EHB stock. Additional research should attempt to improve our understanding of the genetics and movements of animals summering in the EHB arc area and around the Belcher Islands, particularly those seen in the offshore areas.

Several priors showed substantial updating by the model. The estimated rate of growth (*lambda)* was well updated from its flat prior distribution. With median values of 0.028 and 0.031 obtained using the exponential and density dependent growth models respectively. These are similar to the rate of 0.0274 obtained by Doniol-Valcroze et al (2012a,b) for this stock after the last assessment and is within the range of 2 to 4% observed for other species with similar life histories, such as narwhals (Kingsley 1989), pilot whales (Kasuya et al. 1988) and spotted dolphins (Barlow and Boveng 1991). There was little updating of the prior for Struck and Loss in either model, indicating that the model does not have sufficient information about this parameter. In Nunavut, Richard (2008) estimated a mean SL of 13% (range 10-30%) from hunter reports, but this does not include non-reporting. For Nunavik, the model estimated a median SL of 39% (updated only slightly from a prior median of 42%), but this estimate is also likely to include some non-reporting. Moreover, in Nunavik, several different approaches are used in the harvest of beluga depending on whether animals are at the floe edge, near the coast or offshore. In previous assessments the dynamics of the population have been described using an exponential growth model. This approach can be considered appropriate at low stock sizes where growth is expected to be exponential, or over short time-frames, where ecosystem conditions are expected to change little. However, over longer time-frames, ecosystem conditions will fluctuate, which will affect the dynamics of the population. Both models resulted in the same estimate of population size and trend, but the exponential model estimate lambda was an average estimated over the range of the time-series. The density dependent model also estimated a value for lambda, but the actual rate of increase varied with the relative abundance compared to the estimated carrying capacity K, and the shape of the density dependent relationship. We propose that the density-dependent model be used since it is better equipped to provide a more realistic view of lambda, which is unlikely to have remained constant over the last 31 years as the population has changed.

The highest allowable harvests were observed using the SY framework. This framework sets catches at levels that result in a 50% probability of decline in the resource. The SY framework has been applied in the past to the management of the commercial seal hunt, but was rejected because management targets are not explicit, it does not allow for any population growth, and does not leave any buffer for errors in model assumptions, survey estimates or harvest reporting (McLaren et al. 2001). Applying a PA framework resulted in TATs ranging from 17-62, assuming a probability of being above the PRL of 0.5 or better. An alternative framework is to use PBR. The PBR framework does not offer any advantages, since it does not provide any insights as to where the resource lies with respect to possible management objectives and expected harvests may be lower owing to F_R less than 1. We evaluated the probability that the population would attain the Recovery level identified with respect to the Species at Risk Act. For the moment these values should be considered illustrative because they are based on possible pristine abundance, under ecosystem conditions that differ from current conditions. Also, trying to simulated expected recovery over 100 years is unrealistic.

Implementing PA will assist Canada to respect its international agreements (UNESCO 2005; United Nations Convention on the Law of the Sea of December 1982) and the need to establish a management framework, that respects the principles of conservation and the needs of hunters identified under the landclaim (Hammill et al. 2017). A danger in PA frameworks is that too much of the resource remains unharvested, incurring a cost to resource users (Sissenwine et al. 2014). In this study, we identified some different approaches that could be used and the probability that management objectives will be obtained i.e. the population will recover to the Healthy zone within 50 years, at different levels of harvest. However, further discussions with hunters concerning the framework are needed.

WHB BELUGA

The WHB beluga stock is one of the largest in the world. Animals from this stock support harvesting by several communities. One of the objectives of the management strategies to protect the EHB stock has been to try to shift harvesting towards the larger WHB stock. A population model was fitted to the three available abundance surveys and incorporated information on harvesting from communities around Hudson Bay and southern Baffin Island. Under different assumptions for the upper bound for K, the population is either stable (K_{upper}=100,000), or is increasing (K_{upper}=200,000). Unfortunately, independent data on possible historical population size are not available, therefore it is not possible to determine a realistic upper limit for K. The 1987 survey covered a more limited area than did the 2004 and 2015 surveys, so may be negatively biased. Beluga also occur along the Ontario coast and in the northern portion of Hudson Bay, but in the case of the former, animals from the Ontario coast have not been included in the WHB estimates because when surveys have been flown, it was uncertain whether animals along the Ontario coast were resident or had moved there from elsewhere such as the Nelson river (Richard 2005). Surveys have been flown in northern Hudson Bay, but survey estimates were not available for this assessment. With only three surveys, uncertainty about the 1987 survey, uncertainty about vital parameters and links to animals outside of the ‘traditional’ WHB area, it is difficult to examine stock dynamics further. Therefore, it is recommended that TAH levels be estimated using PBR from the aerial survey estimates. Based on the criteria identified in Hammill et al. (2017), the WHB stock might warrant a recovery factor (F_R) of 0.75. This is based on an abundant stock, a survey time series limited to three surveys, therefore limited data, and with trend unknown but not considered to be declining.

The PBR estimate for the WHB stock from the 2015 aerial survey is 502-1004 depending on the F_R that is applied (F_R=0.5 to 1 respectively). These PBR estimates are higher than those obtained by fitting the model to the survey data, but as outlined above, we feel that it is more appropriate to estimate PBR using the survey data. The reported harvest for 2015 is the last year that data are available. Using the PBR approach a Total allowable Harvest (TAH) is estimated as TAH=PBR-(all sources of human related mortality), which includes SL. Applying a Nunavut specific SL rate of 1.18 for beluga (DFO 2008), the current harvest is on the order 584 belugas, which is below the PBR estimate for the WHB stock with a F_R of 0.75 or greater.

In this analysis it has been assumed that harvested beluga belong to the EHB stock, and if not, they must belong to the WHB stock centered around the Nelson, Churchill and Seal River estuaries. We identified above that beluga occur in other areas outside of what has been considered the core WHB area, but abundance information is limited or not available. Data on stock composition of the harvests from many villages are also limited. If they are harvesting from herds or stocks that occur outside of what has been considered here as the core WHB group, then we have over-estimated the impact of this harvest on the core group of WHB animals.

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APPENDICES

APPENDIX 1: INPUT DATA USED IN THE POPULATION MODEL

Appendix 1, Table 1. Reported harvests for communities harvesting beluga whales from the EHB and WHB beluga stocks for 1974-2016. Regions used in the Nunavik management plan are the eastern Hudson Bay Arc (ARC), Hudson Strait-Ungava Bay (HSUB), Sanikilluaq (SAN), Hudson Bay in spring (SPRING, Hudson Bay in Fall (FALL), Ungava Bay in spring (UBSP), Ungava Bay in Fall (UBFA), northeastern Hudson Bay spring (NEHBSP) and Northeast Hudson Bay fall NEHBFA)

YEAR	ARC	HSUB	SAN	SPRING	FALL	UBSP	UBFA	NEHBSP	NEHBFA
1974	119	352	0	0	0	0	0	0	0
1975	137	532	0	0	0	0	0	0	0
1976	143	403	0	0	0	0	0	0	0
1977	181	501	14	0	0	0	0	0	0
1978	120	174	6	0	0	0	0	0	0
1979	211	224	0	0	0	0	0	0	0
1980	220	212	0	0	0	0	0	0	0
1981	61	236	6	0	0	0	0	0	0
1982	73	271	30	0	0	0	0	0	0
1983	69	227	7	0	0	0	0	0	0
1984	97	189	28	0	0	0	0	0	0
1985	78	166	5	0	0	0	0	0	0
1986	43	126	25	0	0	0	0	0	0
1987	53	125	28	0	0	0	0	0	0
1988	52	117	20	0	0	0	0	0	0
1989	84	284	19	0	0	0	0	0	0
1990	53	109	20	0	0	0	0	0	0
1991	106	178	22	0	0	0	0	0	0
1992	78	96	20	0	0	0	0	0	0
1993	67	189	10	0	0	0	0	0	0
1994	82	207	50	0	0	0	0	0	0
1995	55	221	30	0	0	0	0	0	0
1996	56	211	30	0	0	0	0	0	0
1997	51	239	19	0	0	0	0	0	0
1998	50	252	54	0	0	0	0	0	0
1999	57	238	32	0	0	0	0	0	0
2000	62	208	23	0	0	0	0	0	0
2001	73	241	27	0	0	66	0	0	0
2002	5	161	15	0	0	23	0	0	0

YEAR	ARC	HSUB	SAN	SPRING	FALL	UBSP	UBFA	NEHBSP	NEHBFA
2003	8	168	80	0	0	26	0	0	0
2004	3	144	94	0	0	4	0	0	0
2005	1	172	53	0	0	5	0	0	0
2006	0	147	22	0	0	2	0	0	0
2007	21	165	24	0	0	6	0	0	0
2008	23	92	33	0	0	5	0	0	0
2009	21	0	34	68	70	6	0	0	0
2010	16	0	47	138	61	8	7	0	0
2011	19	0	32	115	86	0	17	0	0
2012	13	0	61	208	56	10	2	0	0
2013	8	0	76	150	90	8	0	0	0
2014	22	0	26	208	37	11	0	1	14
2015	36	0	170	106	94	28	3	0	30
2016	11	0	33	117	0	20	0	0	0

Appendix 1, Table 2. Reported harvests from communities along the western Hudson Bay coast. The communities are Arviat, Baker Lake, Cape Dorset (Cape Dorst), Chesterfield Inlet (Chest. In.), Coral Harbour (Coral Harb.), Kimmirut (Kim), Rankin Inlet, Repulse Bay (Repul. Bay), Whale Cove, Hall Beach, Igloolik and Iqaluit.

	Arviat	Baker Lake	Cape Dorst	Chest. In.	Coral Harb.	Kim.	Rankin Inlet	Repul Bay	Whale Cove	Hall Beach	Igloolik	Iqaluit
1977	0	0	7	18	52	26	12	40	30	18	15	0
1978	0	0	21	3	24	3	30	0	37	9	18	5
1979	0	0	7	6	44	35	0	24	0	7	28	2
1980	0	0	43	11	62	12	14	7	8	0	0	18
1981	0	0	1	11	8	16	61	56	22	5	70	44
1982	0	0	3	3	33	4	37	34	6	15	70	22
1983	0	0	46	5	64	0	33	18	8	0	65	0
1984	0	0	0	12	116	9	69	30	24	21	55	2
1985	0	0	21	28	76	9	36	3	19	1	25	19
1986	0	0	2	23	50	19	30	20	35	18	50	20
1987	0	0	9	34	29	34	30	30	30	12	7	36
1988	45	0	10	15	38	9	27	47	16	3	14	44
1989	70	0	18	20	67	28	40	20	27	11	8	40
1990	70	0	39	20	67	21	40	20	27	11	21	2
1991	25	0	37	20	125	28	20	13	25	0	0	11
1992	0	0	36	0	0	20	0	9	27	7	100	31

	Arviat	Baker Lake	Cape Dorst	Chest. In.	Coral Harb.	Kim.	Rankin Inlet	Repul Bay	Whale Cove	Hall Beach	Igloolik	Iqaluit
1993	23	0	35	17	20	13	14	12	19	1	20	35
1994	32	0	26	27	30	3	29	28	37	18	25	28
1995	3	0	20	22	50	20	88	35	2	0	7	4
1996	100	0	25	20	31	8	48	20	35	2	12	35
1997	100	0	37	0	30	4	48		20	8	10	23
1998	9	0	4	15	25	20	35	8	25	0	0	17
1999	58	0	12	0	50	19	0	4	0	0	0	70
2000	100	0	28	1	38	27	45	10	20	5	4	22
2001	100	0	13	25	25	16	35	10	40	8	16	45
2002	115	0	0	18	17	38	130	18	60	0	0	35
2003	300	0	7	20	20	20	25	5	25	15	23	28
2004	100	0	0	7	3	20	30	0	0	12	0	27
2005	100	0	21	0	0	7	100	3	40	2	15	50
2006	45	2	30	3	0	25	60	50	10	0	27	64
2007	50	0	0	12	7	0	38	21	10	10	18	33
2008	100	0	4	3	13	2	50	0	0	3	17	0
2009	0	0	1	0	0	0	66	21	0	0	18	66
2010	200	0	3	0	0 1	33	26	8	35	18	74	26
2011	100	0	8	25	20	17	62	1	45	8	42	18
2012	60	0	0	29	0	14	26	0	120	0	0	0
2013	0	0	15	0	12	0	1	10	50	0	0	84
2014	15	2	0	8	60	17	0	1	30	19	0	**53**
2015	100	2	0	15	100	22	0	11	35	7	0	8

Appendix 1, Table 3. Prior distributions, parameters and hyper-parameters used in Nunavik beluga population model. "est." denotes a parameter that follows a distribution and which is estimated by the model. For each subregion and season, the priors for the proportion of EHB belugas in the harvest are given. pHSUB=proportion EHB in Hudson Strait/Ungava Bay.

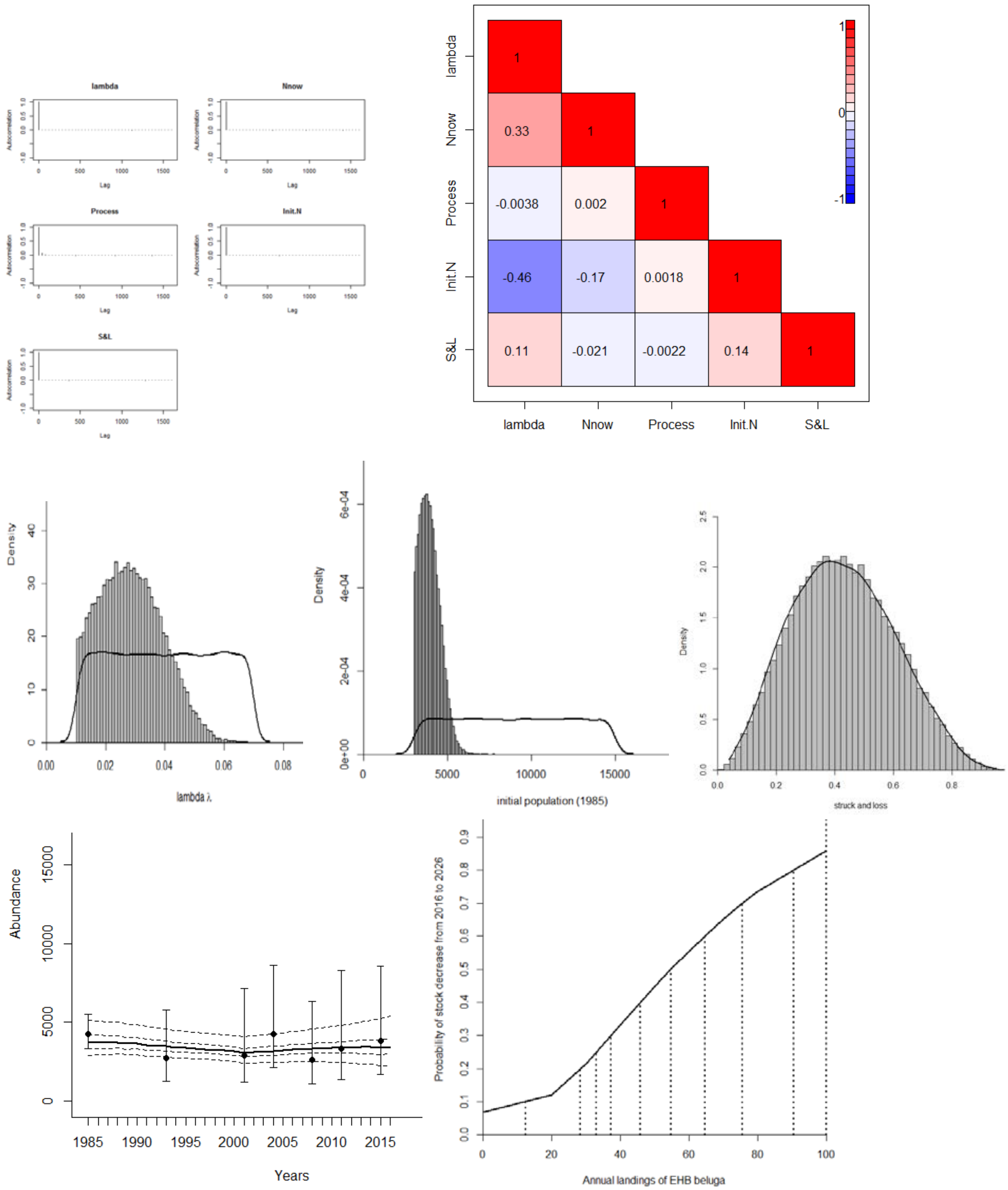
Parameters	Notation	Prior distribution	Hyper-parameters	Parameter Value	Prior Median / Mean	Prior 95CIs
Survey error (t)	εst	Log-normal	μs τs	0 est.	1 / 3.46 e+53*	0 - 6385446*
Precision (Survey)	τs	Gamma	αs βs	2,5 0,4	5.44 / 6.25	1.04 - 16.04
Process error (t)	εpt	Log-normal	μp τp	0 est.	1 / Inf.	0 - Inf.
Precision (Process)	τp	Gamma	αp βp	1,5 0,001	1183.2 / 1500.0	107.9 - 4674.8
Theta	θ	Fixed	- -	- -	2.39	-
Struck-and-lost	SL	Beta	αsl βsl	3 4	0.421 / 0.429	0.118 - 0.777
Initial population	N1974	Uniform	Nupp Nlow	15000 2000	-	-
Carrying capacity	K	Uniform	Nupp Nlow	25000 2000	-	-
Maximum annual growth rate	λmax	Uniform	Nupp Nlow	0.06 .0001-0.06	- .03/.03	- 0.002-0.058
HSUB	PHS	Beta	αhs βhs	45 216	0.171/ 0.172	0.129 - 0.220
Sanikiluaq (extended spring)	PSAN	Beta	αsan βsan	3.47 75.05	0.040/0.044	0.011 - 0.099
Hudson St. (spring)	PHS_SP	Beta	αhs_sp βhs_sp	24.03 198.05	0.107/0.108	0.071 - 0.152
Hudson St (Fall)	PHS_F	Beta	αhs_f βhs_f	37.30 105.54	0.260/0.261	0.193 - 0.336
Ungava B (spring)	PUNG_S	Beta	αung_s βung_s	1.79 19.55	0.072/0.084	0.009 - 0.231
Ungava B (fall, used HS fall)	PUNG_F	Beta	αung_f βung_f	- -	0.009	-
NE Hudson Bay (spring, used HS spring)	PNEHB_S	Beta	αnehb_s βnehb_s	- -	0.009	-
NE Hudson Bay (fall)	PNEHB_F	Beta	αnehb_f βnehb_f	5.56 12.86	0.294/0.302	0.121 - 0.523

APPENDIX 2: OUTPUTS FROM MODEL RUNS TO ESTIMATE EASTERN HUDSON BAY BELUGA ABUNDANCE USING AN EXPONENTIAL GROWTH AND A DENSITY DEPENDENT GROWTH MODEL TO DESCRIBE THE DYNAMICS OF EHB BELUGA WITH DIFFERENT START DATES (1974 AND 1985)

Appendix 2, Table 1. Exponential model 1985 start date. Model priors and posteriors for parameters. The mean, standard deviation (SD), 2.5th , 25th, 50th, 75th and 97.5th quantiles are given for the following model parameters and their priors: maximum rate of increase (lambda), struck and lost (S&L), and population size in 2016 (N2016). $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near 1 indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

	Mean	SD	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
Deviance	115.0	2.6	111.1	113.1	114.6	116.4	121.2	1.001	50000
Lambda	0.028	0.011	0.011	0.02	0.028	0.036	0.05	1.001	28000
Lambda.prior	0.04	0.017	0.012	0.025	0.04	0.055	0.069	1.001	18000
pFALL	0.269	0.037	0.199	0.243	0.268	0.294	0.345	1.001	43000
pHSUB	0.172	0.023	0.13	0.156	0.171	0.187	0.22	1.001	15000
pNEHBFA	0.302	0.104	0.122	0.226	0.296	0.371	0.523	1.001	17000
pNEHBSP	0.112	0.021	0.074	0.097	0.111	0.125	0.156	1.001	50000
pSAN	0.057	0.028	0.015	0.036	0.052	0.073	0.123	1.001	43000
pSPRING	0.112	0.021	0.074	0.097	0.111	0.125	0.155	1.001	50000
pUBFA	0.27	0.037	0.2	0.244	0.268	0.294	0.346	1.001	50000
pUBSP	0.086	0.06	0.01	0.041	0.073	0.117	0.233	1.001	50000
Startpop	3954	603	3059	3478	3882	4344	5277	1.001	24000
Startpop.prior	8987	3467	3306	5993	9001	11997	14696	1.001	50000
SL	0.431	0.174	0.121	0.301	0.424	0.555	0.779	1.001	50000
SL.prior	0.428	0.175	0.118	0.297	0.421	0.553	0.775	1.001	28000
N2016	3546	811	2260	2998	3447	3977	5415	1.001	50000

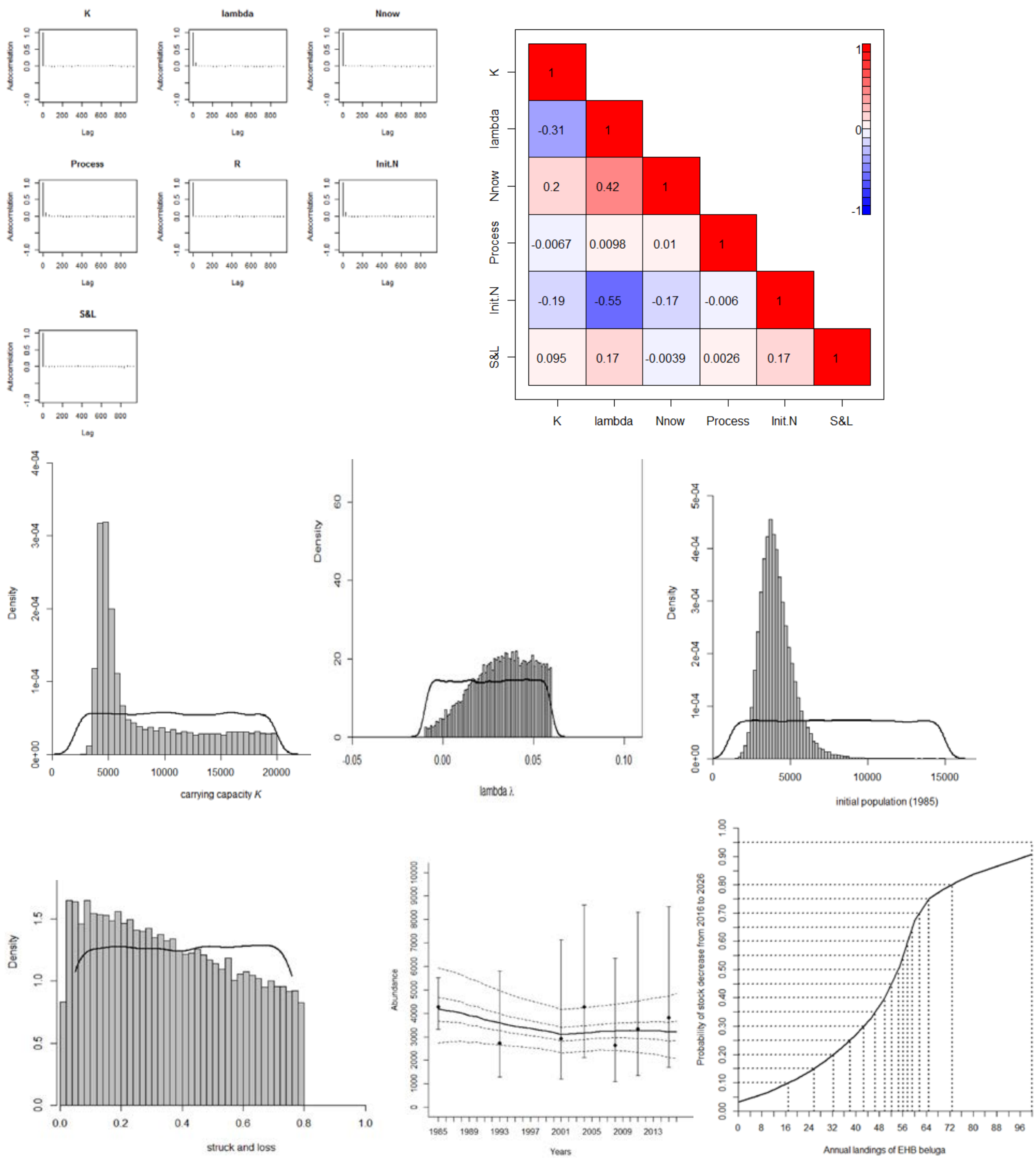
Appendix 2, Figure 1. Exponential model with 1985 start date model showing level of autocorrelation (top left), cross correlation (top right), prior and posterior distributions and population trajectory. Surveys (±95%CL), median (solid), 25^{th}, 75^{th} quantile (inner dotted lines) and 95% CI (outer dotted lines). Theta fixed=2.39, Lambda fixed=0.04.



Appendix 2, Table 2. Density dependent model 1985 start date. Model priors and posteriors for parameters. The mean, standard deviation (SD), 2.5th, 25th, 50th, 75th and 97.5th quantiles are given for the following model parameters and their priors: carrying capacity (K), theta, maximum rate of increase (lambda), struck and lost (S&L), and population size in 2016 (N2016). $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near 1 indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

	Mean	SD	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
K	8227	4811	3769	4579	5640	11412	19130	1.001	25000
K.prior	10979	5214	2435	6468	10933	15533	19582	1.001	20000
Deviance	115	3	111	113	115	117	122	1.001	20000
Lambda	0.033	0.017	-0.001	0.021	0.034	0.047	0.059	1.001	19000
Lambda.prior	0.025	0.02	-0.008	0.008	0.025	0.043	0.058	1.001	19000
pFALL	0.261	0.037	0.192	0.235	0.26	0.285	0.337	1.001	25000
pHSUB	0.171	0.023	0.128	0.155	0.171	0.187	0.219	1.001	24000
pNEHBFA	0.301	0.105	0.121	0.225	0.293	0.37	0.527	1.001	25000
pNEHBSP	0.108	0.021	0.071	0.094	0.107	0.121	0.152	1.001	23000
pSAN	0.044	0.023	0.011	0.027	0.04	0.057	0.099	1.001	25000
pSPRING	0.108	0.021	0.07	0.094	0.107	0.121	0.151	1.001	25000
pUBFA	0.261	0.036	0.192	0.236	0.26	0.286	0.335	1.001	25000
pUBSP	0.083	0.058	0.009	0.039	0.071	0.113	0.229	1.001	21000
Startpop	4354	810	2873	3812	4325	4848	6092	1.001	25000
Startpop.prior	8499	3747	2333	5253	8512	11730	14667	1.001	14000
SL	0.363	0.224	0.025	0.169	0.342	0.547	0.771	1.001	9500
SL.prior	0.404	0.228	0.03	0.206	0.406	0.603	0.779	1.001	19000
N2016	3296	687	2103	2847	3237	3669	4851	1.001	22000

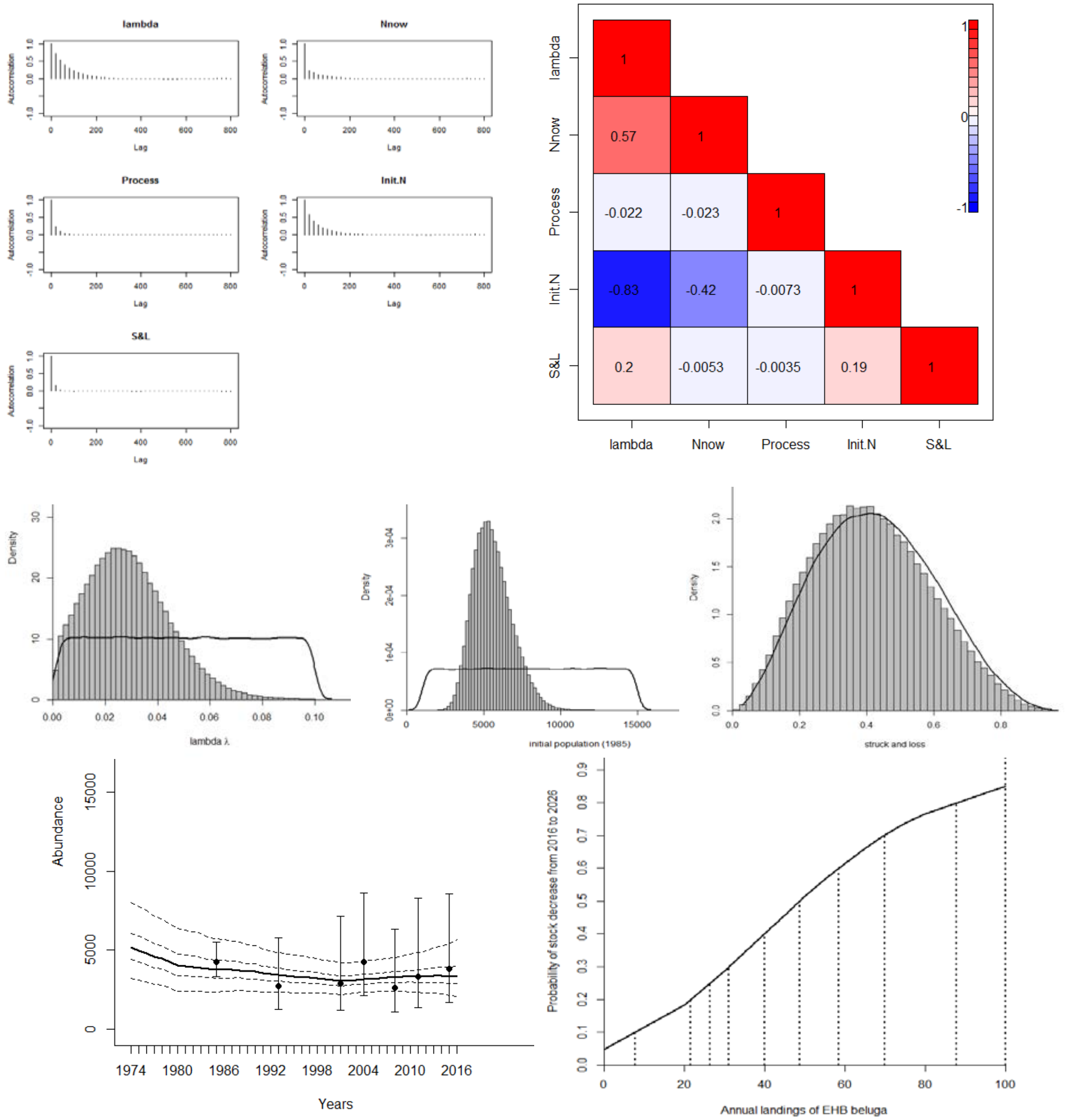
Appendix 2, Figure 2. Density dependent model with 1985 start date model showing level of autocorrelation (top left), cross correlation (top right), prior and posterior distributions and population trajectory. Surveys (±95%CL), median (solid), 25th, 75th quantile (inner dotted lines) and 95% CI (outer dotted lines). Sustainable yield estimate (for comparison with previous assessments).



Appendix 2, Table 3. Exponential model 1974 start date. Model priors and posteriors for parameters. The mean, standard deviation (SD), 2.5th , 25th, 50th, 75th and 97.5th quantiles are given for the following model parameters and their priors: maximum rate of increase (lambda), struck and lost (SL), and population size in 2016 (N2016), proportions of EHB belugas in each subzone. $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near 1 indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

	Mean	SD	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
K	10100	4207	5361	6738	8368	13094	19250	1.001	30000
K.prior	11012	5221	2431	6487	11024	15558	19552	1.001	30000
Deviance	115	3	111	113	115	117	122	1.001	30000
Lambda	0,031	0,016	-0,001	0,02	0,031	0,043	0,058	1.001	24000
Lambda.prior	0,025	0,02	-0,008	0,007	0,025	0,043	0,058	1.001	28000
pFALL	0,261	0,037	0,193	0,236	0,26	0,285	0,336	1.001	15000
pHSUB	0,171	0,023	0,128	0,156	0,171	0,186	0,219	1.001	30000
pNEHBFA	0,301	0,104	0,122	0,224	0,293	0,37	0,52	1.001	30000
pNEHBSP	0,108	0,021	0,071	0,094	0,107	0,122	0,152	1.001	30000
pSAN	0,044	0,023	0,011	0,027	0,04	0,057	0,1	1.001	12000
pSPRING	0,108	0,021	0,071	0,093	0,106	0,121	0,152	1.001	14000
pUBFA	0,261	0,036	0,192	0,236	0,26	0,285	0,334	1.001	30000
pUBSP	0,084	0,058	0,009	0,04	0,071	0,114	0,225	1.001	30000
Startpop	6842	1293	4791	5930	6663	7580	9878	1.001	30000
Startpop.prior	8509	3750	2331	5269	8488	11764	14681	1.001	8900
SL	0,4	0,171	0,106	0,271	0,39	0,52	0,75	1.001	30000
SL.prior	0,428	0,175	0,119	0,297	0,42	0,552	0,777	1.001	28000
N2016	3439	742	2091	2938	3408	3896	5000	1.001	30000

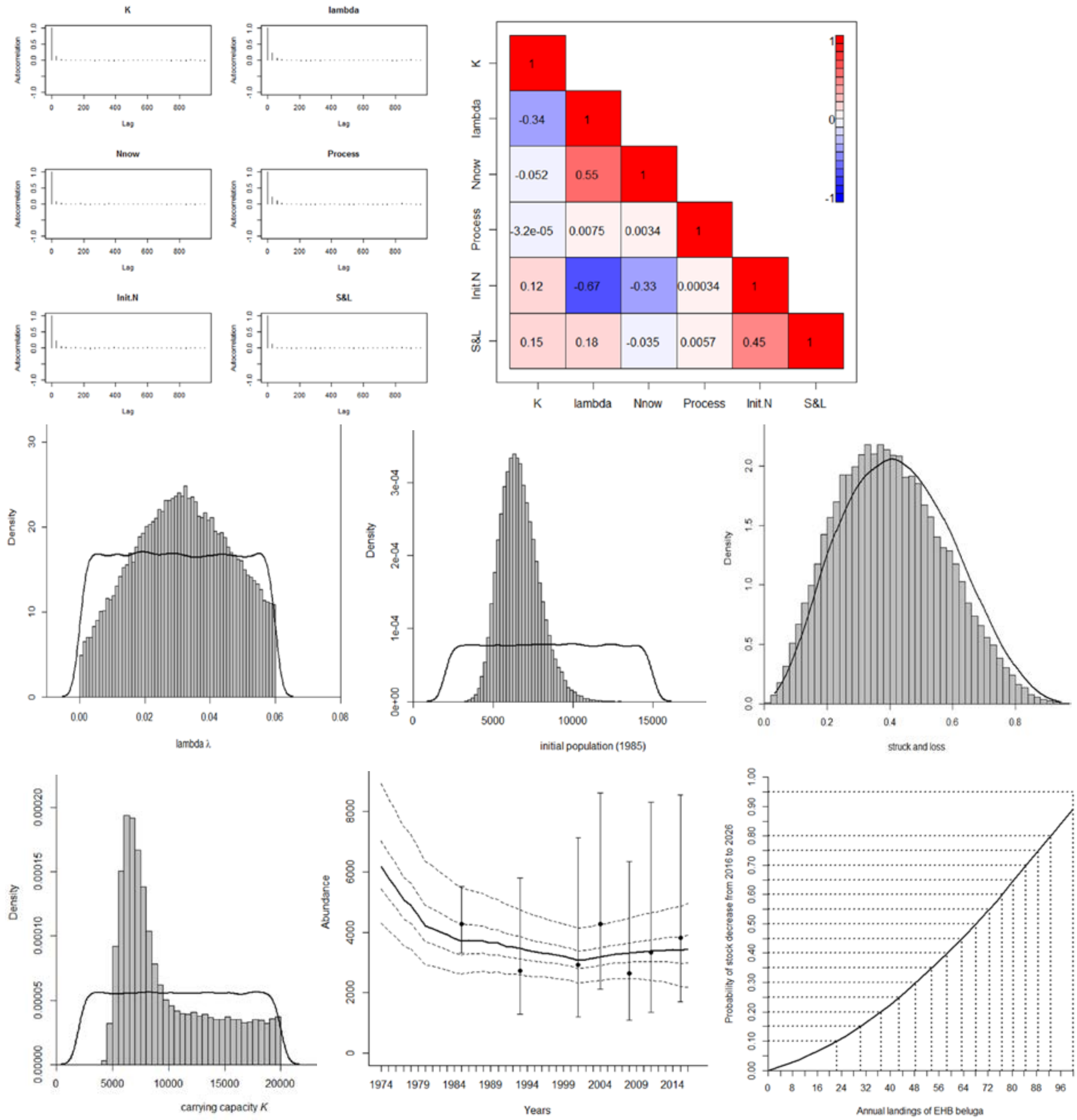
Appendix 2, Figure 3. Exponential model with 1974 start date model showing level of autocorrelation (top left), cross correlation (top right), prior and posterior distributions and population trajectory. Surveys (±95%CL), median (solid), 25th, 75th quantile (inner dotted lines) and 95% CI (outer dotted lines). Sustainable yield estimate (for comparison with previous assessments).



Appendix 2, Table 4. Density dependent model 1974 start date. Model priors and posteriors for parameters. The mean, standard deviation (SD), 2.5th , 25th, 50th, 75th and 97.5th quantiles are given for the following model parameters and their priors: carrying capacity (K), maximum rate of increase (lambda), proportion of EHB belugas in harvests from each subzone, struck and lost (S&L), and population size in 2016 (N2016). $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near 1 indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

	Mean	SD	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
K	10009	4195	5361	6692	8263	12994	19266	1.001	50000
K.prior	11002	5202	2449	6493	10997	15515	19551	1.001	50000
Deviance	115	3	111	113	115	117	121	1.001	50000
Lambda	0.032	0.015	0.004	0.021	0.032	0.044	0.058	1.001	36000
Lambda.prior	0.03	0.017	0.002	0.015	0.03	0.045	0.059	1.001	33000
pFALL	0.261	0.037	0.193	0.235	0.26	0.285	0.336	1.001	50000
pHSUB	0.171	0.023	0.128	0.155	0.17	0.187	0.219	1.001	50000
pNEHBFA	0.302	0.104	0.12	0.226	0.294	0.37	0.524	1.001	50000
pNEHBSP	0.108	0.021	0.071	0.094	0.107	0.122	0.152	1.001	50000
pSAN	0.044	0.023	0.011	0.027	0.04	0.057	0.099	1.001	50000
pSPRING	0.108	0.021	0.071	0.094	0.107	0.121	0.152	1.001	43000
pUBFA	0.261	0.037	0.193	0.235	0.26	0.285	0.336	1.001	50000
pUBSP	0.083	0.058	0.009	0.04	0.07	0.114	0.229	1.001	43000
Startpop	6724	1173	4769	5884	6594	7446	9339	1.001	21000
Startpop.prior	8477	3754	2319	5211	8484	11721	14662	1.001	39000
SL	0.401	0.171	0.106	0.272	0.39	0.52	0.75	1.001	26000
SL.prior	0.429	0.175	0.12	0.296	0.421	0.554	0.777	1.001	29000
N2016	3479	726	2183	2983	3439	3920	5029	1.001	32000

Appendix 2, Figure 4. Density dependent model with 1974 start date model showing level of autocorrelation (top left), cross correlation (top right), prior and posterior distributions and population trajectory. Surveys (±95%CL), median (solid), 25th, 75th quantile (inner dotted lines) and 95% CI (outer dotted lines). Sustainable yield estimate (for comparison with previous assessments).



APPENDIX 3: OUTPUTS FROM MODEL RUNS TO ESTIMATE WESTERN HUDSON BAY BELUGA ABUNDANCE

Appendix 3, Table 1. Output from fitting model to three aerial surveys of beluga abundance in Western Hudson Bay. Model priors and posteriors for parameters. Runs with maximum prior for K=100,000, and median SL prior=0.42 (top) and using median SL prior=0.13 (bottom). The mean standard deviation (SD). 2.5th . 25th. 50th. 75th and 97.5th quantiles are given for the following model parameters and their priors: carrying capacity (K), maximum rate of increase (lambda), struck and lost (SL), Starting population size (startpop) and population size in 2016 (N2016). $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near 1 indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

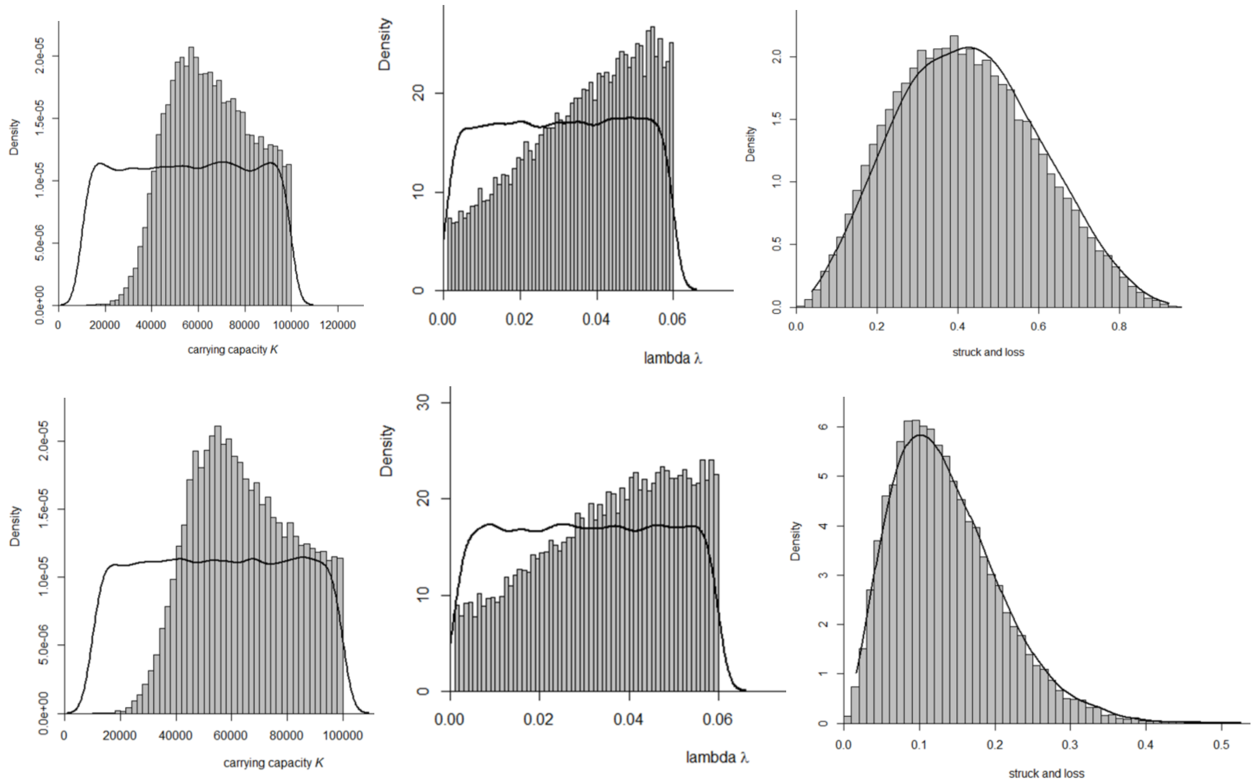
42% SL
K.prior 10,000-100,000

	Mean	SD	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
K	66279	17603	35704	52279	65240	80281	97767	1.001	9000
K.prior	55021	26047	12203	32442	55195	77384	97716	1.001	12000
deviance	67	2	63	65	67	68	71	1.001	25000
lambda	0.036	0.016	0.005	0.025	0.039	0.05	0.059	1.001	21000
lambda.prior	0.031	0.017	0.003	0.016	0.031	0.045	0.058	1.001	12000
startpop	50770	21052	21294	33555	46410	65711	95618	1.001	25000
startpop.prior	54900	25929	12112	32387	54693	77404	97589	1.001	23000
SL	0.416	0.174	0.113	0.284	0.407	0.537	0.768	1.001	25000
SL.prior	0.427	0.174	0.117	0.297	0.422	0.549	0.773	1.001	25000
N2016	48834	12927	25950	39669	47863	57261	76324	1.001	16000

13% SL
K.prior 1,000-100,000

	Mean	SD	2,50%	25%	50%	75%	97,50%	Rhat	n,eff
K	65020	18054	33926	50815	63422	79477	97787	1.001	21000
K.prior	55090	25917	12270	32731	55026	77629	97618	1.001	14000
deviance	66	2	63	65	66	68	71	1.001	9900
lambda	0.035	0.016	0.004	0.023	0.037	0.049	0.059	1.001	10000
lambda.prior	0.031	0.017	0.003	0.016	0.031	0.045	0.059	1.001	25000
startpop	49304	21360	19878	31942	44780	63523	95639	1.001	7200
startpop.prior	54835	26050	12191	32042	55012	77282	97772	1.001	25000
SL	0.134	0.07	0.031	0.082	0.123	0.176	0.3	1.001	12000
SL.prior	0.137	0.072	0.03	0.083	0.126	0.179	0.305	1.001	25000
N2016	49521	12952	26555	40363	48549	57763	77530	1.001	25000

Appendix 3, Figure 1. Prior and posterior distributions from fitting model to Western Hudson Bay estimates of abundance (1987-2015) and harvest data (1977-2015). Carrying capacity (K) had a maximum prior of 100,000. Model run had a median Struck and Lost (SL) prior of 0.42 (top row), or a median SL prior of 0.13 (bottom row).



Appendix 3, Table 2. Output from fitting model to three aerial surveys of beluga abundance in Western Hudson Bay. Model priors and posteriors for parameters . Runs with maximum prior for K=200,000 , and median SL prior=0.42 (top) and using median SL prior=0.13 (bottom). The mean. standard deviation (SD), 2.5th , 25th, 50th, 75th and 97.5th quantiles are given for the following model parameters and their priors: carrying capacity (K), maximum rate of increase (lambda), struck and lost (SL), and population size in 2016 (N2016). $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near 1 indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

42% SL
K.prior 10,000-200,000

	Mean	SD	2.5%	25%	50%	75%	97.5%	Rhat	n.eff
K	105007	47351	38720	63722	95946	144463	194366	1.001	25000
K.prior	104871	54888	14608	57208	104699	152125	195155	1.001	25000
deviance	66	2	62	65	66	68	71	1.001	25000
lambda	0,034	0,016	0,004	0,022	0,035	0,047	0,058	1.001	25000
lambda.prior	0,031	0,017	0,003	0,016	0,031	0,045	0,058	1.001	25000
startpop	44953	19378	19775	29964	40223	55746	92591	1.001	25000
startpop.prior	55172	25974	12166	32900	55166	77630	97738	1.001	25000
SL	0,417	0,173	0,114	0,287	0,408	0,539	0,769	1.001	25000
SL.prior	0,43	0,175	0,12	0,297	0,424	0,553	0,775	1.001	25000
N2016	54540	17571	27262	42436	52167	63809	96324	1.001	25000

13% SL
K.prior10,000-200,000

	Mean	SD	2,50%	25%	50%	75%	97,50%	Rhat	n,eff
K	103608	47513	37536	62089	94642	142809	194184	1.001	25000
K.prior	105916	55126	14850	58173	106487	154208	195296	1.001	18000
deviance	66	2	62	65	66	67	71	1.001	25000
lambda	0,032	0,016	0,004	0,02	0,033	0,046	0,058	1.001	25000
lambda.prior	0,031	0,017	0,002	0,016	0,031	0,045	0,058	1.001	11000
startpop	43382	19239	18422	28679	38953	53396	91948	1.001	25000
startpop.prior	54867	25942	12296	32402	54489	77453	97705	1.001	25000
SL	0,135	0,071	0,03	0,081	0,123	0,176	0,303	1.001	25000
SL.prior	0,136	0,071	0,029	0,082	0,125	0,177	0,301	1.001	16000
N2016	55371	17566	28479	43132	52821	64702	96853	1.001	16000

Appendix 3, Figure 2. Prior and posterior distributions from fitting model to Western Hudson Bay estimates of abundance (1987-2015) and harvest data (1977-2015). Carrying capacity (K) had a maximum prior of 200,000. Model run had a median Struck and Lost (SL) prior of 0.42 (top row), or a median SL prior of 0.13 (bottom row).