



Fisheries and Oceans
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Ecosystems and
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Sciences des écosystèmes
et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2026/058

Arctic Region

Estimated Population Abundance and a Limit Reference Point for Northern Hudson Bay Narwhal (*Monodon monoceros*)

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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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

[http://www.dfo-mpo.gc.ca/csas-sccs/
DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca](http://www.dfo-mpo.gc.ca/csas-sccs/DFO.CSAS-SCAS.MPO@dfo-mpo.gc.ca)



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ISSN 1919-5044

ISBN 978-1-100-00259-0 Cat. No. Fs70-5/2026-058E-PDF

Correct citation for this publication:

Watt, C.A., Zhao, S.T., Duporge, I., Tepker, J., and Marcoux, M. 2026. Estimated Population Abundance and a Limit Reference Point for Northern Hudson Bay Narwhal (*Monodon monoceros*). DFO Can. Sci. Advis. Sec. Res. Doc. 2026/058. iv + 26.

Aussi disponible en français :

Watt, C.A., Zhao, S.T., Duporge, I., Tepker, J., et Marcoux, M. 2026. Estimation de l'abondance de la population et point de référence limite pour le narval (*Monodon monoceros*) du nord de la baie d'Hudson. Secr. can. des avis sci. du MPO. Doc. de rech. 2026/058. iv + 28 p.

TABLE OF CONTENTS

ABSTRACT	iv
INTRODUCTION	1
METHODS	2
SURVEY	2
AVAILABILITY BIAS	3
POPULATION DYNAMICS MODEL	3
Priors	4
Parameter estimation and model diagnostics	5
Future projections and harvest scenarios	5
RESULTS	6
SURVEY	6
POPULATION DYNAMICS MODEL	6
LIMIT REFERENCE POINT	7
DISCUSSION.....	7
ACKNOWLEDGEMENTS	8
REFERENCES CITED.....	9
TABLES AND FIGURES.....	13
APPENDIX.....	22

ABSTRACT

Narwhal (*Monodon monoceros*) are an important subsistence harvest species for Inuit communities in Northern Hudson Bay (NHB). The NHB narwhal population has been assessed through aerial surveys from 1981 – 2018. In August 2024 a new photographic aerial survey was conducted. This survey was designed to repeat the 2018 survey design, as recommended by the Arviq Hunters and Trappers Organization in Nauyasat. The survey covered four key areas commonly used by narwhal: Wager Bay, Roes Welcome Sound, Repulse Bay, and the northern bays of Gore Bay and Lyon Inlet. After adjustment for instantaneous availability bias to account for whales not seen from the aircraft due to diving (adjustment factor $C_a = 3.16$ [CV 20.00%]), the estimated adjusted abundance is 5,800 (CV 19.54%; 95% CI 4,000 – 8,500 [rounded to the nearest hundred]) narwhal.

A population model was fit to five fully-adjusted aerial survey estimates and harvest data from 1951 – 2024 to assess the population trajectory and future population trends under various harvest scenarios. The selected model resulted in a 2025 population estimate of 10,400 (95% CI 7,700 – 13,800), and an estimated starting population of 8,000 (95% CI 2,900 – 13,500) in 1951. Using a risk-based model approach to estimate the probability of population decline over 10 years, the model predicted a 0, 20, 40, 50, 60, 80, and 100% probability of decline with annual harvest quotas of 0, 57, 74, 83, 91, 107, and 250 narwhal per year. The incorporation of the updated 2024 survey estimate and the adjustment of past survey estimates provides greater confidence in the model results and in the risk-based approach for assessing harvest levels. The estimated 2025 abundance and carrying capacity (K) were robust to changes in input model parameters, and thus a limit reference point was calculated using the model estimate of K. The limit reference point was calculated based on 30% of K and was estimated at 3,800 (95% CI 2,900 – 5,600). There is a 100% probability that the NHB narwhal abundance is above the LRP.

INTRODUCTION

Northern Hudson Bay (NHB) narwhal (*Monodon monoceros*) summer in NHB and migrate through Hudson Strait to spend winters in eastern Hudson Strait (Koski and Davis 1994) or southern Davis Strait (Richard 1991, Westdal et al. 2010) (Figure 1). NHB narwhal are spatially and genetically distinct from other narwhal populations in Canada and Greenland (Petersen et al. 2011, de Greef et al. 2024). They are a culturally important species for Inuit communities, with a long history of subsistence harvest (Richard and Pike 1993), and with little commercial harvest (Stewart 2008). Subsistence harvest of NHB narwhal occurs primarily near the community of Nauyasat (formerly Repulse Bay), and to lesser extents in Salluit, Kinngait, Igloodik, Chesterfield Inlet, Coral Harbour, Kimmirut, Rankin Inlet, and Whale Cove (Hudson and Watt 2020) (Figure 1). Monitoring of this narwhal population through aerial survey abundance estimates has been ongoing since the 1980s. The last aerial survey was conducted in 2018 and produced a population estimate of 19,232 (CV 27.8%, 95% CI 11,257 – 32,856) narwhal (Watt et al. 2020).

The NHB narwhal population trajectory has been modelled previously by Kingsley et al. (2013), and Biddlecombe and Watt (2022a). Kingsley et al.'s (2013) model had a high degree of associated uncertainty, which made a risk-based approach for recommending harvest levels unreliable until future surveys were performed (DFO 2012). Biddlecombe and Watt's (2022a) population model included the 2018 survey and long-term harvest information which made it possible to provide advice on recommended landed catch using a modelled abundance estimate. However, it was recommended that a longer time series of survey estimates would help to provide greater confidence with the estimated population abundance and trend (DFO 2022). As such, a new aerial survey was completed in the summer of 2024, which allows updating of the population model, potentially providing increased certainty in the ability of the model to assess the impact of various harvest levels on population dynamics.

Fisheries and Oceans Canada's Sustainable Fisheries Framework establishes a Precautionary Approach (PA) to fisheries management. The PA is a general philosophy to managing threats of serious or irreversible harm where there is scientific uncertainty (DFO 2006, 2009). The Government of Canada developed the Federal Framework for the PA to ensure that caution would be applied consistently across disciplines in the government, and this became policy in 2003 (DFO 2006, 2009). Under this policy, risk tolerance levels are defined (e.g., <5% risk of decline is very low risk, 25 – 50% is moderate risk, and 75 – 95% is high risk), and management is responsible for choosing their risk tolerance level (DFO 2009). In addition to assessing risk of decline, for stocks for which sufficient data are available, reference points can be developed. The limit reference point (LRP) is the point below which serious harm may occur to the stock (DFO 2009). There is limited flexibility in management measures when a stock is below the LRP as the priority is to keep mortality as low as possible for rebuilding plans (DFO 2006, 2009). For management of marine mammal stocks in Canada, a framework for assessing data-rich and data-poor stocks was developed for Atlantic seals (DFO 2025). Under this framework, stocks which are data-poor are recommended to be assessed using a potential biological removal (PBR) approach; when multiple abundance estimates are available and it is possible to model the population dynamics, PBR can be calculated using the modelled estimate of abundance, which is more stable than taking any single abundance estimate (DFO 2025). The model-based approach can also be used to assess risk of varying harvest levels to generate sustainable harvest advice (Biddlecombe and Watt 2022a; Van de Walle et al. 2025). If a stock moves to data-rich and the model is robust to its various assumptions, a LRP can be generated. In this case, the modelled carrying capacity (K) should be used as the reference abundance levels and the LRP can be calculated as 30% of K (DFO 2025).

The objective of this study is to provide 1) an updated estimate of abundance for the NHB narwhal population based on the 2024 survey, 2) advice on sustainable narwhal harvests using the PBR method and the probability that narwhal abundance will decline in 10 years under a range of harvest scenarios, and 3) recommendations and conclusions related to the development of a LRP for the sustainable management of NHB narwhal.

METHODS

SURVEY

The 2024 study area and survey coverage was designed to replicate the areas flown in the 2018 aerial survey which was recommended by the Arviq Hunters and Trappers Organization (HTO) in two in-person meetings leading up to the survey (in January and August 2024). The survey area was divided into four strata: Wager Bay, Roes Welcome Sound, Repulse Bay, and North Bays, which included Gore Bay and Lyon Inlet (Figure 1). In Wager Bay systematic parallel transects, spaced 10 km apart, were used in the 2018 survey to increase coverage compared to the 2011 survey, as recommended by the Arviq HTO. In Repulse Bay and North Bays strata a systematic survey design with a random start was also used with transects 13 km and 5.6 km apart, respectively, to provide uniform coverage probability (Buckland et al. 2001). In Roes Welcome Sound, we used a 15 km zigzag design to maximize coverage and reduce travel time between transects (Buckland et al. 2001).

Photographic surveys were conducted in all strata. The photographic surveys were flown at a target altitude of 2,000 ft (610 m) and speed of 110 knots (204 km/h). A Nikon D850 camera, equipped with a 25 mm lens, mounted at the rear of the aircraft and directed straight down, with the longest side perpendicular to the track-line, was used to photograph continuously along the predefined transect lines. To georeference the photographs the cameras were linked via Bluetooth to a GPS receiver (Bad Elf GPS Pro+) using a module accessory (Foolography Unleashed D200+ Bluetooth Module). The camera was also connected to a laptop computer to control exposure settings, photograph interval, and to save high resolution JPEG and NEF RAW photographs to the computer's hard drive. At the target altitude of 2,000 ft, the ground area covered by each photograph was 875.4 m x 585.2 m. A photographic interval of 6 seconds was used to target ~20% overlap between consecutive photographs along each transect.

Photographs were examined for narwhal using Mobius Artificial Intelligence autodetection algorithm (hereafter referred to as Mobius) with a human-in-the-loop methodology (Boulent et al. 2023), with precision and recall estimated at 79.3% and 95.6% from a larger dataset for the 2023 High Arctic Cetacean Survey (see Marcoux et al. In press). All detections of NHB narwhal were validated by J. Tepker and C. Watt.

For photographs with a proportion masked by sun glare, Mobius created a shapefile to cover the glare and did not search for narwhal within the glare area. Overlapping sections between subsequent photographs were cropped from the first photograph and not included in the final analysis. Areas of land and glare were also subtracted from the total readable area of each photograph.

A strip transect analysis of the individual narwhal detections from the photographs was performed. Narwhal density was calculated by dividing the summed narwhal count by the summed area of readable water on the transects within the stratum. Density was then multiplied by the stratum area to obtain near-surface abundance estimates (equation 1):

$$\hat{N}_{surface} = A_{stratum} \times \frac{\sum_{i=1}^I \hat{N}_{count_i}}{\sum_{i=1}^I A_{transect_i}} \quad (\text{equation 1})$$

where $\hat{N}_{surface}$ is the total number of narwhal detected at the surface in the stratum, $A_{stratum}$ is the area covered by the survey stratum, and I is the number of photographs per survey.

The number of narwhal detected near or at the surface in each photograph was then adjusted for the instantaneous availability bias, C_a described below.

An adjusted abundance estimate $\hat{N}$ was calculated using equation 2:

$$\hat{N} = C_a \times \hat{N}_{surface} \quad (\text{equation 2})$$

The total variance for each strata was calculated by adding the variance of the encounter rate $var(E_n)$ and of the availability bias correction factor $var(C_a)$ following the delta method (Buckland et al. 2001; equation 3):

$$var(\hat{N}) = \hat{N}^2 \times \left\{ \frac{var(E_n)}{(E_n)^2} + \frac{var(C_a)}{(C_a)^2} \right\} \quad (\text{equation 3})$$

The variance of the encounter rate was calculated following S2 in Fewster et al. (2009).

The entire survey was replicated and therefore the final abundance estimate was obtained by taking the average weighted by the variance of the two surveys.

AVAILABILITY BIAS

Near-surface abundance estimates were also adjusted to account for narwhal that were diving and therefore unavailable for observation (i.e., availability bias). Experiments with narwhal shaped models showed that narwhal could be seen and identified by observers at depths up to 2 m but not deeper (Richard et al. 1994), and this depth threshold for visibility has been used to adjust for availability bias in previous narwhal surveys (Richard et al. 2010, Asselin et al. 2012). However, there is uncertainty regarding the maximum depth that narwhal can be seen in a photograph or by observers in a plane, and this should contribute to the variance in the availability bias adjustment factor (NAMMCO-JCNB Joint Working Group 2021).

Availability bias was estimated using data from nine narwhal equipped with satellite-linked time-depth recorders (STDR) near the community of Nauyasat in 2006 and 2007. The proportion of time narwhal spent within 2 m of the surface in the month of August was estimated as 0.316 (CV 0.053) (Westdal et al. 2013) resulting in an instantaneous availability bias of 3.16. The CV on the availability bias, which factors in uncertainty in the depth to which whales can be seen, was estimated to be 20% (NAMMCO-JCNB Joint Working Group 2021) and that is the CV we used for the availability bias estimate in this study.

POPULATION DYNAMICS MODEL

A stochastic stock production model with density dependence acting on the population growth rate was fit using Bayesian Markov Chain Monte Carlo (MCMC) methods. This model utilizes aerial survey and harvest data to estimate population dynamics and was previously used for modelling abundance of the NHB narwhal stock (Biddlecombe and Watt 2022a). A hierarchical state-space model separated two stochastic processes, observation and state processes.

The state process was defined using a discrete formulation of the Pella and Tomlinson model (Pella and Tomlinson 1969, Innes and Stewart 2002), which describes the change in true population size over time. The population size at time t is a multiple of the previous year's population with harvest removals deducted.

$$N_t = N_{t-1} * \left(1 + (R_{max}) * \left(1 - \left(\frac{N_{t-1}}{K} \right)^\theta \right) \right) * \varepsilon_p - R_t \quad (\text{equation 4})$$

Where: R_{max} is the maximum growth rate or rate of population increase,
 K is the environmental carrying capacity,
 θ defines the shape of the density-dependent function (theta),
 ε_p is a stochastic term for the process error,
 R_t are the harvest removals for that year, calculated as reported catches, C_t , that are corrected for the proportion of animals that were struck and lost, $S\&L$:

$$R_t = C_t \cdot (1 + S\&L) \text{ (equation 5)}$$

The observation process links observed data to true population size. We determined survey error by using a multiplicative error (ε_{S_t}) term to link true population size (N_t) to aerial survey estimates (S_t).

$$\ln(S_t) = \ln(N_t) + \varepsilon_{S_t} \text{ (equation 6)}$$

The model was fit using harvest data from 1951 – 2024 (Table 1) and adjusted aerial survey data from 1982, 2000, 2011, 2018, and 2024 (Table 2) to estimate population dynamics for 1951 – 2024. Harvest data was available starting in 1911, but these data were too temporally sparse before 1951 to be included in the model (Stewart 2008). Surveys from 1980 and 2000 were adjusted to account for differences in survey design and analysis, and to incorporate an adjustment for perception bias, by multiplying them by 2.29 and 2.56, respectively (Asselin and Ferguson 2013; Biddlecombe and Watt 2022a; Table 2).

Priors

Prior distributions for the random variables included in the model were informed by knowledge of the species, previous cetacean population models (i.e., Wade 1998, Marcoux and Hammill 2016, Biddlecombe and Watt 2022a), and initial exploratory runs of the model. Maximum population growth rate (R_{max}) for cetaceans is often assumed to be 0.04 (Wade 1998), but we allowed the final model to estimate R_{max} using a uniform distribution ranging from 0.01 – 0.07 as was done in Biddlecombe and Watt (2022a) (Table 3). Parameters were explored with multiple priors (see Table A1) before a final model was assessed. In the final model the shaping parameter θ (theta) was allowed to vary between one and five (reflecting maximum productivity occurring between 50 – 70% of K) (Table 3). Starting population size was assigned a uniform prior distribution from 1,000 to 20,000 and the final model was restricted to only explore possibilities where start population was 20 – 100% of K (Table 3); K was assigned a uniform distribution with a minimum of 5,000 and a maximum of 20,000 (Table 3).

Naujaat is the primary harvest community for NHB narwhal, thus, we based our $S\&L$ prior on the loss rate correction values for Naujaat in 1999 – 2005 (Richard 2008). Mean loss rate correction in Naujaat was 0.25, which we used to assign a moderately informative prior following a $\text{beta}(3.5, 10)$ distribution, with a median of 0.25, and quartiles of 0.17 and 0.33.

The stochastic process error term had a log-normal distribution with a zero location parameter. The precision parameter for process error was assigned an informative $\text{gamma}(1.5, 0.00001)$ distribution. The resulting process error term had quartiles of 0.998 and 1.002. This reflects the fact that narwhal are a long-lived species, and therefore stock dynamics are expected to have low inter-annual variability.

Following an update in Biddlecombe and Watt (2022a), uncertainty associated with aerial surveys was incorporated into model fitting by informing the prior distribution for survey error. The formulation of the prior for the survey error was weighted by the standard error (SE) for each of the abundance estimates from the five surveys incorporated in the model. The survey error term was given a lognormal distribution with a zero location parameter. The precision

parameter for survey error was specific to each survey year using a precision value calculated from each SE independently.

Parameter estimation and model diagnostics

A Gibbs sampler algorithm implemented in JAGS (Plummer 2003) was used to obtain posterior estimates for the parameters included in the model. Results were examined in RStudio (R Core Team 2022, version 4.2.2) using packages *R2jags* (Su et al. 2024, version 0.8-9) and *coda* (Plummer et al. 2024, version 0.19-4). We used a MCMC chain simulation method which required us to check the convergence of sample values in each parameter to a stationary distribution. Model convergence, mixing, and autocorrelation within parameters were investigated in initial runs of the model code.

Initial runs of the five models used three chains, and 10,000 iterations after a burn in of 6,000, while the final model was run using five chains, and 100,000 iterations after a burn in of 60,000, with thinning maintained at 30. Geweke's Diagnostic was used to test similarity between different sections of the chains and Geweke plots were visually inspected to test for mixing within each chain (Geweke 1996). Convergence between chains was validated by comparing the width of the 80% credible interval of the chains pooled with the mean widths of the 80% credible interval for each of the chains individually using the Brooks-Gelman-Rubin (BGR) diagnostic test (Brooks and Gelman 1998).

Future projections and harvest scenarios

We estimated PBR to provide sustainable harvest recommendations. Unlike a risk-based approach, PBR does not focus on probabilities of increase or decline, but rather its built-in management objective is to quantify the maximum number of animals that can be removed from a marine mammal stock while still allowing the stock to reach or stay at its Maximum Net Productivity Level (MNPL) after 100 years (Wade 1998). PBR is the default method for estimating sustainable yield for stocks that are considered data poor (DFO 2025). PBR was calculated using a recovery factor (F_R) of 1, following guidelines for a population > 70% of K (DFO 2025).

The equation for PBR is:

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

Where:

N_{min} is the estimated population size using the 20th-percentile of the posterior distribution resulting from the model or the 20th-percentile of the log-normal distribution (Wade 1998) of the aerial survey estimate,
 R_{max} is the maximum rate of population increase. The default value for cetaceans is 0.04, and
 F_R is a recovery factor (between 0.1 and 1).

As explained below, we used the 2025 population estimate from the model to calculate the N_{min} value.

PBR estimates total removals from a population, which includes animals that are harvested, those that are caught but not landed, unreported harvests, and other sources of human caused mortality. Therefore, the Total Allowable Landed Catch (TALC) is:

$$TALC = PBR / (1 + S\&L)$$

where $S\&L$ is estimated from the model results.

To predict stock trajectory and future sustainable yield of this population, we also projected the model 10 years into the future under different harvest scenarios ranging from 0 – 200 narwhal landed annually, in intervals of 50. The current quota for NHB narwhal is 147 narwhal per year. The probability of population decline over 10 years was presented as a risk-based approach for assessing harvest levels; often used for populations that are considered data rich (DFO 2025).

Finally, we estimated the LRP for NHB narwhal. The LRP was calculated based on 30% of the modelled K following recommendations for marine mammal management in Canada (DFO 2025).

RESULTS

SURVEY

Photographic aerial surveys of four strata were flown from August 13 – 19, and conditions were good throughout the survey period (Table 4; Table A2). The estimated abundance from survey 1 and 2 was 5,394 (CV 31.50%) and 6,220 (CV 24.82%) respectively. Taking an average of the two surveys weighted by the CV provides a final abundance of 5,847 (CV 19.54%; 95% CI 4,001 – 8,545).

POPULATION DYNAMICS MODEL

Variables K, population size in 2025 (N_{2025}), process error, initial population size (N_{1951}), and S&L converged for all chains. Autocorrelation was relatively low in most variables, and the BGR statistics were close to 1 for all variables, indicating convergence of each chain and each model (see Figure A1; Table A3). However, there was some autocorrelation in start population, and this was not improved with increased thinning or number of burn ins. In early model considerations, multiple runs with varied priors were performed and the model was robust to changes in priors (Figure 2; Table A1). The selected model is presented here.

The model describes population abundance over time, with the latest aerial survey estimate being the lowest in the time series (Figure 3). The model posterior distributions resulted in a median maximum growth rate (R_{max}) of 0.037, the median K was estimated as 12,830, and θ was estimated as 1.97 (Figure A2). The median starting population in 1951 was estimated as 7,955 (95% CI 2,889 – 13,457), and N_{2025} was estimated as 10,397 (95% CI 7,701 – 13,813) (Figure 3; Table A3).

For a risk-based approach to assessing harvest levels, the population trajectories for six harvest scenarios were plotted using the model results (Figure 3). These trajectories determined that after 10 years, the probability of population decline was 0, 20, 40, 50, 60, 80, and 100% with annual TALC of 0, 57, 74, 83, 91, 107, and 250 narwhal per year (Table 5, Figure 4). The average takes over the last 10 years were 112 narwhal (Table 1) and this corresponds to an estimated 87% probability of decline in the NHB narwhal population in ten years.

The 2025 modelled population estimate was used in the PBR calculation because there was more confidence in the model estimate than in the individual aerial survey estimates and based on the previous approach used in the NHB narwhal assessment (Biddlecombe and Watt 2022a). Based on modeled abundance, a recovery factor F_R of 1, and a default maximum growth rate of 4% per year, the PBR threshold was 183 narwhal. TALC was calculated as 147, using the model estimate for S&L (0.25) and the 2025 abundance estimate.

LIMIT REFERENCE POINT

The LRP was calculated as 30% of the model estimated K (DFO 2025) resulting in a LRP of 3,849 (95% CI 2,880 – 5,646) narwhal.

DISCUSSION

In this study, we used Bayesian methodology to fit a stochastic Pella-Tomlinson model (Pella and Tomlinson 1969, Innes and Stewart 2002) to narwhal aerial survey data (1982 – 2024) and a time series of catch history data (1951 – 2024). The median estimated start population (in 1951) was 7,955 and has remained relatively steady over time to a 2025 estimate of 10,397 narwhal. Narwhal maximum population growth can vary, depending on the vital rates of the population (Kingsley 1989). In our model $R_{\max}$ was estimated as 0.04, which is the commonly assumed $R_{\max}$ for cetaceans ($\lambda_{\max} = 1.04$) (Wade 1998). However, the posterior distributions for theta, lambda, and S&L were not updated (Table A3) and therefore, it is recommended that these parameter estimates not be used outside of this analysis. In addition, the issues with autocorrelation for start population may reduce confidence in the model estimates.

This is the first time the NHB narwhal population has been surveyed using photographic survey methods, which reduces the strip width. Previous studies of narwhal surveys conducted using photographic methods found no significant difference with observer based aerial surveys (Bröker et al. 2019), and estimates from narwhal in Eclipse Sound were similar using the two methods (Doniol-Valcroze et al. 2015; Marcoux et al. 2019). However, photographic surveys of beluga whales estimated a lower abundance than visual surveys once the visual surveys were adjusted for perception and availability biases (St-Pierre et al. 2023). A significant benefit of using photographic surveys in the NHB region where narwhal and beluga whales overlap in their distribution (Watt et al. 2020) is the ability to assess photographs for species identification. In the 2018 visual survey there was unquantified uncertainty on the species when whales were far from the transect line; however, these sightings were still included in the narwhal abundance estimate (Watt et al. 2020). In the photographic survey species identification can be assessed by multiple readers to reach consensus if there is uncertainty. In this survey, all narwhal identified by observers in the aircraft were found within the photographs at the end of each day after the flights; however, a comparison of visual versus photographic survey methods was not conducted here.

The aerial survey estimate was significantly lower in 2024 compared to the estimate in 2018. The survey design did not change as per the recommendation of the Arviq HTO in two in-person meetings that occurred prior to the survey (in January and August 2024). The 2018 survey was conducted over 11 days as a result of poor weather conditions and only the North Bays strata was repeated. The 2024 survey was conducted over seven days during good survey weather conditions and all strata were repeated in that timeframe. We strove to conduct the survey in the shortest amount of time possible to reduce the chances of larger scale directional narwhal movements. In addition, the survey was timed to occur within the period where the narwhal are known to aggregate in the area to avoid missing whales occurring outside of the surveyed region; during the 2024 survey there were no sightings on the edges of the surveyed regions suggesting the survey extent was sufficient (Figure 1). The timing of the survey was similar in 2018 (August 3 – 14) and 2024 (August 13 – 19), with the goal of overlapping the residency period for narwhal in the region based on migratory information from satellite telemetry data (Westdal et al. 2010), information provided by the Arviq HTO, and informed by previous harvest statistics (Hudson and Watt 2020). Killer whales (*Orcinus orca*) can change the behaviour of narwhal (Breed et al. 2017), and it was reported to C. Watt that four killer whales were seen at

the southern end of Lyon Inlet on August 12, 2024 prior to the survey. No killer whales were sighted by the surveyors during the survey.

The model shows that the NHB narwhal population has effectively remained stable over the time series from 1951 – 2024. Previous assessments suggested there was confidence in the modelled population estimates and that these estimates could be used to assess recommended harvest levels either using the risk-based approach or via PBR (DFO 2022). The preferred approach for informing the NHB narwhal harvest quota depends on confidence in stock assessment information and management objectives. Using PBR (typically for data-poor stocks), the TALC was 147. Using a risk-based model approach to estimate the probability of population decline over 10 years, the model predicted a 0, 20, 40, 50, 60, 80, and 100% probability of decline with annual TALC of 0, 57, 74, 83, 91, 107, and 250 narwhal per year, respectively, in the NHB narwhal population in ten years. A 5% probability of decline under the risk-based approach is achieved at a harvest level of 21 narwhal annually. In the last 10 years, the average annual narwhal harvest was 112 narwhal per year. The last assessment suggested takes of 112 narwhal per year would result in a ~65% chance of decline and this assessment suggests that chance has increased to 87%. Although the population has been largely stable from 1951-2025, there has been a general trend of increasing harvest (Table 1).

We calculated the LRP based on 30% of K as recommended by DFO (2025). For comparison, the previously modelled estimate of K was 16,779 (95 % CI 11,378 – 28,936) (Biddlecombe and Watt 2022a), and this would result in an estimated LRP of 5,034 (95% CI 3,413 – 8,681). Although this estimated LRP is higher, the confidence intervals overlap, and the confidence interval on the 2025 modelled estimate is smaller. We suggest the more recent K be used since, in addition to another survey estimate adding confidence to the model, environmental changes are occurring at an unprecedented rate in the Arctic (e.g., Rantanen et al., 2022) and these changes may be impacting K. For example, incorporation of environmental variables of sea ice and sea surface temperature in a population model for beluga whales (*Delphinapterus leucas*) in Cumberland Sound resulted in a reduction in K (Biddlecombe and Watt 2022b). The impact changing environmental variables may have on K for NHB narwhal was not evaluated here.

The addition of the 2024 survey estimate extends the time series of abundance estimates and provides more information for modeling the population dynamics for NHB narwhal. The risk-based method assesses the probability of population decline from the current abundance whereas PBR strives to keep a population at or above its MNPL (Wade 1998), which can allow for decline if the population is already above that level. With the addition of the 2024 survey, there is more certainty associated with the model results from this study compared to previous NHB narwhal population models (Kingsley et al. 2013, Biddlecombe and Watt 2022a). Sustainable harvest levels can be informed using population modelling with the risk-based approach or via PBR depending on management objectives. The LRP calculated from the modeled K, which was robust to changes in prior parameters, suggests the probability that the NHB narwhal population is above the LRP is 100%.

ACKNOWLEDGEMENTS

We thank the Arviq Hunters and Trappers Organization, surveyors Philip Angotautok, Isaki Kripanik, Annie Angotualuk, Daniel Tuktudjuk, John-Ell Tinashlu, and Patrick Putulik. Thanks also to Ken Borek pilots T. McKerral, C. Raduy, L. Owen, and J. Lyon. Thanks to V. Williams for providing harvest information and hunters for reporting their harvests. We thank the late M. Kingsley for developing the initial population model, T. Doniol-Valcroze, A. Mosnier, M. Hammill, and R. Hobbs for model improvements. Thank you also to reviewers for providing comments that improved the final version of this document.

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TABLES AND FIGURES

Table 1. Reported harvests from all communities that harvest Northern Hudson Bay narwhal from 1951 – 2024. Data for 1951 – 1953 are from Stewart (2008); data for 1953 – 2024 are from Mansfield et al. (1975), Kemper (1980), Strong (1989), and DFO harvest statistics 1988 – 2017 (Hudson and Watt 2020) and unpublished data from DFO Resource Management (2018-2024).

Year	Reported catch	Year	Reported catch	Year	Reported catch
1951	0	1985	16	2019	82
1952	0	1986	7	2020	184
1953	0	1987	16	2021	115
1954	0	1988	38	2022	122
1955	0	1989	16	2023	184
1956	0	1990	17	2024	130
1957	175	1991	36	-	-
1958	35	1992	20	-	-
1959	15	1993	14	-	-
1960	0	1994	6	-	-
1961	0	1995	14	-	-
1962	0	1996	45	-	-
1963	0	1997	0	-	-
1964	0	1998	28	-	-
1965	23	1999	157	-	-
1966	100	2000	45	-	-
1967	73	2001	108	-	-
1968	2	2002	67	-	-
1969	0	2003	43	-	-
1970	0	2004	120	-	-
1971	5	2005	86	-	-
1972	14	2006	94	-	-
1973	1	2007	88	-	-
1974	0	2008	29	-	-
1975	0	2009	118	-	-
1976	8	2010	103	-	-
1977	8	2011	92	-	-
1978	6	2012	56	-	-
1979	31	2013	115	-	-
1980	26	2014	96	-	-
1981	41	2015	47	-	-
1982	23	2016	73	-	-
1983	11	2017	113	-	-
1984	27	2018	68	-	-

Table 2. Estimates of Northern Hudson Bay narwhal abundance from aerial surveys in their summering range used in population dynamics modeling. Total Estimates are the values calculated from the surface estimates using an availability bias adjustment factor (C_a) of 3.16 (CV 0.20), and the coefficient of variation (CV) of the total estimate. Fully Adjusted Estimates have been adjusted for both perception and availability bias for visual surveys and instantaneous availability bias for photographic surveys. CDS = conventional distance sampling, MRDS = mark-recapture distance sampling.

Survey Year	Total Estimate	CV	Observation Method	Analysis Method	Adjustment Ratio	Fully Adjusted Estimate	Citation
1982	2,906	0.52	Systematic visual	600 m Strip	2.56	7,440	Richard 1991, Asselin and Ferguson 2013
2000	4,978	0.40	Systematic visual	CDS	2.29	11,401	Bourassa 2003 (CV in Richard 2008), Asselin and Ferguson 2013
2011	12,485	0.26	Systematic visual	MRDS	1.00	12,485	Asselin et al. 2012
2018	19,232	0.28	Systematic visual	MRDS	1.00	19,232	Watt et al. 2020
2024	5,847	0.20	Systematic photographic	438 m Strip	1.00	5,847	This paper

Table 3. Prior distributions, parameters, and hyper-parameters used in the final Northern Hudson Bay narwhal population model. “dist.” denotes a hyper-parameter with its own prior distribution.

Parameters	Notation	Prior distribution	Hyper-parameters	Values
Survey error (t)	ε_{st}	<i>Log-normal</i>	μ_s	0
			τ_s	<i>dist.</i>
Precision (survey)	τ_s	*	-	-
Process error (t)	ε_{pt}	<i>Log-normal</i>	μ_p	0
			τ_p	<i>dist.</i>
Precision (process)	τ_p	<i>Gamma</i>	α_p	1.5
			β_p	0.00001
Density dependence shape function	θ	<i>Uniform</i>	N_{upp}	3
			N_{low}	1
Struck-and-lost	<i>S&L</i>	<i>Beta</i>	α_{sl}	3.5
			β_{sl}	10
Initial population	N_{1951}	<i>Uniform</i>	N_{upp}	100% K
			N_{low}	20% K
Carrying capacity	K	<i>Uniform</i>	N_{upp}	20,000
			N_{low}	5,000
Max. growth rate	R_{max}	<i>Uniform</i>	N_{upp}	0.07
			N_{low}	0.005

* weighted by the standard error from each survey

Table 4. Survey coverage for each stratum of the 2024 survey of Northern Hudson Bay narwhal. The total area (km²) of the stratum, the number of transects, area covered by photos (km²), encounter rate (ER, narwhal/km²), CV of encounter rate (CV_{ER}), surface estimate, adjustment for availability bias (C_a) and CV (CV_{C_a}), as well as fully adjusted abundance (N[^]) and CV of abundance (CVN[^] (%)) are presented. Total abundance is the average of the individual survey abundances weighted by the CV.

Survey Stratum	Date	Area	# Transects	Area covered by photos	# Unique narwhal	ER	CV _{ER}	Surface estimate	C _a	CV _{C_a}	N [^]	CVN [^] (%)	95% CI
¹ Roes Welcome Sound	13 Aug	4,791	9	286	0	-	-	0	3.16	0.20	0	-	-
¹ Wager Bay	14 Aug	2,869	13	222	14	0.063	0.461	181	3.16	0.20	573	-	-
¹ North Bays	16 Aug	1,254	17	148	31	0.210	0.308	263	3.16	0.20	831	-	-
¹ Repulse Bay	15-16 Aug	13,815	15	745	68	0.0912	0.361	1261	3.16	0.20	3,990	-	-
-	-	-	-	-	-	-	-	-	-	-	5,394	31.50	-
² Roes Welcome Sound	17-18 Aug	4,791	9	289	11	0.0381	0.766	182	3.16	0.20	577	-	-
² Wager Bay	16 Aug	2,869	13	205	34	0.166	0.484	476	3.16	0.20	1,506	-	-
² North Bays	18 Aug	1,254	17	159	22	0.139	0.514	174	3.16	0.20	549	-	-
² Repulse Bay	18-19 Aug	13,815	15	792	65	0.0821	0.271	1134	3.16	0.20	3,587	-	-
-	-	-	-	-	-	-	-	-	-	-	6,220	24.82	-
TOTAL	-	-	-	-	-	-	-	-	-	-	5,847	19.54	4,001-8,545

Table 5. Probability (P) that the NHB narwhal population, subjected to different levels of annual landed catch, will decline from the modelled 2025 population abundance estimate after 10 years of harvest.

P (%)	Landed Catch
0	0
5	21
10	43
20	57
30	66
40	74
50	83
60	91
70	100
80	107
90	116
95	124
100	250

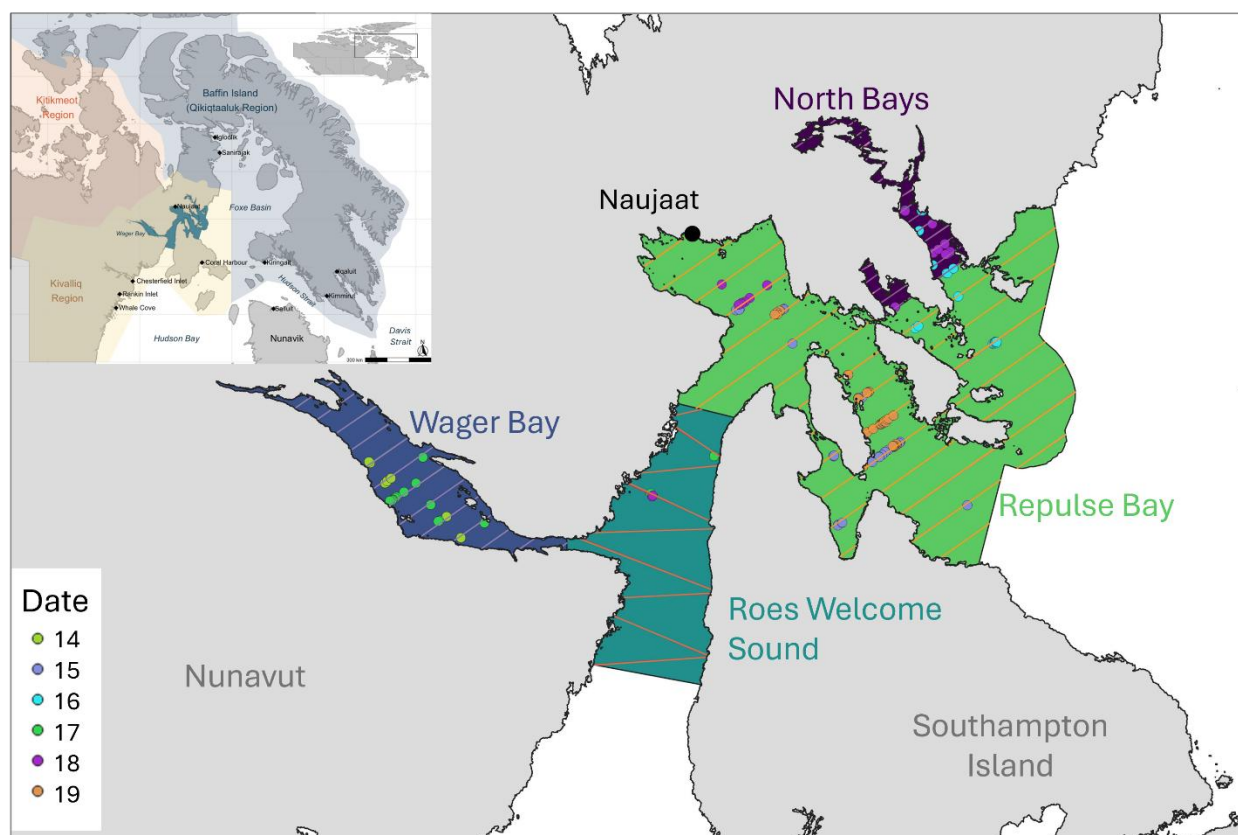


Figure 1. Map indicating narwhal detections (points) on transect lines in four strata surveyed in the 2024 Northern Hudson Bay narwhal survey. Different colored points indicate different days in August the detections were made.

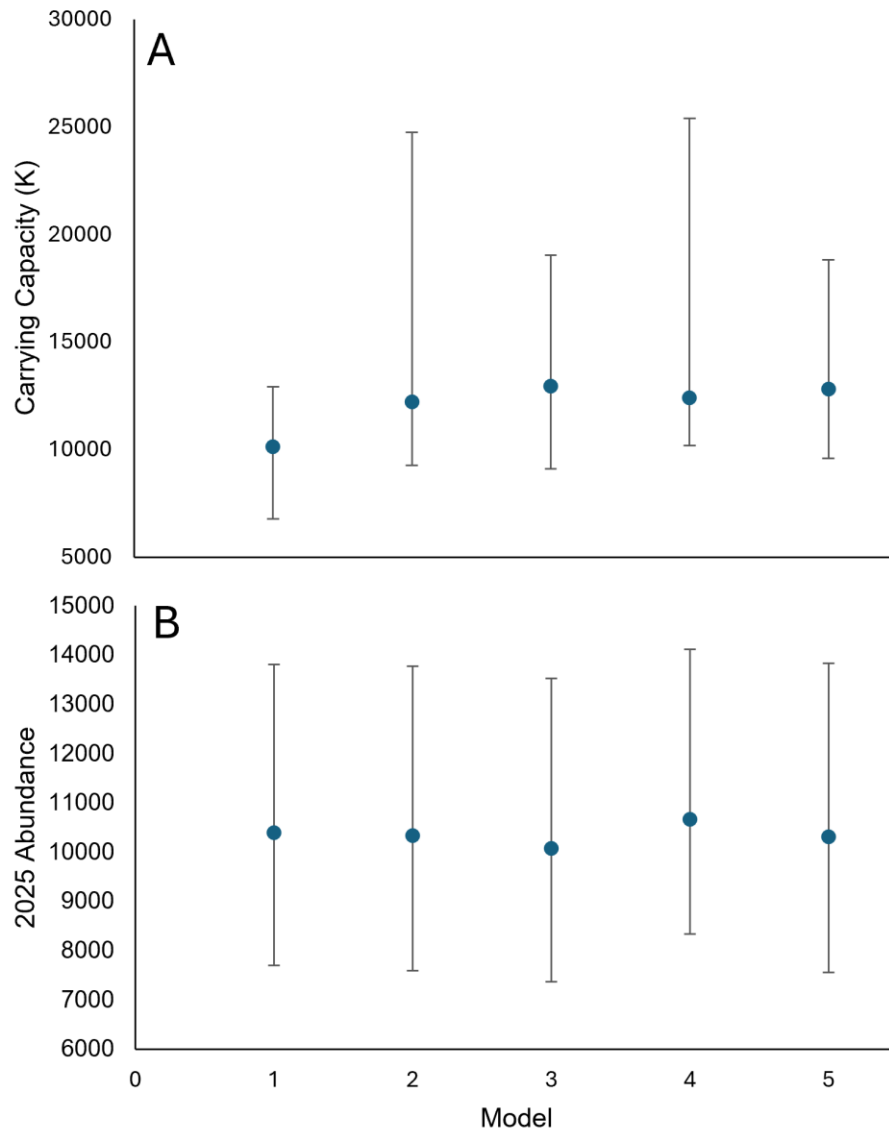


Figure 2. Sensitivity of median A) carrying capacity and B) 2025 abundance ($\pm$ 95% CI) to the hyper-parameters used in prior distributions for the Northern Hudson Bay narwhal population (see Table A1).

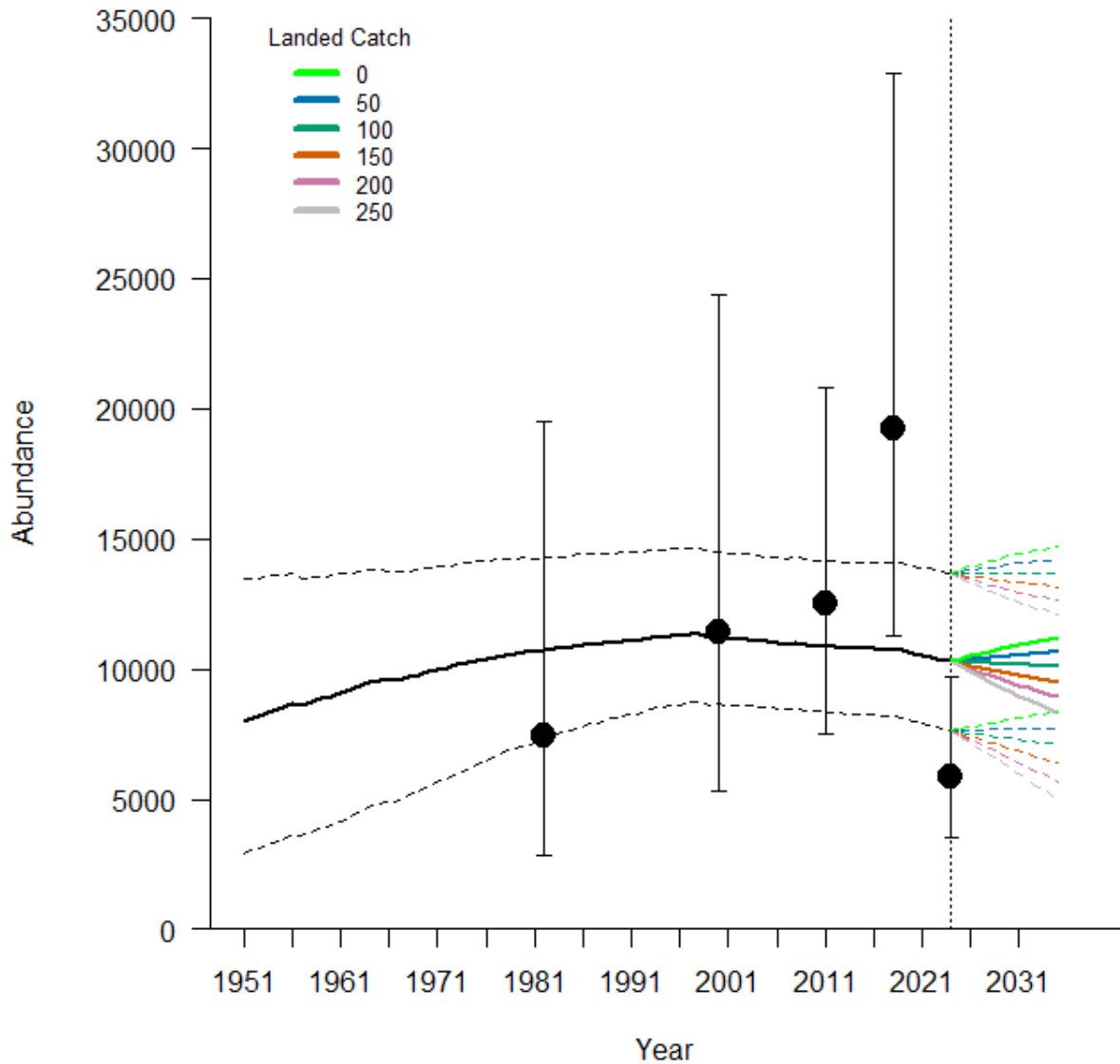


Figure 3. Model estimates of Northern Hudson Bay (NHB) narwhal abundance from the model fitted to five adjusted aerial survey estimates from 1982–2024 (black dots $\pm$ 95% log-normal CI) and harvest data from 1951–2024. Solid line shows the median estimates and dashed lines show the 95% confidence intervals. Future population projections for NHB narwhal under five different harvest scenarios are also shown separated by the vertical dotted line.

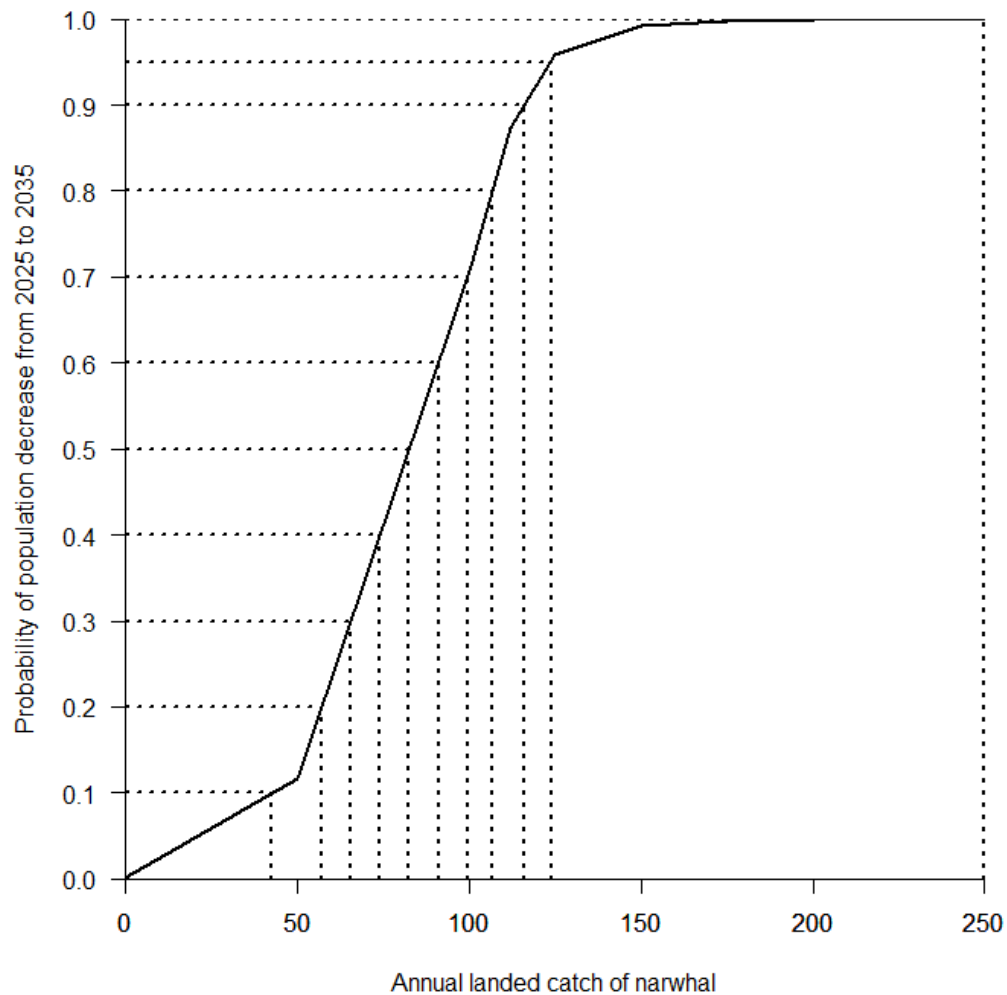


Figure 4. Probability of the Northern Hudson Bay narwhal stock decreasing from the 2025 abundance estimate after 10 years of harvest, estimated by the model, as a function of the number of reported narwhal removed from the stock each year. Dotted lines show the corresponding probability of decline (y-axis) for various annual levels of harvest (x-axis).

APPENDIX

*Table A1. Trial runs of the Northern Hudson Bay narwhal population model which evaluated changes to theta, the carrying capacity, λ_{Max} , and the start population. All model runs started with catch data from 1951. The final model presented in the paper is in **bold**.*

Model	Theta (Θ)	Carrying Capacity (K)	Lambda _{Max} (λ_{Max})	Start population
1	Uniform(1,3)	dgamma(8,0.0015)	Uniform (0.005,0.07)	Uniform(100,30000)
2	2.39	Uniform(5000,30000)	Uniform (0.005,0.07)	Uniform(5000,30000)
3	1	Uniform(5000,20000)	Uniform(0.005,0.07)	Uniform(1000,20000)
4	Uniform(1,5)	Uniform(10000,30000)	Uniform(0.01,0.07)	Uniform(1000,20000)
5	Uniform(1,3)	Uniform(5000,20000)	Uniform(0.005,0.07)	20-100% K

Table A2. Daily summary of strata/transects flown during the Northern Hudson Bay narwhal survey in 2024.

Date	Plane	Time (CDT)	Stratum	Survey Replicate	Transects	Beaufort sea state
13-Aug	C-GXXB	1:08 PM	Roes Welcome Sound	1	1-9	0-3
14-Aug	C-GXXB	9:47 AM	Wager Bay	1	1-13	1
15-Aug	C-GXXB	8:45 AM	Repulse Bay	1	1-15	3
16-Aug	C-GKGB	11:04 AM	Repulse Bay, North Bays	1	22-18, 22-16	0, 0
	C-GXXB	10:48 AM	North Bays	1	1-17	1-3
17-Aug	C-GKGB	10:03 AM	Wager Bay	2	1-13	0
	C-GXXB	12:29 PM	Roes Welcome Sound	2	1-3	0
18-Aug	C-GKGB	11:17 AM	Repulse Bay, Roes Welcome Sound	2	1-4, 4-9	0, 0
	C-GXXB	10:31 AM	North Bays	2	1-22	0-1
19-Aug	C-GKGB	9:39 AM	Repulse Bay	2	5-10, 21-23	1
	C-GXXB	10:49 AM	Repulse Bay	2	11-20	3

Table A3. Model outputs for the Northern Hudson Bay narwhal stock using 1951–2024 catch history and 1982–2024 adjusted survey estimates. 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), shaping parameter (theta), process error (prec.process), survey precision (prec.survey), starting population (startpop), struck and lost (S&L), and population size in 2025 (N2025). $\hat{R}$ is the Brooks-Gelman-Rubin statistic; values near one indicate convergence of chains. N.eff is the number of effective runs after considering autocorrelation.

	Mean	sd	2.50%	25%	50%	75%	97.50%	Rhat	n.eff
K	13202.29	2308.54	9599.34	11549.99	12829.64	14482.27	18820.34	1.00	140000.00
K.prior	12511.00	4327.92	5377.99	8767.16	12509.27	16260.37	19628.40	1.00	320000.00
Theta	0.61	0.22	0.23	0.42	0.61	0.80	0.98	1.00	450000.00
Theta.prior	1.98	0.58	1.05	1.48	1.97	2.48	2.95	1.00	280000.00
deviance	2.00	0.58	1.05	1.50	2.00	2.50	2.95	1.00	170000.00
lambda	101.57	1.43	100.23	100.70	101.10	101.94	105.59	1.00	190000.00
lambda.prior	0.04	0.02	0.01	0.02	0.04	0.05	0.07	1.00	3e+05
prec.process	0.04	0.02	0.01	0.02	0.04	0.05	0.07	1.00	5e+05
prec.process.prior	150145.90	122635.64	10468.89	60538.97	118533.59	205851.27	467403.11	1.00	97000.00
prec.surv	149641.40	122480.56	10834.34	60340.40	117812.17	204741.06	467131.40	1.00	5e+05
prec.surv.prior	10.57	5.49	2.70	6.55	9.63	13.59	23.75	1.00	5e+05
startpop	10.58	5.50	2.68	6.55	9.64	13.59	23.80	1.00	2e+05
startpop.prior	7935.63	2940.29	2888.73	5565.98	7954.95	10169.69	13457.41	1.00	350000.00
struck.and.lost	7935.63	2940.29	2888.73	5565.98	7954.95	10169.69	13457.41	1.00	350000.00
struck.and.lost.prior	0.26	0.12	0.07	0.18	0.25	0.34	0.52	1.00	5e+05
N2025	0.26	0.12	0.07	0.17	0.25	0.33	0.51	1.00	5e+05

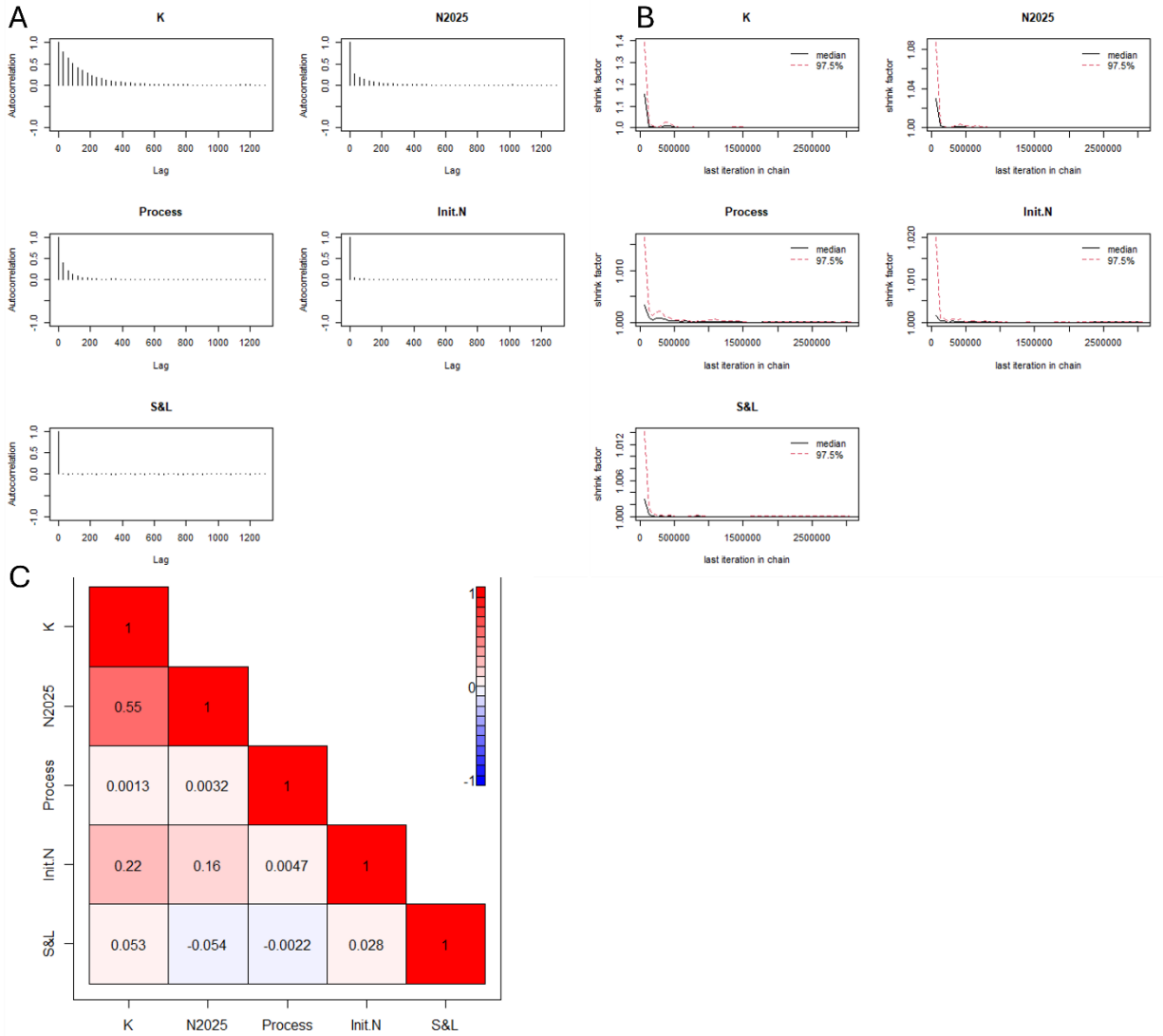


Figure A1. The model was fit to harvest data (1951 – 2024) and adjusted aerial survey data (1982 – 2024). Plots show change in A) autocorrelation, B) BGR test results, and C) cross correlation for the Northern Hudson Bay narwhal population.

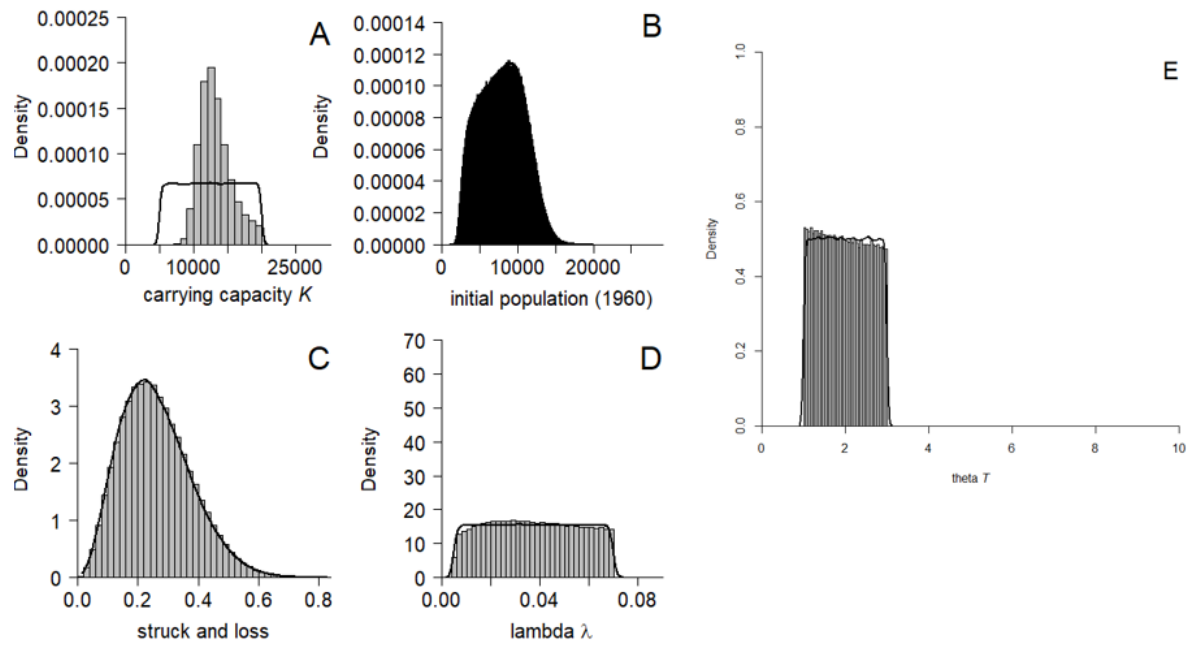


Figure A2. Priors (lines) and posteriors (histograms) for A) carrying capacity, B) initial population, C) struck and lost (S&L), D) $\lambda_{\max}$, and E) θ for the Northern Hudson Bay narwhal population.