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Canadian Science Advisory Secretariat (CSAS)

Research Document 2023/051

Arctic Region and Ontario and Prairie Region

Evaluation of a Provision to Carry Over Unused Licences for Eastern Canada-West Greenland Bowhead Whales (*Balaena mysticetus*) in Canada

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June 2023

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/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-49131-8 Cat. No. Fs70-5/2023-051E-PDF

Correct citation for this publication:

Higdon, J.W., Young, B.G., and Ferguson, S.H. 2023. Evaluation of a Provision to Carry Over Unused Licences for Eastern Canada-West Greenland Bowhead Whales (*Balaena mysticetus*) in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2023/051. iv + 23 p.

Aussi disponible en français :

*Higdon, J.W., Young, B.G., et Ferguson, S.H. 2023. Évaluation d’une disposition visant le report des permis non utilisés pour les baleines boréales de l’est du Canada et de l’ouest du Groenland (*Balaena mysticetus*) au Canada. Secr. can. des avis sci. du MPO. Doc. de rech. 2023/051. iv + 24 p.*

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ABSTRACT

In response to Resource Management's request for Science Advice on a proposed system of flexible licence allocations for Eastern Canada-West Greenland (EC-WG) bowhead whales (*Balaena mysticetus*), population model scenarios were simulated to estimate the sustainability of Canadian license carry-overs or credits to subsequent years. Methods to explore the sustainability of flexible catch limits were similar to those applied to narwhal (*Monodon monoceros*), beluga (*Delphinapterus leucas*), and Atlantic walrus (*Odobenus rosmarus rosmarus*) catch limits, but simplified by using a fixed number of licences available per allocation block rather than updating allowable catch limits based on population status. As a communal venture with logistical challenges, the unique nature of bowhead whaling will likely limit licence demand compared to other harvested marine mammals that have catch limit quotas (e.g., narwhal). A deterministic Pella-Tomlinson logistic growth population model was used to explore various harvest scenarios, including no harvest and a fixed Potential Biological Removal (PBR) level of 52 whales annually. These models, simulating population trajectories over 100 years, provide confidence that harvest at PBR (an order of magnitude higher than current subsistence harvests) will have no major effects on population recovery at a range of initial population sizes (N_0) and carrying capacity (K) estimates that reflect available knowledge of bowhead whale status. Under the model scenarios, carry-over provisions at current annual licence limits (ca. 6 per year) should have little to no impact on EC-WG bowhead population status over the long-term. These results informed additional corroborative modelling for a 40-year time period to examine the use of 5-year and 10-year allocation blocks with moderately high (compared to current demand) licence totals (i.e., 50 per five-year block, 100 per 10-year block). Various carry-over scenarios were explored, including an extreme case in which all licences (n = 50 or 100) could be carried over through the entire allocation period. Other scenarios included front-loading and back-loading of harvests, with all quota (50 or 100 whales) taken in the first or last year of each 5 or 10-year block. Licence (and harvest) carry-over had little impact on simulated EC-WG bowhead whale population growth trajectories under the model assumptions used, and harvests at current and slightly higher levels are expected to be sustainable with the implementation of a flexible licence allocation system that allows carry-over. This advice is dependent on a number of assumptions regarding current and historic bowhead abundance, population biology, and ecosystem condition. As better information becomes available these models can be revisited, but based on our present level of understanding, licence carry-over provisions can improve resource access for Inuit while allowing continued population growth.

INTRODUCTION

Bowhead whales (*Balaena mysticetus*) are widely distributed throughout the circumpolar Arctic, and exist in four populations: Bering-Chukchi-Beaufort (B-C-B) Seas, Eastern Canada-West Greenland (EC-WG), Okhotsk (OKS) Sea, and East Greenland-Svalbard-Barents (EG-S-B) Sea (Baird and Bickham 2021). Whales from the EC-WG population are subject to subsistence hunts by Inuit in Canada (Nunavut, Nunavik) and West Greenland (Figure 1). The Canadian co-management regime currently in place for EC-WG bowhead whales lacks a provision to carry over unused bowhead whale licences (or some proportion of them) to a subsequent year(s). To address this, DFO Resource Management has requested Canadian Science Advisory Secretariat advice on the sustainability of implementing a carry-over provision for unused licences related to Inuit subsistence harvest of EC-WG bowhead whales. Similar carry-over provisions are authorized for subsistence harvests of EC-WG bowhead whales in West Greenland and Bering-Chukchi-Beaufort (B-C-B) bowhead whales in Alaska (IWC 2021a,b).

The hunting of EC-WG bowhead whales in West Greenland was established in 2007, under an International Whaling Committee (IWC) quota of two whales per year with a provision for carrying over both from one year to the next (IWC 2021a). Quotas have remained at two whales per year, with average annual catches of one whale per year. No whales were hunted in 2008, and three were taken in each of 2009 and 2010 (under a carried-over quota of four whales in 2009, quota of three in 2010) (IWC 2021a). One whale was killed in 2011, followed by three years of no harvest. A single whale was again hunted in 2015 (from a quota of four including carry-over allowances), and no whales were hunted in 2016 and 2017. The quota block for 2008–2012 was 50% utilized, while the 2013–2017 quota block was only 6% utilized (IWC 2021a). For B-C-B bowhead whales (the most-studied and largest (> 16,000 animals) population, Baird and Bickham 2021), the total number of whales struck per year cannot exceed 67, and any unused portion of a strike quota from any year can be carried over and added to the strike quota of any subsequent year in the block, to a maximum of 15 unused strikes (IWC 2021b). The 6-year block for 2013–2018 for B-C-B bowhead whales thus allowed a total landing of 336 whales (IWC 2021b). In addition, 15 unused strikes from the 2008–2012 quota were also carried over (IWC 2021b).

Licence allocations for Canadian bowhead whale hunts have increased over time as better information on population abundance has become available. In 2007 and earlier, one licence was issued for all of Nunavut every 2–3 years, which increased to two whales per year in 2008 and from 2 to 3 in 2009 (NWMB 2008, 2009). These decisions also took into account two possible strikes by Nunavik whalers in addition to two in West Greenland (NWMB 2008). In 2012 the Board decided to maintain a total allowable harvest (TAH) of 3 bowheads (one per region) (NWMB 2012). The Board also recommended that NTI and Makivik Corp. (Nunavik) work together to develop a Nunavut-Nunavik bowhead sharing agreement (NWMB 2012). In 2015, the NWMB increased the TAH to five whales (two each for the Kivalliq and Qikiqtaaluk regions, one for the Kitikmeot region) (NWMB 2015). Not every available licence has been issued, e.g., 4 of 5 licences were issued in 2019, 3 of 5 in 2020 (and one community decided to not go ahead due to concerns around COVID-19) (Tranter 2020). Inuit of Nunavik resumed their subsistence hunt for bowhead whales in 2008. In each of 2008 and 2009, DFO authorized the harvest of one bowhead whale within the Nunavik Marine Region (NMR). The Nunavik Marine Region Wildlife Board (NMRWB) established levels of Total Allowable Take (TAT) for bowhead whales in the NMR. In 2011, the NMRWB established a TAT of one bowhead whale, but a hunt was not conducted that year. In 2012, the NMRWB established a TAT of one bowhead whale. In total, one whale was taken by Nunavik in 2008, 2009 and 2017. In Canada, the EC-WG bowhead whale fishery is subject to provisions of the Nunavut Agreement (NA), the Nunavik Inuit Land Claims Agreement (NILCA), the *Fisheries Act* and its supporting regulations.

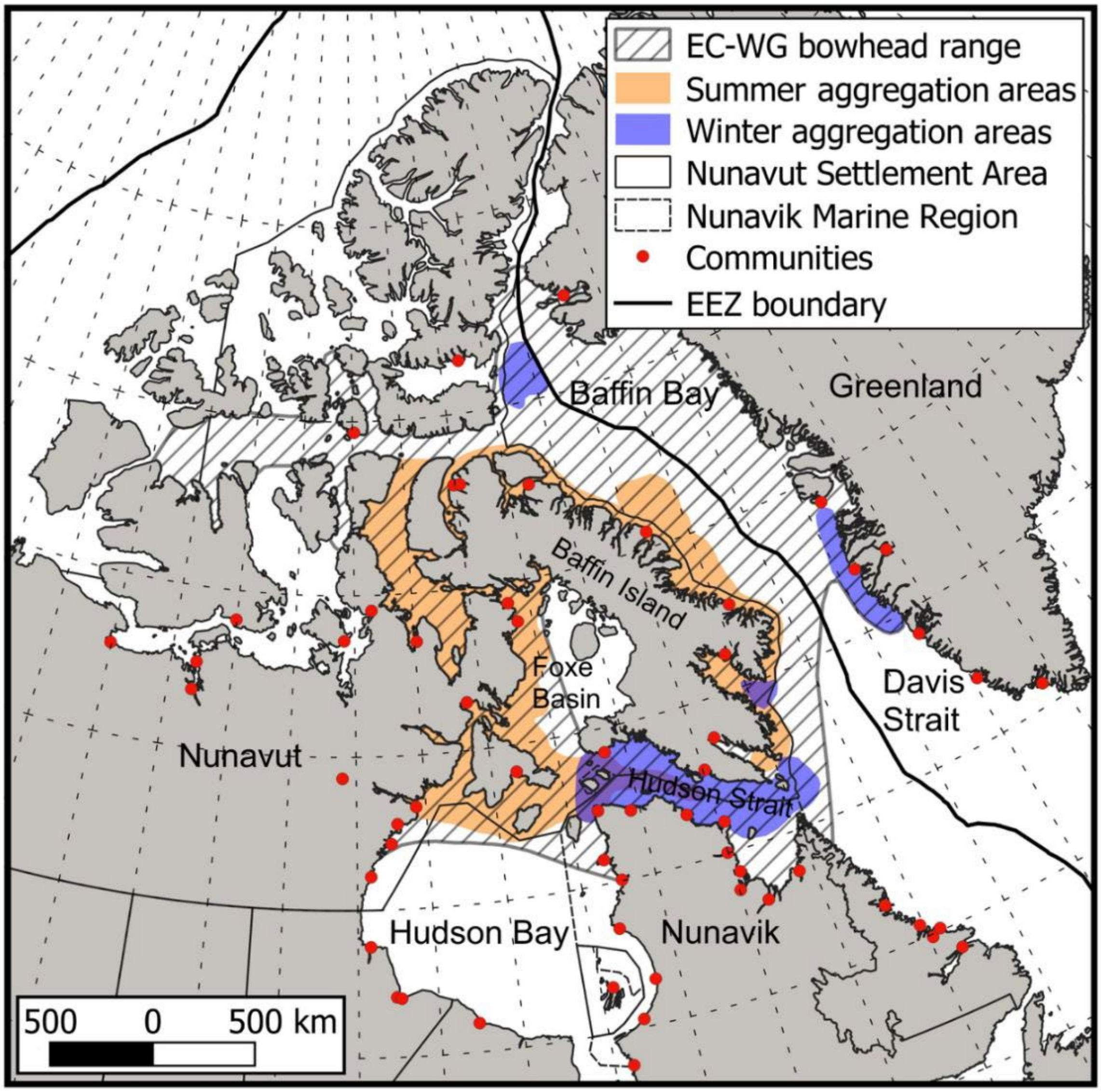


Figure 1. Range of the Eastern Canada-West Greenland bowhead whale population, showing overall range, key summer and winter aggregation areas, in addition to local communities and boundaries of the Nunavut Settlement Area and Nunavik Marine Region (from Ferguson et al. 2021).

Canada's current bowhead whale management approach restricts Inuit from carrying over unfilled annual EC-WG bowhead whale quota to subsequent harvest seasons. DFO has committed to developing an evidence-based approach in its assessment of potentially viable co-management measures. DFO Science Advice will help determine whether a less restrictive harvest limitation, that enables carry-over of unused annual licences including the possibility of a multi-year block allocation of the TAT, can be implemented within the Nunavut Settlement Area/Nunavik Marine Region (NSA/NMR) while continuing to provide for the conservation and protection of the EC-WG bowhead whale population. This information is critical to determine the appropriate level of restriction of Inuit right to hunt bowhead whales (*Nunavut Land Claims Agreement* s.5.3.3.(a)).

The present analysis is in response to requests by Resource Management for peer-reviewed science to address the following questions:

1. Is it sustainable to carry over unused strikes (or some proportion of them) from one year to a subsequent year(s)?; and if so,
2. What are the probabilistic risks associated with the time interval within which unused strikes could be carried over before resetting the accumulation to 0?

The EC-WG bowhead whale population is thought to be in the "Healthy Zone" of DFO's Precautionary Approach framework (Ferguson et al. 2021), though it is possible that the population is in the "Cautious Zone" (between N_{30} and N_{50}) (also see NWMB 2008). Note that there is no departmental peer-reviewed framework for a Precautionary Approach (PA) to EC-WG bowhead whale management at present. We considered carry-over scenarios to be sustainable if, at the end of the modelled trajectories, the bowhead whale population continued to grow towards carrying capacity (K) and move from the "Cautious Zone" to "Healthy Zone" or remain in the "Healthy Zone", depending on the starting population size used in simulations (see below). A probabilistic assessment of risk was not possible given the model structure used, and we assessed differences in scenario endpoints in relation to population growth to determine if there was any management risk to different carry-over scenarios. The model scenarios are meant to support informed discussion with co-management partners and provide information to help the NWMB and NMRWB decision-making process.

The assessment used a deterministic logistic population growth model (Higdon and Ferguson 2016, Ferguson et al. 2021) to address these questions, using an approach broadly similar to (but simplified from) that used to assess the sustainability of carry-over provisions for beluga (*Delphinapterus leucas*) (Doniol-Valcroze et al. 2014), narwhal (*Monodon monoceros*) (Richard and Young 2015) and Atlantic walrus (*Odobenus rosmarus rosmarus*) (Hammill et al. 2016) harvest management.

METHODS

POPULATION MODEL

The population model used for the assessment is a standard discrete time deterministic logistic growth model as used by the International Whaling Commission (IWC) (Baker and Clapham 2004, Higdon and Ferguson 2016, also see Ferguson et al. 2021). It is a variant of the standard Pella-Tomlinson (or theta-logistic, where z = theta) model and does not include any modelling of the Allee Effect. Stochastic versions of the same model have been used for DFO advice for other marine mammals (e.g., Doniol-Valcroze et al. 2014, Richard and Young 2015, Hammill et al. 2016). The logistic population model, with z = 1, is also the underlying model for the Potential

Biological Removal (PBR) calculation (Wade 1998). The model, which projects forward, was built using an Excel spreadsheet and is defined as follows:

$$N_{t+1} = N_t + r_{max} \times N_t(1 - (N_t \div K)^z) - (C_t \times \Omega)$$

Where:

N_t = total population size during year t,

r_{max} = intrinsic rate of increase,

K = carrying capacity, assumed to be equal to abundance before exploitation (i.e., P_t=0),

z = the exponent setting the maximum sustainable yield level (MSYL); or the size of the population, relative to K, at which the maximum number of whales can be taken without changing the population size

C_t = the recorded catch in terms of numbers of whales during year t, and,

Ω = correction for whales killed and lost (or struck and lost that subsequently died from their injuries)

Model scenarios were conducted using a range of parameter values, as described below. We used a range of values for key parameters to explore a range of possible scenarios, as an alternative to using an assessment model that has to be fit to various abundance estimates. This was done in an attempt to avoid some of the issues associated with trying to fit a model to a series of abundance estimates with considerable uncertainty (see Ferguson et al. 2021). Furthermore, there is uncertainty regarding the impacts of environmental change on bowhead whale life-history and we have little information by which to reliably inform stochastic model processes. Deterministic models were therefore used, and the results and associated advice need to be considered in this context (see Discussion).

PARAMETER VALUES

The model requires an estimate of the current population size (N_t when t = the starting year of the model run, or N_0) and the carrying capacity (K), defined as the pre-exploitation population size (Higdon and Ferguson 2016, Ferguson et al. 2021). Estimates for r_{max} and z (the shaping parameter) are also required.

Several estimates for current (or recent) population size are available. The High Arctic Cetacean Survey (HACS), conducted in August 2013, provided abundance estimates for Baffin Bay narwhal stocks and EC-WG bowhead whales (Doniol-Valcroze et al. 2015, 2020). The visual aerial survey data were analyzed using distance-sampling and double platform with mark-recapture methods and estimates were adjusted for availability bias using analysis of satellite-linked time-depth recorders. The fully adjusted abundance estimate for the EC-WG bowhead whale population was 6,446 (95% CI: 3,838–10,827) (Doniol-Valcroze et al. 2020). This estimate is negatively biased due to incomplete coverage of the bowhead summer range (no surveys in Foxe Basin, Lancaster Sound and northern Hudson Bay). Genetic capture-mark-recapture (gCMR) has also been used to estimate EC-WG bowhead whale abundance (Petersen et al. 2014, Frasier et al. 2015, 2020). Frasier et al. (2020) developed an analytical technique to account for unsampled locations and infer individuals that were missed in these locations to obtain more accurate abundance estimates when not all sites are sampled. Using biopsies and samples from hunted whales, the estimated (2013) size of the EC-WG bowhead whale population was 11,747 individuals (95% highest density interval 8,169–20,043) (Frasier et al. 2020). These estimates suggest that a range for N_0 of 5,000–12,500 animals will provide sufficient simulation coverage to address scientific uncertainty on current abundance.

Numerous authors have attempted to estimate historic (pre-exploitation) EC-WG bowhead whale population size, using a variety of methods. Historically, it was thought that two closed populations, in Hudson Bay and Davis Strait/Baffin Bay, occurred in this area, which is now known to be incorrect (COSEWIC 2009). Mitchell and Reeves (1981) estimated historic population size for the Davis Strait stock near the onset of commercial exploitation to be 11,000 (and 575 for Hudson Bay stock as revised by Woodby and Botkin 1993). Similar estimates of 11,800 for Davis Strait and 450 for Hudson Bay were generated by Woodby and Botkin (1993) using a different model and similar catch series. Allen and Keay (2006) estimated a pristine population size for the Davis Strait stock as just over 18,000 whales in 1719. They also used an older catch history (Ross 1974, 1979) than that updated by Higdon (2010), which extended farther back in time (to include Basque whaling in the Labrador Sea and Gulf of St. Lawrence in the 1500s) and included additional harvest data that was not available to Ross (1974, 1979). Witting (2011) used a Bayesian population model and the catch history in Higdon (2010) and examined whether population dynamics were best described by density-regulated growth or by inertia dynamics (see Witting 2002 for details on inertia dynamics models). These models did not include Basque harvests and pre-1700s Inuit harvests, and the catch series was not corrected for those whales that were killed but lost. Bayes factors supported inertia dynamics and rejected density-regulated growth. Witting (2011) estimated a population dynamic equilibrium of 30,000 (90% CI: 24,000–35,000) whales in 1719 using the inertia dynamics model. Witting (2011) also reported the results of the density regulated growth model, which, while less supported, estimated a population dynamic equilibrium abundance of 16,000 (90% CI: 12,000–25,000) animals. This was broadly similar to the historical population size estimate of about 18,500 whales prior to the start of Basque whaling that was generated by Higdon and Ferguson (2016) using the same model as the one employed in this assessment of licence carry-over.

Overall, the various estimates suggest a pre-exploitation population size (carrying capacity) of between 11,000 and 30,000 whales. Earlier estimates (e.g., Mitchell and Reeves 1981, Woodby and Botkin 1993) used older harvest data and did not extend their models back to the start of the commercial whaling period. Other estimates (e.g., Allen and Keay 2006, Witting 2011) extended the models back to the start of data availability for the West Greenland bowhead fishery in 1719 (but note that the West Greenland fishery had started prior to this, Higdon 2010). Only Higdon and Ferguson (2016) (also see Ferguson et al. 2021) modeled pre-exploitation abundance at the start of the Basque whaling era in the early 1500s. Based on these estimates and their source material, we used K = 12,500, 15,000, 17,500, and 20,000 as estimates of carrying capacity for model simulations to reflect uncertainty in historic abundance. At the lower range of these K values, the current population size (using the genetic estimate in Frasier et al. 2020) would be approaching carrying capacity.

The Pella-Tomlinson model also requires parameter values for r_{max} (intrinsic rate of increase), z (the shaping parameter, i.e., the exponent setting the MSYL), C_t (the anthropogenic mortality during year t (generally limited to hunt mortality based on data availability)), and Ω (the correction for whales killed and lost). No estimates of rate of increase are available for EC-WG bowhead whales, but it has been calculated for the B-C-B population. George et al. (2004) calculated an annual rate of increase of 3.4% (95% CI = 1.7–5%) from 1978 to 2001. Schweder et al. (2009) estimated the yearly growth rate to be 3.2% (95% CI = 0.5–4.8%) between 1984 and 2003. Givens et al. (2013) calculated that the population increased at a rate of 3.7% (95% CI = 2.9–4.6%) from 1978 to 2011. This estimate is not used for PBR calculations however, as the population is currently being harvested and not growing at its maximum rate (as it is already at a substantial fraction of estimated carrying capacity), and these B-C-B population estimates are current/realized rates of increase and not the potential maximum rate (Muto et al. 2020). The cetacean maximum theoretical net productivity rate of 4% is instead used in Potential

Biological Removal (PBR) calculations (Muto et al. 2020). We also used $r_{max} = 0.04$ as the default value, but did conduct some modelling using $r_{max} = 0.03$ to assess sensitivity (see below). The shaping parameter for most model scenarios was set at 2.39 to represent MSYL at 60% of K, which is conventionally assumed for large whales (Baker and Clapham 2004, Higdon and Ferguson 2016). Model sensitivity to the shaping parameter was assessed by exploring some scenarios using $z = 1$ (which replicates the PBR model process, Wade 1998) (see below). The catch levels modeled are highlighted in the following section, and we assumed that all whales struck during the model runs were killed and landed; thus, no loss correction was employed.

HARVEST ESTIMATES FOR MODELLING

The bowhead whale hunts in Nunavut (and Nunavik) are a communal hunt, where the catch is shared and distributed to the whole community and with other communities in the region (Williams et al. 2005). Hunts are also logistically intensive, and require significant planning and effort both pre- and post-harvest. There have been 51 licences issued in Canada (Nunavut and Nunavik) for the 1996–2019 period, with 33 whales landed from 38 strikes (ca. 87%) (each licence allows for two strikes) (Table 1). The sex ratio of harvests has been balanced (15 male, 17 female, 1 no data) (DFO unpublished data). No whales were struck in 16 hunts, one hunt saw two whales struck and lost (and therefore no whale landed as the strike limit was reached), and another hunt saw 1 whale struck and lost with no other whales struck. Two other hunts struck and lost a whale before successfully striking and landing another (Table 1).

More recently, the number of Canadian licences issued per year has ranged from 2 to 6 (mean 3.9) over the ten years 2010–2019. Only once (2017) have 6 licences been issued (i.e., 5 in Nunavut, 1 in Nunavik) (Table 1). Canadian landed harvests for the 10-year period 2010–2019 have ranged from 1 to 3 whales per year (average 2.2). The current harvest limit in Canada is six bowhead whales per year (5 in Nunavut, 1 in Nunavik). West Greenland hunters could take two per year assuming no licences are carried over, for a total of 8 across the entire EC-WG bowhead whale population. It is possible that Nunavut (e.g., two Kitikmeot communities) or Nunavik could request an additional licence. A base harvest limit of 10 whales per year was therefore used for the 40-year simulations, with 5-year blocks of 50 animals and 10-year blocks of 100 animals. No modelling of strikes was conducted, we assumed all future hunts led to successful landings. The data for previous hunts (Table 1) show relatively few animals struck and lost.

Table 1. Recent (1996–2019) hunts for Eastern Canada-West Greenland (EC-WG) bowhead whales in Canada (Nunavut, Nunavik). West Greenland hunts are not shown (see text). Source: DFO, unpublished data.

Jurisdiction	Region	Hunts allocated	No harvest	Landed	Total struck
Nunavik	N/A	5	2	3	3
Nunavut	Kitikmeot	11	6	5	8
	Kivalliq	17	5	12	12
	Qikiqtaaluk	18	5	13	15
Totals	**-**	**51**	**18**	**33**	**38**

PRELIMINARY MODELLING OVER 100 YEARS

Preliminary modelling examined the effects of full removals (harvest plus other anthropogenic mortalities) at PBR levels compared to scenarios with no harvests. DFO (2015) calculated a PBR of 52 whales per year for the EC-WG bowhead population, using the results from the 2013 aerial survey. This calculation used the standard r_{max} for cetaceans, equal to 0.04, and a Recovery Factor (RF) of 0.5 (see Wade 1998 for details on the PBR process). N_{min}, calculated as the 20th percentile of the confidence range around the abundance estimate in the PBR process, was 5,200. DFO (2015) did not calculate PBR using the genetic capture-mark-recapture estimate in Frasier et al. (2015) due to the need to conduct a more thorough assessment of the assumptions used. This assessment has now been conducted (Frasier et al. 2020) and a revised gCMR estimate is available. That population estimate would result in a higher PBR (105 whales per year using the same r_{max} and RF as DFO 2015) than that calculated in DFO (2015), making the current PBR conservative.

Preliminary analyses allowed us to examine model trajectories using assumptions that closely paralleled the PBR process (albeit with a different shaping parameter) and determine population response to removals at much higher levels than current. These models indicated that population growth and recovery under a consistent harvest of 52 whales per year was not greatly different (with respect to final population size as a proportion of K) than trajectories with no harvests at the end of 100-year time horizon (see Results section). Subsequent, more detailed modelling of carry-over provisions used a shorter 40-year time-frame (i.e., eight 5-year blocks, four 10-year blocks) to investigate the shorter-term effects during the parts of the 100-year simulations where population trajectories were most sensitive to harvest at PBR levels.

MODELLING SHORT-TERM (40 YEAR) IMPACTS OF CARRY-OVER

The 40-year models explored population trajectories under two base scenarios: no harvest and 10 whales/year (i.e., a consistent harvest of 10 annually, which is higher than current harvest levels). Two licensing blocks were used for assessment of carry-over provisions, 5 years (n = 8 blocks) and 10 years (n = 4 blocks), with total licences per block of 50 for 5-year blocks and 100 for 10-year blocks. A licence limit of 10 per year was used here, rather than the higher PBR limit, to provide results that more closely reflect current and potential near-future licence allocation levels. These model simulations were compared against the two base scenarios. Front-loaded and back-loaded scenarios (see Doniol-Valcroze et al. 2014, Richard and Young 2015, Hammill et al. 2016) were assessed, where all harvests (i.e., 50 whales in 5-year blocks, 100 whales in 10-year blocks) occurred at either the first or last year of each block. Two additional carry-over scenarios were modelled. The first used a 100% carry-over process with no temporal constraints, i.e., all unused licences could be carried over to subsequent years for the entirety of the block, until the block ended (after 5 or 10 years) and the total licence allocation reset. This is a conservative assessment as it does not limit carry-over allowances to a minimum number per year or limit the number of years that licences can be carried over. It is also unrealistic to some extent, as harvests were set as a random number between zero and the total available licences each year; therefore it allows unrealistically high harvests towards the end of the harvest blocks. The second scenario considered a carry-over level of 50% (i.e., maximum of 5 carry-over) which was additionally limited to single-year carry-over only (i.e., harvests of between 0 and 15 per year maximum).

Models used a starting population size (N_0) of 10,000 whales and examined the same four carrying capacity values (K = 12,500; 15,000; 17,500; 20,000) as the initial 100-year simulations. Other model parameters were also set as per initial simulations (i.e., no struck/lost correction, shaping parameter = 2.39, r_{max} = 0.04; but see Results regarding sensitivity analyses). The models with carry-over provisions were run for 1,000 simulations and compared to the two base case trajectories and resulting abundances of no harvests and a consistent harvest of 10 whales/year.

MODEL SENSITIVITY TO PARAMETER CHOICES

The model scenarios used a range of N_0 (starting population size) and K (carrying capacity) estimates. These values were informed by available estimates of current population size (Doniol-Valcroze et al. 2020, Frasier et al. 2020) and by historic models of exploitation (e.g., Allen and Keay 2006, Witting 2011, Higdon and Ferguson 2016), and the use of a range of possible values provides information on scenario uncertainty. The simulation results are also sensitive to the selection of parameter values for r_{max} (intrinsic rate of increase) and z (shaping parameter that sets the MSYL). The values used for scenario modelling were default choices, with $r_{max} = 0.04$ (default value for large cetaceans in the PBR formulation, Wade 1998), and $z = 2.39$ (MSYL = 60% of K, as usually assumed for large whales, Baker and Clapham 2004). To assess model sensitivity to alternate parameter values, we ran some models (both 100- and 40-year) using a lower $r_{max} = 0.03$ and $z = 1$ (a symmetric productivity curve where MSYL is 50% of K, i.e., “slower” recovery, which also parallels the approach used for PBR; Wade 1998).

RESULTS

PRELIMINARY MODELLING OVER 100 YEARS

Initial deterministic models explored 100-year population trajectories for different combinations of starting population size (N_0), carrying capacity (K; i.e., pre-exploitation population size), and harvest levels. These models included combinations of N_0 = 5,000, 7,500, 10,000 and 12,500 whales; K = 12,500, 15,000, 17,500, and 20,000 animals, and harvests of 0 or 52 whales per year (i.e., no harvest vs. harvest at PBR level).

In the absence of any harvests, all population simulations are fully recovered (defined for our purposes as > 90% of K) at the end of the 100-year time period (Figure 2, left panels). Populations are recovered (defined here as 70% of K, i.e., the target reference point under the Precautionary Approach framework, Stenson et al. 2012) by year 32 for all scenarios with N_0 = 5,000, and fully recovered (defined here as 90% of K) by year 48. Populations are recovered (i.e., 70% of K) by year 21 for all scenarios with N_0 = 7,500, and fully recovered (i.e., 90% of K) by year 37. Scenarios with higher starting populations (i.e., N_0 = 10,000 or 12,500) recover sooner (and some scenarios, e.g., N_0 = 10,000, K = 12,500, start at over 70% of K). When simulations are run using an annual removal of 52 whales (i.e., current PBR level), recovery is slowed to some extent (and varies by scenario) but all populations are still fully recovered (N_{100} > 90% of K) by simulation end (Figure 2, right panels).

Differences in population trajectories between the no harvest and PBR level harvest scenarios are most pronounced with smaller starting population size, as expected (i.e., N_0 = 5,000 or 7,500 compared to 10,000 or 12,500) (Figure 3). The greatest differences in the simulation results appear around 20–40 years into the 100-year simulations (Figure 3) for most scenarios. Differences (measured as the change in population size relative to K) also show that the period around 20–40 years into the simulations are the most sensitive to harvest at PBR levels for most scenarios, particularly for N_0 = 7,500 or 10,000 (Figure 4).

Overall, these model results indicate that relatively high harvests (52 whales/year, much higher than recent harvests of 1–3 whales per year, Table 1) have no significant impact on EC-WG bowhead whale population growth over the long-term (Table 2), as would be expected given the conservative nature of the PBR calculation, which assumes z = 1 and thus results in much slower growth at fractions of K up to 60–70% (Wade 1998) (and the fact that PBR was calculated using the 2013 aerial survey results which are also conservative due to incomplete coverage). The much lower removals under current harvest levels are therefore expected to have no major effect on population growth and recovery under a flexible quota scenario.

However, additional modelling was conducted to explore this in greater detail under shorter time frames of 40 years to capture the time period of the trajectories with the greatest difference in population growth (Table 2).

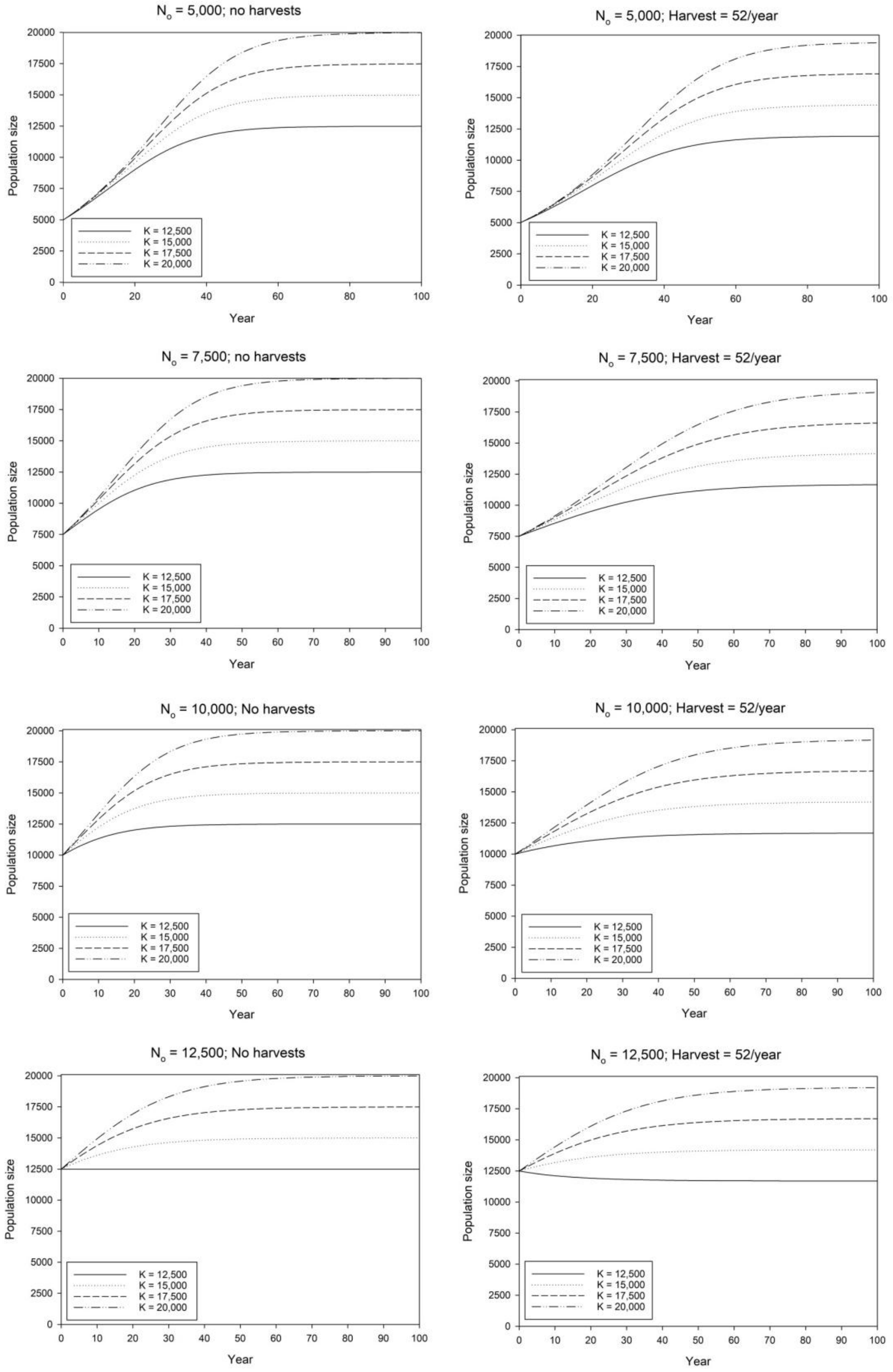
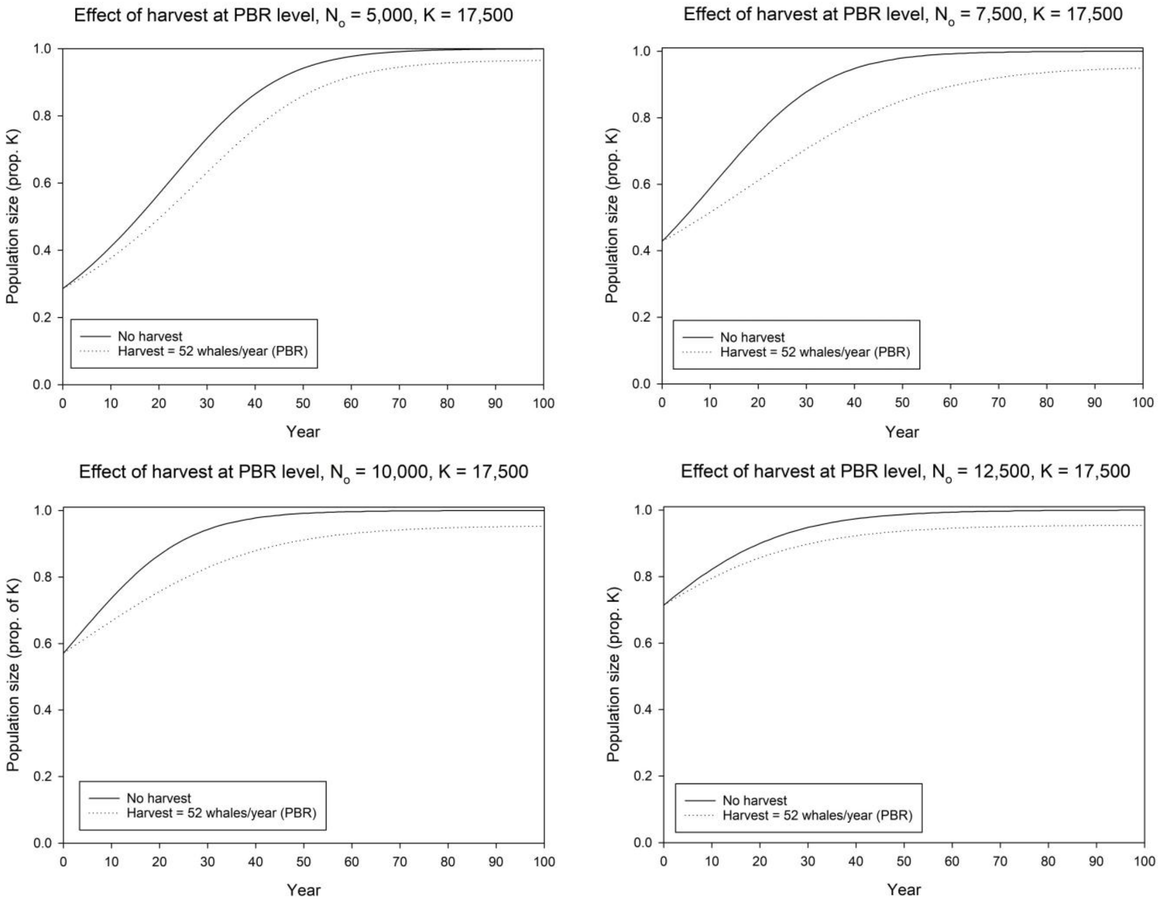


Figure 2. Results of 100-year simulations of a Pella-Tomlinson logistic growth model for EC-WG bowhead whales with no harvests (left panels) and annual harvests equal to Potential Biological Removal (PBR, n = 52 whales) (right panels), for a range of starting population size (N_0) and carrying capacity (K) values.



Effect of harvest at PBR level, N_o = 5,000, K = 17,500

Effect of harvest at PBR level, N_o = 7,500, K = 17,500

Effect of harvest at PBR level, N_o = 10,000, K = 17,500

Effect of harvest at PBR level, N_o = 12,500, K = 17,500

Figure 3. Effects of harvests of EC-WG bowhead whales at PBR levels (52 whales/year) for various initial population sizes (N_0) and assuming K = 17,500 (for illustrative purposes, also see Table 2).

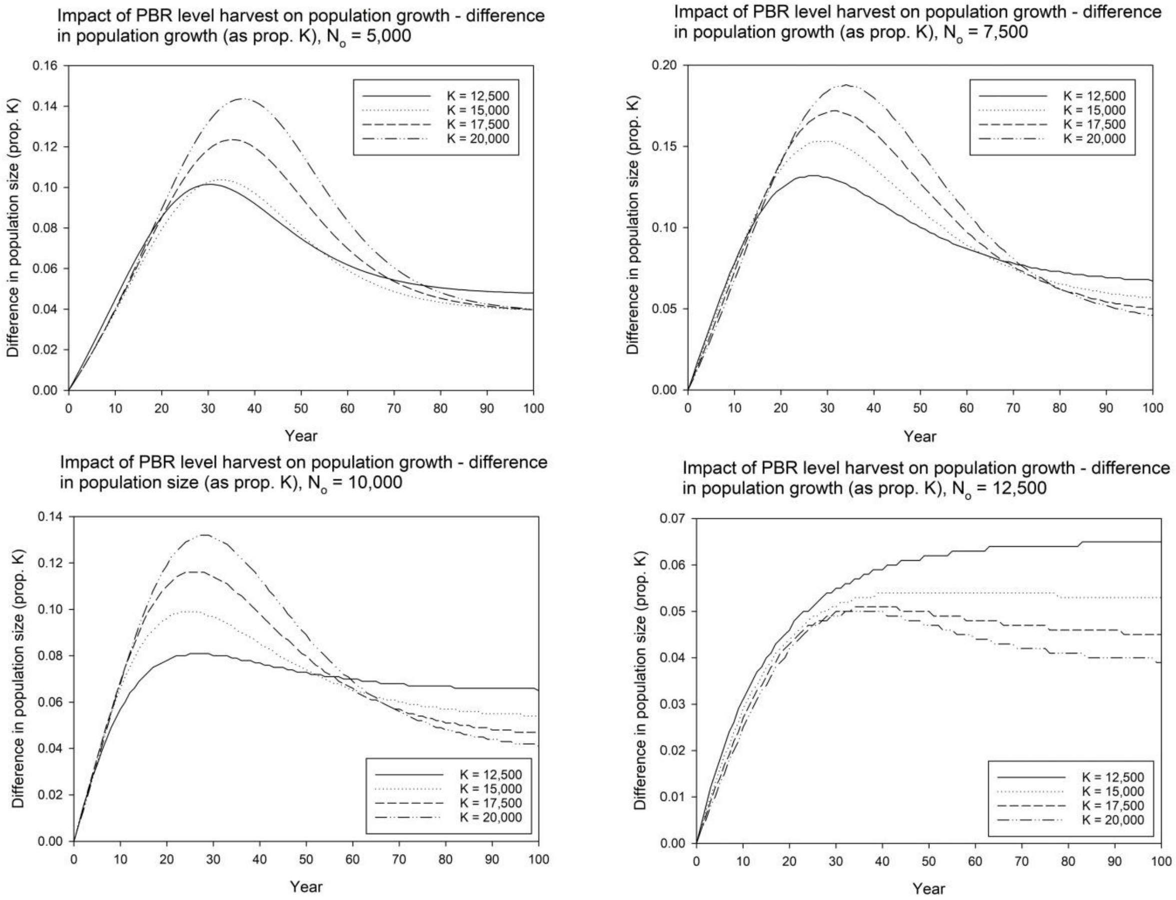


Figure 4. The effect of harvests at PBR levels (52 whales/year) on bowhead whale population growth over 100 years, for four different starting population (N_0) sizes and four different carrying capacity (K) values. Graphs show the differences in population size (measured as the proportion of K) over time with harvests of 52 whales per year (PBR level) compared to scenarios with no harvests. For all but the highest starting population size (N_0 = 12,500), the biggest effects on population recovery (i.e., changes in proportion of K reached) occur early (around 20–40 years) in the 100-year scenarios. As such, additional modelling of carry-over scenarios considered a shorter (40-year) scenario.

Table 2. Population recovery (expressed as a proportion of carrying capacity K) after 100 years for deterministic logistic growth models with no harvest and with annual harvests at Potential Biological Removal (PBR, n = 52 whales) levels, for a range of current population size (N_0) and carrying capacity (K) estimates. Also shown are the year(s) with the greatest difference between no harvest and PBR removals during the 100 year trajectory and the percent difference for these years. All models used r_{max} = 0.04 and z = 2.39.

N_o	K	Prop. K at N_o	Population size at year 100 (prop. K)		Year(s) of greatest difference	Percent difference
			No harvest	52/year		
5,000	12,500	0.400	1.000	0.952	30–31	10.2%
	15,000	0.333	1.000	0.960	33	10.4%
	17,500	0.286	1.000	0.966	35	12.4%
	20,2000	0.250	0.999	0.969	36	14.3%
7,500	12,500	0.600	1.000	0.933	26–28	13.2%
	15,000	0.500	1.000	0.943	27–31	15.3%
	17,500	0.429	1.000	0.950	31–32	17.2%
	20,000	0.375	1.000	0.954	34	18.8%
10,000	12,500	0.800	1.000	0.935	25–29	8.1%
	15,000	0.667	1.000	0.946	23–27	9.9%
	17,500	0.571	1.000	0.953	24–28	11.6%
	20,000	0.500	1.000	0.958	27–29	13.2%
12,500	12,500	1.000	1.000	0.935	83–100	6.5%
	15,000	0.833	1.000	0.947	39–77	5.4%
	17,500	0.714	1.000	0.954	34–43	5.1%
	20,000	0.625	0.999	0.960	32–40	5.0%

MODELLING SHORT-TERM (40 YEAR) IMPACTS OF CARRY-OVER

The models used to assess licence carry-over effects were run for a 40-year timeframe, guided by the results of the preliminary models discussed above. The same Pella-Tomlinson logistic population model was used, and parameters were similar to the 100-year models. All assessments were done using N_0 = 10,000. Models with carry-over provisions (n = 1,000 simulations) were compared against models (single runs) with harvests of either zero or 10 bowhead whales per year as well as the front-loaded and back-loaded harvest models (where all licences are filled during the first or last year of the allocation block).

Simulations showed that even extreme carry-over provisions allowing harvests of an unrealistically high number of whales (> 50 whales/year towards the end of a 10-year licence block) have no appreciable impact on EC-WG bowhead whale population growth (Tables 3, 4). Models using a 10-year harvest block (Table 4) result in more variable population trajectories than those using the 5-year blocks (Table 3), owing to the increase in available licences as the block ages and the more chaotic removals (random removals from zero up to the available licence allocation). Carry-over provisions result in virtually the same population recovery levels as consistent harvests of 10 whales per year (Tables 3, 4). There is no difference in a 5-year and 10-year allocation block in this scenario, which is to be expected given the one-year carry-over limit. Of note, this “base” case of 10 whales per year is in itself high compared to current and anticipated near future harvest levels. Front-loaded and back-loaded harvests result in much more chaotic annual changes in population growth trajectories (Figure 5), but in all scenarios the EC-WG bowhead population recovery is similar at the end of the 40-year.

scenario. No matter which extreme is considered, carry-over models do not result in population growth trajectories that vary significantly from a no harvest model. This is expected given the lack of long-term significant effect from annual harvests at PBR levels (n = 52) as shown in previous model simulations.

Table 3. Population sizes at N_{40}, comparing various base cases with unlimited carry-over (no annual reset, all unused licences allowed to be carried over within the block) and carry-over limited to 5 whales per year, with an annual reset (i.e., max 15 whales harvested in any given year), for five-year allocation blocks (also see Figure 5). All simulations used 10,000 whales as the starting population size (N_0), with $r_{max} = 0.04$ and $z = 2.39$.

K	Final population size at N40, with range for carry-over assessments (n = 1,000 simulations)					
	No harvest	10 whales/year	Front-loaded	Back-loaded	Unlimited carry-over	Limited carry-over (5/year)
12,500	12,432	12,321	12,340	12,300	12,335 (12,302–12,367)	12,355 (12,324–12,375)
15,000	14,807	14,687	14,705	14,667	14,701 (14,677–14,729)	14,725 (14,699–14,749)
17,500	17,109	16,977	16,994	16,958	16,996 (16,961–17,035)	17,018 (16,985–17,042)
20,000	19,325	19,178	19,193	19,160	19,195 (19,168–19,230)	19,227 (19,202–19,253)

Table 4. Population sizes at N_{40}, comparing various base cases with unlimited carry-over (no annual reset, all unused licences allowed to be carried over within the block) and carry-over limited to 5 whales per year, with an annual reset (i.e., max 15 whales harvested in any given year), for ten-year allocation blocks. All simulations used 10,000 whales as the starting population size (N_0), with $r_{max} = 0.04$ and $z = 2.39$.

K	Final population size at N40, with range for carry-over assessments (n = 1,000 simulations)					
	No harvest	10 whales/year	Front-loaded	Back-loaded	Unlimited carry-over	Limited carry-over (5/year)
12,500	12,432	12,321	12,340	12,300	12,222 (12,159–12,321)	12,355 (12,323–12,377)
15,000	14,807	14,687	14,705	14,667	14,586 (14,534–14,649)	14,724 (14,695–14,745)
17,500	17,109	16,977	16,994	16,958	16,871 (16,818–16,931)	17,017 (16,999–17,045)
20,000	19,325	19,178	19,193	19,160	19,058 (19,008–19,129)	19,224 (19,197–19,246)

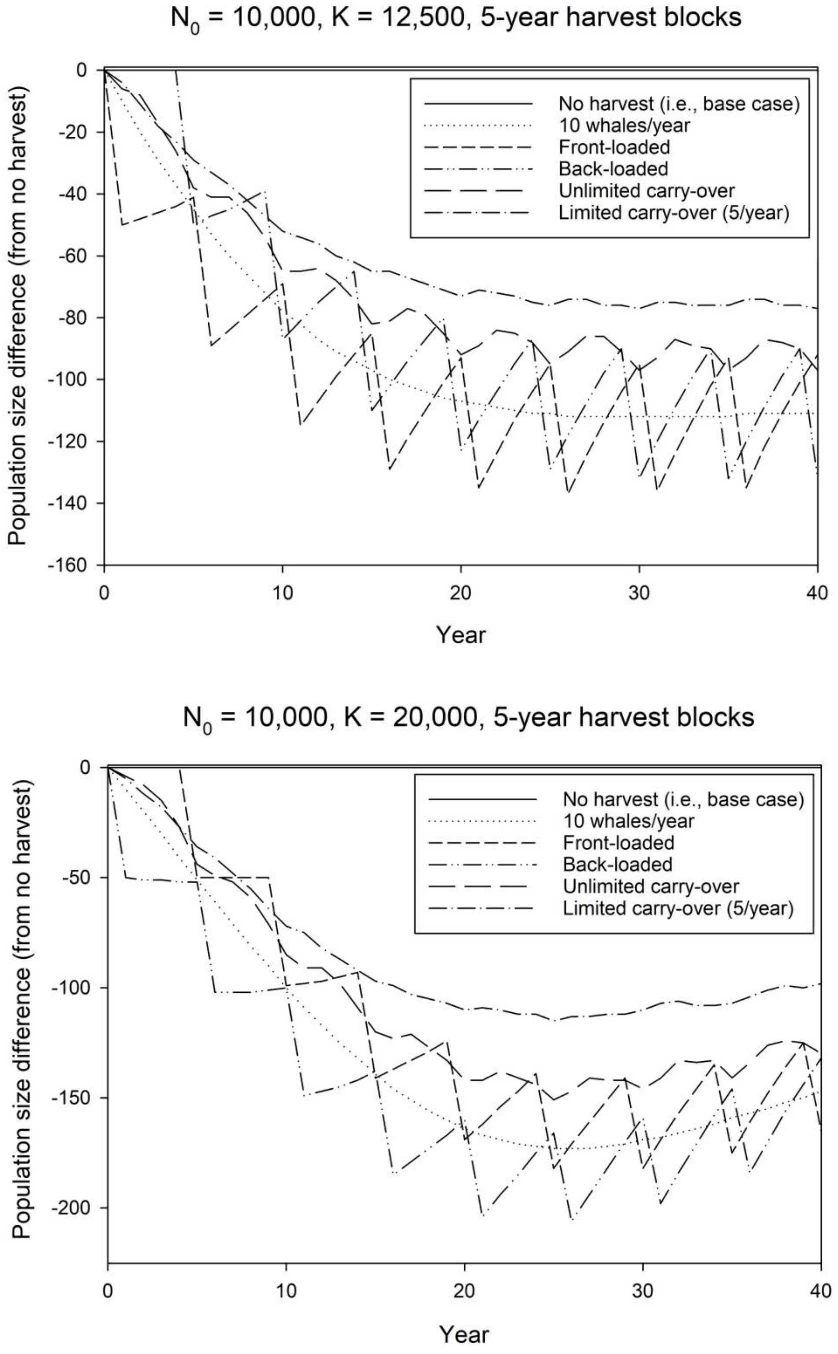


Figure 5. Comparisons of changes in population growth for two example scenarios with different harvest allocations and 5-year allocation blocks (see Table 3). Top panel: N_0 = 10,000, K = 12,500; bottom panel: N_0 = 10,000, K = 20,000. Graphs show changes in absolute population size compared to scenario with no harvest (solid line at 0). Front-loading and back-loading harvests lead to more chaotic population trajectories compared to other scenarios. None of the scenarios lead to significant declines in abundance compared to the base case with no harvest (see Table 3). Two scenarios shown for illustrative purposes, and other scenarios (different K values, 10-year blocks instead of 5-year, etc.) are similar (Tables 3, 4). All scenarios used r_{max} = 0.04 and z = 2.39.

MODEL SENSITIVITY TO PARAMETER CHOICES

The model results presented (100-year and 40-year simulations) provide confidence that modest carry-over provisions for bowhead whale licences are sustainable based on the parameter values employed. The model results are, however, highly dependent on these parameter values. The parameter values for N_0 and K were informed by available information on current abundance (Doniol-Valcroze et al. 2020, Frasier et al. 2020) and models of historic abundance (e.g., Allen and Keay 2006, Witting 2011, Higdon and Ferguson 2016), and the ranges of values used help address uncertainty. The results are also sensitive to the selection of other parameter values, however, specifically r_{max} and z. We explored the sensitivity of the default parameter values (r_{max} = 0.04; z = 2.39) by re-running some models with alternate values. Specifically, we used lower values for both parameters, with r_{max} = 0.03 (i.e., reduced reproductive potential) and z = 1.0 (MSYL at 50% of K), to assess theoretical scenarios where EC-WG bowhead whales would show a slower response to population reduction.

Figure 6 shows 100-year population trajectories comparing r_{max} = 0.3 and 0.04 and z = 1.0 and 2.39, for N_0 = 10,000 and K = 15,000, under scenarios of no harvest and harvest at PBR. These scenarios are presented for illustration, but patterns are broadly similar for other combinations of N_0 and K. Under no harvest, all scenarios are fully recovered (i.e., > 90% of K) at the end of the 100-year model runs, even when both r_{max} and z are reduced. When the full PBR limit (52 whales) is removed annually, model runs with lower r_{max} and z values still show positive population growth, albeit with slightly reduced recovery (ca. 84% of K at N_{100}, vs ca. 96% of K at N_{100} when r_{max} = 0.04 and z = 2.39). Results of the 40-year carryover assessment models with slower reproduction and population response were also generally similar to the base models. Even the most conservative models, with N_0 = 5,000, showed positive population growth under realistic carry-over scenarios. For example, a model with 50% carry-over in a 10-year licensing block (i.e, 100 licences total, 50% carry-over, maximum 15 whales harvested per year) still allows the population to grow from 5,000 at N_0 to over 9,000 at N_{40} (mean = 9,088, range 9,036–9,126, n = 1,000 model runs) with K = 15,000, r_{max} = 0.03, and z = 1.0.

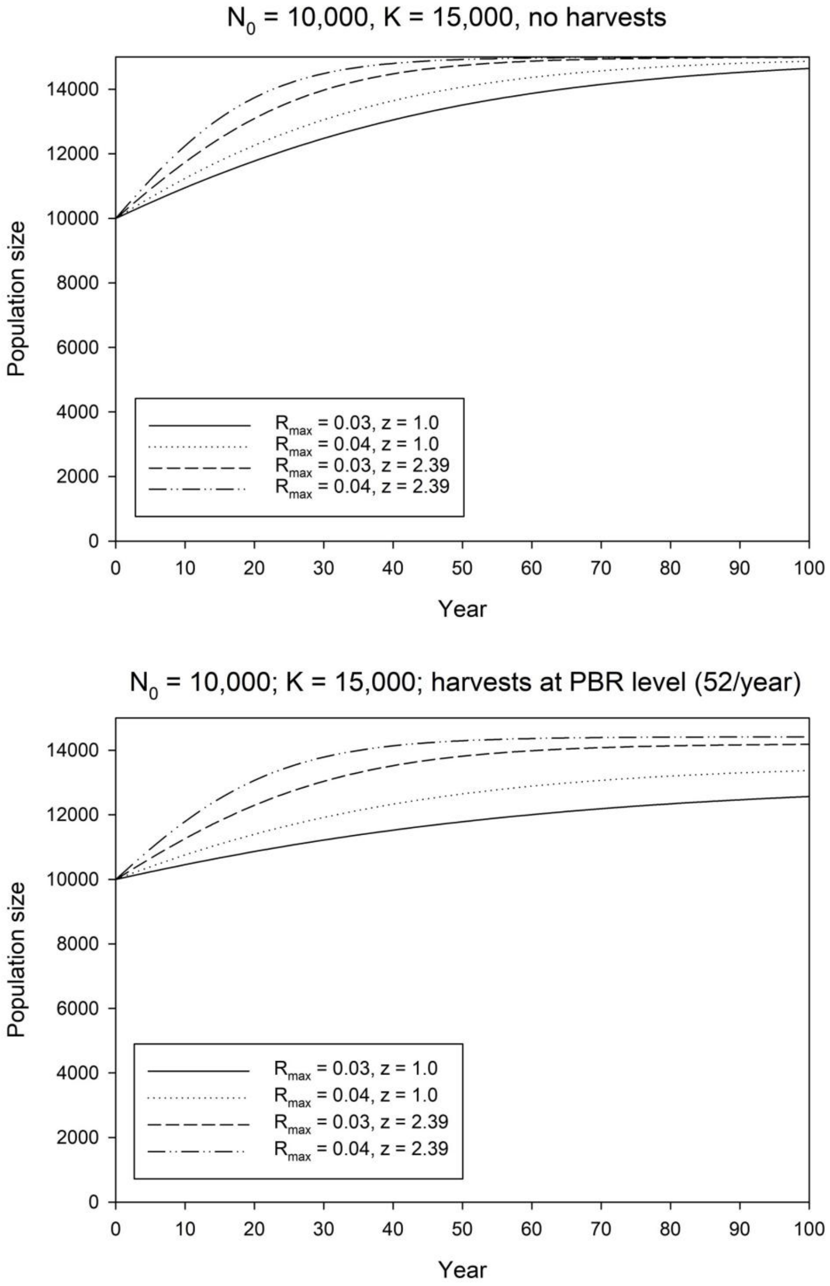


Figure 6. Effects of alternate parameter values for r_{max} and z on 100-year population trajectories. Graphs show population trajectories for N_0 = 10,000 and K = 15,000 with r_{max} = 0.3 and 0.04 and z = 1.0 and 2.39, for no harvest (top) and harvest at PBR (52 whales per year).

DISCUSSION

The sustainability of flexible licence allocations for EC-WG bowhead whale subsistence harvests was examined using a Pella-Tomlinson logistic growth population model. The approach used in this assessment is broadly similar to that used in other DFO assessments of carry-over provisions (Doniol-Valcroze et al. 2014, Richard and Young 2015, Hammill et al. 2016). To reflect uncertainty in our knowledge of population status, a range of starting population sizes (N_0) and carrying capacity (K) values were used in model simulations as an alternative to attempting to fit a model to uncertain abundance data and life-history information. For most models, the parameter values for r_{max} and z matched those used in previous assessments of EC-WG bowhead whale population growth (Higdon and Ferguson 2016, Ferguson et al. 2021).

All model scenarios indicate that any of the harvest allocations and carry-over provisions for bowhead whale licences assessed will be sustainable under the model and parameter value assumptions used here. Specifically, in response to the two questions proposed by DFO Resource Management:

A) IS IT SUSTAINABLE TO CARRY OVER UNUSED STRIKES (OR SOME PROPORTION OF THEM) FROM ONE YEAR TO A SUBSEQUENT YEAR(S)?

Yes, carry-over models show that there is little effect on EC-WG bowhead whale population trajectories and final population sizes under these model scenarios, even with unrealistically permissive carry-over scenarios that allow all licences to be carried over throughout a harvest block. Under the carry-over scenarios assessed, the modelled bowhead whale population continued to grow towards carrying capacity (K). Models that limit carry-over to 50% of the modeled 10 whale annual licence allocation, and for one-year only, are no different than conservative models of consistent harvests. Furthermore, all models used a high harvest limit when compared to recent removal levels (10 whales per year rather than the typical harvest of 3–4 or less in recent years), which adds confidence to these model assessments.

B) WHAT ARE THE PROBABILISTIC RISKS ASSOCIATED WITH THE TIME INTERVAL WITHIN WHICH UNUSED STRIKES COULD BE CARRIED OVER BEFORE RESETTING THE ACCUMULATION TO 0?

Models examined 5- and 10-year allocation blocks for harvests. Strikes were not specifically modelled, we instead assumed that all strikes resulted in landings. The differences between 5- and 10-year blocks varied depending on the scenario used. Under a conservative scenario where unused licences (up to half the yearly allocation) could be carried over for one year only, there was no difference between a 5- and 10-year block. This is expected however, given the conservative one-year carry-over limit. Under a more permissive scenario, 10-year allocation blocks resulted in a slightly lower population size after 40 years compared to 5-year allocation block, but the differences were negligible (ca. 1% of K, and < 3.5% of the most recent aerial survey-derived current (2013) population estimate) (and as previously noted this is an extremely permissive allocation model that allows unrealistically high harvests). While the model structure did not permit a probabilistic assessment of risk, scenario endpoints indicate that there is little management risk with respect to expected population growth using the parameters selected with a 5-year or 10-year allocation block, under reasonable harvest levels.

Other scenarios could be examined, for example allowing carry-over for a set number of years greater than one but less than the allocation block length, or for lower (or higher) allocation levels. But given the results of the 100-year simulations with removals at PBR levels (52 whales/year) and the 40-year simulations with highly permissive carry-over provisions and conservative allocations, any scenario that accurately reflects current and likely future bowhead whale licence requests can operate under a flexible allocation scenario while better information on bowhead population status and life-history is obtained.

CAVEATS AND UNCERTAINTY

The deterministic results and recommendations presented here are dependent on the model and parameter assumptions used. The assumptions used in the primary models (e.g., $r_{max} = 0.04$, $z = 2.39$) are reasonable based on current understanding of bowhead whale population dynamics, but could be updated pending new information (e.g., data on EC-WG bowhead whale life-history, C. Matthews, DFO, pers. comm.). Furthermore, the 100-year models with PBR-level harvests were broadly similar with a reduced population growth rate ($r_{max} = 0.03$) or with alternate shaping parameters. Additionally, 40-year models with extremely conservative parameter values ($N_0 = 5{,}000$, $r_{max} = 0.03$, $z = 1$) still allow population growth under carry-over scenarios. These sensitivity analyses suggest that the uncertainty that exists can be adequately managed for as long as licence allocations are not excessive.

However, confidence in the model scenarios depends on accurate parameter values that reflect bowhead whale population status and life history. As with most Arctic marine mammals, the EC-WG bowhead population may be under considerable environmental stress associated with climate change which may result in increased natural (e.g., increased killer whale (*Orcinus orca*) predation, increased disease prevalence) and non-harvest related anthropogenic (e.g., increased ship strikes, increased ocean noise disturbance) mortality, decreased reproduction (e.g., food shortages), and lowered carrying capacity (e.g., decreased range). The impact of climate change and anthropogenic activities on bowhead whales is not well understood (magnitude or direction). Climate-driven shifts in ocean circulation patterns have altered the closely-related North Atlantic right whale's (*Eubalaena glacialis)* habitat use and led to reduced reproductive output and greater exposure to anthropogenic mortality from vessel strikes and fishing gear entanglement (Meyer-Gutbrod et al. 2021). In contrast, subadult bowhead whales in the B-C-B population have shown trends of increasing body condition with warming ocean temperatures and changing ice conditions, which has been associated with increased duration of the open-water season and changes in upwelling potential from wind stress, possibly leading to increased primary production (George et al. 2015, Harwood et al. 2015). Stochastic models could focus some of the uncertainty, but a better understanding of climate change effects is required.

The logistic growth model employed here is structured such that the population can only increase provided removals are not excessive (i.e., removals > recruitment), and stochasticity was not explicitly included due to the uncertainties noted above. Given this fact, we have focused on the differences in end values of the various scenario trajectories rather than the growth trajectories themselves. Scenario comparisons emphasize these minimal differences but as noted, are dependent on the assumptions (i.e., parameter values) employed. As better information (e.g., updated abundance estimate, life-history parameters, impacts of killer whale predation or shipping-related morality, environmental carrying capacity) becomes available to allow an informed consideration of demographic and environmental relationships, more complex models could be used (e.g., selection-delayed age- and sex-structured population dynamics models that model predation (Witting 2013) or multi-model ensembles). Witting (2013) developed comprehensive models for the B-C-B bowhead whale population, but sufficient information for similar models of the EC-WG population was not available.

Despite these uncertainties, the remarkable recovery of the EC-WG bowhead whale population from near extinction to the current abundance, in combination with the logistical challenges (Williams et al. 2015) for local subsistence hunters to manage a larger allocation, results in confidence that co-management organizations can develop licence carry-over provisions in the short term. Our understanding of bowhead abundance, trend and demographic rates, and impact of climate change remains limited, and as such research efforts to obtain the needed data to validate and update the model are required. The upper bound of potential annual (or other) licence limits is constrained by estimates of sustainability, while the lower (and more realistic) bound will be set by cultural and subsistence need coupled with the logistics involved in harvesting and utilizing large cetaceans. A 10-year block for carrying over catches was assessed here, but this may be too long to provide management flexibility in the face of environmental change and the establishment of additional information on bowhead status. While the details of any carry-over provision will need to be established, a 5-year block will serve to maintain flexibility and more closely align with both the systems used in other jurisdictions (6-year IWC blocks in Alaska and Greenland) and Canada's 5-year Integrated Fisheries Management Plan management cycle. The model scenarios used here also assume that West Greenland harvests do not appreciably increase over time, and close international cooperation on bowhead whale management is required (Ferguson et al. 2021). Management agencies will need to establish the details of a carry-over system, and while these model results provide confidence that reasonable carry-over provisions will not have negative effects on bowhead population growth under the assumptions employed, other considerations are also required (e.g., harvest and utilization logistics, availability of whaling equipment, level of community interest in conducting hunts).

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