Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2016/112

Quebec and Central and Arctic Regions

Evaluating impacts of a flexible quota system on walrus harvesting

M.O. Hammill[1], A. Mosnier[1], R. Young[2]

[1]Science Branch
Fisheries and Oceans Canada
Institute Maurice Lamontagne,
850 route de la Mer
Mont-Joli, QC. G5H 3Z4

[2]Science Branch
Fisheries and Oceans Canada
Freshwater Institute,
501 University Crescent
Winnipeg, MB, R3T 2N6

December 2016

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.

Research documents are produced in the official language in which they are provided to the Secretariat.

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

Correct citation for this publication:

Hammill, M.O., Young, R.A., and Mosnier, A. 2016. Evaluating impacts of a flexible quota system on walrus harvesting. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/112. iv + 17 p.

TABLE OF CONTENTS

ABSTRACT IV
RÉSUMÉ IV
INTRODUCTION 1
MATERIALS AND METHODS 2
SIMULATION MODEL (A) 2
SIMULATION MODELS (B) 3
Model specification 4
PRIORS 6
PARAMETER ESTIMATION AND MODEL DIAGNOSTICS 7
FUTURE PROJECTIONS AND HARVEST SCENARIOS UNDER THE PRECAUTIONNARY APPROACH 7
Simulation B1 7
Simulation B2 8
RESULTS 8
SIMULATION MODEL (A) 8
SIMULATION MODEL (B) 10
Model Convergence 10
DISCUSSION 15
LITERATURE CITED 16

ABSTRACT

Various model scenarios were run to determine the sustainability of a system allowing flexible catch limits of walruses involving carry-overs or credits between years over a five-year period. Two modeling approaches were examined. In the first, population numbers are projected over a period of 100 years with harvest rates based on PBR updated from estimates of the population every ten years. Results of model runs indicate that modelling scenarios with harvest debits or credits from year to year were not significantly different from the base model with no credit or debit between years. These results indicate that a flexible harvest limit system can be sustainable, as long as the five year total remains less than or equal to the total quota for the five years (i.e. five times the PBR), as was the case in our model runs.

Évaluation des impacts d’un système de quota flexible sur la récolte de morse

RÉSUMÉ

Divers scénarios ont été simulés pour déterminer la durabilité d'un régime permettant des limites flexibles de prises de morses ainsi que des reports ou des crédits entre les années sur une période de cinq ans. Deux approches de modélisation ont été examinées. Dans la première, le nombre d'individus d'une population est projeté sur une période de 100 ans et les taux de prise sont fondés sur le prélèvement biologique potentiel (PBP) mis à jour à partir des estimations de la population tous les dix ans. Les résultats des modèles simulés indiquent que les scénarios de modélisation comprenant des débits ou des crédits du quota d'une année à l'autre n'étaient pas très différents du modèle de base qui ne comprenait pas de débit ou de crédit entre les années. Ces résultats indiquent qu'un régime souple de prélèvement peut être durable, tant que le total des cinq années reste inférieur ou égal au quota total pour les cinq années (c'est-à-dire cinq fois le PBR), comme ce fut le cas pour nos modèles.

INTRODUCTION

The primary goal of a management model is to use data to make decisions that result in meeting management objectives that are usually defined by law, regulation or some management body (Taylor et al. 2000). In the case of harvesting, these data are evaluated and advice is provided on acceptable harvest or removal levels that will respect the management objectives. In recent years there has been a trend within the Department to developing multi-year management plans, where Total Allowable Harvests are established over a 2-5 year period. The multi-year framework reduces energy allocated to annual assessments meaning that researchers can allocate more effort to longer term research, and provides stability and predictability to stakeholders in knowing what catches might be over the term of the management plan. Evidence from other fields such as weather and economic forecasting where considerably more resources have been invested has shown that the risks of ‘getting it wrong’ increase as projections into the future increase. One way to reduce the negative impact of ‘getting it wrong’ is to adopt a more risk adverse approach to providing advice on acceptable harvest levels over multiple years.

The Potential Biological Removal (PBR) method has been used to establish Total Allowable Harvests in Canada for stocks that are considered to be ‘Data Poor’, so as to generate an allowable harvest that has a very low probability of causing significant harm to the stock. It was developed in tandem with the *Marine Mammal Protection Act* (MMPA) in the United States, which identified specific management objectives for this group of animals. The main management objective of the MMPA is to allow a stock to reach or maintain its ‘Optimum Sustainable Population’, which is defined as a population level between carrying capacity and the population level at maximum net productivity (MNPL) (Wade 1998), which can also be considered the population size that provides Maximum Sustainable Yield (MSY). Marine mammals are considered to reach maximum productivity between 50 and 85% of K (Taylor and DeMaster 1993). In most simulations, theta (θ) is set to 1, which assumes that MNPL occurs at 50% K (e.g., Wade 1998). Simulation trials have shown that the PBR method performs well with respect to the management objective under different types of bias and uncertainty (Wade 1998).

In this study, we address requests for advice from Ecosystem and Fisheries Management concerning what form of flex-quota, or carry-over provisions, could be established for use in the management of walrus once a Total Allowable Harvest (TAH) is established for a management unit.

The questions posed were:

1a. 100% carry-over for 1 year only

1b. if 1a is not sustainable, is there any proportion of carry-over that is sustainable?

1c. if 1a and 1b are sustainable, could unused TAH from each season be accumulated for use in subsequent harvest seasons for consecutive years, potentially indefinitely until the existing TAH is modified?

2a. In any given harvest season can any portion of the next year’s TAH be used in the current harvest season? In this scenario, the next year’s TAH is reduced by the amount borrowed back for use in the current season.

2b. If a 100% borrow back from year 2, to use in year 1, is not sustainable, is there any proportion less than 100% that is sustainable?

3. May the 5 year sum of annual TAH for each walrus MU be applied as an overall walrus harvest limit that may be prosecuted at any time during this 5 year consecutive period?

MATERIALS AND METHODS

The request for advice was to examine if the PBR was taken each year, or if multiples of the PBR could be taken in any year, as long as the total harvest over the period of the management plan did not exceed the PBR calculation for the entire plan. PBR assumes that there is a 95% probability that the population will increase to a level above MSY within 100 years, or if already above MSY the population will remain above MSY. In this study, MSY was set at 0.5 K.

Two modelling approaches were examined.

SIMULATION MODEL (A)

The first adopted the framework presented by Richard and Young (2015), which used a discrete form of the generalized logistic equation minus a harvest which was set at the PBR level. The carrying capacity (K) was set at 20,000 walruses. This simulation framework examined the impact of different harvest scenarios on a starting population of 5,000 and 10,000 animals.

The model used here is:

$$N_{t+1} = W_t{*}\ [N_t + N_t \bullet R_{max}\ [\ 1 - (N_t\ /K)^{\theta}] - O_t \bullet PBR\ ],$$

where:

N_t = population size at year t;

R_{max} = maximum net recruitment rate, set at 0.08

K = the pre-exploitation size or carrying capacity of the population, Fixed at 20,000.

θ = the density dependent shape parameter, set at θ =1, which means that MNPL=0.5 K,

where MNPL is the Maximum Net Productivity Level which approximates the population size at which it is possible to obtain Maximum Sustainable Yield (MSY).

O_t = the multiplier on PBR in year t, which was adjusted to simulate carry-over or borrow back harvests between years

PBR_t = Potential Biological Removal in year t. where

$PBR = N_{min,t} \bullet 0.5 \bullet R_{max} \bullet F_r$

F_r = recovery factor = 0.5 or 1, depending on whether the starting population (N_0) was above or below MSY then F_r = 0.5, or above MSY then F_r = 1.

$N_{min,t}$ is the minimum population estimate for the stock, which is estimated as the 20% percentile of the log-normal distribution of the estimated population size ($E(N_t)$), and is calculated as :

$N_{min,t} = E(N_t) / [\exp(z_{20} \bullet \mathrm{sqrt}[\ln(1+CV^2)])]$,

with z_{20} = 0.842 (standard normal variate for 20th percentile) and a coefficient of variation (CV) = 0.3.

The PBR estimate was updated every decade with a new ‘aerial survey’ estimate. This PBR was applied for 10 years until another ‘survey’ was completed and the PBR was updated again.

The ‘aerial survey estimate was obtained by sampling from the model $E(N_t)$ assuming a lognormal distribution of mean N_t and CV of 30%, as follows:

$E(N_t) = Exp(Log(N_t / (1 + (CV0.5))) + z_r \bullet ((Log(1 + CV^2))0.5))$ where z_r is a random normal deviate = $(-2*Log(Uniform(0,1))*Cos(2*\pi*Uniform(0,1))$.

To simulate natural variability, the scenarios were run with an additional random parameter for variability in recruitment/mortality W_t, where:

$W_t = Exp(z_p*s_{pro} - s_{pro}^2/2)$, s_{pro} is the process error,

and z_p is a normal deviate (Hilborn and Mangel 1997 Equation 7.39 and 7.40).

The process error was set at 0.05 with the assumption that the population dynamics of the long-lived walruses, and probably many long-lived slow-reproducing mammals, are not highly variable (e.g., Ahrestani et al. 2013; Doniol-Valcroze et al. 2013).

In the simulations, total harvests over the management period did not exceed PBR. No adjustment was made for struck and lost. It was assumed that this would be estimated separately as TAH = PBR - struck and lost.

Modelling scenarios were developed to address each question as follows (where the vector indicates the year of the management plan):

a. Base - constant harvest in year x: where O_t = (1,1,1,1,1),
b. Front -100% borrowback in year x: where O_t = (2,0,2,0,1),
c. Back - 100% carryover in year x: where O_t = (1,0,2,0,2)
d. 5X - Sum of all 5 years TAH taken in one year x, where for x = 1, O_t = (5,0,0,0,0)

In all scenarios, 1,000 projections were run for each population and harvest scenario. The projection was carried for 100 years with PBR updates every ten years.

SIMULATION MODELS (B)

- In a second approach, we conducted the simulation using the Hudson Bay-Davis Strait stock assessment model (Hammill et al. 2016a)
- The model was fitted to the nine aerial surveys that have been completed since 1954 (Table 1). Details related to these surveys and adjustments to account for animals not hauled out at the time the surveys were flown are described in Hammill et al. (2016a,b).

Table 1. Abundance observations from Nottingham/Fraser/Salisbury island complex and the Walrus – Coats island complex (from Hammill et al. 2016b)

Location / Survey type	Date	Number (SE)	Proportion hauled out (SE)	Adjusted number (SE)	Source
Hudson Strait to Southampton Island	Sept 2014	2,144	0.30 (0.173)	7,147 (4,122)	Hammill et al. 2016a
Hudson Strait	Mar-Apr 2012	55		5,254 (1,591)	Elliot et al. 2013
Walrus-Coats Island-Southampton Island					
Aerial surveys	August 1954	2,900 (435)	0.30 (0.173)	9,667 (5,760)	Loughrey 1959
Aerial/boat surveys	Aug 1961	2,650	0.30 (0.173)	8,833 (5,094)	Mansfield 1962
Aerial surveys	July-Aug. 1976	254-1,491 (Mean=820 SE=442)	0.30 (0.173)	2,733 (2,156)	Mansfield and St. Aubin 1991
Aerial surveys	July –Aug 1977	6-2,171 (Mean=65, SE=670)	0.30 (0.173)	2,707 (2,692)	Mansfield and St. Aubin 1991
Aerial surveys	Aug 1988	757+92	0.30 (0.173)	2,830 (1,632)	[1]Richard 1993
Aerial surveys	July 1989	1,231+97	0.30 (0.173)	4,427 (2,553)	[1]Richard 1993
Aerial surveys	Aug 1990	1,373+461	0.30 (0.173)	6,113 (3,526)	[1]Richard 1993

[1] Richard, P.R. 1993. Summer distribution and abundance of walrus in northern Hudson Bay, western Hudson Strait and Foxe Basin: 1988-1990. AFSAC meeting 17-18 February 1993. Background report. 21 p.

Model specification

The hierarchical state-space model used to provide advice (Hammill et al. 2016b) considers survey data to be the outcome of two distinct stochastic processes: a state process and an observation process.

The state process describes the underlying population dynamics and the evolution of the true stock size over time, using a discrete theta-logistic model, i.e., a re-parameterization of the Pella-Tomlinson model (Pella and Tomlinson 1969; Innes and Stewart 2002). Population size in each year N_t (from 1954 to 2014) is a multiple of the previous year's population size, with removals deducted:

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

where λ_{max} is the maximum growth rate, K is environmental carrying capacity and theta (θ) defines the shape of the density-dependent function. ε_{p_t} is a stochastic term for the process error and R_t are the removals for that year. Reported removals from 1954-2014 were included in the model (Table 2). Future removals were estimated assuming that the TAH was set using the PBR approach. Removals were calculated as reported catches, C_t, corrected for the proportion of animals that were struck and lost (SL) and O_t , the multiplier on PBR in year t, which was adjusted to simulate carry-over or borrow back harvests between years:

$$R_t = C_t \cdot (1 + SL) \cdot \mathrm{Ot}$$

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

$$S_t = N_t \cdot \varepsilon_{s_t}$$

with $\varepsilon_{s_t} \sim logN(0, \tau_s)$ and τ_s the precision parameter (see prior section below).

Table 2. Adjusted harvest statistics for communities harvesting walrus from the Hudson Bay-Davis Strait for the period 1954–2014. In years where there were no reports, the five year average harvest was used to replace the blank cell. Data from communities in Ungava Bay, and Hudson Strait, plus Akulivik, Coral Harbour, Repulse Bay, Chesterfield Inlet, Rankin Inlet and Arviat.

Year	Harvest	Year	Harvest	Year	Harvest
1954	603	1969	284	1995	193
1955	528	1970	307	1996	187
1956	462	1971	328	1997	120
1957	448	1972	310	1998	97.8
1958	543	1973	367	1999	66
1959	391	1974	377	2000	97
1960	426	1975	454	2001	81
1961	400	1976	244	2002	139
1962	300	1977	279	2003	90
1963	311	1978	198	2004	95
1964	324	1979	277	2005	111
1965	288	1980	339	2006	155
1966	338	1981	306	2007	118
1967	384	1982	352	2008	93
1968	311	1983	323	2009	93
1969	284	1984	233	2010	94
1970	307	1985	211	2011	88
1971	328	1986	273	2012	114
1972	310	1987	175	2013	59
1973	367	1988	243	2014	72
1974	377	1989	168		
1975	454	1990	211		
1976	244	1991	229		
1977	279	1992	187		
1978	198	1993	220		
1979	277	1994	194		

PRIORS

The basic inputs and priors from the stock assessment were used to provide the initial fit of the model (Table 3).

We know little about carrying capacity and the theta density-dependence parameter for walrus. Marine mammals are considered to reach maximum productivity at around 60% of K (range 50-85% of K), (Taylor and DeMaster 1993), which results in theta lying around 2.39 (range between 1 and 7. We assumed a prior with a gamma (6.1, 2.3) distribution for theta which results in a median value of 2.5 and quartiles at 1.9 and 3.3 (Table 3). This results in maximum productivity occurring at 61% of K, with quartiles at 58 and 64% of K. Reported harvests underestimate the number of walrus killed because of animals wounded or killed but not recovered, as well as an absence of harvest reports for some communities in different years. We gave the struck-and-lost correction factor (*SL*) a moderately informative prior following a Beta (3, 4) distribution, with a median of 0.42 and quartile points at 0.29 and 0.55.

Table 3. Prior distributions, parameters and hyper-parameters used in Hudson Bay-Davis Strait walrus population model "dist." denotes a hyper-parameter with its own prior distribution. The same parameters were used for the Foxe Basin Model except for the Struck and Loss parameter. In Foxe Basin, this parameter followed a Beta (2, 4).

Parameters	Notation	Prior distribution	Hyper parameters	Values
Survey error (t)	εs_t	Log-normal	μ_s τ_s	0 gamma(1.5, 0.001)
Precision (survey)	τ_s	*Gamma*	α_s β_s	2.5 0.4
Process error (t)	εp_t	Log-normal	μ_p τ_p	0 gamma(2.5, 0.4)
Precision (Process)	τ_p	Gamma	α_p β_p	1.5 0.001
Density dependence Shape (theta)	θ	Gamma	α_s β_s	6.1 2.3
Density dependence Shape (theta)	θ	Fixed		1
Struck-and-lost	SL	Beta	α_{SL} β_{SL}	3 4
Initial population	N_{1954}	Uniform	N_{upp} N_{low}	30,000 500
Carrying capacity	K	Uniform	N_{upp} N_{low}	35,000 500
Maximum annual growth rate	λ_{max}			1.08

The stochastic process error terms ε_{p_t} were given a log-normal distribution with a zero location parameter. The precision parameter for this lognormal distribution was assigned a moderately informative prior following a gamma (1.5, 0.001) distribution. These parameters were chosen so that the resulting error multiplier would have a median of 1 and quartiles of 0.98 and 1.02 reflecting our belief that walrus stock dynamics are not highly variable.

The uncertainty associated with each survey is poorly estimated. Therefore, this uncertainty was incorporated into the fitting process only by guiding the formulation of the prior distribution of the survey error. The survey error term ε_{s_t} followed a log-normal distribution with a zero location parameter. Its precision parameter was given a moderately informative prior following a gamma (2.5, 0.4) distribution. These parameters were chosen so that the resulting CV on the survey estimates would have quartiles of 35% and 55%, which are approximately equivalent to the range of what we consider to be plausible CV for the survey abundance estimates.

PARAMETER ESTIMATION AND MODEL DIAGNOSTICS

We obtained posterior estimates of all the parameters using a Gibbs sampler algorithm implemented in JAGS (Plummer 2003). Results were examined using packages R2jags and coda developed in the R programming language. Initial runs of the code were made to investigate convergence and mixing (i.e., the extent and spread with which the parameter space was explored by the chain), as well as autocorrelation. Following these initial runs, we kept one sample every 20 iterations from 5 chains of 160,000 iterations, after a burn-in of 10,000 samples, for a total of 40,000 samples. For the projections, 1 in every 10 iterations was retained from 5 chains of 50,000 iterations after a burn-in of 5,000. We tested for mixing of the chains using Geweke's test of similarity between different parts of each chain (Geweke 1996), and for convergence between chains using the Brooks-Gelman-Rubin (BRG) diagnostic, which compares the width of 80% Credible Interval (CI) of pooled chains with the mean of widths of the 80% CI of individual chains (Brooks and Gelman 1998).

FUTURE PROJECTIONS AND HARVEST SCENARIOS UNDER THE PRECAUTIONNARY APPROACH

The objective was to test whether a flexible quota would allow variable harvesting and still respect the management objective. This was examined in two ways using the stock assessment model.

Simulation B1

The model was fitted to the 1954–2014 survey data, the PBR was estimated and a total Allowable Landed Catch (TALC) was estimated taking into account the Struck and Lost estimated by the model. The population was projected forward for 30 years using a fixed TALC and the following scenarios, where the harvest in each year was a multiple of the annual TALC*O_t.

Base: O_t ~ (1,1,1,1,1)

Front: O_t ~ (2,0,2,0,1)

Back: O_t ~ (1,0,2,0,2)

Extended: O_t ~ (1,0,2,0,2)(2,0,2,0,1)

5X: Ot ~(5,0,0,0,0)

Simulation B2

In the previous simulation the PBR and thus the TALC were fixed during the whole period of model projection. Here we consider recalculate the TALC at the end of each management plan cycle. To do so, we use the following protocol:

- As for the previous simulation, the model was fitted to the 1954–2014 survey time series. A first total Allowable Landed Catch (TALC) was estimated taking into account the Struck and Lost estimated by the model.
- Projected harvests were divided into 5 year blocks to represent a 5 year management plan cycle. Three scenarios were considered in which harvest in each year was equal to TALC*O_t :
    - o Base: O_t ~ (1,1,1,1,1)
    - o Front: O_t ~ (2,0,2,0,1)
    - o Back: O_t ~ (1,0,2,0,2)
    - o 5X: Ot ~ (5,0,0,0,0)
- The population was then projected forward five years.
- At the end of five years, a new PBR was estimated, using the cv that was generated by the model for year five of the projection, where cv=$sd_{year\ 5}$/mean population $estimate_{year\ 5}$. A revised TALC was then calculated from the new PBR.
- A new population estimate or pseudo-aerial survey estimate (PASE) was drawn randomly from the population size values obtained from the runs.
- The model was refitted, taking into account the new PASE, thus avoiding an overly large error around the population estimates that would impact the next PBR calculations. The model was projected forward 5 years using the revised TALC.
- This routine was repeated six times to represent a 30 year projection. In each scenario the same pattern of harvests were maintained throughout the scenario. This meant that the actual harvests could vary between the 5 year blocks, depending on the estimated population, but the proportion of the overall TALC (TALC*Ot), harvested in each year identified for the scenario, remained the same over the 5 years.

RESULTS

SIMULATION MODEL (A)

In the first simulation, the population was projected forward 100 years. The median for all projections for each scenario resulted in the population moving above the threshold or MSY within 20 years (Figure 1). Some differences between harvest scenarios in population trajectories were observed, but all estimates of the median trajectory lay within the 95% confidence interval for the base scenario, which had a constant harvest during each five year block.

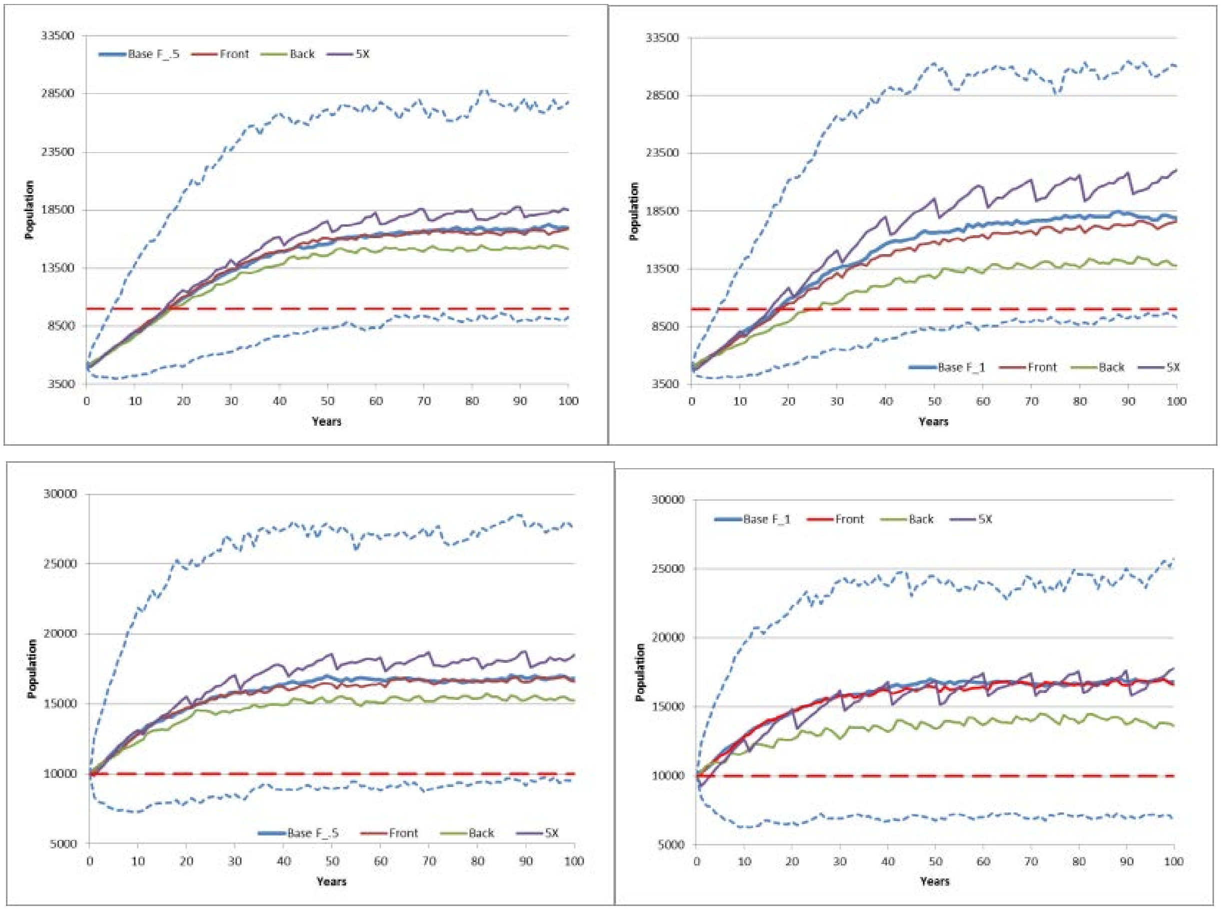

*Figure 1. Projected changes in abundance for a population subject to the different harvest scenarios projected forward 100 years. The red dashed line is the abundance at the Maximum Sustainable Yield (MSY) level. The dotted lines represent the 95% confidence intervals for a population projected forward with the same harvest taken in each 5 year block (Base scenario). Projections assumed a population that started below MSY levels (N=5000) and a recovery factor of 0.5 (top left), a starting population at the MSY level (N=10,000) and a recovery factor of 0.5 (bottom left), a starting population below MSY (N=5,000) and a recovery factor of 1 (top right) and a starting population at MSY (N=10,000) and a recovery factor of 1 (bottom right). Annual harvests varied according to the scenario, but the overall harvest in a 5 year block did not exceed 5*PBR.*

In all runs, over 75% of the populations were above the threshold of MSY within 100 years (Figure 2).

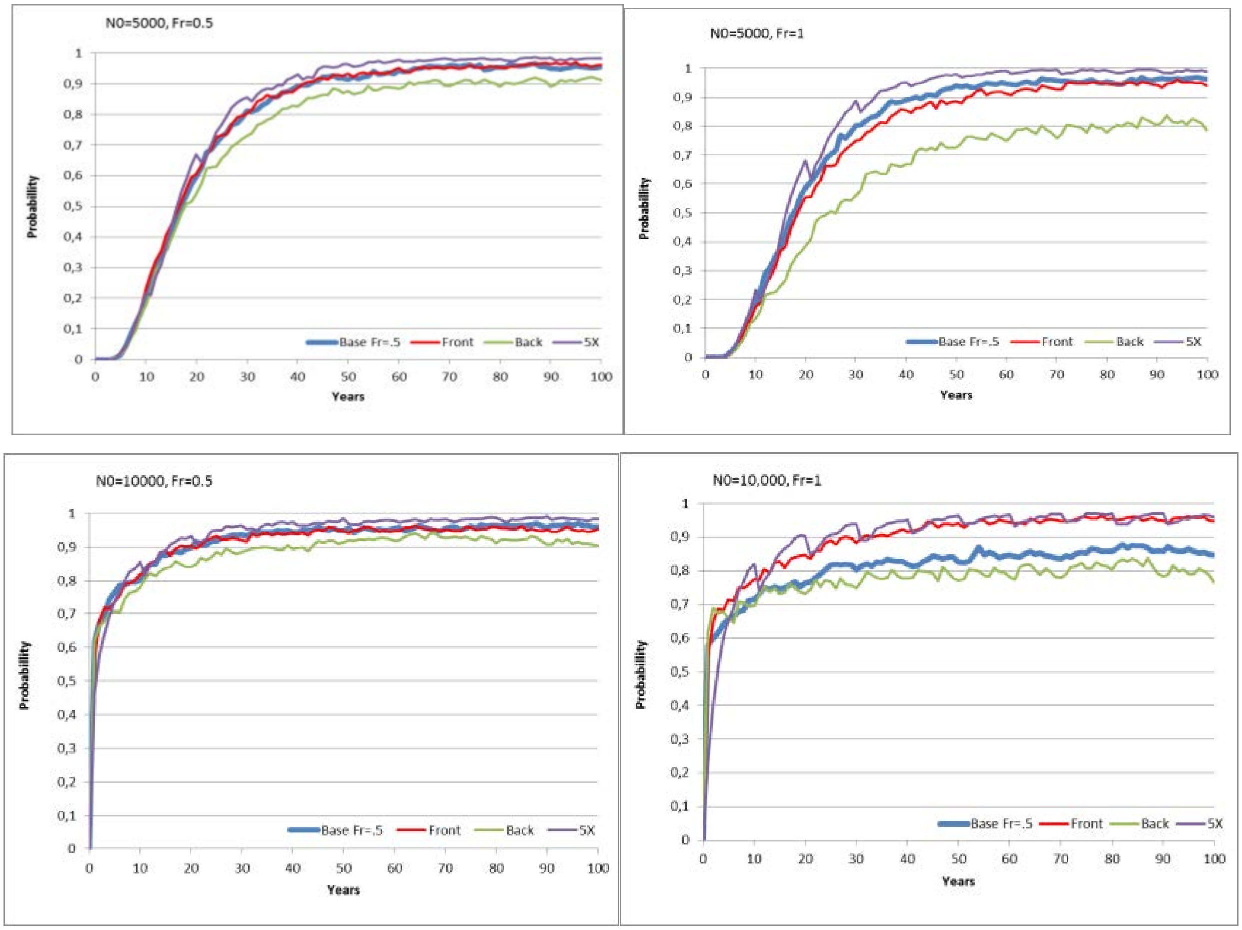

*Figure 2. Probability that the population exceeds the threshold (MSY) of 10,000 animals in year of projection, for different starting populations, recovery factors and harvest scenarios for a population projected forward 100 years, from a start of 5,000 (top row) or 10,000 animals (bottom row), K=10,000, and R_{max}=0.08. Harvests were set using PBR with a Recovery factor (F_r) of 0.5 (left column) or 1.0 (right column). The PBR was updated every 10 y. Annual harvests varied according to the offset identified for the scenario, but the overall harvest in a 5 year block did not exceed 5*PBR. The harvest offsets (Harvest=PBR*O_t) were: Base O_t~(1,1,1,1,1), Front O_t~(2,0,2,0,1), Back O_t~(1,0,2,0,2), and 5X O_t~(5,0,0,0,0).*

SIMULATION MODEL (B)

For the next set of simulations the stock assessment model (see Hammill et al. 2016a) was used to examine the impacts of the flexible quota system.

Model Convergence

Each of the five chains showed rapid mixing and reached a stationary distribution (Geweke's diagnostic, all Z-scores < 1.96). There was some evidence of cross correlation between the carrying capacity (K), the starting population and struck and lost (S&L)(Figure 3).

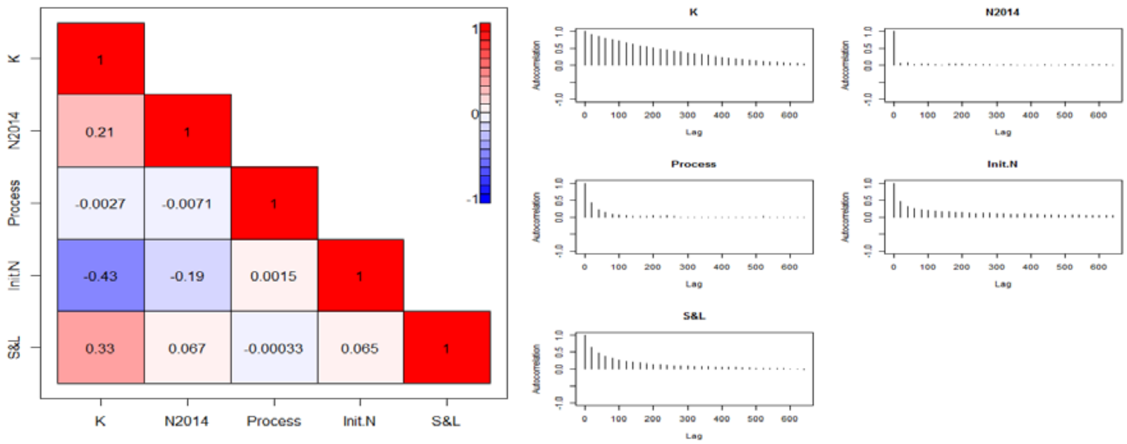

Figure 3 Cross-correlation and autocorrelation plots from the 30 year projection model run. In this run, carrying capacity (K), struck and lost (S&L), and the initial population (init.N) had priors outlined in Table 3.

Simulation B1: 30 year projection

The first set of simulations using the assessment model fitted to the 1954-2014 survey data, and projected forward 30 years using the same PBR over the entire projection. In this scenario the model was allowed to estimate K and the density dependent shaping parameter (θ). It resulted in median for K = 10,000, θ =2.4 and an estimated population in 2014 of 6,800 individuals. Thus in this scenario, the population was above the MSY threshold at the start of the simulation period. In the first run, all harvest scenarios resulted in similar estimates of abundance after the 30 year projection. These scenarios also allowed the population to increase, and the probability that the population was above the Maximum Net Productivity Level was greater than 95% after only 20 years (Fig. 4). The scenario where five times the annual PBR was taken in the first year, and then no harvesting occurred in the subsequent four years had the most variable impact on the population, but in all harvest scenarios, the median estimate of abundance remained above MSY and the population estimates all fell within the 95% Credibility Interval for the Base harvest scenario ($O_t \sim 1,1,1,1,1$) (Figure 4).

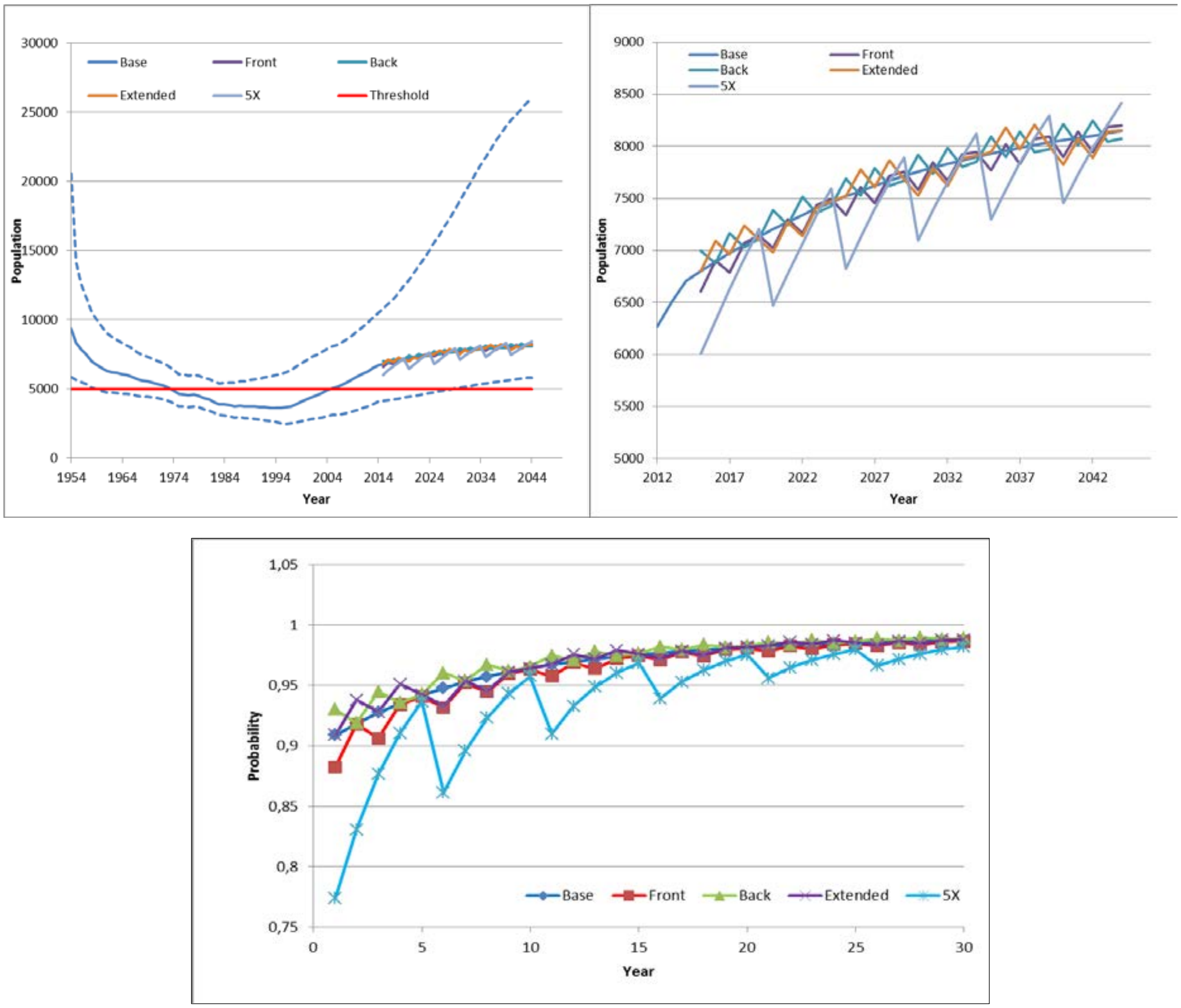

Figure 4. Trajectory of walrus population subjected to different harvest strategies (top) and the probability that the population will be above the MSY threshold after 30 years (bottom). In this scenario the median K=10,000, θ =2.4 and the estimated population in 2014 was 6,800. The threshold was set at 50% of carrying capacity (i.e., 5,000 animals). The dotted lines are the 95% Credibility intervals from the Base run. The harvest scenarios assumed the same Potential Biological Removal (PBR) over the projection period, and that it was taken in 5 year blocks, where the harvest was allowed to vary as multiples of PBR, within the 5 year block, but the overall harvest in that block did not exceed the allowable harvest level. The harvest scenarios were : Base= $O_t \sim (1,1,1,1,1)$; Front = $O_t \sim (2,0,2,0,1)$; Back = $O_t \sim (1,0,2,0,2)$ Extended= $O_t \sim (1,0,2,0,2,2,0,2,0,1)$ and 5X= $O_t \sim (5,0,0,0,0)$.

In subsequent runs, θ was fixed to 1, this resulted in a median K=17,900, and a population in 2014 of 6,100 i.e. the population at the start of the simulation period was below the threshold of 8,950 (Figure 5). Under all simulations the population increased, but the probability that the population was above the threshold was only 0.5 after 30 years. The scenario where five times the annual PBR was taken in the first year, and then no harvesting occurred in the subsequent four years had the most variable impact on the population as was observed in the first simulation.

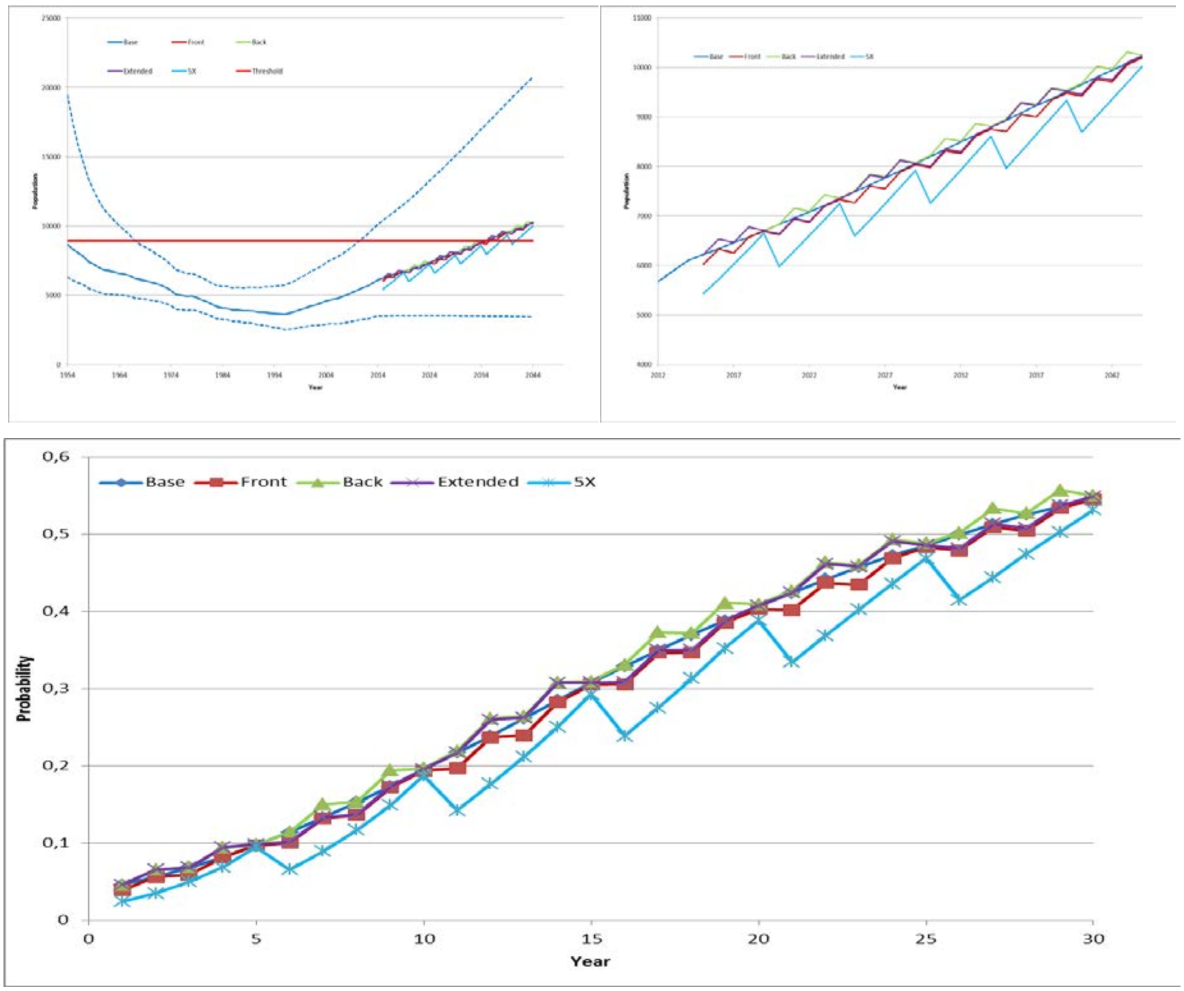

Figure 5 Trajectory of walrus population subjected to different harvest strategies (top) and the probability that the population will be above a management threshold after 30 years (bottom). In this scenario the median K = 10,000, theta = 2.4 and the estimated population in 2014 was 6,800. The threshold was set at 50% of carrying capacity. The harvest scenarios assumed the same Potential Biological Removal (PBR) over the projection period, and that it was taken in 5 year blocks of time, where the harvest was allowed to vary as multiples of PBR, within the 5 year block, but the overall harvest in that block did not exceed the allowable harvest level. The harvest scenarios were : Base = O_t ~ (1,1,1,1,1); Front = O_t ~(2,0,2,0,1); Back = O_t ~(1,0,2,0,2) Extended = O_t ~ (1,0,2,0,2,2,0,2,0,1) and 5X = O_t ~ (5,0,0,0,0).*

Simulation B2: 30 year projections with population updates every 5 years

In this set of simulations, θ =1. The model was fitted to the survey data (1954–2014), and the population was projected forward for 30 years in 5 year blocks, with the PBR and population also updated every five years. Only three scenarios were examined: Base, Front and Back. For these three scenarios, the Base run showed a population increase to just under 12,000 animals after 30 years, while the Front and Back harvest scenarios both ended up with populations of 10,000 animals, although there is considerable overlap in the 95% Credibility Intervals. The larger population increase observed with the Base run was due to the higher aerial survey estimates observed over the last decade of the simulation (Figure 6). No differences in the probability that the population was above MSY were observed among runs for the first 15 years of the projections. After the first 15 years, the Front harvest scenario started to diverge from the

Base scenario, which persisted for another 15 years. During the last 5 years all scenarios converged on the Base scenario (Figure 7)

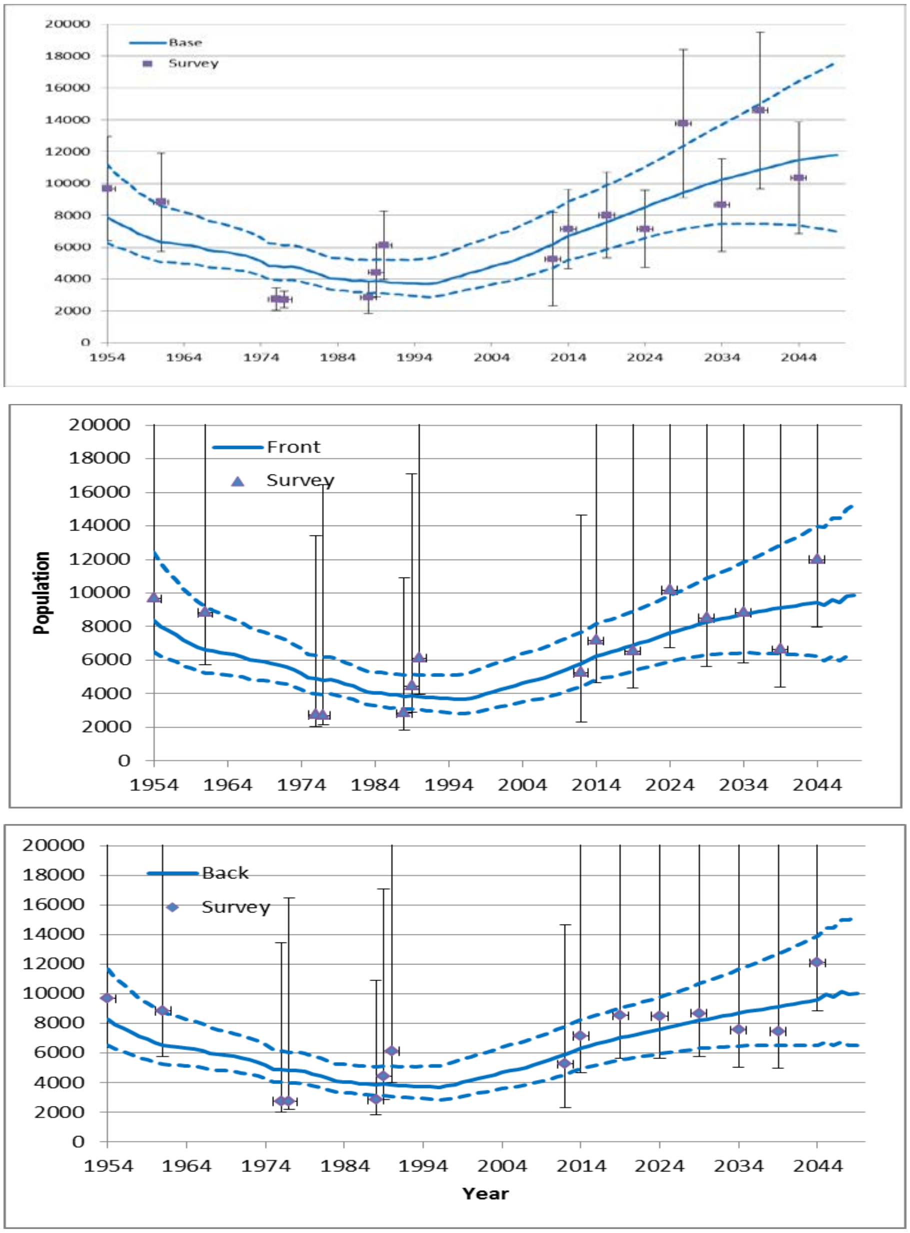

Figure 6 Population trajectory from fitting the assessment model to actual (1954–2014) and pseudo aerial survey points (2019–2044). The population estimate was updated every 5 years with a pseudo survey, and the PBR estimate was updated as well. Three different runs were made: Base scenario where an equal PBR was taken every year, a Front harvest [$O_t \sim (2,0,2,0,1)$] and a Back harvest [$O_t \sim (1,0,2,0,2)$], where the number taken in a single year was a multiple of the PBR.

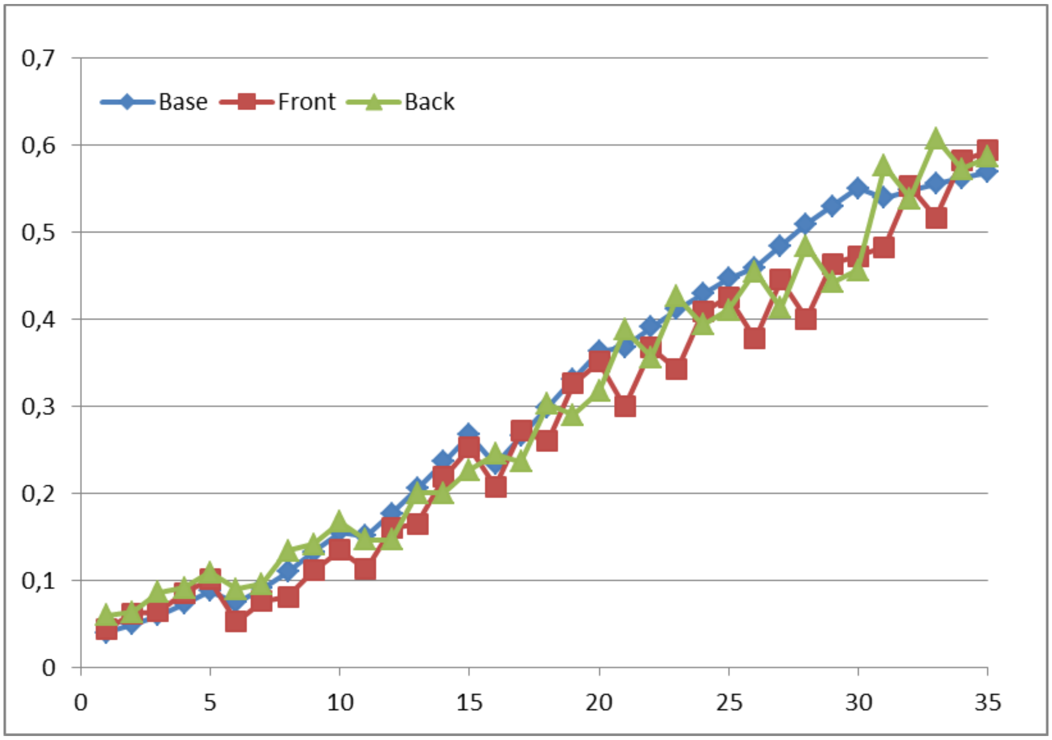

Figure 7. The probability that the population was above the Maximum Sustainable Yield (MSY) Level during projections extending 30 years into the future. Three different runs were made: Base scenario where an equal PBR was taken every year, a Front harvest [$O_t \sim (2,0,2,0,1)$] and a Back harvest [$O_t \sim (1,0,2,0,2)$], where the number taken in a single year was a multiple of the PBR. At the end of the five years, the population was updated and the PBR was re-calculated.

DISCUSSION

In this study, we assumed that the age and sex structure of the catch was similar to that of the population. If certain age or sex classes are targeted, then effects will differ from those modelled in this study. For example, if adult females were targeted, we have underestimated the impact of harvesting on the population. We used two general approaches to examine the impact of a flexible TAH system on a simulated population of Atlantic walruses. In the first approach, we used the same general approach as that developed in Wade (1998) to evaluate the effectiveness of PBR in meeting the management objective that a population subject to PBR removal levels will recover to MSYwithin 100 years, or if above MSY to remain above MSY. However, the initial modeling by Wade (1998) was deterministic. In this study, we included a small amount of process error, to represent some uncertainty in how the population might vary, as did Richard and Young (2015), in their analysis of the sustainability of a flexible system of harvesting for narwhal. Overall, the addition of process error to the analysis meant that the probability that the population would be above MSY after 100 years remained high, but was generally less than 0.95. Some differences in population trajectories were observed, but these differences were not consistent between scenarios, indicating they were due more to variability/uncertainty in net productivity, than to the type of harvest scenario applied during the simulation.

In the second series of simulations we used the stock assessment model to evaluate the potential impact of a flexible harvest system on model behaviour and trend in the population. The stock assessment model incorporated more uncertainty in model parameters including additional uncertainty in S&L, survey precision, and fitted parameters such as K, and in some simulations uncertainty in the shape of density-dependence relationship. Moreover, in some simulations, new ‘survey’ estimates were generated every 5 years by drawing randomly from the values available from the MCMC runs, without assuming a distribution. Refitting the model to the new ‘population estimate data’, new values of PBR were calculated at the end of each management plan period and applied to the next management plan simulated. Overall, the population did not appear to increase above MSYas quickly using the stock assessment model, but the results were generally the same as those obtained in the first series of simulation.

In both cases, the use of a flexible quota system is unlikely to have an impact on the population as long as the overall harvest does not exceed levels identified under a regime of constant harvest levels (i.e. the total quota for the 5 years of the management plan). However, the simulations also show that uncertainty due to natural variability or uncertainty in model parameters can have an important impact on the dynamics of the population, where possible combinations of reduced productivity (due to higher mortality or lower reproduction) and higher harvests can lead to slower population growth.

In this study, harvest levels as much as five times the annual rate did not have an appreciable impact on the population over the long term. Although, high harvests in a single year, combined with harvest closure during multiple years is not likely a desirable outcome, such conditions may further limit population recovery if they coincide with an unusual natural mortality event or reproductive failure. While this population model includes several sources of uncertainty, it does not consider the impact of the harvests over the population age structure, and its potential long term effect on the population dynamics. Overall, the best strategy appears to be to minimize as much as possible, variability in harvesting between years.

LITERATURE CITED

Ahrestani, F.S., Hebbelwhite, M. and Post, E. 2013. The importance of observation versus process error in analysis of global ungulate populations. Scientific Reports 3, 3125; DOI: 1038/srep3125: p.1-10.

Brooks, S. P. and Gelman, A. 1998. Alternative methods for monitoring convergence of iterative simulations. J. Comput. Graph. Stat. 7:434–455.

Doniol-Valcroze, T., Gosselin, J.-F., and Hammill, M.O. 2013. Population modeling and harvest advice under the precautionary approach for eastern Hudson Bay beluga (*Delphinapterus leucas*). DFO Can. Sci. Advis. Sec. Res. Doc. 2012/168. iii + 31 p.

Elliot, R.E, Moulton, V.D., Raborn, S.W. and Davis, R. A. 2013. Hudson Strait marine mammal aerial surveys, 10 March to 2 April. Report prepared by LGL Ltd for Baffinland Iron Mines Corp. 107 p. (LGL Report No. TA8129-2. Prepared by LGL Limited, King City, ON for Baffinland Iron Mines Corporation, Toronto, ON. 87 p.).

Geweke, J. 1996. Evaluating the Accuracy of Sampling-based Approaches to the Calculation of Posterior Moments, In Bayesian Statistics 4 Edited by Bernardo, J.M., Berger, J.M., Dawid, A.P., and Smith, A.F.M. Oxford University Press:169–193.

Hammill, M.O., Doniol-Valcroze, T., Mosnier, A., Gosselin, J.-F. 2016a. Modelling walrus population dynamics: A direction for future assessments. DFO Can. Sci. Advis. Sec.Res. Doc. 2016/50. V+47 p.

Hammill, M.O., Mosnier, A., Gosselin,J.-F., Higdon, J.W., Stewart, D.B.,Doniol-Valcroze, T., Ferguson, S.H. and Dunn, J.B. 2016b. Estimating abundance and total allowable removals for walrus in the Hudson Bay-Davis Strait and south and east Hudson Bay stocks during September 2014. DFO Can. Sci. Advis. Sec.Res. Doc.2016/036. v + 37p.

Hilborn, R. and Mangel, M. 1997. The Ecological Detective: confronting models with data. Princeton University Press. 315 p.

Innes, S. and Stewart, R.E.A. 2002. Population size and yield of Baffin Bay beluga (*Delphinapterus leucas*) stocks. NAMMCO Sci. Publ. 4: 225–238.

Loughrey A.G. 1959. Preliminary investigation of the Atlantic walrus *Odobenus rosmarus rosmarus* (Linnaeus). Can. Wildl. Serv. Bull. (Ott.) (Series 1) 14: 123 p.

Mansfield, A.W. 1962. Present status of the walrus population at Southampton and Coats islands, . *In* H.D. Fisher (In Charge), Fisheries Research Board of Canada, Arctic Unit (Montreal, Quebec), Annual Report and Investigator's Summaries, April 1, 1961 to March 31, 1962. (No. 16). p. 41-52

Mansfield, A.W., and St. Aubin, D.J. 1991. Distribution and abundance of the Atlantic walrus *Odobenus rosmarus rosmarus*, in the Southampton Island-Coats Island region of northern Hudson Bay. Can. Field-Nat. 105: 95–100.

Pella, J.J. and Thomlinson, P.K. 1969. A generalized stock production model. Bull. Inter-Amer. Tropical Tuna Comm. 13: 420–496.

Plummer, M. 2003. A program for analysis of Bayesian graphical models using Gibbs sampling, in: Proceedings of the 3rd International Workshop on Distributed Statistical Computing. Vienna, Austria.

Richard, P.R. and Young, R. 2015. Evaluation of the sustainability of a flexible system of total allowable annual catches of narwhals (*Monodon monoceros*). DFO Can. Sci. Advis. Sec. Res. Doc. 2015/006. v + 13 p.

Taylor B.L., and DeMaster, D.P. 1993. Implications of non-linear density dependence. Mar. Mamm. Sci. 9: 360–371.

Taylor, B.L., Wade, P.R., DeMaster, D.P. and Barlow, J. 2000. Incorporating uncertainty into management models for marine mammals. Biol. Cons. 14: 1243–1252.

Wade, P. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. Mar. Mamm. Sci. 14: 1–37.