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Impacts of a flexible Total Allowable Take system on beluga conservation in the Nunavik Marine Region

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Subsistence harvest of beluga whales by Nunavik communities is directed towards a mixture of several stocks, including the depleted Eastern Hudson Bay stock (EHB). The 2013 reported harvest comprised 8 beluga taken in eastern Hudson Bay, 158 in Hudson Strait and Ungava Bay in the spring and 87 in the fall, 76 near Sanikiluaq, and 10 in the Long Island/James Bay area. Harvests in Nunavik have been stable in the past five years.

We updated the EHB beluga stock model with the 2013 harvest data The model continues to suggest that the stock has been stable in recent years, with some indication of modest population growth. The 2013 abundance was estimated at 3240 individuals (95% CI 1833–5614).

At the request of the Nunavik Marine Region Wildlife Board, we assessed whether a flexible TAT system would increase the probability of decline of the EHB stock. Our simulations, using a modified version of the current EHB assessment model, show that flexible allocation of takes over 3-year management periods has little impact on the conservation of EHB beluga. Only the most unbalanced scenarios had a measurable effect on the risk of stock decline. For instance, catching the entire 3-year TAT in the first year of each management period reduced the number of EHB catches associated with a 50% probability of decrease from 62 per year to 60. In contrast, catching the entire 3-year TAT in the last year of each management period increased this number to 64, suggesting that delaying catches can be beneficial.

However, we lack information on population age structure and on the sex/age composition of the harvest. Harvesting a disproportionate amount of reproductive females in a single year, for instance, would have negative effects on the stock that cannot be anticipated by the model. Similarly, large harvests in a given year may increase the risk of removing entire family units, which could impact genetic diversity as well as the vertical transmission of migration route that is presumably the mechanism for site fidelity.

It would be beneficial to develop a more realistic model structured by age and sex, possibly using the composition of harvest samples as a proxy of population structure. Until more information is available, harvest limits under a flexible TAT system should be based on the results of the most unbalanced scenario, in which removing 180 EHB beluga in each 3-year period has a 50% probability of causing stock decline, while lower harvests would likely allow some recovery.

Impacts d’un système flexible de total autorisé de captures sur la conservation du beluga dans la région du Nunavik

RÉSUMÉ

La chasse aux bélugas à des fins de subsistance par les communautés du Nunavik vise un mélange de plusieurs stocks, dont celui de l'est de la baie d'Hudson (EBH). En 2013, les prises rapportées étaient constituées de 76 bélugas tués près de Sanikiluaq (Nunavut), de 8 dans l'est de la baie d'Hudson, de 158 dans le détroit d'Hudson et la baie d'Ungava au printemps et de 87 à l'automne, ainsi que de 10 bélugas dans la baie James et la région de Long Island. Les prises au Nunavik sont restées stables au cours des cinq dernières années.

Le modèle de population, mis à jour avec les données de 2013, continue à suggérer que la taille stock est stable depuis quelques années, avec la possibilité d’une croissance modeste. L’abondance en 2013 a été estimée à 3240 individus (95% IC 1833–5614).

À la demande du Conseil de gestion des ressources fauniques de la région marine du Nunavik, nous avons examiné si un système souple de total autorisé des captures (TAC) augmenterait la probabilité de déclin du stock de l’EBH. Nos simulations, basées sur une version modifiée de modèle actuel, montrent que l’allocation souple des prises sur des périodes de gestion de 3 ans aurait peu d’effet sur la conservation des bélugas de l’EBH. Seuls les scénarios les plus déséquilibrés ont un impact mesurable sur le risque de déclin du stock. Ainsi, prendre le TAC de 3 ans tout entier dès la première année de chaque période de gestion aurait pour conséquence de réduire le nombre de prises associée à un risque de déclin de 50% de 62 bélugas par an à 60. En revanche, prendre le TAC tout entier lors de la troisième année de chaque période de gestion augmenterait ce chiffre à 64, ce qui suggère que le fait de retarder les prises pourrait être bénéfique.

Cependant, il nous manque beaucoup d’information sur la structure d’âge de la population et sur la composition des prises en termes de sexe et d’âge. Si des prises disproportionnées de femelles en âge de se reproduire avaient lieu au cours d’une même année, par exemple, cela aurait des conséquences négatives sur le stock que le modèle ne peut pas prévoir. De même, des prises importantes en une seule année pourraient augmenter le risque de retirer des unités familiales au complet, ce qui pourrait avoir des effets sur la diversité génétique du stock ainsi que sur la transmission des routes de migration qui constitue probablement le mécanisme de la fidélité des bélugas à leurs sites d’estivage.

Il serait avantageux de développer un modèle plus réaliste structuré par âge et par sexe, qui pourrait utiliser la composition des échantillons de chasse comme indicateur de la structure de population. En attendant d’avoir davantage d’information, les limites de prises pour un système souple de TAC devraient être basées sur les résultats du scénario le plus déséquilibré, dans lequel la capture de 180 bélugas de l’EBH pour chaque période de 3 ans correspond à un risque de 50% de déclin du stock. Des prises moins élevées favoriseraient probablement la récupération du stock.

INTRODUCTION

Subsistence hunting of beluga (*Delphinapterus leucas*) in Nunavik is directed towards a migratory population that winters in Hudson Strait and the Labrador Sea. Photo-identification, satellite telemetry and genetic studies have shown that beluga exhibit strong seasonal site fidelity to specific congregation areas during summer (Caron & Smith, 1990; de March & Postma, 2003; Lewis et al., 2009). Current management schemes recognize the existence of at least two discrete summer stocks in Hudson Bay: the western stock (WHB) numbers ~57,000 individuals (Richard, 2005), while the eastern stock (EHB) was depleted by commercial hunts in the 19th century (Reeves and Mitchell 1987). Despite interbreeding on wintering grounds (Turgeon et al., 2012), cultural conservatism of maternally-transmitted migration routes seems to prevent substantial exchange between these stocks (Colbeck et al., 2012), thus making EHB beluga vulnerable to local extirpation (Cosewic, 2004).

The Nunavik Marine Region Wildlife Board (NMRWB) shares responsibilities with DFO for a co-management system that is "governed by and implements the principles of conservation" (Anonymous 2008). Managers and resource users aim at maintaining a sustainable harvest, while encouraging the recovery of the EHB stock. Monitoring, however, is complicated by large uncertainty in abundance estimates (Gosselin et al. 2009) and by mixing of stocks along migratory routes (Turgeon et al. 2012). A population model incorporating information on catch levels and stock composition was fitted to aerial survey estimates using Bayesian methods (Hammill et al. 2009). The 2012 update of the model indicated that the current stock size was likely stable at ~3200 but that a harvest exceeding 60 EHB beluga would have a 50% probability of causing a decline (Doniol-Valcroze et al. 2013).

Beluga hunting in Nunavik is managed through a combination of seasonal and regional closures (Lesage et al. 2009; Lesage & Doidge 2005), and total allowable takes (TAT). The current TAT was effective for a period of three years and expires at the end of the 2013 harvesting season. For the next multi-year plan, the NMRWB is considering the creation of a flexible TAT system. Currently, communities that respect their allocations feel "penalized" when hunting closes before their allocated TAT is harvested, because of overharvest by other communities. A multi-year TAT would make communities accountable for overharvesting in a given season and would help to ensure that all communities are able to hunt their own allocations. Before the NMRWB gives full consideration to this option, it has requested scientific advice on whether such a system would increase the probability of decline of the EHB stock and whether there is a level of harvest that, if exceeded in any given year, poses a clear threat to the conservation of beluga (e.g. if the entire 3-year TAT was harvested in a single year).

In this context, our objectives were:

a) to update the stock estimates with the 2013 harvest data, and

b) to modify the existing population model to determine sustainable harvest levels under a flexible TAT system and acceptable year-to-year variation of these levels.

MATERIALS AND METHODS

AERIAL SURVEYS

Census data comprised six estimates from systematic visual aerial surveys. All surveys were flown along similar parallel line designs (Fig. 1). Details on survey methods and analyses are available in Smith and Hammill (1986), Kingsley (2000), Hammill et al. (2004), Gosselin et al. (2009) and Gosselin et al. (2013). The resulting abundance estimates (SE) were 4278 (557), 2727 (1092), 2922 (1404), 4269 (1581), 2646 (1244) and 3351 (1639), for 1985, 1993, 2001, 2004, 2008 and 2011, respectively.

HARVEST RECORDS AND GENETIC ANALYSES

Harvest data are available from annual reports of landed catches (summarized in Lesage et al. 2009). All beluga harvested directly in the eastern Hudson Bay arc during the summer are assumed to belong to the EHB summer stock. Harvest in other areas and during spring and fall, however, is directed towards migrating whales from a mixture of stocks (Fig. 2). Genetic variation at mtDNA loci has been used to assess the contribution of each summering stock to the harvest and how these contributions vary spatially and seasonally (Turgeon et al 2012).

Prior to 2009, it was assumed that 17% (SE 2.3%) of whales hunted by communities outside of the eastern Hudson Bay arc in 1985–2008 were from the EHB stock (Turgeon et al. 2012). Since 2009, harvesting seasons have been separated into a spring-summer period and a fall period. Therefore, for 2009–2013, it was assumed that 13% (SE 5.2%) of animals killed in Hudson Strait and Ungava Bay in the spring and summer, and 21%(SE 5.1%) of those killed during the fall, were EHB beluga. It was assumed that 12% (SE 3.8%) of beluga killed by Sanikiluaq hunters in any year belonged to the EHB stock. Uncertainty associated with these proportions was incorporated in the model in the form of prior distributions.

In 2013, the reported Nunavik harvest (March 20 – November 6) was composed of 8 beluga taken in eastern Hudson Bay, 158 in Hudson Strait and Ungava Bay in the spring and 87 in the fall, 76 near Sanikiluaq (P. Hall, pers. comm.), and 10 in the Long Island/James Bay area. The Long Island/James Bay harvest is not considered in the model because these beluga are believed to belong to a separate population (Postma et al. 2012). In addition to the 263 beluga landed, 5 were reported wounded but lost.

MODEL SPECIFICATION

The hierarchical state-space model currently used to provide harvest advice (Doniol-Valcroze et al. 2013) considers survey data to be the outcome of two distinct stochastic processes: a state process and an observation process (Fig. 3). The state process describes the underlying population dynamics and the evolution of the true stock size over time, using an exponential-growth model. Stock size in each year N_t (from 1985 to 2011) is a multiple of the previous year's, with removals deducted:

$$N_t = N_{t-1} \cdot e^r \cdot \varepsilon_{P_t} - R_t$$

where r is the instantaneous growth rate, εp_t is a stochastic term for the process error and R_t are the removals for that year. Removals are calculated as reported catches, C_t, corrected for the proportion of animals that were struck and lost, SL:

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

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

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

Existing information, traditional knowledge and expert opinions were used to formulate prior distributions for the random variables included in the model (Table 1). Justification and sources for the choice of priors are available in Doniol-Valcroze et al. (2013).

PARAMETER ESTIMATION AND MODEL DIAGNOSTICS

Parameter estimates are refined by updating the prior to a posterior distribution using a Gibbs sampler. In previous assessments, parameter estimation was conducted using WinBUGS 1.4.3 (Lunn et al. 2000). However, the need to project abundance estimates many years into the future and the growing number of simulations required to test harvest scenarios have resulted in increasingly long runtimes. Therefore, we migrated the model to another Gibbs sampler algorithm, JAGS (Plummer 2003). To ensure continuity in model results, we ran the model from the previous assessment in both WinBUGS and JAGS with identical formulation and priors, and the same number of iterations, burn-in and thinning factor. We checked for any significant difference in the posterior distributions.

Posterior distributions were examined in the R programming language (R Core Team 2013), using package *R2JAGS*. Every 50th point was kept from 5 MCMC chains of 1,000,000 iterations, after a burn-in of 50,000 samples, for a total of 100,000 samples. Mixing and convergence of the chains as well as sensitivity to the choice of prior distributions were tested in Doniol-Valcroze et al. (2013). Because this assessment uses the same data and priors, these tests are not repeated here.

FUTURE PROJECTIONS AND HARVEST SCENARIOS

The model was extended into the future for 24 years to predict stock trajectory under 15 harvest scenarios, with yearly catch levels ranging from 0 to 200 EHB beluga. For this assessment, we modified the model in two ways to implement flexible, 3-year TAT. First, model predictions are now projected into the future in 3-year steps, each simulating a 3-year management period.

Second, for each step *s*, the realized harvest follows a multinomial distribution:

$$C_s \sim Mult(N_s, \pi)$$

where N_s is equal to the 3-year TAT (i.e., three times the annual catch level) and π is a vector of 3 probabilities summing to 1 that represent the target proportions of the TAT for each year of the plan. This framework allows us to introduce stochasticity in the way the TAT will be filled across the 3 years of each management plan.

We ran and compared four model formulations. Model M1 used the previous framework, i.e., projecting catches in 1-year steps with no flexibility among years. Model M2 used the 3-year step with π = {0.33,0.33,0.33}, simulating approximately equal catches among the three years of each management period. For instance, with N_s = 180, the resulting catch in each year will have mean 60 with SD 6.3 (CV 11%). Model M3 used π = {1,0,0} to describe an extreme situation where, for each 3-year step, the full 3-year TAT is taken during the first year. Model M4 used π = {0,0,1} to describes the opposite situation where all catches are forwarded into the last year of each 3-year step.

We estimated the probability of stock decline after 12 years for each harvest level by calculating the proportion of simulations in which the stock size in 2025 was below that of 2013.

RESULTS

JAGS VS. WINBUGS

Each chain of the model ran approximately 25 times faster when using JAGS than when using WinBUGS. The posterior distributions of the model runs were identical (Fig. 4). Median values were within 0.01% of one another for both the growth rate *r* (WinBugs: median=2.74% with 95% CI -0.67 – 6.13; JAGS: median=2.73% with 95%CI -0.71 – 6.12) and the 2012 abundance estimate (WinBugs: median=3229 with 95%CI 1896 – 5406; JAGS: median=3227 with 95%CI 1893 – 5413).

ABUNDANCE ESTIMATES AND POPULATION TRAJECTORY

The model estimated a 1985 stock size of 3947 beluga with a 95% CI of 2547 – 6526. The lowest abundance point was estimated for the year 2001 at 3016 individuals (95% CI 2139–4327), and the 2013 abundance was 3240 individuals (95% CI 1833–5614). At current harvest levels, stock abundance seems to have increased slightly over the last few years (Fig. 5).

IMPACTS OF FLEXIBLE TOTAL ALLOWABLE TAKES

Future stock trajectories of EHB beluga under a flexible TAT system (M2) did not differ from those predicted by the non-flexible model (M1). Extreme cases M3 and M4 did differ on short time scales, showing a saw-tooth pattern within each 3-year step (Fig. 6). However, all trajectories are similar in the long term, despite the median and 95% CI limits for M3 being slightly lower than those of M2.

According to M1 (i.e., with fixed yearly TATs), removing 62 EHB beluga per year for 12 years would have a 50% probability of causing a decline in the stock relative to its 2013 estimate (Fig. 7). Limiting the harvest of EHB animals to 28 animals would reduce the probability of decline to 25%. Conversely, a harvest of 106 EHB beluga would have a 75% probability of leading to stock decline. The numbers are identical when running model M2. However, they are slightly lower under model M3: removing 27, 60, and 102 beluga corresponds to a 25%, 50% and 75% risk of decline, respectively. Under M4, removing 29, 64, and 112 beluga corresponds to a 25%, 50% and 75% risk of decline, respectively.

DISCUSSION

ABUNDANCE ESTIMATES AND POPULATION TRAJECTORY

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

This update of the EHB beluga stock model contains no new data except catch statistics for the 2013 hunting seasons. Therefore, its results are similar to previous assessments. The model estimates that the 2013 harvest was equivalent to 54 EHB beluga and continues to suggest that the stock has been stable in recent years, with some indication of modest population growth. With a median value of 2.75%, however, the estimated rate of growth r remains lower than what is expected from a depleted odontocete stock. Although the maximum natural growth rate of beluga populations is unknown, 4% is usually proposed as a default value for cetaceans (Wade 1998). Such high rates have been observed in other beluga stocks (Richard 2005), although other beluga populations that are small relative to their presumed carrying capacity have been shown to exhibit low growth rates (Kingsley 1998, Hobbs et al. 2008).

Harvests in Nunavik have been relatively stable in recent years. Harvest around the Belcher Islands, however, has increased drastically in the last two years (76 in 2013, 61 in 2012, 32 in 2011). If 12% of these whales belonged to the EHB stock, this increase represents removal of an additional 5 EHB beluga. Although these whales are not included directly in the management plan (i.e., they are not subtracted from the Nunavik quota), they are included in the model and thus affect harvest advice for subsequent years. Currently, the harvest in Sanikiluaq is monitored but not controlled, except for a municipal motion prescribing that whales should be taken before July 15th or after September 30th. An earlier version of the municipal motion stopped hunting at the beginning of July, which was a good strategy to minimize the impact on the EHB stock in view of the low proportions of EHB whales detected by haplotype analyses for the spring and fall (Turgeon et al. 2009). The recent changes in harvest dates may have made EHB animals more vulnerable to capture but there is still considerable uncertainty in our understanding of the seasonal movements of beluga whales around the Belcher Islands (Doniol-Valcroze and Hammill 2012).

IMPACTS OF FLEXIBLE TOTAL ALLOWABLE TAKES

Subsistence hunting of beluga whales remains a central component of Inuit culture and identity in Nunavik and an important foundation of their mixed economy (Gunn, 2001; Tyrrell, 2008). The cumulative effects of past commercial hunts, increasing industrial activities and environmental changes in Hudson Bay could jeopardize harvest regimes that were historically sustainable (Hovelsrud et al., 2008; Wenzel, 2009). Non-sustainable exploitation represents a threat to food security because it impairs the future availability of food sources. The Nunavik Inuit Land Claims Agreement recognizes this by protecting Inuit harvesting rights while implementing principles of conservation for long-term sustainability.

There is ample evidence from both terrestrial conservation and fisheries that stakeholder involvement throughout the management process is crucial to reach consensus (Richard and Pike 1993). Flexibility and pragmatic implementation by managers can improve acceptance of the rules and hence the sustainability of resource use (Bunnefeld et al. 2011). Flexible multi-year plans have been used in other species of large mammals. For instance, several polar bear populations are managed within a flexible quota system in which over-harvesting in a given year results in fully compensatory reductions to the following year’s quota (Rogan et al. 2004).

At the request of the NMWRB, we assessed whether a flexible TAT system would increase the probability of decline of the EHB stock. Our simulations, using a modified version of the current EHB assessment model, clearly show that flexible allocation of takes over 3-year management periods has little impact on the conservation of EHB beluga. Only the most unbalanced scenarios had a measurable effect on the number of beluga associated with a given risk of stock decline. For instance, catching the entire 3-year TAT in the first year of each management period (M3) reduced the number of EHB catches associated with a 50% probability of decrease from 62 per year to 60. In contrast, catching the entire 3-year TAT in the last year of each management period (M4) increased this number to 64, suggesting that delaying catches can be beneficial.

We note, however, that we lack information on population age structure and on the sex/age composition of the harvest. We have assumed that harvest composition was homogeneous among years and hunting sites. If this is not the case, flexible TAT systems could result in harvests that are skewed in terms of age class and sex composition. Harvesting a disproportionate amount of reproductive females in a single year, for instance, would have negative effects on the stock that cannot be anticipated by the model. Similarly, large harvests in a given year may increase the risk of removing entire family units, which could impact genetic diversity as well as the vertical transmission of migration route that is presumably the mechanism for site fidelity (Colbeck et al. 2012).

Therefore, it would be beneficial to develop a more realistic model structured by age and sex, possibly using the composition of harvest samples as a proxy of population structure. Determining the age, sex and stock identity of all whales captured during each single hunting event would be useful to better inform models on harvest structure and homogeneity. Photographic aerial surveys could also yield insights into the proportion of young-of-the-year. Until more information is available, and within the constraints of our modelling framework, harvest limits under a flexible TAT system should be based on the results of the most unbalanced scenario (M3), in which removing 180 EHB beluga in each 3-year period has a 50% probability of causing stock decline, while lower harvests would likely allow some recovery.

In any case, it is important to emphasize that setting catches at levels that result in a 50% risk of decline in the resource is not considered precautionary, and that rebuilding the resource to levels observed in the early 1980s is unlikely using this strategy. As proposed in Doniol-Valcroze et al. (2013), developing a precautionary framework would facilitate sustainable management of Nunavik beluga and recovery of this stock. It is also important to emphasize that any attempt to increase the number of whales in the EHB stock will at some point result in a higher sustainable harvest, which would ultimately benefit resource-users.

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Table 1. Prior distributions, parameters and hyper-parameters used in Nunavik beluga population model. "est." denotes a parameter that follows a distribution and which value is estimated by the model.

Parameters	Notation	Prior distribution	Hyper-parameters	Values
Survey error (t)	εs_t	Log-normal	μ_s	0
			τ_s	est.
Precision (survey)	τ_s	Gamma	α_s	2.5
			β_s	0.4
Process error (t)	εp_t	Log-normal	μ_p	0
			τ_p	est.
Precision (process)	τ_p	Gamma	α_p	1.5
			β_p	0.001
Growth rate	r	Beta*	α_r	2
			β_r	3
Struck-and-lost	SL	Beta	α_{SL}	3
			β_{SL}	4
Initial population	N_{1985}	Uniform	N_{upp}	12,500
			N_{low}	500
Proportion EHB (*HS, all seasons*)	P_{HS}	Beta	α_{HS}	45
			β_{HS}	216
Proportion EHB *(Sanikiluaq)*	P_{SAN}	Beta	α_{SAN}	8.3
			β_{SAN}	60
Proportion EHB *(HS, spring)*	P_{SPRING}	Beta	α_{SPRING}	5.5
			β_{SPRING}	38
Proportion EHB *(HS, fall)*	P_{FALL}	Beta	α_{FALL}	13.5
			β_{FALL}	50

* was rescaled to the range -0.04 to +0.08

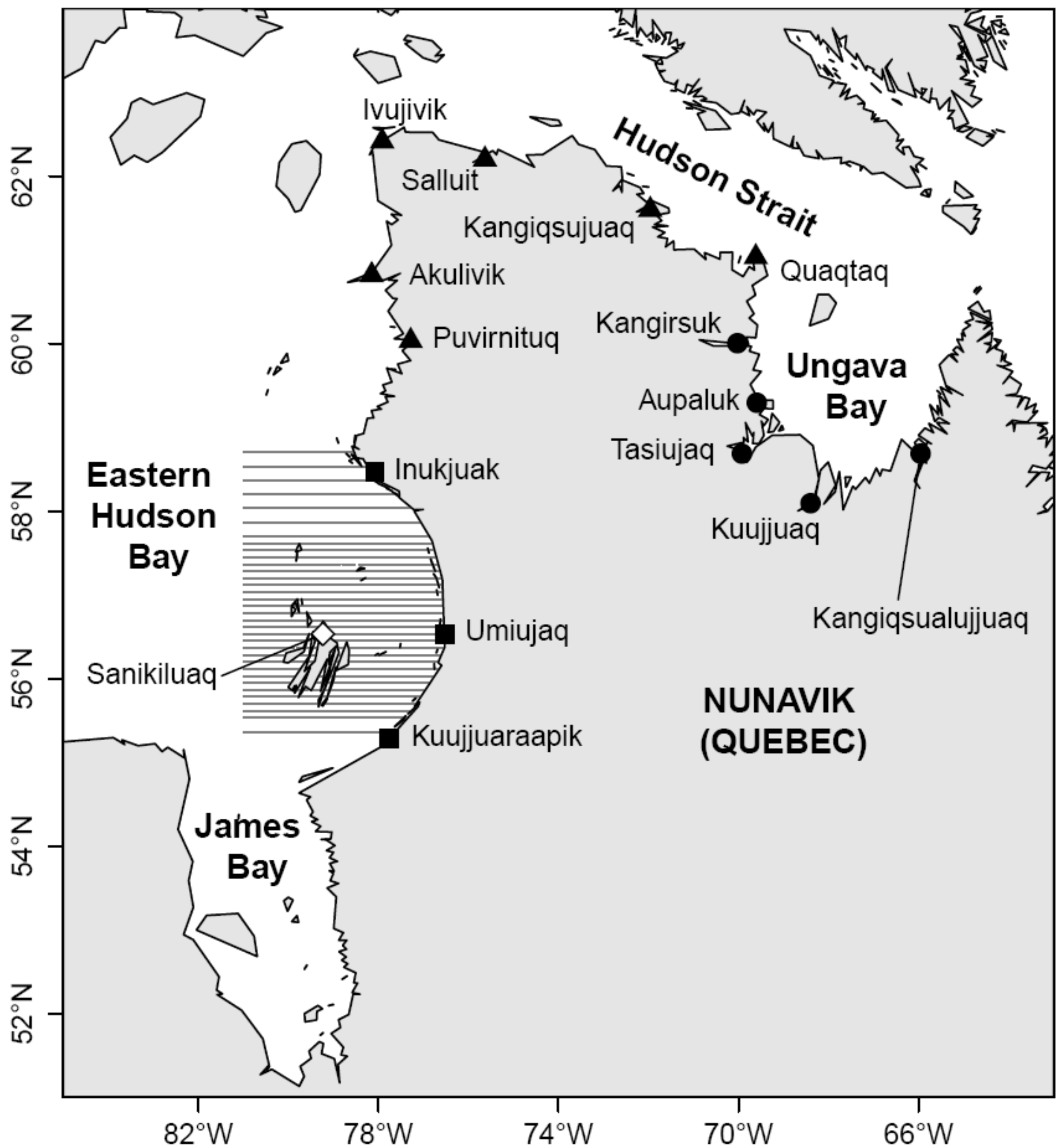

Figure 1. Map of Nunavik communities and aerial survey lines in the eastern Hudson Bay arc used to estimate abundance of the EHB beluga stock during summer. Squares: eastern Hudson Bay arc communities. Triangles: Hudson Strait and north-eastern Hudson Bay communities. Circles: Ungava Bay communities. White lozenge: Sanikiluaq (Belcher Islands, Nunavut).

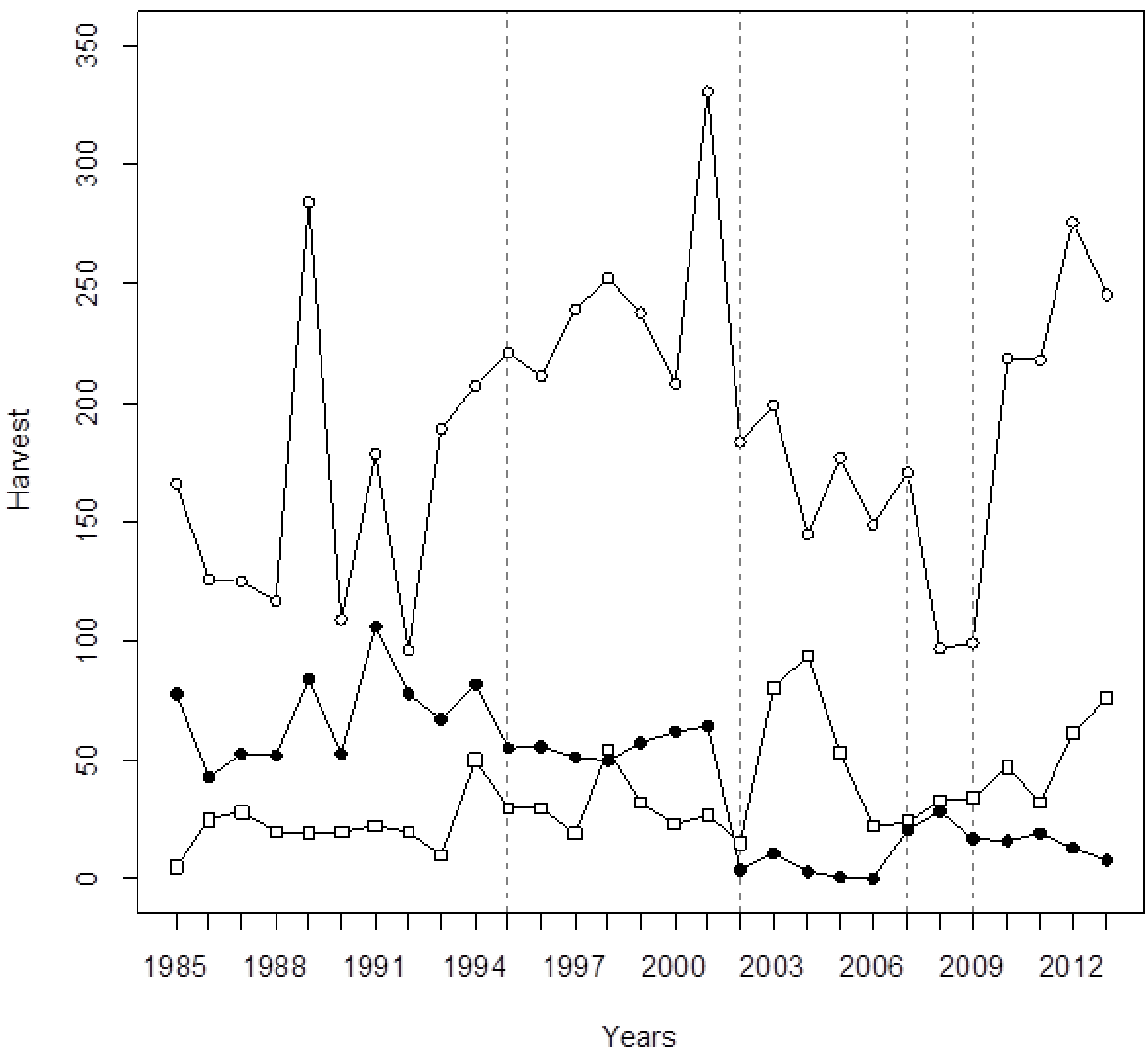

Figure 2. Beluga harvest in Nunavik for the period 1985 – 2013, broken down by region. Open circles: Hudson Strait and Ungava Bay. Closed circles: eastern Hudson Bay arc. Squares: Sanikiluaq (Belcher Islands, Nunavut). Vertical dashed lines indicate main management periods. 1985: Introduction of quotas; 1995: Seasonal closures of estuaries in eastern Hudson Bay. Puvirnituq shifts harvest from Nastapoka river to Hudson Strait; 2002: Complete closure of eastern Hudson Bay arc and Ungava Bay; 2007: Hunting resumes in eastern Hudson Bay arc and Ungava Bay, but Nastapoka, Little Whale and Mucalic river estuaries remain closed. Sanikiluaq starts restricting summer catches; 2009: Separation of Hudson Strait harvest into spring and fall periods, allowing higher total catches.

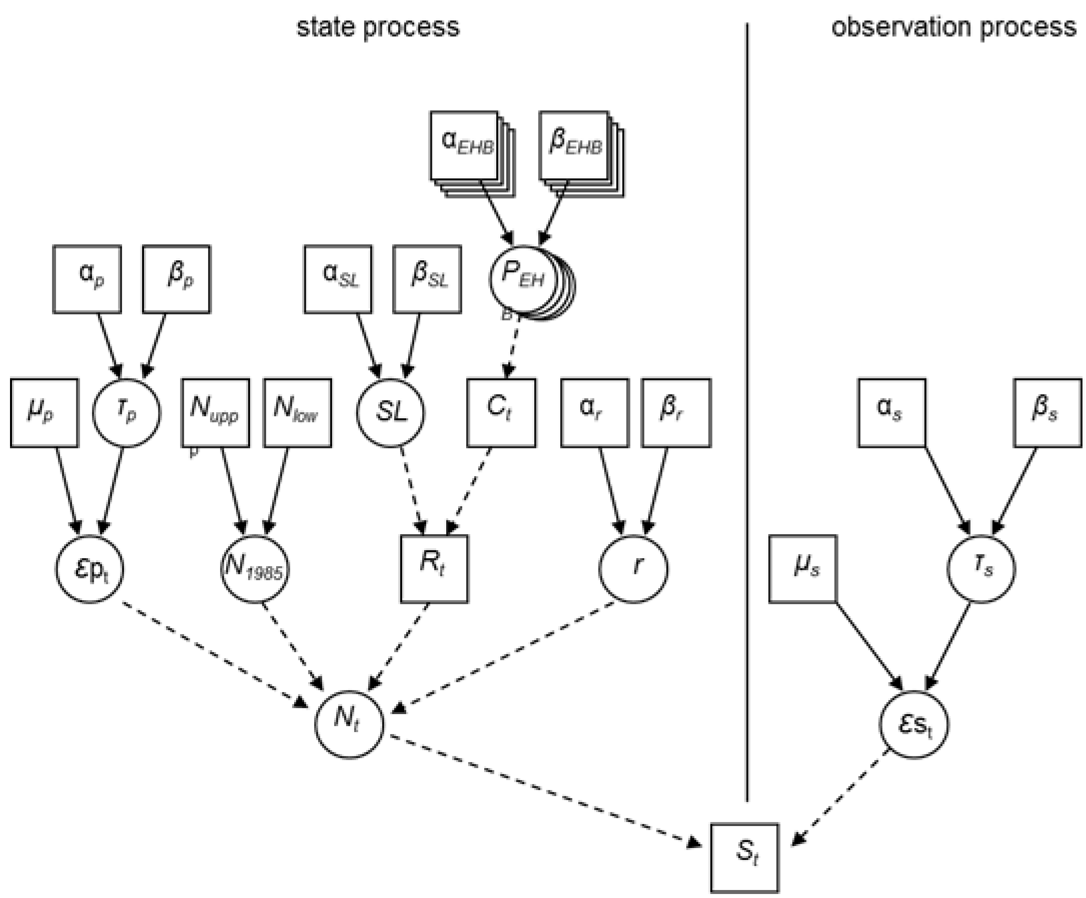

Figure 3. Directed acyclic graph for the beluga population model. Square nodes represent fixed values (observed data or prior parameter values). Circular nodes represent parameters to be estimated (cf. Table 1). Edges represent relationships between variables, with broken lines representing deterministic relationships and solid lines representing stochastic relationships. t subscript represents variables that take a different value for each year. St: Survey estimate at time t. Nt: Abundance estimate at time t. Rt: Total removals for year t (including struck-and-lost, SL). Ct: Catches of EHB beluga based on harvest in all Nunavik regions. PEHB: Proportions of EHB beluga in regions other than the EHB arc (Sanikiluaq, Hudson Strait for all seasons, in spring and in the fall). Other symbols and values are defined in table 1.

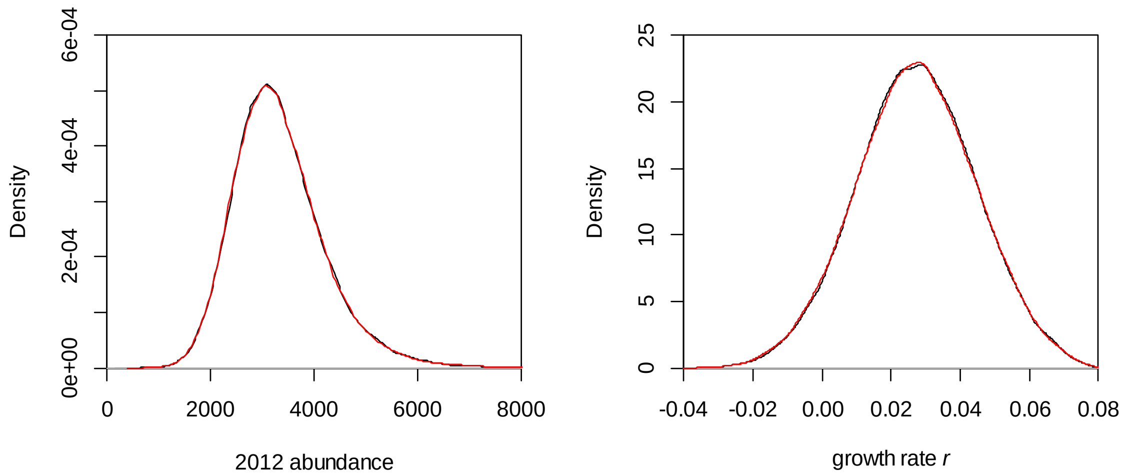

Figure 4. Posterior distributions of the EHB population model runs using WinBUGS (black) and JAGS (red) for the 2012 abundance estimate and the growth rate parameter.

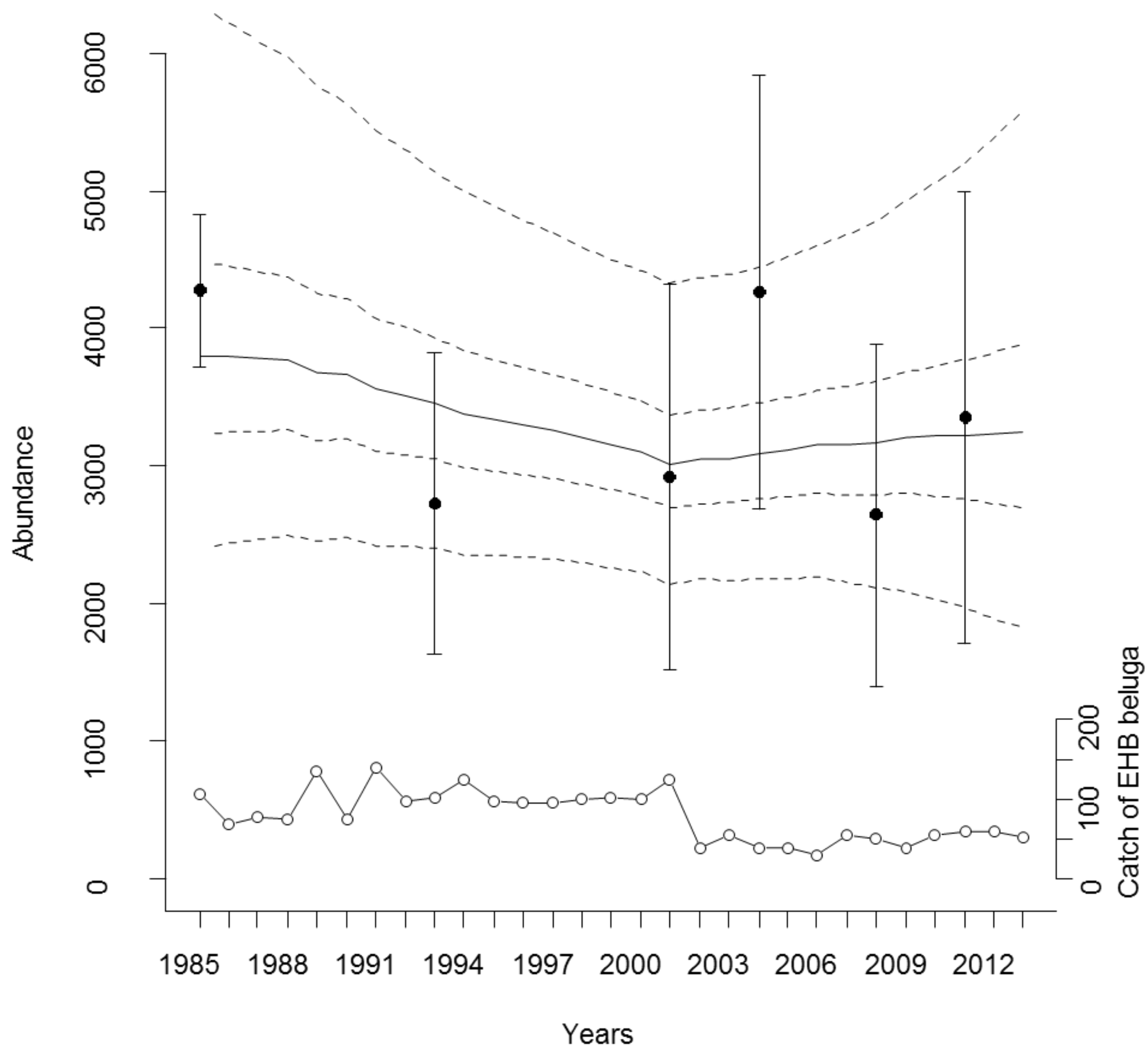

Figure 5. Model estimates of eastern Hudson Bay (EHB) beluga abundance. Solid line: median estimates. Dashed lines: 25% and 75% quantiles. Dotted lines: 2.5% and 97.5% quantiles (= Bayesian Credible Interval). The model was fitted to aerial survey estimates corrected for animals at the surface (closed circles, ±SE). Right y-axis: Catch of EHB beluga (open circles) based on the landings in different regions of Nunavik multiplied by the estimated proportions of EHB whales in each harvest.

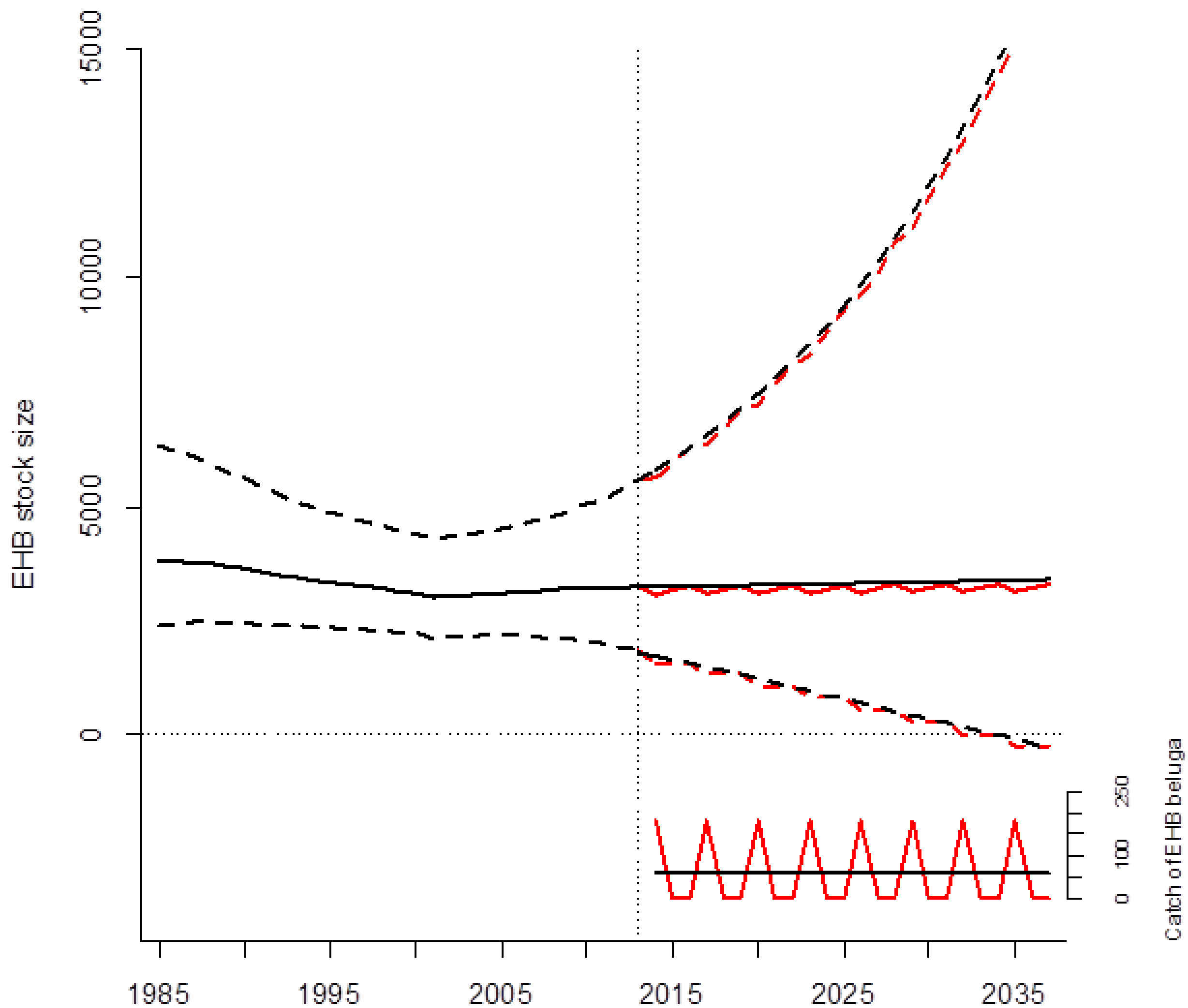

Figure 6. Future stock trajectories of EHB beluga under flexible TAT systems with equal catches among years (M2, black), or in which all beluga are caught in the first year of each 3-year period (M3, red), with a harvest limit of 180 EHB beluga per 3-year. Solid lines: median estimates. Dashed lines: 95% CI. Right y-axis: future catches of EHB beluga.

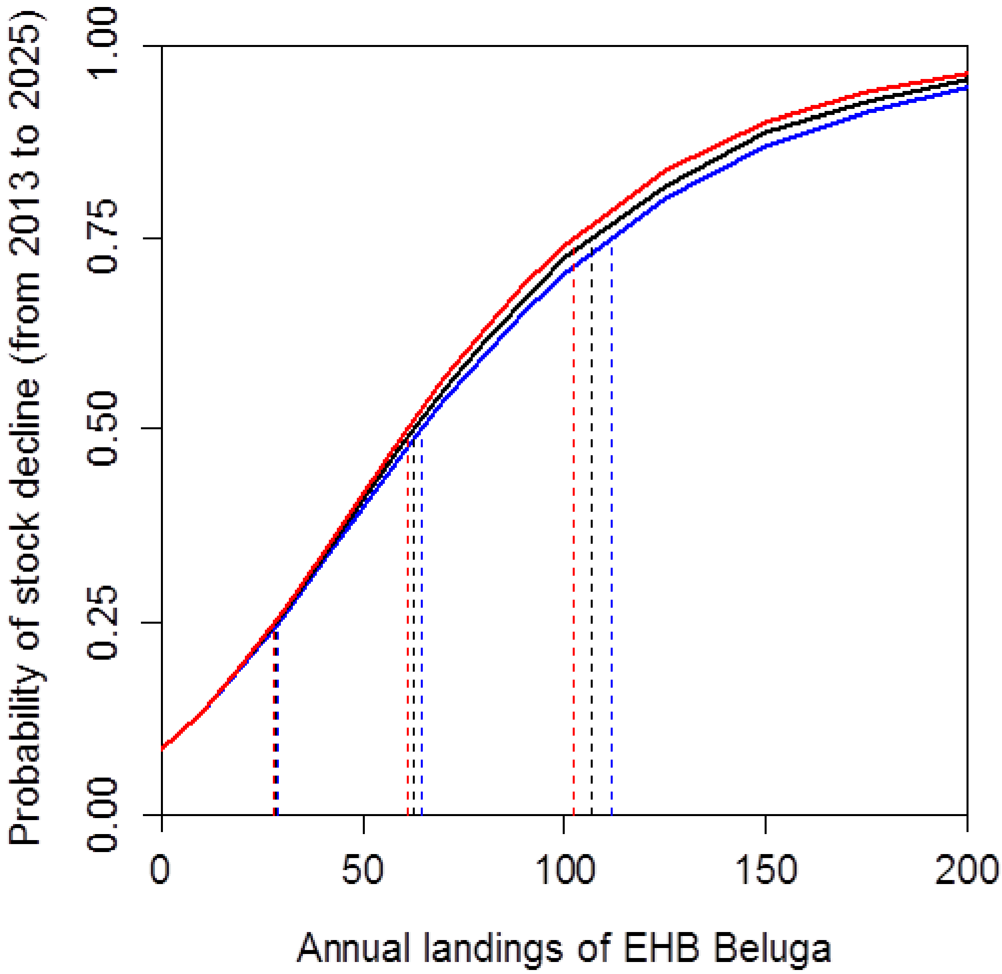

Figure 7. Probability of EHB stock decline after 12 years of harvest as a function of annual landings, under models with equal catches among years (M2, black), in which all beluga are caught in the first year of each 3-year period (M3, red) or in the last year of each 3-year period (M4, blue). Dashed lines indicate levels of harvest corresponding to 25%, 50% and 75% probability of decline.