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Impact of harvesting on population trends of beluga in eastern Hudson Bay

Impact de la chasse sur la tendance de la population de bélugas de l'est de la Baie d'Hudson

Hugo Bourdages[1]
Véronique Lesage[1]
Mike O. Hammill[1]
Brigitte de March[2]

[1] Fisheries and Oceans Canada, Maurice Lamontagne Institute,
P.O. Box 1000, 850 route de la Mer, Mont-Joli, QC G5H 3Z4

[2] Fisheries and Oceans Canada, Freshwater Institute,
Winnipeg, Manitoba R3L 1W3

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Abstract

Inuit people from the Nunavik have traditionally harvested beluga along the eastern Hudson Bay (EHB), Hudson Strait and Ungava coasts of northern Quebec. Quotas and other management measures exist since 1986, and are revised periodically. The current management plan and recommendations for harvest levels in the Nunavik region were established in April 2001 based on the best available data, *i.e.* population size in 1985 and 1993, and harvest statistics from 1974–2000. This study presents different scenarios of past and future harvests, while incorporating new information on beluga abundance in James Bay, EHB, Hudson Strait, and Ungava Bay, genetic composition of the harvests, and harvest statistics from 2001. Harvest statistics indicate that the communities of Nunavik exceed quotas each year. Both a relatively simple model using population estimates, removals and rate of increase, and a more complex model introducing additional variables on stage-specific biological parameters were used to examine the impact of harvesting on the growth of the eastern Hudson Bay beluga population. The two models yielded very similar results. They both indicated a decline in EHB beluga population since 1985, a population size in 2001 of approximately 2045 individuals (2090 vs 2001), and an underreporting of harvests prior to 1995 by a factor of 2.23-2.22.

The short- and longer-term impacts of future harvesting on the EHB beluga population were examined under different scenarios. However, the probability of decline on the short-term changed little between a harvest of 0 (48%) or 150 (56%) beluga from the EHB stock owing to the uncertainty surrounding the current estimates of population size. However, more certainty of a decline is acquired over time, and the influence of the number of removals per year is revealed more clearly over a longer time period. There is a 70–80% certainty of a decline in five or 10 years if over-harvesting practices similar to what was observed in 2001 (*i.e.* 125–150 EHB beluga) continue in the future. Reducing the quota to 25 beluga results in a 45% probability of a smaller stock in five years, whereas a complete cessation of EHB beluga harvesting results in a 35-40% probability that the stock will show now further decline in 5 years. Using minimum population estimates of 1657 and 1423 individuals for EHB beluga for Model 1 and 2, respectively, and a maximum annual rate of increase of 4%, the potential biological removal (PBR) is 15 individuals, assuming a recovery factor of 0.5 (for a threatened population which is not in decline). The PBR decreases to 9 beluga if this threatened population is assumed to be declining (recovery factor of 0.3), and to 3 beluga if it is considered endangered (recovery factor of 0.1).

In contrast with the EHB population, numbers of beluga in James Bay appear to have increased since 1985 to an estimated 10,504 beluga in 2001 (assuming an annual rate of increase of 0.03 to 0.04). The model fitted best the data when it was allowed to optimise the rate of increase. In this scenario, this population grew at a rate of 0.087 and was estimated to number 15,954 beluga in 2001.

Résumé

Les Inuits du Nunavik pratiquent traditionnellement une chasse au béluga le long des côtes de l'est de la baie d'Hudson, du Détroit d'Hudson et de la baie d'Ungava. Des quotas et autres mesures de gestion existent depuis 1986 et sont révisées périodiquement. Le plan actuel de gestion et les recommandations concernant les niveaux de chasse au Nunavik ont été établis en avril 2001 à la lumière des meilleures données disponibles, soit les estimations de taille de population de 1985 et 1993 et les statistiques de chasses de 1974 à 2000. Divers scénarios de chasse passée et future sont présentés dans cette étude, en incorporant de nouvelles informations relatives à l'abondance des bélugas dans la baie James, l'est de la Baie d'Hudson, et la baie d'Ungava, la composition génétique de la chasse, et les statistiques de chasse de 2001. L'ensemble des statistiques de chasse indique que les communautés du Nunavik excèdent chaque année leur quota de chasse. Un modèle simple utilisant des estimations de taille de population, les statistiques de chasse et des taux de croissance, ainsi qu'un modèle plus complexe incorporant des variables additionnelles concernant certains paramètres biologiques spécifiques au stade de vie ont été utilisés pour examiner l'impact de la chasse sur la croissance de la population de béluga de l'est de la baie d'Hudson. Les deux modèles présentent des résultats similaires. Ils indiquent tous deux un déclin de la population de l'est de la baie d'Hudson depuis 1985, une population en 2001 de l'ordre de 2045 individus (2090 vs 2001), et une tendance à sous-rapporter les prises de la chasse avant 1995 par des facteurs de 2.23-2.22.

Les effets à court et long terme d'une poursuite de la chasse sur la population de bélugas de l'est de la baie d'Hudson ont été examinés à l'aide de divers scénarios. Toutefois, la probabilité d'un déclin à court terme varie peu que le prélèvement de bélugas de l'est de la baie d'Hudson soit de 0 (48%) ou 150 (56%) individus, étant donnée l'incertitude actuelle entourant les estimations de la taille de la population. Néanmoins, l'examen des tendances sur une plus longue période de temps augmente la certitude d'un déclin, et révèle plus clairement l'influence du nombre de bélugas tué par année sur la tendance de la population. Si elle se poursuit, la sur-chasse telle qu'observée en 2001 (soit 125–150 bélugas de l'est de la Baie d'Hudson) résultera avec une certitude de 70–80% en une population plus petite dans cinq ou dix ans. Une réduction du quota à 25 bélugas résulterait avec une certitude de 45% en un stock moindre dans cinq ans, alors qu'un arrêt complet de la chasse au béluga de l'est de la baie d'Hudson mènerait avec une certitude de 35-40% à une population dans cinq ans qui aurait cessé de décroître. Un prélèvement potentiel biologique (PPB) de 15 béluga est obtenu en utilisant une estimation minimale de la population de 1,657 et 1,423 individus pour l'est de la baie d'Hudson pour les Modèles 1 et 2, respectivement, et en assumant un taux annuel maximum de croissance de 4%, et un facteur de rétablissement de 0.5 (pour les populations menacées non en déclin). Le PPB décroît à 9 bélugas si l'on considère que cette population menacée est en déclin (facteur de rétablissement de 0.3), et à 3 bélugas si on la considère en danger de disparition (facteur de rétablissement de 0.1).

Contrairement à la population de l'est de la baie d'Hudson, le nombre de bélugas dans la baie James semble avoir augmenté depuis 1985 à 10,504 bélugas en 2001 (en assumant un taux de croissance annuel de 0.03 à 0.04). Le modèle s'ajuste le mieux aux données lorsque le taux de croissance annuel est optimisé. Pour ce scénario, la population se serait accrue à un taux annuel de 0.087 et s'estimait à 15,954 bélugas en 2001.

Introduction

Beluga in northern Quebec and adjoining waters are divided into three stocks, based on the summer distribution of animals: an Ungava Bay stock, eastern Hudson Bay stock and a western Hudson Bay stock (Reeves and Mitchell 1989; Richard *et al.* 1990; Richard 1993). Beluga also occur during summer in James Bay, the Belcher Islands, and along the Ontario coast of Hudson Bay (Figure 1). However, the stock relationships of these animals to other animals in Hudson Bay remain unclear. The great majority of beluga from these regions are suspected to overwinter in Hudson Strait (Jonkel 1969; Sergeant 1973; Finley *et al.* 1982; Richard *et al.* 1990; Brooke 1995: report from the community agent of Akulivik). Beluga from two other management stocks, the Baffin Bay and Southeast Baffin Island stocks, may also contribute to these winter aggregations (Richard and Orr 1986).

Molecular genetic findings to date support a division between an eastern Hudson Bay (EHB) and a western Hudson Bay (WHB) stock, and the presence of a mixture of stocks in Hudson Strait during winter (Brennin *et al.* 1997; Brown Gladden *et al.* 1997, 1999; de March *et al.* 2001). However, a high degree of genetic overlap was observed between the beluga from the different sampling sites, *i.e.* statistical differences among presumed populations arose from differences in allele frequencies and not from the occurrence of different alleles (de March *et al.* 2001). A small number of beluga belonging to the EHB stock (≅13%) are harvested in the Belcher Islands, but the majority of animals that are taken might either be members of the western Hudson Bay stock, or form a unique stock on their own (de March *et al.* 2001).

The Ungava Bay and eastern Hudson Bay (EHB) populations were classified as '*Endangered*' and '*Threatened*' respectively by COSEWIC in 1989, primarily as a result of aerial surveys flown in 1985 (Reeves and Mitchell 1989). These surveys provided population estimates of approximately 1,200 (SE=300) in James Bay, and 1,000 (SE=200) beluga in eastern Hudson Bay, while too few animals were seen in Ungava Bay to estimate abundance using standard survey techniques (Smith and Hammill 1986).

Attempts were made to reduce hunting after the 1985 survey (reviewed in Lesage *et al.* 2001). After the 1993 aerial survey, a 5-year management plan was implemented (Anonymous 1996). This plan ended in March 2001. Although no new abundance data were available, science recommendations regarding possible harvest levels were needed to develop a new management plan in 2001. Based on available abundance estimates from 1985 and 1993 (Smith and Hammill 1986; Kingsley 2000), harvest levels (Lesage *et al.* 2001), and making assumptions about the stock composition of the harvest in Hudson Strait and possible population growth rates, a harvest of a maximum of 40 animals from the eastern Hudson Bay population was recommended (Hammill 2001). The new management plan agreed upon with Nunavik Inuit in April 2001 limited harvesting to 25 animals per community, with four Hudson Strait communities being allowed to harvest 30 individuals each. Ungava Bay communities were encouraged to take their quota outside of the Bay. Eastern Hudson Bay communities were allowed to kill a maximum of 15 individuals from each of the Nastapoka and Little Whale River estuaries. The rest of their quota was to be taken from James Bay (30 beluga) and Hudson Strait (65 beluga). Other measures, which included seasonal closures of some estuaries, were also incorporated into the plan (Anonymous 2001).

In 2002, the government of Canada is expected to present the Species at Risk Act (SARA) to the House of Commons. Once signed into law, the new Act requires that recovery plans be established for species considered as '*Endangered*' or '*Threatened*' by COSEWIC. The Act also prohibits the harvesting of animals that will interfere with its recovery.

The current management plan and recommendations for harvest levels in the Nunavik region were established based on the best available data, *i.e.* population size in 1985 and 1993, and harvest statistics from 1974–2000 (Smith and Hammill 1986; Kingsley 2000; Hammill 2001; Lesage *et al.* 2001). The Department of Fisheries and Oceans committed to revise this management plan, should new scientific information become available.

This study presents different harvest scenarios, while incorporating new information on beluga abundance in James Bay, EHB, Hudson Strait, and Ungava Bay, genetic composition of the harvests, and harvest statistics from 2001 (de March *et al*. 2001; B. de March, unpublished data; Gosselin *et al*. 2002; D. Baillargeon, Fisheries and Oceans Canada, Quebec, pers. comm.). Suggestions are made for harvest levels for the 2002 season, keeping in mind uncertainties concerning the current size and trend of the EHB population, the proportion of EHB beluga in the Hudson Strait harvest, the stock identity of beluga in James Bay, and the need to allow EHB beluga population to rebuild as per SARA.

Materials and Methods

The growth of the eastern Hudson Bay population was examined using two different approaches.

Model 1

Model 1 assumed that changes in population size could be described by a simple model:

[1] $$N_{t+1} = N_t e^{r\Delta t} - h_{t+1}$$

where N is the estimated number of beluga at time t and t+1, h is removals from the population, and r represents a rate of increase (r). In the current model, Δt is equal to 1.

Model 2

The second model uses a matrix approach where beluga are grouped into distinct age stages (i) with stage-specific survival rates and fecundity rates:

[2] $$\mathbf{N}_{t+1} = \mathbf{N}_t \bullet \mathbf{A} - \mathbf{h}_{t+1}$$

In this model, the number of beluga in each stage at time t and t+1 is represented as a vector **N**:

[3] $$\mathbf{N} = \begin{bmatrix} N_1 \\ N_2 \\ \vdots \\ N_i \end{bmatrix}$$

Probabilities of surviving and staying in the same stage during a time step (P), probabilities of surviving and growth to the next stage by the subsequent time step (G), and fecundity rates (F), defined as the number of females produced during a given year, are incorporated into a Leslie matrix (**A**) (Leslie 1945) (Figure 2):

[4] $$\mathbf{A} = \begin{bmatrix} P_1 & 0 & F_3 & \cdots & F_{i-1} & F_i \\ G_1 & P_2 & 0 & \cdots & 0 & 0 \\ 0 & G_2 & \ddots & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & P_{i-1} & 0 \\ 0 & \cdots & \cdots & 0 & G_{i-1} & P_i \end{bmatrix}$$

The probability of surviving and staying in stage *i* during a time step (P_i) can be calculated using:

[5] $$P_i = \frac{(1 - p_i^{d_i - 1})}{(1 - p_i^{d_i})} p_i$$

where the annual survival rate (p_i) is constant during a given stage *i* of duration d_i.

The probability of surviving and growing to the next stage by the subsequent time step (G_i) is calculated as:

[6] $$G_i = \frac{(1 - p_i)}{(1 - p_i^{d_i})} p_i^{d_i}$$

Removals of individuals from each stage at time *t* is expressed as a vector, **h**:

[7] $$\mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_i \end{bmatrix}$$

Estimating population size

Abundance estimates for beluga in EHB are available from three aerial surveys conducted in 1985, 1993 and 2001 (Table 1). The 1985 survey was a visual, strip transect survey of James Bay, eastern Hudson Bay and Ungava Bay (Smith and Hammill 1986). The two subsequent surveys in 1993 and 2001, flew the same transect lines as in 1985, but used a line transect instead of a strip transect design (Kingsley 2000; Gosselin *et al.* 2002). Correction factors were developed to account for differences in abundance indices resulting from changes in survey techniques between 1985 (strip transect) and the 1993 and 2001 surveys (line transect) (Gosselin *et al.* 2002). The ratios of the line transect to the strip transect estimate were 1.47 and 1.86 for EHB for 1993 and 2001, and 1.37 and 1.67 for James Bay during the same two surveys. An average of these values, *i.e.* 1.668 and 1.519, was used as a correction factor to adjust the estimates obtained in 1985 for EHB and James Bay, respectively.

Correction factors were also required to account for animals under the water, and consequently not visible, when the survey plane passed overhead. Satellite telemetry studies of eastern Hudson Bay beluga indicate a proportion of individuals within 4 m from the surface of 0.540 (SE 0.050) (Kingsley *et al.* 2001) or 0.591 (SE 0.041) (M.O. Hammill and D.W. Doidge, Unpublished data). However, it is difficult to link the proportion of time that animals spend near the surface to what might be visible from an aerial survey platform. Kingsley and Gauthier (in press) examined the question of visibility of beluga during aerial surveys in the St Lawrence River estuary. They estimated to 0.478 (SE 0.063) the proportion of beluga visible from an aerial survey platform (P_0) in these waters. This parameter was assumed to follow a normal distribution, and was used here to obtain an estimate of population size (*N*), by correcting abundance estimates obtained using the line transect approach (N_{survey}) for the proportion of animals visible from the survey platform (P_0), and adding to these estimates the number of beluga observed in estuaries ($N_{estuary}$) (Table 1):

[8] $$N = N_{survey} / P_0 + N_{estuary}$$

Other parameters

Beluga are medium sized odontocetes with a life history characterised by an early reproduction (age 4-7 y), low reproductive rates (crude birth rate: 0.26-0.47) and a long lifespan (longevity = 35 years) (Table 2; Sergeant 1973; Burns and Seaman 1985; Doidge 1990; Heide-Jorgensen and Teilman 1994; Kingsley *et al.* 1995). Little information is available on the natural rate of increase in beluga populations. Doidge (1990) compared results from two aerial surveys and suggested an annual growth rate of 3.6% for western Hudson Bay beluga. However, he suggested caution in using this result because of methodological differences between surveys. Kingsley *et al.* (1995) suggested a somewhat lower maximum annual growth rate of 2.6% for beluga in eastern Hudson Bay. Rates of increase from other species with similar life histories were examined for their suitability to be applied to an exploited beluga population (Table 2). Estimated rates of increase for odontocetes vary from 0.02 in spotted dolphins to a high 0.111 for harbour porpoise. Life-history parameters of beluga suggest a rate of increase falling in between that of the killer whale and the harbour porpoise. A rate of increase of 0.03-0.04, similar to narwhals, pothead and spotted dolphins would appear to be reasonable. The rate of increase (*r*) was set at 0.035 in Model 1, and was assumed to follow a uniform distribution with upper and lower limits of 0.04 and 0.03, respectively.

Beluga were assigned to one of four stages on the basis of their age following Doidge (1990), and assuming two growth layer groups are deposited each year: newborns (< 1 y), juveniles (1–5 y), young adults (6–21 y) and older adults (22–38 y). This classification resulted in stage duration of 1, 5, 16 and 17 years for stages 1 to 4, respectively. Annual survival rates were set to 0.75, 0.96, 0.98 and 0.94 for stages 1 to 4, based on analogies to Orcas and Tursiops and an assumption that the rate of increase is 1.035 (Olesiuk *et al.* 1990; Wells and Scott 1990; in Richard *et al.* 2001). Distributions of this parameter within the different stages were unknown, and were assumed to be uniform (Table 3). Fecundity rates of 0.165 and 0.092 females per year, following a normal distribution, were applied to stages 3 and 4, respectively (Burns and Seaman 1985; Doidge 1990).

Catch data from 1985 to 2001 were available from harvest studies, and catch statistics obtained from each of the harvesting communities (Lesage *et al.* 2001; D. Baillargeon, Fisheries and Oceans, Quebec, Unpublished data). These harvest statistics include animals that were struck and lost (Table 4).

The contribution to the harvest by animals from each stage was estimated using the age structure of harvests by Nunavik communities in 1980 (n = 36), 1983–1987 (n = 151), and 1993–2001 (n = 335) (Appendix 1). Proportions of beluga in stages 1 to 4 were 0.046, 0.142, 0.673 and 0.137 for animals harvested in 1980 and in 1983–1987, and 0.006, 0.227, 0.764 and 0.003 for beluga harvested between 1993 and 2001. The former set of values was used in the simulations prior to 1990, whereas the second set of values was applied to the period 1990–2001.

Information on the proportion of beluga with EHB-type haplotypes harvested in Hudson Strait and Ungava Bay were incorporated into both models. These data were available from a recent genetic study which examined beluga harvested in EHB (n = 123), Hudson Strait (n = 131), and Ungava Bay (n = 32) during 1983–1999 (de March *et al.* 2001; B. de March, unpublished data). This study indicates that a proportion of 0.22 (SE = 0.036) of the beluga harvested in Hudson Strait, and 0.31 (SE = 0.082) of those taken in Ungava Bay could belong to the EHB stock. Therefore, these contributions to the harvest by EHB beluga were attributed to each of the communities of Hudson Strait (*i.e.* 0.22 to Ivujivik, Salluit, Kangirsujjuaq, and Quartaq), and Ungava Bay (*i.e.* 0.31 to Kangirsualujjuaq, Kuujjuaq, Tasiujaq, Aupaluk, and Kangirsuk).

Scenarios

The impacts of harvesting on population trends of beluga in eastern Hudson Bay were examined following different scenarios that were intended to reflect presumed or known hunting practices and harvest compositions (Table 5).

The first two scenarios were examined using both types of models. In a first scenario, also examined in Hammill (2001), beluga harvests from the five Nunavik Hudson Bay communities, *i.e.* Kuujjuaraapik, Umiujaq, Inukjuaq, Puvirnituq, and Akulivik, are assumed to exclusively comprise eastern Hudson Bay animals. A second scenario accommodates the possibility of Akulivik harvesting a small proportion of beluga from eastern Hudson Bay, and the change in harvest location by Puvirnituq hunters over time. This community harvested beluga mostly at the Nastapoka estuary in eastern Hudson Bay before 1995, but shifted most of its hunting efforts towards spring and fall herds of beluga near Hudson Strait (Ivujivik area) during 1995–2001 (Lesage *et al.* 2001; D.W. Doidge, Unpublished data). The genetic characteristics of the beluga harvested by Akulivik in front of town are poorly understood (n = 1 beluga, with a western Hudson Bay haplotype; B. de March, Unpublished data). Beluga hunting occurs mainly during September–October in this community, possibly on migrating individuals either from WHB, EHB or James Bay (Lesage *et al.* 2001). Therefore, a simulation was run, assuming only the three communities from the EHB arc (*i.e.* Kuujjuaraapik, Umiujaq, and Inukjuaq) were taking 100% of their harvest from the EHB stock. Puvirnituq was attributed a removal of 100% from this stock prior to 1995, and 22% during 1995–2001. Akulivik was assumed to have taken 22% of their harvest from the EHB stock during the entire period. The communities from Hudson Strait and Ungava Bay were attributed removals of 22% and 31% EHB beluga, respectively (B. de March, Unpublished data). The composition of the harvests in this scenario is the most plausible of those presented in this study, and was retained as the baseline for the subsequent scenarios.

Four additional simulations were run, using Model 1 and an EHB harvest proportion of 0.22 for both Akulivik (from 1985 to 2001), and Puvirnituq (from 1995 to 2001). The population rate of increase, which varied between 0.03 and 0.04 in the first two simulations under model 1, was optimised in a third simulation. Both this parameter and a correction factor for declared harvests prior to 1995 (see Lesage *et al.* 2001) were optimised in a fourth scenario. A fifth simulation examined the influence of a group of 52 beluga that was observed on a transect during the 2001 survey on the estimated population size (Gosselin *et al.* 2002), by calculating a Windsorized mean for this survey, and using the best scenario identified under model 1. A Windsorized mean consists in replacing an abnormally high or low observation might by the second highest or lowest observation to reduce its influence on the mean and variance (Rivest 1994).

Two other simulations were also run using Model 2, while making the same assumptions as in Model 1 about the composition of the harvests in Puvirnituq (100% EHB before 1995, then 22%), Akulivik and the Hudson Strait communities (22% EHB), and Ungava Bay communities (31% EHB). In one scenario, Model 2 was fitted while setting catch-at-stage 3 and 4 proportional to the stage structure of the population in the preceding year, instead of keeping them constant over the entire time series as in the first two scenarios. Another simulation fitted model 2, while allowing this parameter to change according to the age structure of the population in the precedent year, but also while optimising a correction factor for declared harvests prior to 1995.

Model 1 was also used to predict changes in the abundance of James Bay beluga, and examine the rate of increase of the beluga population in that area, by fitting to the 1985, 1993, and 2001 population size estimates. No removals were included in the model (h = 0) because no harvesting normally occurs in that area. First, the model was fitted while allowing the rate of increase to vary between 0.03 and 0.04 (Scenario 1). This parameter was optimised in a second simulation (Scenario 2).

Optimisation

A model is fitted by minimising the mean sum of squares (MSS) of the estimated population size (N) from 1985, 1993 and 2001, using the software Risk Optimizer (Palisade Corporation 2000). Runs are constrained to values that lay within 2 standard deviations of the 1985, 1993 and 2001 population size estimates (Table 1). The model starts with an initial population, and samples (Latin Hypercube) values from the defined functions for each parameter (*e.g.* values for the expected proportion of harvest from the EHB population, expected rate of increase for each year, correction factor for animals visible at the surface, and stage-specific survival rates and reproduction rates). Sampling is repeated 1000 times (replicates) and generates a distribution of 1000 MSS. These constitute a simulation. The model calculates the MSS, stores the value and randomly selects a new initial population size to carry out a new simulation. After 1000 simulations, or when a change less than 0.2% is observed over the last 70 valid simulations, the model retains the simulation which generated the smallest MSS.

Projection

Levels of harvesting that could be sustained in the eastern Hudson Bay population were examined. Harvesting levels were set to maintain current population size (replacement yield) in 2001, and also to establish harvest levels that would allow the population to increase. Uncertainty in the population trajectory was examined by drawing 1000 random samples of the parameters that were known to be variable, *i.e.* the rate of increase (Model 1), the fraction of the total harvest by HS and Ungava Bay communities coming from the EHB population (Models 1 and 2), stage-specific survival rates and reproduction rates (Model 2), and the correction factor for animals not visible at the surface (Models 1 and 2). Trajectories were examined for removals of 0 to 200 beluga per year, using the software @Risk (Palisade Corporation 2000).

Potential biological removal

The potential biological removal level (*PBR*) is a measure of mortality limit put forward under the U.S. Marine Mammal Protection Act. The *PBR* is defined as ‘the maximum number of individuals, not including natural mortalities that may be removed from a marine mammal stock while allowing that stock to reach or maintain its optimum sustainable population’ (MMPA, Section 3 in Wade 1998). This value is the product of three factors, *i.e.* minimum population estimate of the stock, one-half the maximum net productivity rate, and a ‘recovery’ factor of between 0.1 and 1.0 depending on the status of the stock (Wade 1998). A PBR was calculated for eastern Hudson beluga. The minimum population estimate was calculated as the lower limit of the two-tailed 60% confidence interval of the log-normal distributed best abundance estimate, *i.e.* equivalent to the 20th percentile of the log-normal distribution (Wade 1998). The best abundance estimate for the EHB population was defined as the population size predicted by each model for 2001 under the best scenario (*i.e.* model with the least MSS). The maximum productivity rate was set at 0.04, the default value for cetaceans. *PBR* was initially calculated using two different ‘recovery’ factors commonly used for endangered (0.1) and threatened (0.5) stocks to reflect its current official status as per COSEWIC (threatened), and worst case scenario (endangered). *PBR* was recalculated while decreasing the recovery factor from 0.5 to 0.3 to account for the decline in the population and anticipation that the population may be listed as endangered in the future (Wade and Angliss 1997).

Results

Using equation 8, estimated population size (*N*) for the eastern Hudson Bay population in 1985, 1993 and 2001 were 3849, 2137, and 2453 beluga, respectively (Table 1). Using these estimates in the models, the EHB population has declined since 1985, regardless of the model or scenario that is used to examine its trends (Figure 3–11).

Model 1 fitted the data best when the rate of increase of the population was optimised at r = 0.0268, a correction factor was introduced for declared harvests prior to 1995, and while assuming a harvest of 22% EHB beluga for Akulivik (1985–2001) and Puvirnituq (1995–2001) (Table 6). Model 2 also fitted the data best when correcting for declared harvests prior to 1995, when making the same assumptions about the harvest compositions for Akulivik and Puvirnituq, and also while allowing catch-at-age to vary with the age structure of the population. Adjusting catch-at-age for stages 3 and 4 according to changes in the age structure of the population in the preceding year, but not accounting for possible misreporting of harvests prior to 1995, did not improve the fit of

Model 2 (Table 6). The estimated correction factors for declared harvests prior to 1995 were similar using the two models (2.23 vs. 2.22 for Models 1 vs 2), and suggest some underreporting of harvests prior to 1995. Model 1 and 2 yielded similar population estimates for EHB beluga in 2001 under these scenarios, with 2090 and 2001 individuals, respectively (Table 6). The composition of the harvests had little effects on the results from the two models (Table 6: *i.e.* MSS were similar under both scenarios with the two models).

The influence of the group of 52 beluga on the estimated population size and simulation results was examined using the best scenario identified under model 1, *i.e.* while optimising both *r* and *h*, and attributing a harvest of 22% EHB beluga to Akulivik (1995–2001) and Puvirnituq (1995–2001). The replacement of the largest group (52 beluga) by the second largest group (18 beluga) in the calculation of the mean (*i.e.* Windzorized mean) and variance resulted in a population estimate of 1687 (SE = 559) for 2001, and the best fit (*i.e.* the smallest MSS) of all of the scenarios examined with the two models (Table 6). The replacement of this group reduced the estimated rate of increase from 0.0268 to 0.0225 for the EHB population, but increased little the harvest underreporting correction factor prior to 1995 (2.23 vs 2.37).

Three factors were allowed to vary in the models: the population rate of increase (Model 1) or the parameters entering the Leslie matrix (*i.e.* survival and fecundity rates), the correction factor applied to the aerial survey estimates to account for animals visible at the surface, and the fraction of the harvest that is made up of animals from the eastern Hudson Bay population. Of these factors, both models were most sensitive to changes in the aerial survey correction factor, followed by the rate of increase (Model 1) or survival rates (Model 2), and then the proportion of EHB animals in the Hudson Strait and Ungava Bay harvests (Figure 12). Increases in the correction factor for animals visible from the survey platform, the population rate of increase (Model 1), or the stage-specific survival rates (Model 2) had a positive impact on the estimated population size. In contrast, the proportion of beluga from EHB that are harvested in Hudson Strait and Ungava Bay correlated negatively with population size estimates.

The short- and longer-term impacts of future harvesting on the EHB beluga population were examined under the different scenarios (Figures 3–11). The level of uncertainty around the past population trajectories is also reflected in future trajectories under different harvest scenarios. Regardless of total removals in 2002, there is a 50% chance that the stock will decline in 2002. This probability of decline on the short-term changes little between a harvest of 0 (48%) or 150 (56%) beluga from the EHB stock owing to the uncertainty surrounding the current estimates of population size. However, more certainty of a decline is acquired over time. In addition, the influence of the number of removals per year is revealed more clearly over a longer-term period. Under the best identified scenarios using model 1 and 2, a quota similar to what was recommended under the 1995–2001 management plan (*i.e.* 50-60 beluga from the EHB stock), would result in a 50% probability that the EHB stock will be smaller in five years or 10 years (Figures 6c, 11c). The certainty of a decline increases to 70–80% if overharvesting practices, similar to what was observed in 2001 (*i.e.* 125–150 EHB beluga) continue in the future. Reducing the quota to 25 beluga results in a probability of 45% that the stock will be less than today in five years. A complete cessation of EHB beluga harvesting would result in a 35-40% probability that the stock would show now further decline in 5 years.

Using a minimum population estimate of 1657 and 1423 individuals for the eastern Hudson Bay stock for Model 1 and 2, respectively, and a maximum rate of increase of 4% per year, the potential biological removal is estimated at 15 individuals, assuming a recovery factor of 0.5 (for a threatened population which is not in decline). The PBR is reduced to 9 beluga if this threatened population is assumed to be declining (recovery factor of 0.3), and to 3 beluga if this population is considered endangered (recovery factor of 0.1) (Table 7).

In contrast with the EHB population, numbers of beluga in James Bay appear to have increased since 1985 (Figure 13). A rate of increase of between 0.03 and 0.04 yielded an estimate of 10,504 beluga in 2001 for that area. The model fitted best the data when it was allowed to optimise the rate of increase. In this scenario, this population grew at a rate of 0.087 and was estimated to number 15,954 beluga in 2001.

Discussion

In this study, both a relatively simple model using population estimates, removals and rate of increase, and a more complex model introducing additional variables on stage-specific biological parameters were used to examine the impact of harvesting on the growth of the eastern Hudson Bay beluga population. The two models yielded very similar results. They both indicated a decline in EHB beluga population since 1985, a population size in 2001 of approximately 2045 individuals (2090 vs 2001), and an underreporting of harvests prior to 1995 by a factor of 2.23-2.22.

The models indicate that the EHB beluga population has continued to decline since 1993. This contrasts with the aerial survey results (Gosselin *et al.* 2002), which suggest that little change has occurred since the previous aerial survey (Kingsley 2000). However, the 2001 aerial survey estimate is extremely sensitive to the detection of a single group of 52 animals along one of the survey lines. This group, which represents 33% of the total number of animals sighted, increases the estimates of total abundance, and also has an important impact on the survey variance (Gosselin *et al.* 2002). Although there is no reason to exclude this observation, it points to the difficulties in trying to evaluate small populations of highly aggregated animals. The replacement of this large group by the second largest group detected during the 2001 survey (*i.e.* Windsorized mean) decreased substantially the EHB population estimate for 2001 from 2090 (SE = 587) to 1687 (SE = 559) beluga (Table 6).

Several other indices also provide evidence of a decline in the EHB beluga population. Comparisons between the 1985, 1993, and 2001 surveys, which flew along the same transect lines, indicate that fewer animals are found in inshore areas in the more recent studies. Fewer whales were also counted on the 1993 (N = 150 whales) and 2001 (N = 160) survey lines compared to the 1985 survey (N = 200 whales), in spite of a 61% wider searching zone in the 1993 and 2001 surveys. Furthermore, a reduction in the distribution of sightings indicates a contraction in the offshore range of beluga in the study area (Figure 8, Gosselin *et al.* 2002). Shore-based observations conducted during 1983 and 1984 (Caron and Smith 1990) reported maximum counts of 100+ beluga in the Nastapoka during July and August, compared to sightings of 40-60 and 25 animals at a time in 1993 (Doidge 1994) and 2001 (Doidge and Lesage 2001), respectively. Maximum counts during a study to capture beluga to deploy satellite transmitters at the Nastapoka River were less than 25 animals during a 3-week period in August 1998, and a one-month period in July 1999 (M.O Hammill and D.W. Doidge, Unpublished data). Individually, the changes observed in these indices may reflect changes in whale distribution owing to increases in vessel traffic in inshore areas, or sampling error associated with individual surveys. However, analysis of the age structure of the catch indicates that there has also been a substantial decline in the median age of the harvest in the estuaries, and a sharp reduction in the proportion of worn teeth (older animals) in the catch (Lesage *et al.* 2001). Taken together, the different indices indicate that the eastern Hudson Bay beluga population has declined since 1985, and in spite of management efforts, this decline has continued since 1993.

The correction factor (2.09) (Kingsley and Gauthier in press) used to adjust aerial survey estimates to account for animals under the water is the most influential of the parameters introduced in the models. The value used in this study is much higher than estimates from satellite telemetry data. If this correction factor has been overestimated, then eastern Hudson Bay beluga are much less abundant than the model suggests, while the converse would also be true. The influence of the choice of the correction factor for animals visible from an aerial survey platform (P_0) was examined in a sixth scenario by replacing the value obtained in the study of St Lawrence beluga, and used in the other scenarios, by the average of three values available from the literature, *i.e.* 0.536, SE = 0.025 (Kingsley *et al.* 2001; Kingsley and Gauthier in press; M.O. Hammill and D.W. Doidge, Unpublished data). The results from this simulation indicate quite clearly the sensitivity of the model to the correction factor for beluga visible from the survey platform (Table 6; Figure 14). The use of an average value of 0.536 instead of the value of 0.478 proposed by Kingsley and Gauthier (in press) resulted in a decrease in the population size estimate in 2001 from 2090 to 1856, and an increase in the fit of the model.

The model was also sensitive to the values used as rates of increase and age-specific survival rates. The influence of the rates of increase on the outcome of simulations is not unexpected given the relatively large range of values that was used in the models. The influence of survival rates on the outcome of simulations is also unexpected, but may be slightly overestimated due to the assumed distribution of this parameter (uniform as opposed to a normal distribution for fecundity rates).

Harvest compositions had little impact on the results. This finding is unexpected, and is most probably an artefact of important missing parameters in the models. Simulations using both models indicate that a correction factor for undeclared harvest prior to 1995 should be included to reflect best the trends in the abundance of beluga in EHB. Consequently, the importance of any parameter included in models with no correction for undeclared harvests, and which could contribute to an increase in overall harvests of EHB beluga, would be underestimated as it would serve as a buffer for undeclared harvests. No correction factor for declared harvests were included in scenario 1 and 2. The attribution of a larger harvest of EHB beluga to Puvirnituq and Akulivik in scenario 1 (100%) than in scenario 2 (22%) compensated partially for the lack of a correction factor for undeclared harvests. The larger harvest of EHB beluga in two communities in scenario 1 (relative to scenario 2) increased slightly the fit of the model by increasing the overall number of beluga harvested from the EHB stock.

Genetic information is still extremely scarce and highly season- and community-specific (B. de March, Unpublished data) and thus, most probably underestimate the spatio-temporal variance of harvest composition. Communities from northeastern Hudson Bay (Akulivik and Puvirnituq) and the western entrance to the strait (Ivujivik and Salluit) harvest beluga during both the fall and spring (Lesage *et al.* 2001) but yet, provided little or no samples from their fall hunts (except for Puvirnituq). The information on the genetic composition of the harvests at this particular time of the year is critical in order to predict accurately EHB population size and trajectory. Beluga from western Hudson Bay may not follow the same migration route in the fall when their migration is unrestricted by ice, and spring when the presence of ice might force WHB beluga closer to the Nunavik coast (Environment Canada 2001). If this is the case then the contribution by WHB beluga to the harvests of northeastern Hudson Bay and western Hudson Strait communities may be smaller during the fall than spring. The predictions of the models are currently based primarily on the spring harvest, and assume a large contribution (78%) by beluga from stocks other than EHB. If a larger fraction of the harvest is comprised of EHB beluga in the fall than spring, then the EHB stock may be smaller, and may be declining faster than predicted by the model.

The presence of EHB animals in the harvest of Ungava Bay was unexpected. Unfortunately, the stock relationships of Ungava Bay animals to the EHB and WHB beluga stocks has not been examined in detail (de March *et al.* 2001). Therefore, these samples may indicate that there is little difference (genetically) between EHB and Ungava Bay animals, or they indicate that EHB animals may migrate as far east as Ungava Bay. Nonetheless, these findings underline the importance of limiting hunting in this area, given the low numbers of animals seen in Ungava Bay, and the possibility of harvesting EHB beluga.

Only three systematic aerial surveys have been flown to estimate beluga abundance in eastern Hudson Bay and James Bay (Smith and Hammill 1986; Kingsley 2000; Gosselin *et al.* 2002). The absence of a regular time series of abundance data means that a greater reliance is placed on the accuracy of the harvest statistics to model changes in the population. Both models suggest significant underreporting of harvests prior to 1995. These findings are not unexpected, considering the variable participation of the different communities to the program during this period (Lesage *et al.* 2001). Contradictions between transmitted catch statistics and information obtained in talking to community councils suggest that more recent harvests might be also underestimated to some extent (Lesage *et al.* 2001; D. Baillargeon, Unpublished data). If this is the case, then the model will artificially underestimate the rate of increase of the population, so that it still can meet the criteria introduced for population sizes.

The rates of increase obtained in this study are lower than the 3–4% maximum rate of increase for beluga, or other species with similar life-histories, that are accepted as standards in some jurisdictions (Wade 1998). However, the rate of increase estimated from model 1 (r = 0.0268) when assuming some underreporting of harvests prior to 1995, and a reduction of takes from EHB beluga by Puvirnituq from 100% to 22% after 1994, is similar to the rate of increase obtained by Kingsley *et al.* (1995) for this population (r = 0.026). These rates of increase are also similar to what is expected from a population with an age at sexual maturity of 7 years, a three year calving interval and with calve and non-calve survival rates of 0.75 and 0.95 (Reilly and Barlow 1986). A lower rate of increase (0.023) is obtained when a Windsorized mean is calculated to reduce the effect of the large group of 52 animals observed during the 2001 aerial survey. This value is low for the species, and also indicates a continued underreporting of harvests after 1994. Overexploitation of mature females and emigrations of whales to other areas are other factors that might also contribute to a lower rate of increase predicted by the model. The management plan calls for the protection of females accompanied by calves. However, catch statistics indicates that females are killed as often as males, and that lactating females, and at least a small number of calves are taken by EHB communities (Lesage *et al.* 2001; D.W. Doidge, Unpublished data).

The estimate of the size of the EHB beluga population varies from 2001 to 2453 depending on method (modelling or survey estimate) and type of model (simple or more complex). The absence of a suitable time series of survey estimates, uncertainty associated with the different parameters, and particularly the large CV associated with the aerial survey, limits our capability to ascertain the effects of future harvesting on EHB beluga. In this study, a complete closure of the beluga hunt would result in only a 60% chance that the stock will have stopped declining in 5 years. Assuming that population size is 100% certain, *i.e.* 2001 beluga using model 1, then removals allowing no rebuilding of this stock could be 40 beluga (Figure 15). Lower removals than those presented are needed to allow this stock to increase. A reduction of harvesting to 20 beluga might allow the population to begin rebuilding at a rate of about 1% per year. The *PBR* approach, using a minimum population estimate and then applying a safety factor according to the risk of extinction of the population, indicates that maximum removals of ≤ 15 beluga would allow this stock to rebuild.

James Bay beluga

The rate of increase obtained for beluga in James Bay is unrealistically high for this species. The high rates observed are due in part to a likely under-estimate of abundance from the 1985 survey due to the presence of a large, unsurveyed area covered with ice in the northwestern part of James Bay during the 1985 survey (Kingsley 2000). However, even if this was the case, numbers of beluga in James Bay show a very high increase between the 1993 survey and 2001. Richard *et al.* (1990) identified large numbers (1300) of beluga along the Ontario coast of Hudson Bay during aerial surveys flown 1987. Little is known about seasonal movements and the stock relationships between WHB and EHB beluga in the southern part of Hudson Bay and in James Bay. It may be that considerable movement or exchange of animals occurs between the two coasts in this area, which, depending on the timing of aerial surveys within the context of seasonal movements of beluga in the area, would have a significant impact on survey estimates for Jams Bay. Clearly, a better understanding of the migration patterns of beluga from eastern and western Hudson Bay is needed in order to understand inter-annual fluctuations in numbers of beluga in different areas.

Conclusions

Beluga populations recover very slowly from overharvesting. If the EHB beluga population increases annually at a rate of only 2.7%, then it will take approximately 30 years for the population to double. A major reduction in harvests of this population is required. Although complete closure of harvesting would be ideal, this would likely result in the loss of beluga harvesting skills in Nunavik communities. At the same time, if significant reductions do not occur, the loss of these skills will only be a matter of time.

A regular program to monitor population changes should have been implemented to monitor changes in population size. Regular monitoring would have provided cross validation of harvest statistics, assumptions about the composition of harvest from Hudson Strait, and would have provided an earlier warning of an apparent decline in the EHB beluga stock and would have allowed for more accurate estimate of current population size. This study indicates quite clearly the limitations of using imprecise survey estimates of small, patchy populations to model predictions.

Management considerations

During 1995 to 2000, northern Quebec beluga were managed under a five year management plan (Anonymous 1996). Owing to the combination of the 5-year plan and Program Review, this plan was not supported by a research program to monitor changes in population parameters, enforcement of harvest quotas, and regular meetings with clients to discuss concerns related to the resource. During 2001, a new agreement on beluga management was signed for 3 years. This new agreement provided for changes in harvesting quotas should new information become available. New information on beluga abundance in eastern Hudson Bay, Ungava Bay and James Bay was obtained in 2001, in addition to new genetic information. It is recommended that recent research efforts are maintained, and the management plan reviewed using the new information presented in this document.

The general model developed here assumes that harvesting takes animals proportional to their representation in the population. Previous modelling efforts (Kingsley *et al.* 1995) have shown that harvests could be increased slightly if harvesting is directed towards males, and if females with calves are protected. The protection of females with calves has been a component of previous management plans, but catch data indicate that females and males are being harvested equally (Lesage *et al.* 2001). Although it is important to continue to stress the need to protect females with calves, if this population is to recover, a reduction in overall harvests is essential. At the same time, a greater effort to collect age structure, sex ratio, and reproductive data is needed for regular monitoring and to permit the refinement of models and predictions.

The 2001 management plan attempted to reduce harvesting of EHB animals by shifting hunting effort towards James Bay and Hudson Strait, where animals from the EHB herd were less likely to be killed. Hunting success in James Bay was limited in 2001, and nothing is known about the stock relationships of these animals to other beluga groups in Hudson Bay. Information on the stock composition of the Hudson Strait and Ungava Bay harvests indicates that 22% and 31% of the harvested animals from these areas belong to the EHB population. The beluga population in Ungava Bay likely numbers less than 200 animals (Gosselin *et al.* 2002). The low population size, in addition to the presence of EHB animals in the harvests from this area underline the need to stop hunting in Ungava Bay. Although only 22% of the Hudson Strait harvest consists of EHB animals, current high harvest levels must be reduced substantially to halt the decline in the EHB population. However, the current information on the fraction of EHB animals in the Hudson Strait is based on very small samples. Improvements in the participation of Inuit hunters to provide samples for genetic analyses from their harvests may help us to identify particular times of the year, or regions when the changes of harvesting EHB animals are minimized.

Current harvesting is concentrated in nearshore and estuarine areas, particularly in EHB where a strong decline in numbers has occurred. Whether this decline is due to over-harvesting of animals that prefer to use estuaries, a result of excessive disturbance in estuaries, or a combination of the two factors, a reduction in hunting effort in these areas would help to maintain an accessible resource to hunters once the population showed signs of recovery. It is recommended that the duration of the current closure to hunting in the key areas of Little Whale and Nastapoka rivers and Richmond Gulf be extended in order to provide animals a respite from hunting.

Recommendations

Closure of Ungava Bay to all beluga hunting;

A reduction of harvesting of EHB beluga to ≤ 20 animals. This could be achieved by a complete closure of hunting in EHB, which would allow a maximum quota of 100 beluga in Hudson Strait assuming that 20% of this harvest consists of EHB, or by a combination of a much reduced harvest in EHB, and in Hudson Strait;

Continued improvement in the biological sampling program is needed to better understand the stock composition of animals harvested in Hudson Strait;

Research is needed to understand the stock relationships between the EHB and western Hudson beluga and those animals occurring in James Bay, as well as nearby herd along the Ontario coast of Hudson Bay.

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Table 1. Estimates of population size (*N*) of beluga in eastern Hudson Bay and James Bay, as obtained by correcting estimates of detectable beluga (N_{survey}) during strip-transect (1985) and line-transect (1993 and 2001) surveys (Smith and Hammill 1986; Kingsley 2000; Gosselin *et al.* 2002) for the proportion of beluga visible at the surface, following $N = N_{survey} / P_0 + N_{estuary}$ where P_0 = 0.478 (Kingsley and Gauthier in press), and adding the number of beluga observed in estuaries ($N_{estuary}$) during these surveys.

Area	Year	N_{survey} (SE)	$N_{estuary}$	N
Eastern Hudson Bay	1985	1615 (275)	474	3849
	1993	1014 (421)	18	2137
	2001	1155 (507)	39	2453
James Bay	1985	1842 (440)	-	3850
	1993	3141 (787)	-	6565
	2001	7901 (1744)	-	16513

Table 2. Population parameters for odontocete populations.

Parameter	Beluga	Narwhal	Killer whale	Pilot whale	Harbour porpois e	Spotted dolphin
Longevity (y)	35		80	46	20	33-45
Age first birth (y)	4-7	6	14	7	4.5	13
Crude birth rate (y)	0.26-0.47	0.3-0.38	0.154	0.37-0.40	0.4-0.83	0.33-0.4
Max. rate of increase	0.03-0.038	0.03-0.04	0.025-0.029	0.028	0.096-0.111	0.02-0.04
Sources	Doidge 1990; Burns and Seaman 1985	Kingsley 1989	Olesiuk *et al.* 1990; Brault and Caswell 1993	Kasuya *et al.* 1988	Caswell *et al.* 1998	Barlow and Boveng 1991; Chivers and Myrick 1993

Table 3. Stage-specific biological parameters used in population models.

Stage	Proportion of harvests		Survival rate[b]			Fecundity rate		
	1985-1989	1990-2001[a]	P_i	Range	Distribution	F_i[c]	SE[d]	Distribution
1	0.0457	0.0060	0.75	0.65–0.85	Uniform			
2	0.1421	0.2269	0.96	0.92–1	Uniform			
3	0.6731	0.7642	0.98	0.96–1	Uniform	0.165	0.0494	Normal
4	0.1371	0.0030	0.94	0.88–1	Uniform	0.092	0.0277	Normal

[a] D.W. Doidge, Makivik Corporation, Kuujjuaq, unpublished data
[b] Based on analogies to *Orca* and *Tursiops* and assumption that rate of increase λ = 1.035 (Olesiuk *et al.* 1990; Wells *et al.* 1990, in Richard *et al.* 2001)
[c] Burns and Seaman 1985; Doidge 1990
[d] Assuming CV = 30%, based on analogies to *Orca* and *Tursiops* (Richard *et al.* 2001)

Table 4. Number of beluga harvested by the different communities of the Nunavik between 1985 and 2001 (updated from Lesage *et al.* 2001; D. Baillargeon, Fisheries and Oceans Canada, Quebec Region, Unpublished data).

	Year																
Community	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Kuujjuaraapik	40	10	11	0	8	8	12	16	12	22	14	15	11	14	14	8	15
Umiujaq	-	3	15	12	18	12	24	24	19	18	21	19	19	18	24	19	17
Inujjuaq	11	7	11	17	17	11	20	16	13	19	20	22	21	18	19	35	25
Puvirnituq	-	23	16	23	41	22	50	22	23	23	36	38	33	36	27	29	50
Akulivik	11	12	12	12	19	9	18	16	16	20	18	15	24	17	22	12	33
EHB total	62	55	65	64	103	62	124	94	83	102	109	109	108	103	106	103	140
Ivujivik	35	5	24	19	118	20	31	2	37	24	38	34	22	44	37	36	13
Salluit	22	24	20	16	53	17	28	19	37	46	40	32	46	54	33	28	57
Kangirsujuaq	32	22	28	28	28	24	39	28	29	34	22	25	25	22	27	26	34
Quartaq	34	21	21	15	35	18	29	22	32	35	28	23	31	32	24	26	60
HS total	123	72	93	78	234	79	127	71	135	139	128	114	124	152	121	116	164
Kangirsuk	7	9	8	7	11	10	12	3	12	10	10	16	16	13	19	12	24
Aupaluk	3	3	1	2	3	5	9	0	3	6	6	8	8	4	13	8	7
Tasiujaq	9	14	4	11	9	3	2	2	7	12	11	6	14	17	21	13	23
Kuujjuaq	2	10	5	2	8	3	3	4	12	9	10	5	13	10	8	7	20
Kangirsualujjuaq	3	5	2	1	0	0	7	0	4	11	2	9	7	3	7	11	17
Killiniq	8	1	0	4	-	-	-	-	-	-	-	-	-	-	-	-	-
UB total	32	42	20	27	31	21	33	9	38	48	39	44	58	47	68	51	91
Nunavik total	217	169	178	169	368	162	284	174	256	289	276	267	290	302	295	270	395

Table 5. Scenarios examined using a simple model (Model 1) using population estimates, removals and rate of increase, and a more complex model (Model 2) introducing additional variables on stage-specific biological parameters.

Scenario	Harvest of EHB beluga (%)				Rate of increase (r)	Correction factor for declared harvest prior to 1995	Catch-at-stage 3 and 4
	Kuujjuaraapik, Umiujaq, Inujjuaq	Puvirnituq[a], Akulivik	Hudson Strait communities	Ungava Bay communities			
Model 1							
1	100	100	22	31	0.03–0.04	No	-
2	100	22	22	31	0.03–0.04	No	-
3	100	22	22	31	Optimised	No	-
4	100	22	22	31	Optimised	Optimised	-
5[c]	100	22	22	31	Optimised	Optimised	-
6[d]	100	22	22	31	Optimised	Optimised	-
Model 2							
1	100	100	22	31	-	No	Constant
2	100	22	22	31	-	No	Constant
3	100	22	22	31	-	No	Proportional[b]
4	100	22	22	31	-	Optimised	Proportional[b]

[a] Values indicated in the table for this community are effective from 1995–2001 only. Harvest levels were assumed to be 100% prior to 1995.
[b] Proportional to the stage structure of the population in the preceding year.
[c] Using a Winsorized mean for the 2001 population estimate.
[d] Using an average of three values available from Kingsley *et al.* 2001, Kingsley and Gauthier in press, and M.O. Hammill and DW. Doidge, unpublished data, for estimating the proportion of animals visible from an aerial survey platform (P_0 = 0.536, SE = 0.025)

Table 6. Population size estimates (and SE) for eastern Hudson Bay and James Bay beluga, as predicted by a simple model using population estimates, removals, and rates of increase (*r*) (Model 1), and a more complex model introducing additional variables on stage-specific biological parameters (Model 2). A correction for declared harvests prior to 1995 (*h*) was introduced in some scenarios.

Scenario	Model estimate of population size (SE)			MSS	*r*	*h*
	1985	1993	2001			
Eastern Hudson Bay						
Model 1						
1	2944 (233)	2869 (326)	2385 (471)	453453		
2	2886 (233)	2892 (326)	2773 (471)	533659		
3	3339 (263)	2901 (315)	2292 (395)	289985	0.0151	
4	3781 (305)	2672 (431)	2090 (587)	140606	0.0268	2.2341
5	3781 (307)	2426 (425)	1687 (559)	50250	0.0225	2.3658
6	3312 (162)	2418 (280)	1856 (420)	133875	0.0283	1.9160
Model 2						
1	2947 (233)	2670 (405)	1781 (701)	516500		
2	2954 (233)	2787 (416)	2332 (737)	412797		
3	3002 (237)	2898 (405)	2634 (727)	443167		
4	3662 (296)	2578 (515)	2001 (845)	144416		2.2199
James Bay						
Model 1						
1	6000 (459)	7939 (641)	10504 (954)	14207182		
2	3955 (303)	7943 (637)	15954 (1432)	741513	0.0872	

Table 7. Potential biological removal (Wade 1998) from the eastern Hudson Bay stock in 2002 under the assumptions of scenario 4 of Model 1 and 2 (see Table 5), and different values of 'recovery factor' F_R.

	*PBR**	
F_R	Model 1	Model 2
0.1	3.31	2.85
0.3	9.94	8.54
0.5	16.57	14.23

* $PBR = N_{MIN} \frac{1}{2} R_{MAX} F_R$, where R_{MAX} is 0.04 and $N_{MIN} = \frac{\hat{N}}{\exp\left(z\sqrt{\ln(1+CV(N)^2}\right)}$.

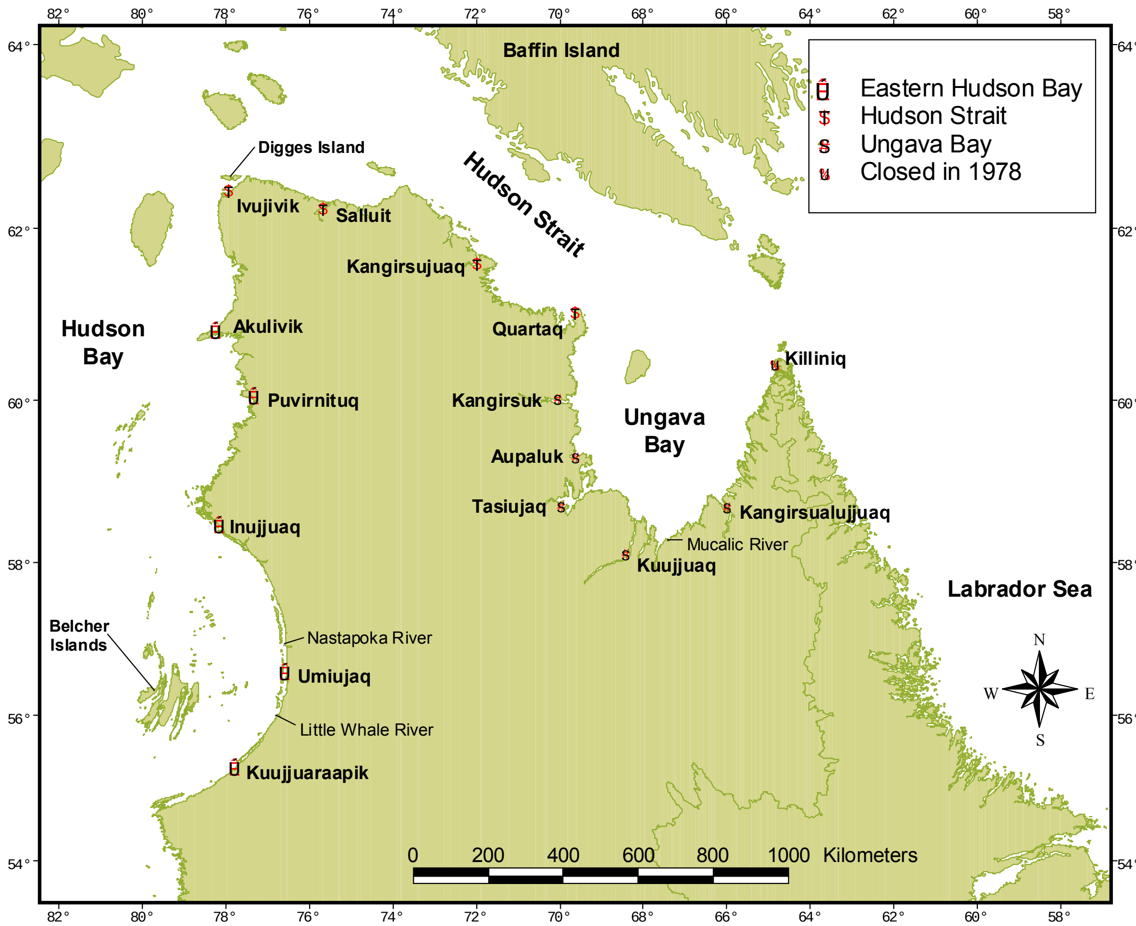

Figure 1. Location of communities in northern Quebec (Nunavik).

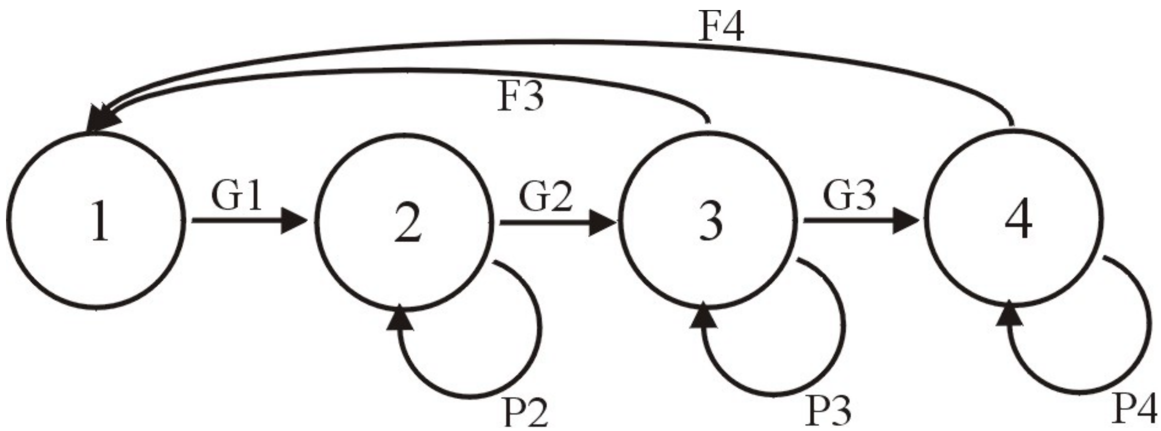

Figure 2. Flow chart depicting a four stage structured population (1 = newborn, 2 = juveniles, 3 = young adults, and 4 = older adults) projection model. G_i represents the probability of surviving and growing to the next stage by the subsequent time step, P_i is the probability of surviving and staying in the same stage during a time step, and F_i is the fecundity rate. Each line represents a transition of one time step.

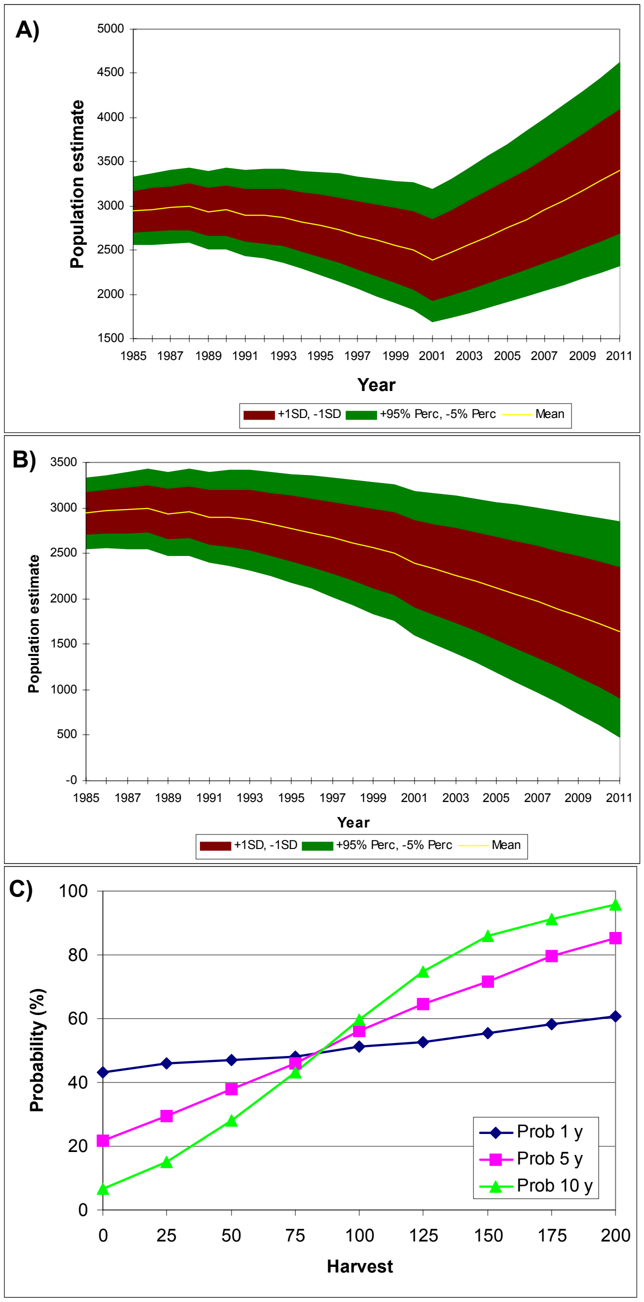

Figure 3. Trajectories of EHB beluga population from 1985 to 2011, using model 1, and assuming r = 0.03–0.04, and a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2010. Trajectories are calculated assuming 100% of all of the communities from eastern Hudson Bay is made up of EHB animals. C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

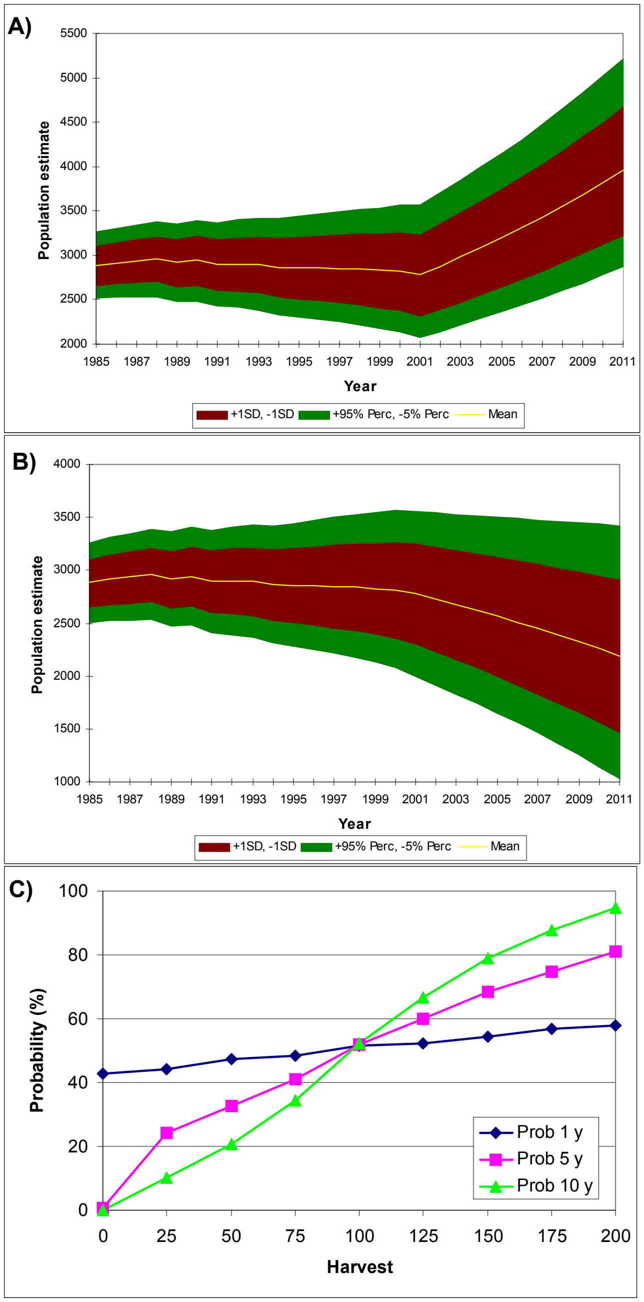

Figure 4. Trajectories of EHB beluga population from 1985 to 2011, using model 1, and assuming r = 0.03–0.04, and a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

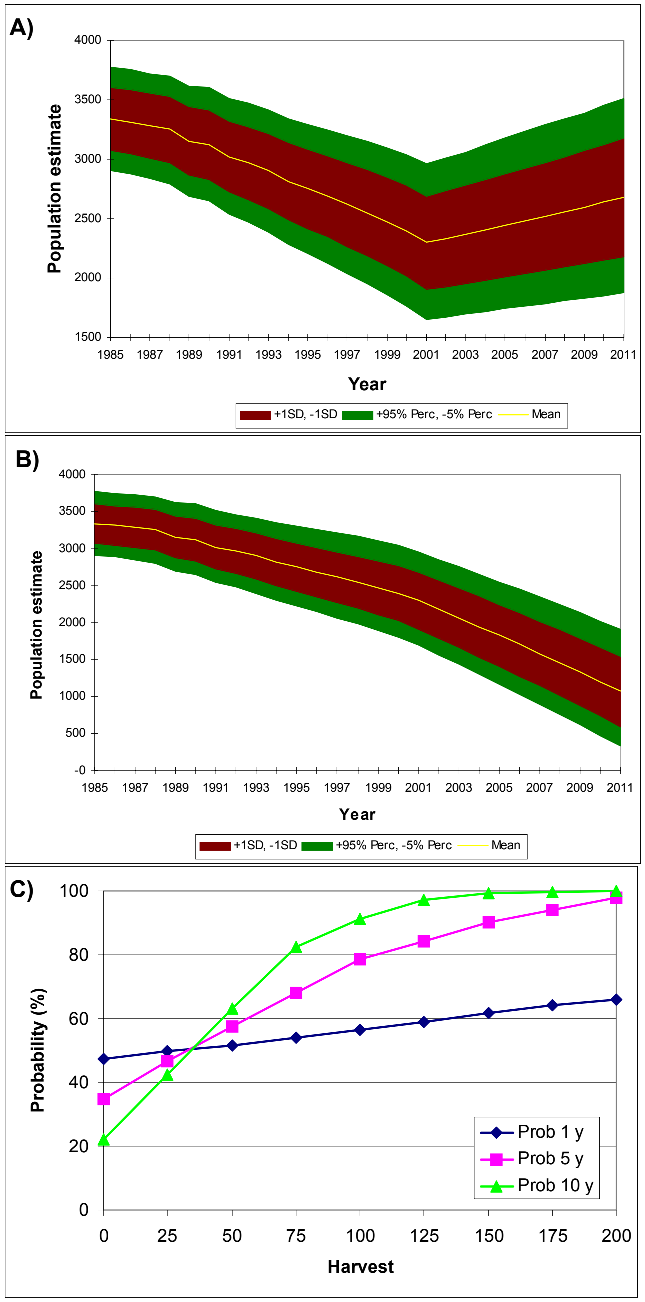

Figure 5. Trajectories of EHB beluga population from 1985 to 2011, using model 1, and assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011, and while optimising *r*. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

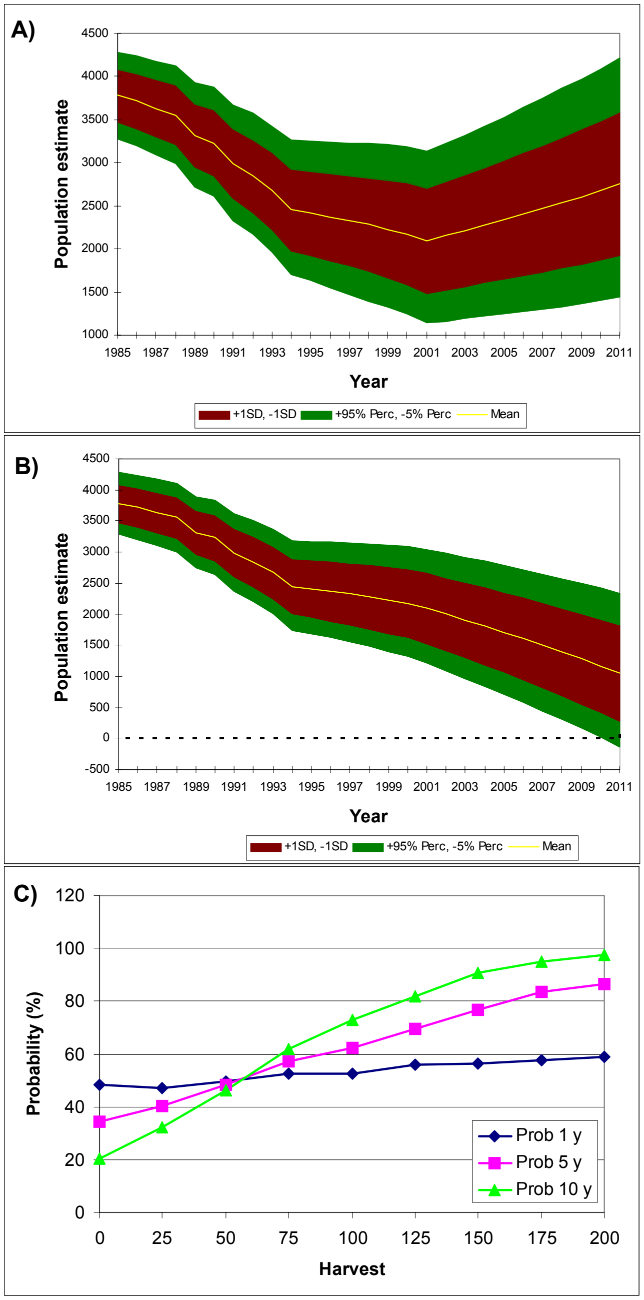

Figure 6. Trajectories of EHB beluga population from 1985 to 2011, using model 1, and assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011, and while optimising *r*, and correcting for declared harvests prior to 1995. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006, and 2011 as a function of harvest levels.

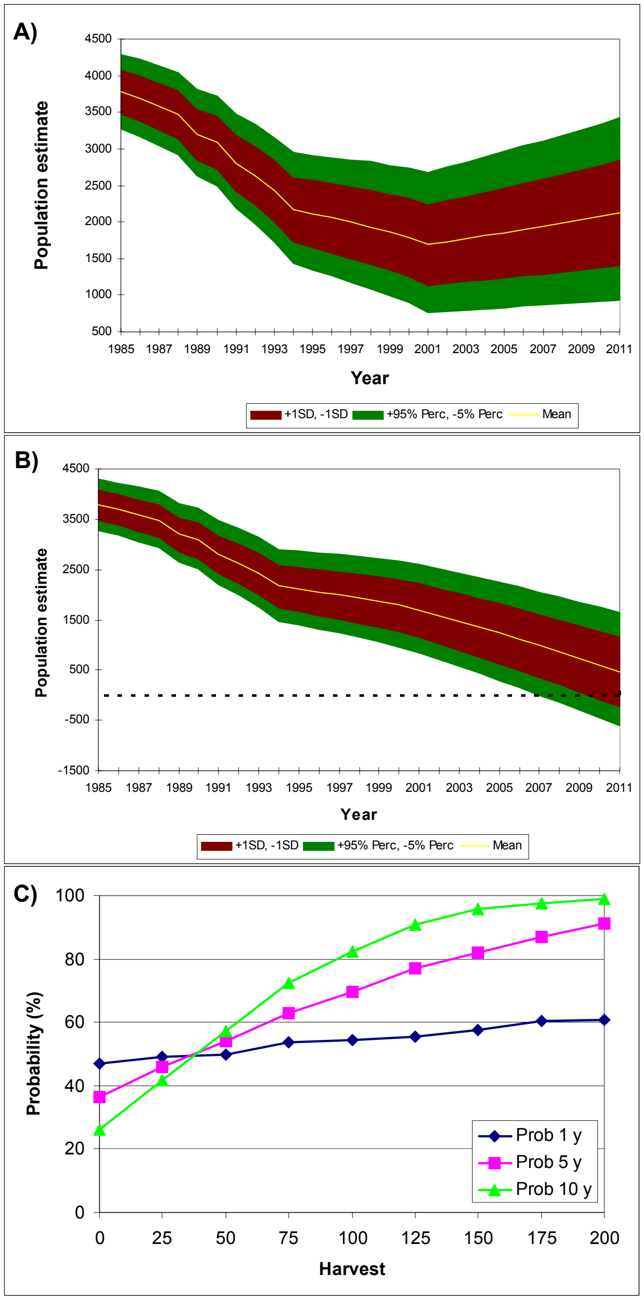

Figure 7. Trajectories of EHB beluga population from 1985 to 2011, using model 1 and assuming population size is 1937 beluga in 2001, and a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011, and while optimising *r*, and correcting for declared harvests prior to 1995. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

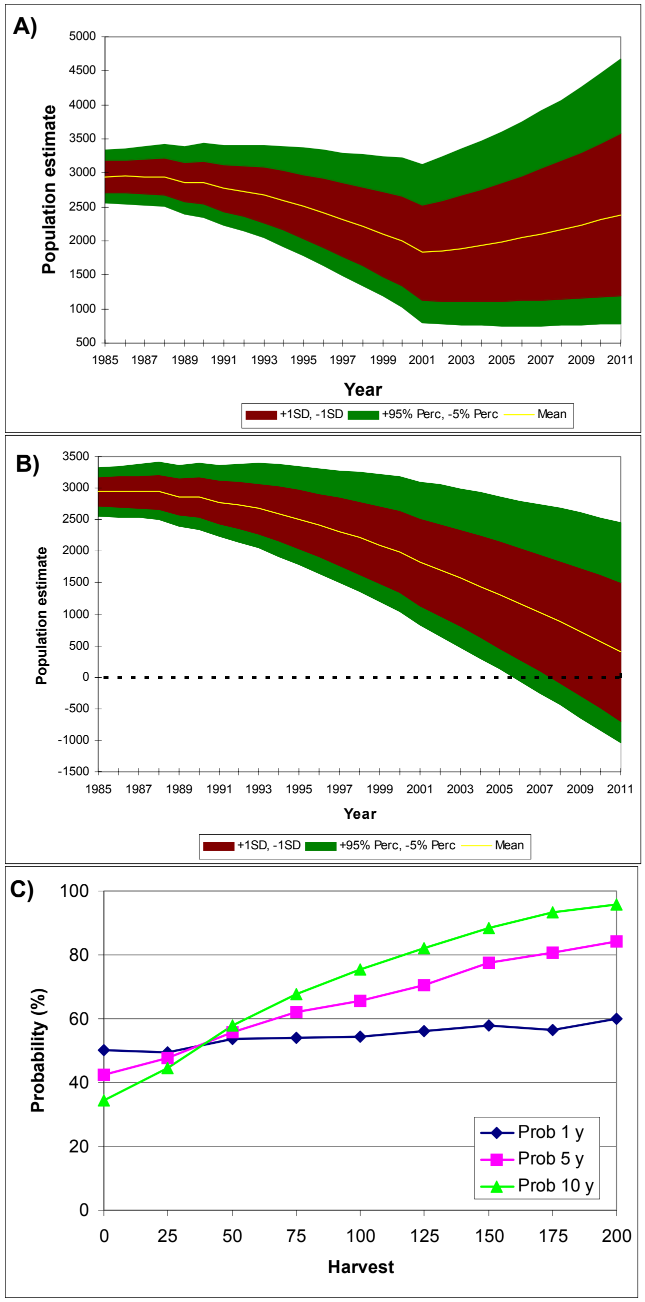

Figure 8. Trajectories of EHB beluga population from 1985 to 2011, using model 2, and assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011. Trajectories are calculated assuming 100% of all of the communities from eastern Hudson Bay is made up of EHB animals. C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

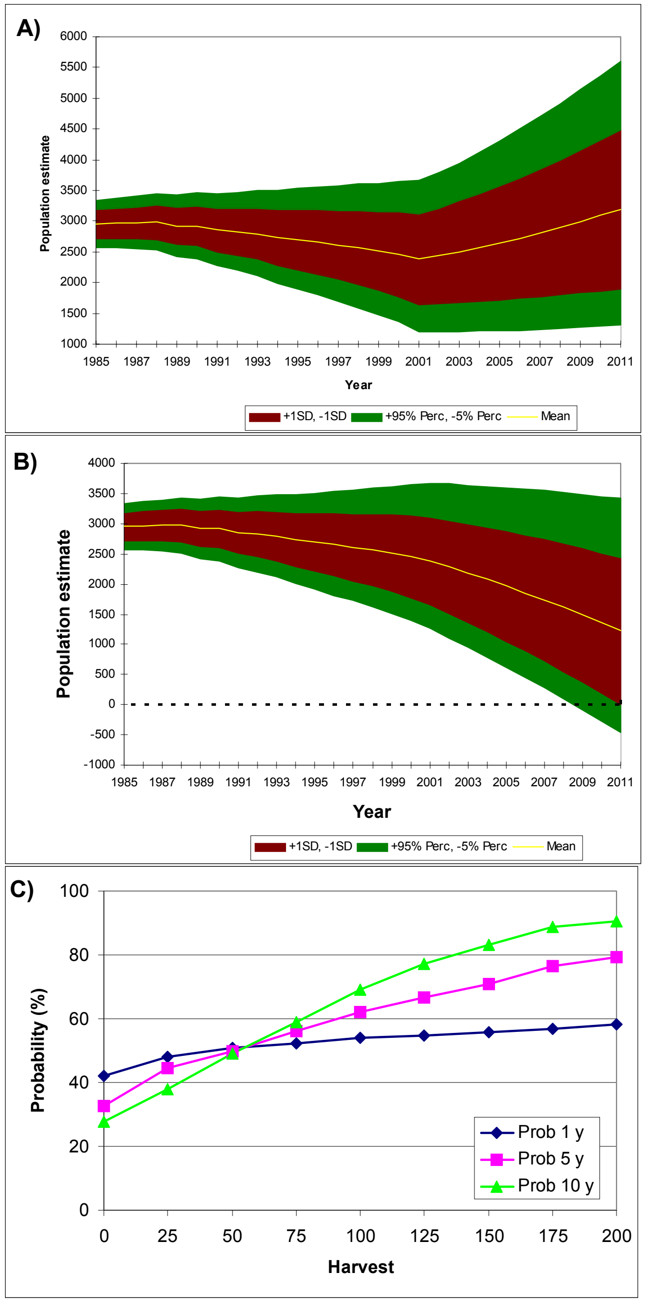

Figure 9. Trajectories of EHB beluga population from 1985 to 2011, using model 2, and assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

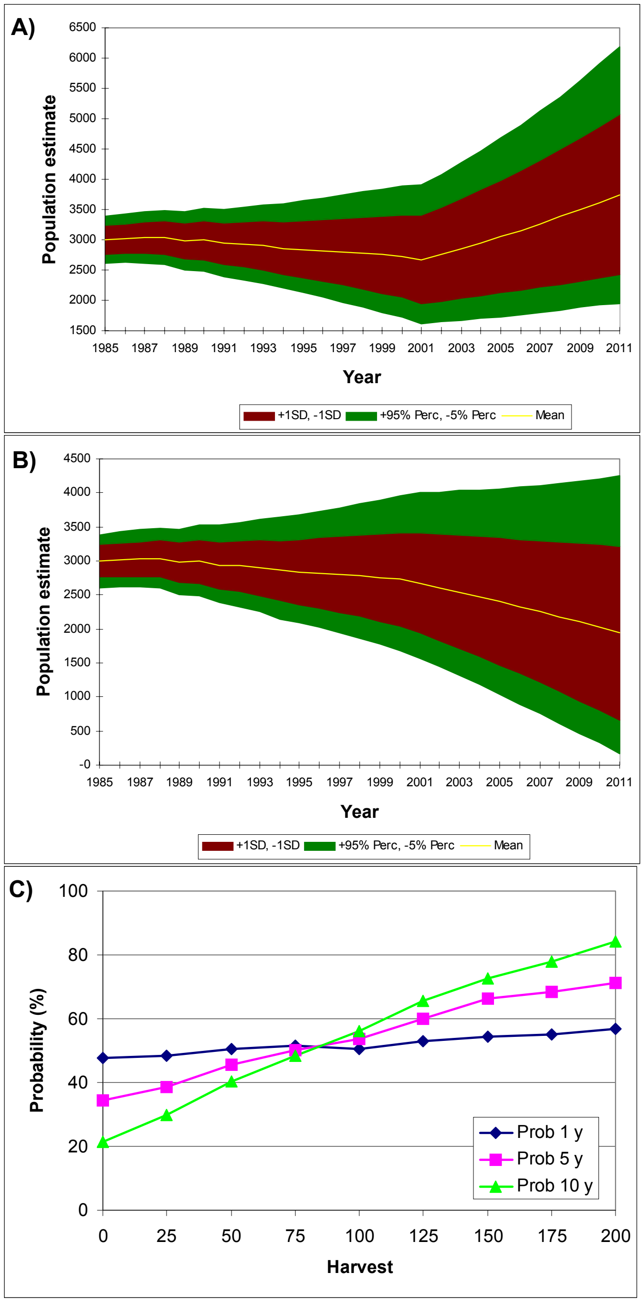

Figure 10. Trajectories of EHB beluga population from 1985 to 2011, using model 2, assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011, and catch-at-stage is proportional to the age structure of the population during the preceding year. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

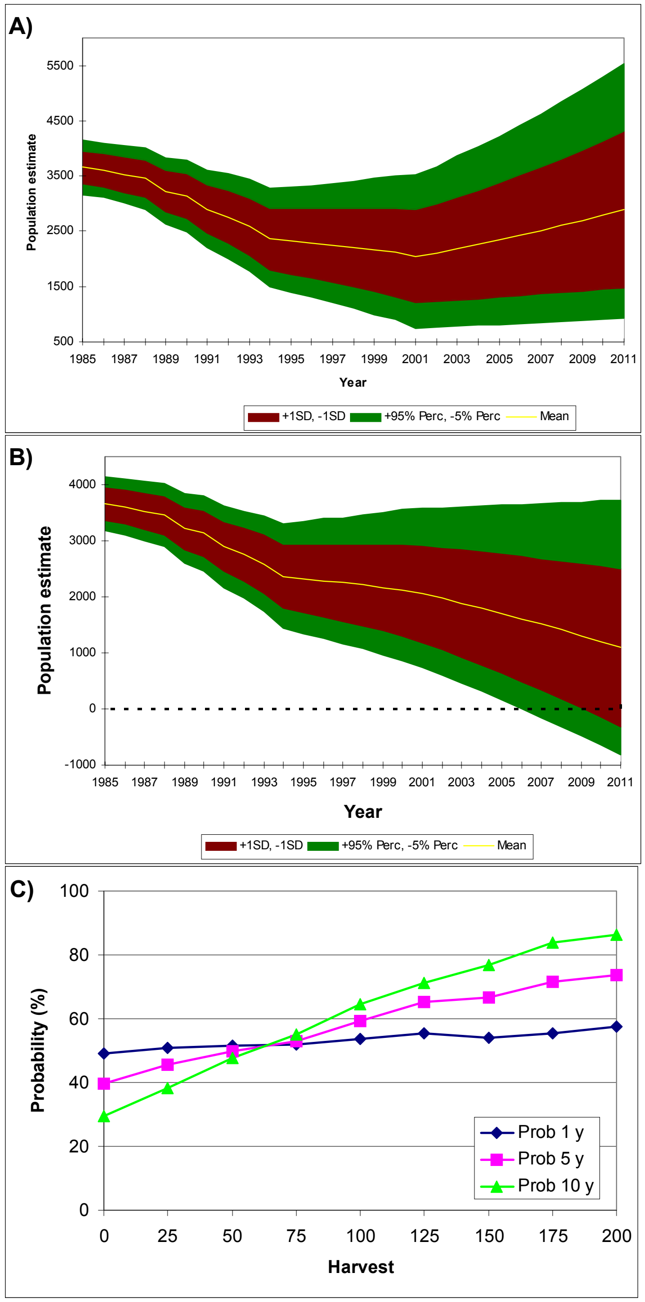

Figure 11. Trajectories of EHB beluga population from 1985 to 2011, using model 2, assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011, assuming catch-at-stage is proportional to the age structure of the population during the preceding year, and while correcting for declared harvests prior to 1995. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006 and 2011 as a function of harvest levels.

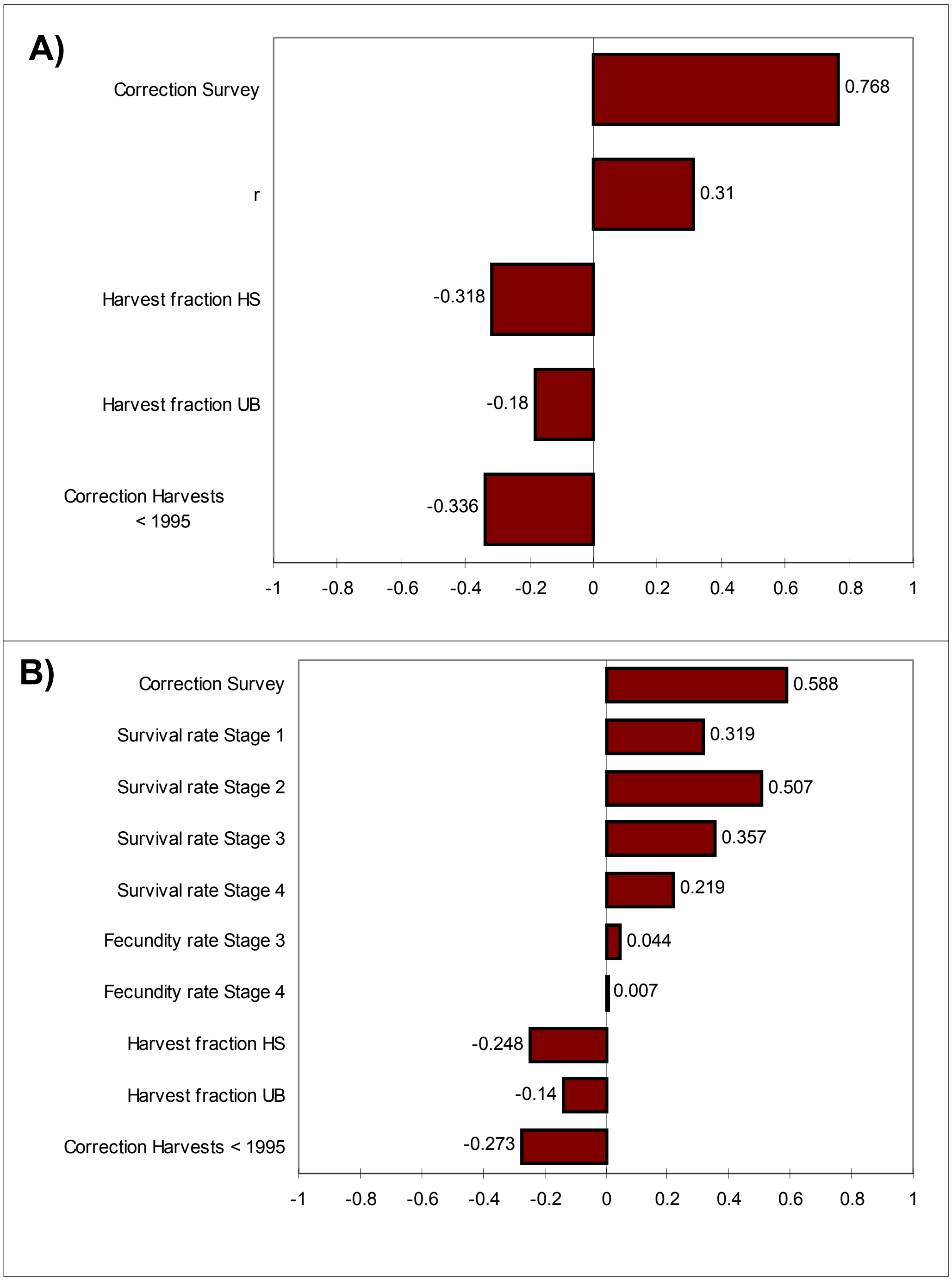

Figure 12. Sensitivity of population estimates of a) Model 1 scenario 4, and b) Model 2 scenario 4 to changes in input parameters.

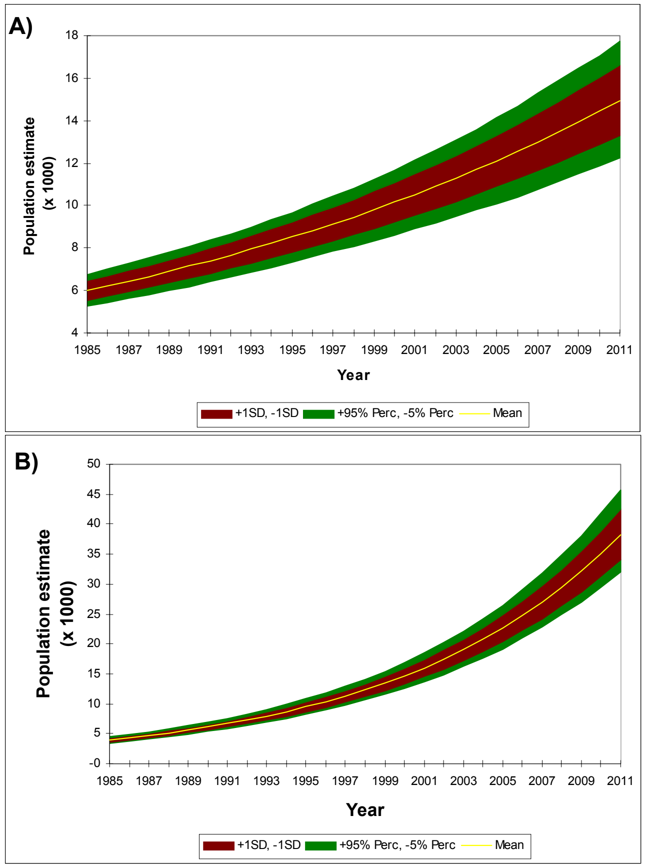

Figure 13. Trajectory of James Bay beluga population from 1985 to 2011, assuming no removals, and while a) fixing *r* at 0.03–0.04 or b) optimising *r*.

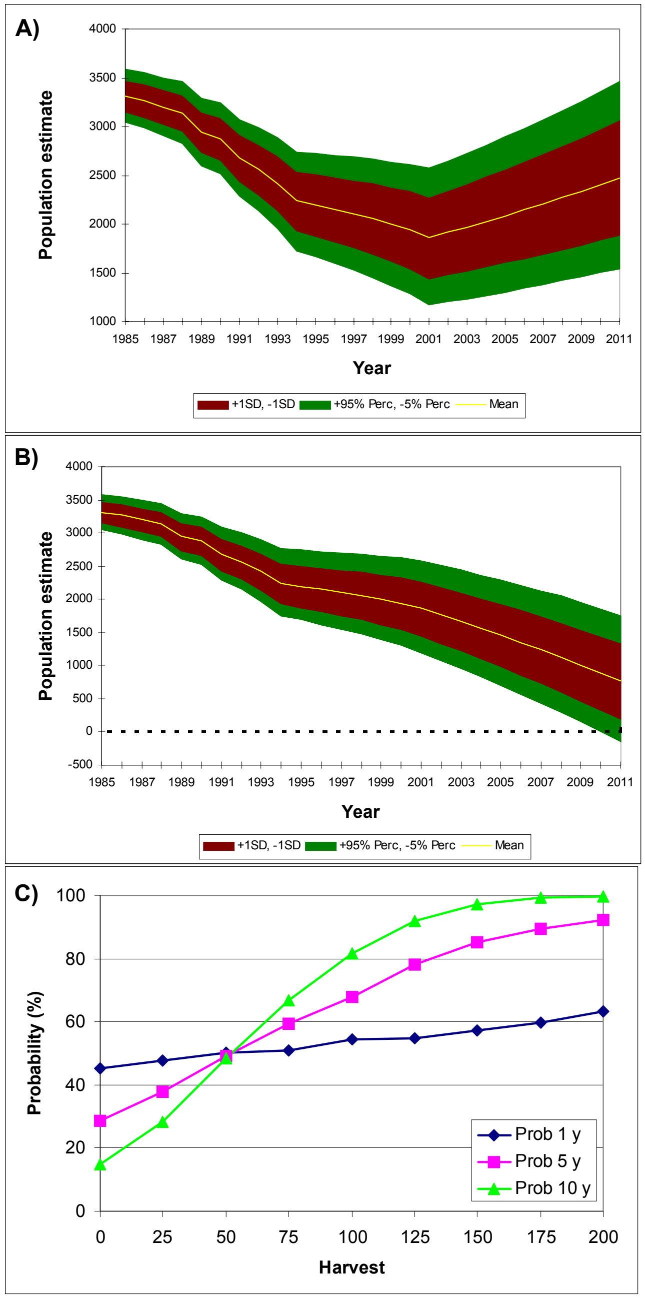

Figure 14. Trajectories of EHB beluga population from 1985 to 2011, using model 1 and an average value of 0.536 instead of the value of 0.478 proposed by Kingsley and Gauthier (in press) to correct for beluga visible from the survey platform, and assuming a) zero beluga, and b) 150 beluga per year are taken from the EHB population between 2002 and 2011, and while optimising *r*, and correcting for declared harvests prior to 1995. Trajectories are calculated assuming the harvest of two communities from eastern Hudson Bay is less than 100% (Akulivik: 22%; Puvirnituq: 100% prior to 1995, then 22%). C) Probability of the stock declining in 2002, 2006, and 2011 as a function of harvest levels.

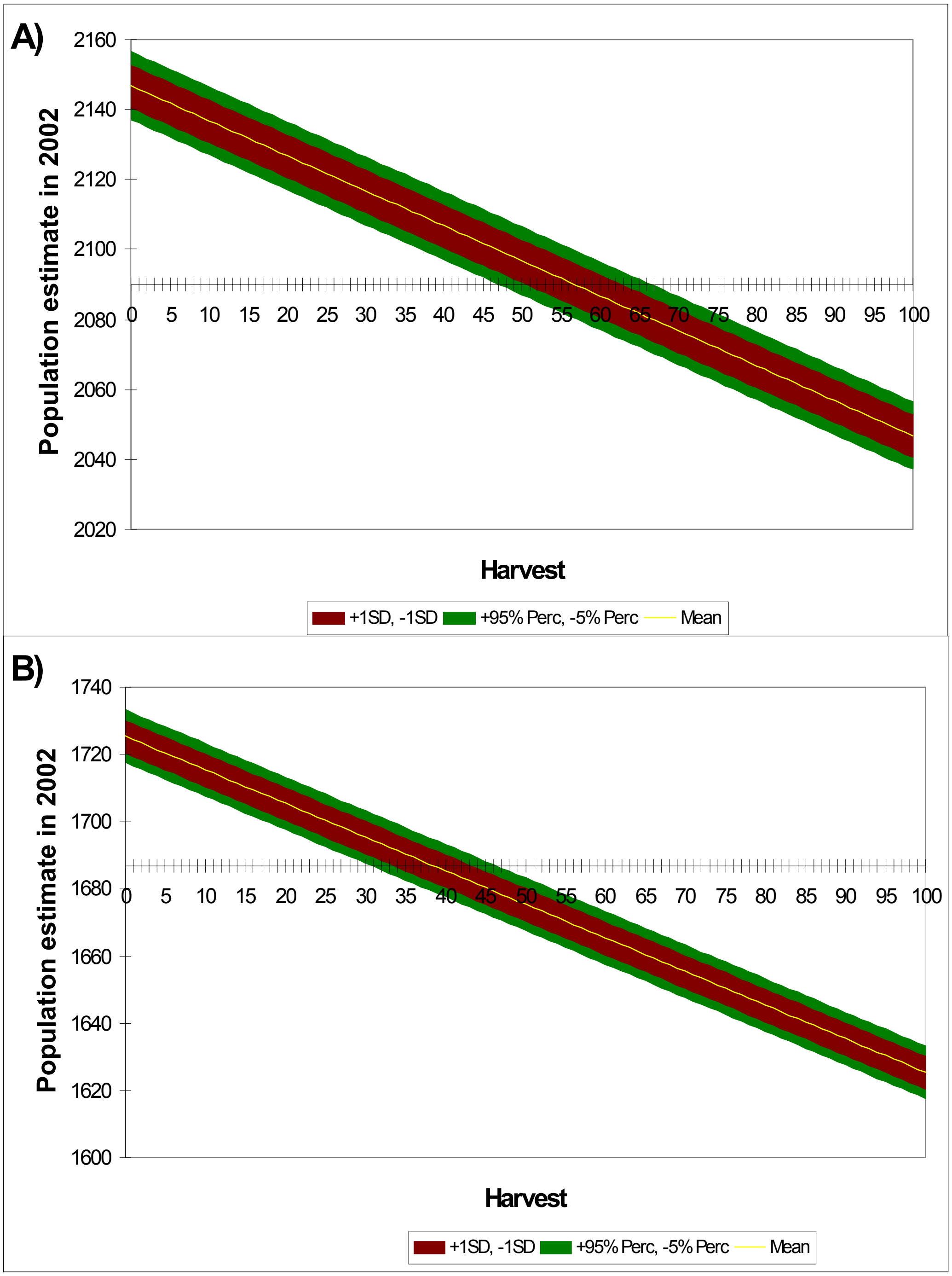

Figure 15. Impact of harvest on the population estimate in 2002, assuming *r* = 0.0218–0.0318 , and EHB population size in 2001 is a) 2090 (SE=0) beluga, and b) 1687 (SE = 0) beluga.

APPENDIX 1

Age distribution of beluga harvested during 1980, 1983–1987, and 1993–2001 in Nunavik

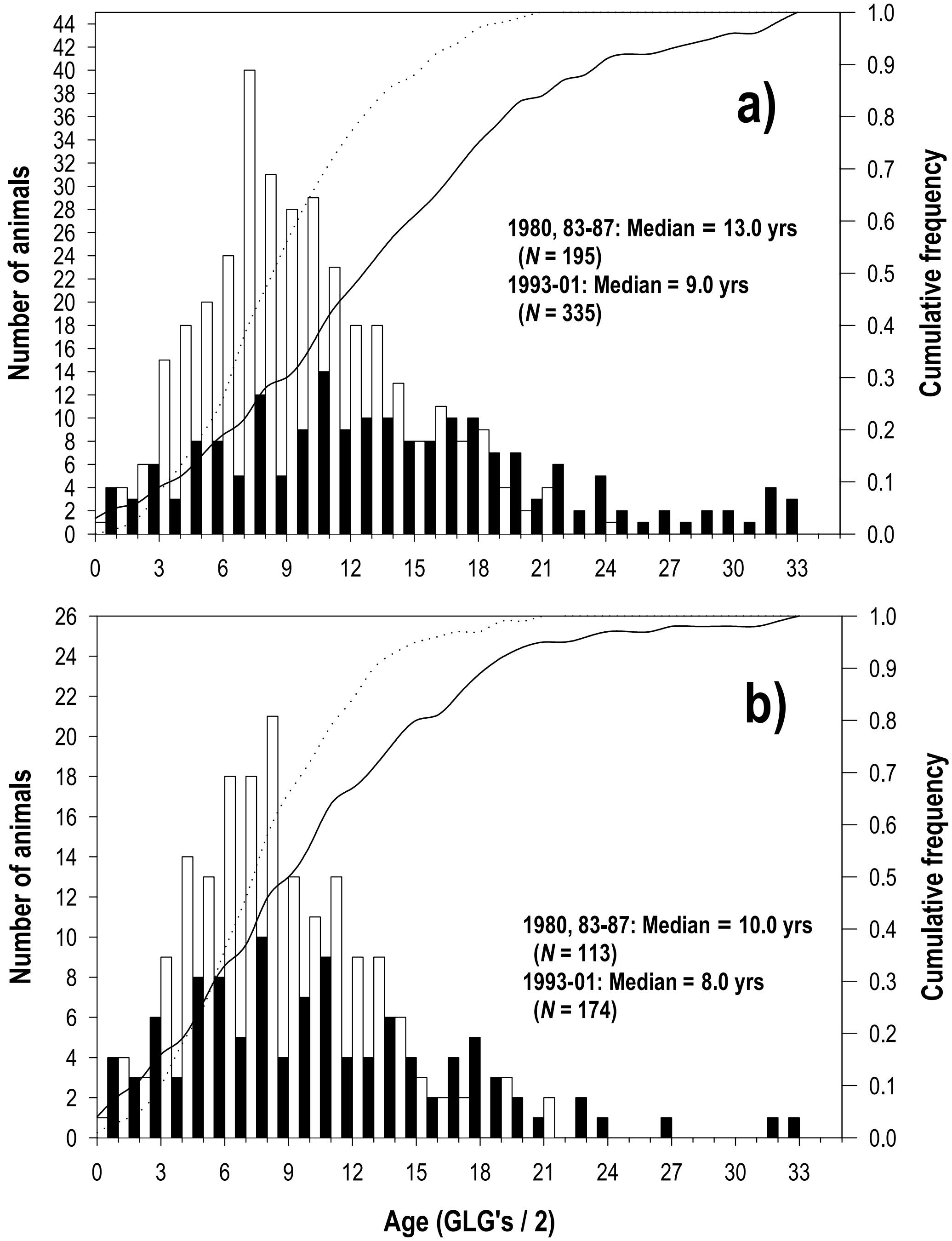

Figure 16. Age of beluga harvested in northern Quebec during 1980, 1983–1987 (black bars and plain curve; Doidge 1990) and 1993–2001 (clear bars and dotted curve), presented as age frequencies (bars) and cumulative frequencies (curves), and using worn and unworn teeth (a) or unworn teeth only (b).

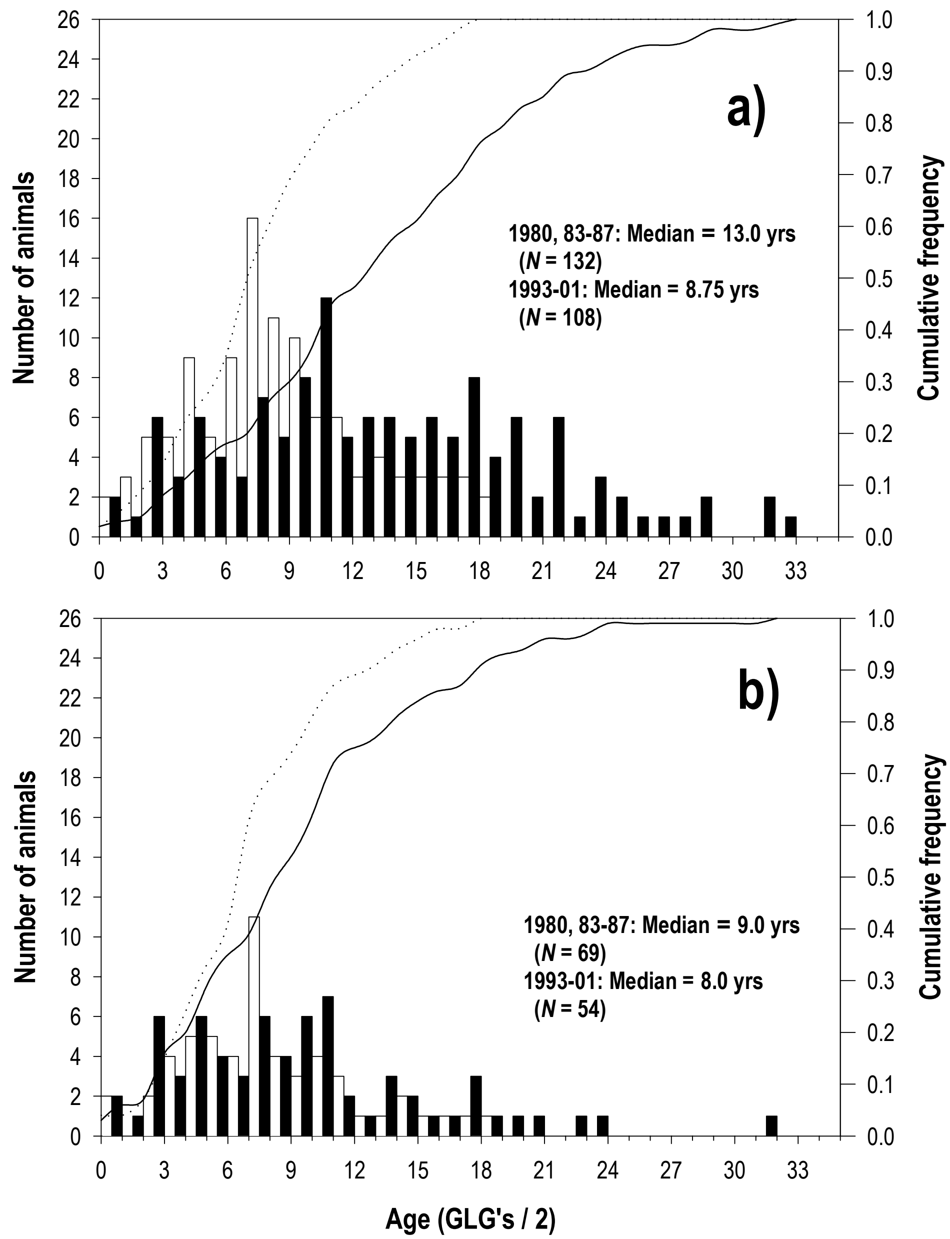

Figure 17. Age of beluga harvested in eastern Hudson Bay during 1980, 1983–1987 (black bars and plain curve; Doidge 1990) and 1993–2001 (clear bars and dotted curve), presented as age frequencies (bars) and cumulative frequencies (curves), and using worn and unworn teeth (a) or unworn teeth only (b).

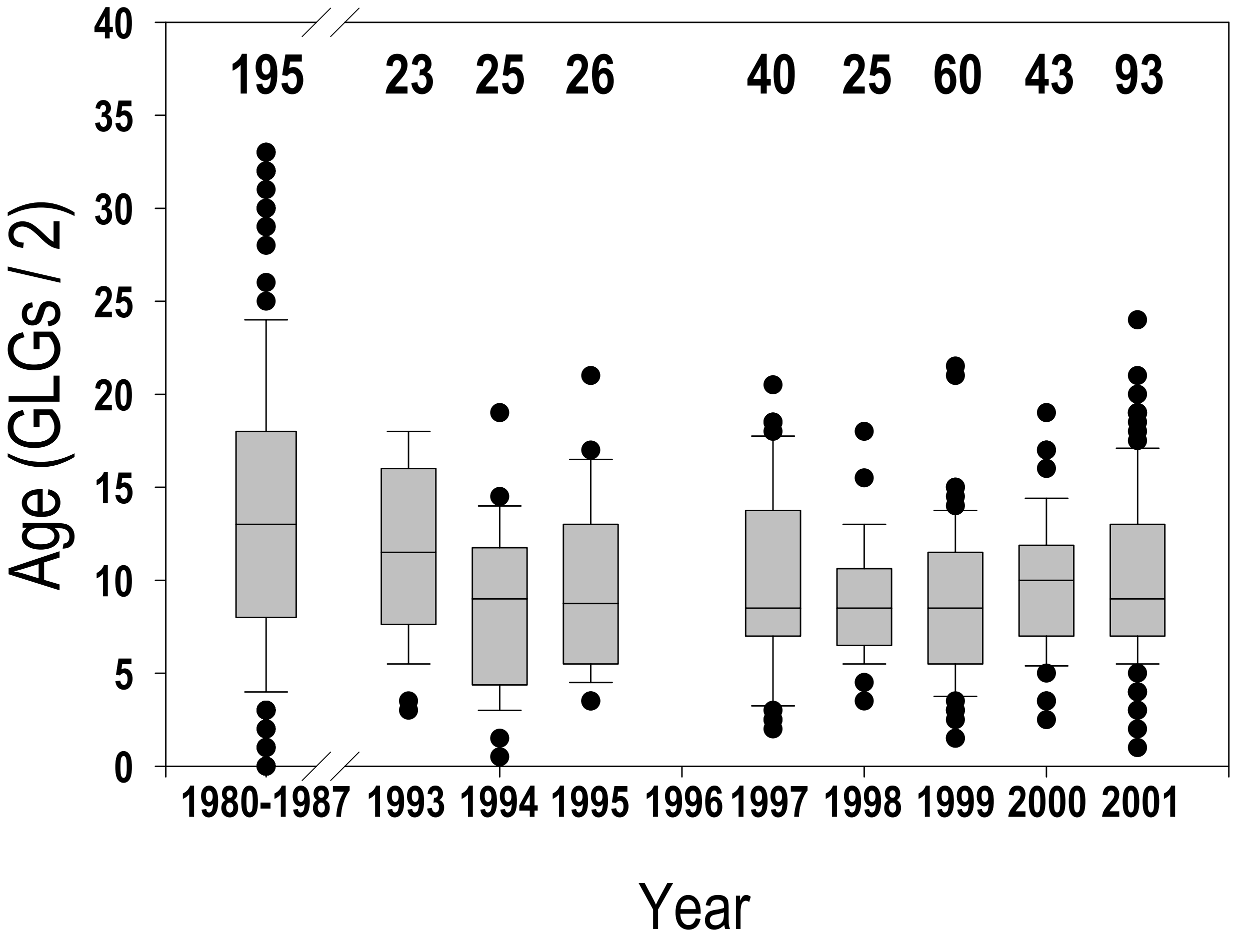

Figure 18. Age distribution of beluga harvested during 1993—2001 in Nunavik. Horizontal lines in grey boxes represent median ages. The bottom and top edges of a box are located at the sample 25th and 75th percentiles, whereas the vertical lines extend to the sample 10th and 90th percentiles. Each value located within the first and last 10th percentiles is indicated by a dot. Numbers on the graph indicate the sample size for each year.

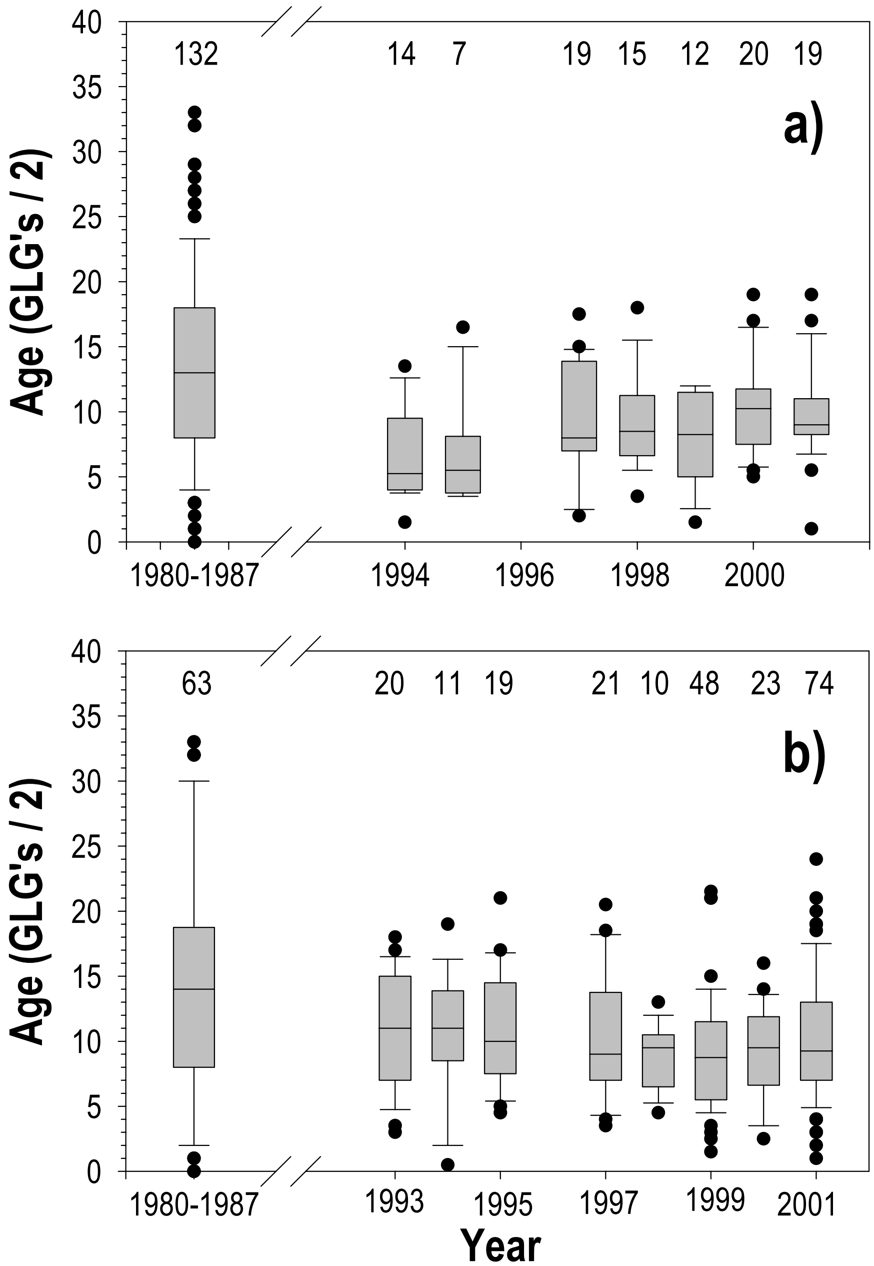

Figure 19. Age distribution of beluga harvested during 1993—2001 in a) eastern Hudson Bay and b) in Hudson Strait and Ungava Bay. Horizontal lines in grey boxes represent median ages. The bottom and top edges of a box are located at the sample 25th and 75th percentiles, whereas the vertical lines extend to the sample 10th and 90th percentiles. Each value located within the first and last 10th percentiles is indicated by a dot. Numbers on the graph indicate the sample size for each year.

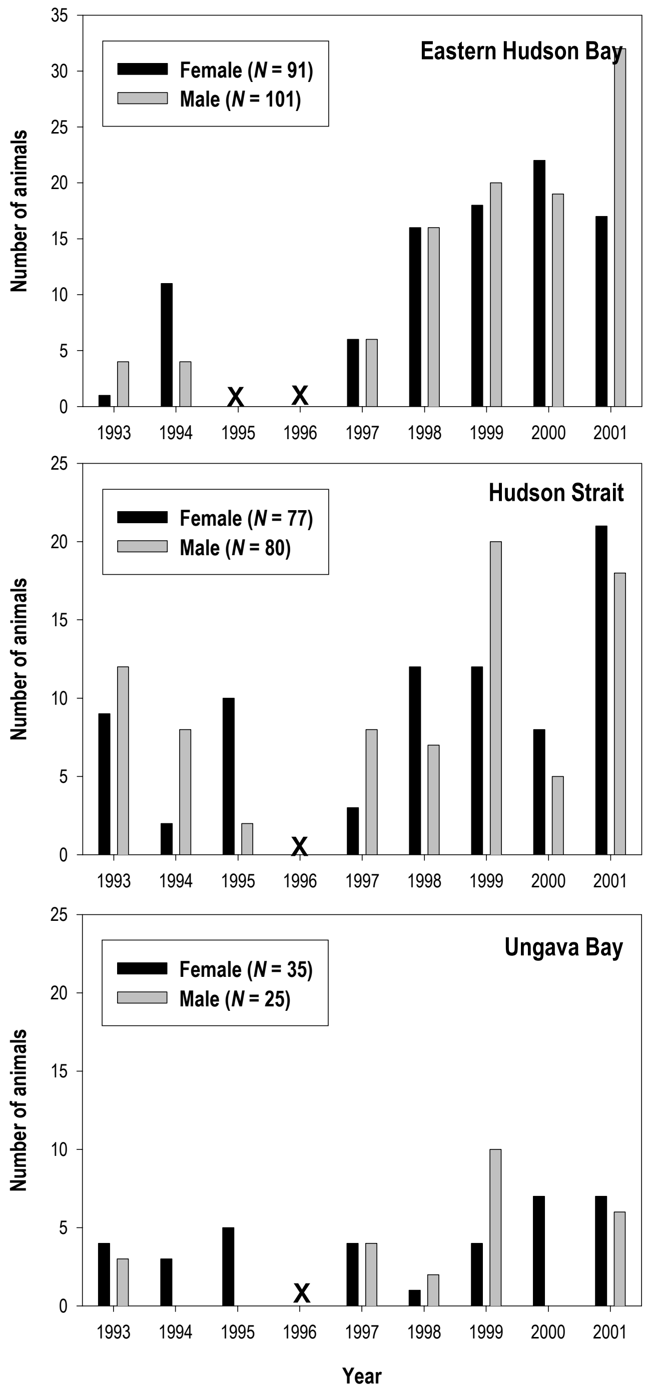

Figure 20. Proportion of male and female beluga taken by communities from eastern Hudson Bay, Hudson Strait, and Ungava Bay, 1993–2001. An ‘x’ indicates a lack of data.