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Abundance Estimates of Northwest Atlantic Harp seals and Management advice for 2014

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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

A population model was used to examine changes in the size of the Northwest Atlantic harp seal population between 1952 and 2014. The model incorporated information on reproductive rates, reported removals, estimates of non-reported removals and losses through bycatch in other fisheries to determine the population trajectory. The model was fit to 12 estimates of pup production from 1952 to 2012, and to annual estimates of age-specific pregnancy rates between 1954 and 2013. Pup production declined throughout the 1960s reaching a minimum in 1971, and then increased to a maximum in 2008. Pup production and total population size in 2012 are estimated to be 929,000 (SE=148,000) and 7,445,000 (SE=698,000), respectively. The maximum estimated population size, Nmax, was estimated to be 7.8 million animals in 2008. Projecting forward to 2014, the estimated pup production is 853,000 (SE=202,000) and total population size is 7,411,000 (SE=656,000). The population appears to be relatively stable, showing little change in abundance since the 2004 survey, although pup production has become highly variable among years. Data on age-specific pregnancy rates indicate that herd productivity has declined compared to the 1980s and early 1990s. However, relatively few reproductive samples have been obtained in recent years which contributes to our uncertainty surrounding the population estimate.

Estimation de l'abondance des phoques du Groenland de l'Atlantique nord-ouest et conseil de gestion pour 2014

RÉSUMÉ

Un modèle de population a été utilisé pour examiner les changements dans la taille de la population de phoques du Groenland de l'Atlantique Nord-Ouest entre 1952 et 2014. Le modèle intègre des informations sur les taux de reproduction, les prélèvements déclarés, les estimations des prélèvements non déclarés et les pertes dans les prises accessoires dans d'autres pêcheries pour déterminer la trajectoire de la population. Le modèle a été ajusté à 12 estimations de production de nouveau-nés de 1952 à 2012, et aux estimations annuelles des taux de grossesse par âge entre 1954 et 2013. La production de nouveau-nés a diminué tout au long des années 1960 pour atteindre un minimum en 1971, puis a augmenté à un maximum en 2008. La production de nouveau-nés et la taille de la population totale en 2012 sont estimés à 929 000 (SE = 148 000) et 7 445 000 (SE = 698 000), respectivement. La taille maximale estimée de la population, Nmax, a été estimée à 7,8 millions d'animaux en 2008. En ce qui concerne la projection pour 2014, la production de nouveau-nés est estimée à 853 000 (SE = 202 000) et la taille de la population totale à 7 411 000 (SE = 656 000). La population semble être relativement stable, montrant peu de changements dans l'abondance depuis le relevé de 2004, bien que la production de nouveau-nés soit devenue très variable entre les années. Les données sur les taux de grossesse selon l'âge indiquent que la productivité du troupeau a diminué par rapport aux années 1980 et au début des années 1990. Cependant, relativement peu d'échantillons de l’appareil reproducteur ont été obtenus au cours des dernières années, ce qui contribue à notre incertitude entourant l'estimation de la population.

INTRODUCTION

Phocid lifehistories are characterized by foraging at sea, with a requirement to return to a solid substrate for reproduction (Kovacs 1995). Throughout much of the year, animals are dispersed widely at sea where they are often below the surface and hence difficult to count. During the breeding season, mature animals aggregate, and although adults may not always be hauled-out, the young are available to be counted using visual or photographic surveys (Bowen et al. 1987; Stenson et al. 1993, 2002, 2003, 2010, 2014a). An estimate of total population size can then be obtained by incorporating the estimates of young of the year (YOY) into a population model along with information on reproductive and/or mortality rates (Roff and Bowen 1986; Skaug et al. 2007).

The harp seal (*Pagophilus groenlandicus*) assessment incorporates information on annual age-specific reproductive rates, reported harvests, struck and loss, bycatch, and ice-related mortality of young of the year (YOY), into an age-structured model to estimate total population size since 1952. The model is fitted to estimates of pup production obtained from periodic aerial surveys and mark-recapture studies by adjusting the initial population size in 1952 and adult mortality rates (Hammill et al. 2011a). The basic model was first developed in the early 1980's (Roff and Bowen 1983), but has since undergone a series of improvements including consideration of struck and loss, and incorporating unusual mortality related to poor ice conditions (Shelton et al. 1992, Sjare and Stenson 2002; Hammill and Stenson 2003) (Table 1).

More recently, two significant changes occurred (Table 1). First, the model formulation was changed from describing the dynamics of the population assuming exponential growth to a model describing the dynamics of the population assuming density-dependent changes in young of the year mortality. In the 2010 and 2011 assessments, environmental carrying capacity was set at the assumed value of 12 million animals (Hammill et al. 2011a) which was similar to the estimated pre-hunt level (Hammill et al. 2011b). Secondly, unusually high reproductive rates were observed in 2007 and 2008, resulting in much higher than expected pup production (Stenson and Wells 2010; Stenson et al. 2010) in spite of an overall declining trend in reproductive rates among animals aged 8 years and older. Consequently, the manner in which the reproductive data were incorporated into the model was changed (Hammill and Stenson 2011; Hammill et al. 2011a). Until 2010, it was assumed that pregnancy rates did not change dramatically between years, and therefore averaged, or smoothed, values were used. In the 2010 formulation, the actual pregnancy rate data were used if the sample sizes exceeded a threshold of 10 samples in a single year. If fewer samples were available, the population model used a value predicted by a smoothing model. This approach was taken because, while it was assumed that changes in measured pregnancy rates reflected real variability in reproductive rates, small sample sizes were considered to be unreliable measures.

Expert reviews provided by the Intergovernmental Panel on Climate Change (IPCC) make it clear that climate change will induce temperature changes and associated adjustments in ocean circulation, ice coverage and sea level. (McCarthy et al. 2001). Such changes are expected to impact marine ecosystems through changes in population parameters, predator-prey relationships and distribution (Simmonds and Isaac 2007). Sea ice cover in the area occupied by overwintering harp seals varies periodically, with positive and negative extremes approximately 6 yr apart (Johnston et al. 2005). The spatial analysis of extreme anomalies reveals that changes occur primarily in the Gulf of St. Lawrence, but have also occurred off the east coast of Newfoundland, suggesting that both areas react similarly to seasonal shifts and climatic variation (Johnston et al. 2005). Over the last decade, the frequency of below average ice cover has increased markedly (Bajzak et al. 2011). In years, where there is very little ice-cover, ice-related mortality (Mice) of nursing and weaned YOY is likely quite high. For example, there was very little ice cover in 1981 and Mice was considered to have been particularly high. Among cohort samples collected in later years, this year class appears to have disappeared (Sergeant 1991). Other evidence for high Mice includes the reports of large numbers of carcasses on the beaches or large numbers of drifting carcasses in the water. Increased mortality among YOY due to poor ice conditions was first incorporated into the assessment model in 2003 (Hammill and Stenson 2003). This mortality was thought to occur during the first 4-8 weeks after birth, when the ice was needed as a platform for nursing or resting. In the assessment model, this mortality occurred prior to the start of the commercial hunt. Although it was recognized that it was important to consider mortality, it has not been possible to quantify it accurately. Instead, based on expert opinion an index value representing the proportion of pups surviving from birth to the start of the commercial hunt (Sice), was assigned at the end of each year, to be incorporated into the next assessment. In addition, to account for ice-related mortality (1- Sice) in the year that it occurred, Sice was also incorporated into the projection model when evaluating the impact of future harvests on the population. For the current assessment, an attempt has been made to develop a quantitative index (Hammill and Stenson 2014).

At the 2010 National Marine Mammal Peer review (NMMPR) meeting, it was suggested that the model should be fit to observed changes in the annual reproductive rate data, as well as to the estimates of pup production obtained from the aerial surveys. This approach appeared advantageous because, whereas there are only 11 aerial survey estimates available since 1950, there are 30+ years of reproductive rate data available. This revision was presented to NMMPR in 2012, where the model fitted to both the reproductive rate data and to the aerial survey estimates, by adjusting estimates of adult mortality rates (M), initial population size (α), and environmental carrying capacity (K) to minimize the sum of squares differences between observed reproductive rates and survey estimates and model predictions for these estimates. These estimates of α, K and M are then incorporated into a projection model to evaluate whether different harvest scenarios respected the management objective, over the duration of a management plan.

A major difficulty in determining the impact of future catches is to predict how reproductive rates may change in the future, as well as how the unregulated Greenland subsistence harvest may change. In previous assessments we have modeled the future reproductive rates by allowing the model to select from a sample of reproductive rates observed during the last 5 years. As for Greenland catches, future harvests were assumed to followed a uniform distribution with a minimum of 70,000 and a maximum of 100,000 animals (average=85,000).

In this assessment we present an update to estimates of harp seal abundance as a result of new information from a pup production survey flown in 2012, as well as new information on reproductive rates and catches. In addition, Fisheries Management has requested that we examine the impacts of different harvest scenarios on the population over the next 5 years (2014-2018). These scenarios include an analysis that identifies the risk that the Harp seal population will drop below 50% and 70% of Nmax with annual catches of 300,000, 400,000, 500,000 and 600,000 and a composition of a) 30% adults / 70% beaters, b) 10% adults / 90% beaters, or c) 5% adults / 95% beaters?

We were also requested to identify the ‘triggers’ that would indicate a need to reassess the population and TAC within the multi-year management plan.

MATERIALS AND METHODS

Modelling the dynamics of the Northwest Atlantic harp seal population occurs in two steps. In the first, using Monte Carlo resampling, the model is fitted to independent estimates of the total pup production, and the pregnancy rates observed for seals 8 years old and older (referred to as 8+) by adjusting initial population size (*α*), adult (i.e. one year old and older, referred to as 1+) mortality rates (*M*) and the carrying capacity (*K*). The model integrates data on removals and ice-related mortality. It is considered that the dynamics of the population can be described by assuming density dependent mortality acting on both juvenile survival and pregnancy rates of the 8+ individuals. It is also assumed that the sex ratio is 1:1.

A second component of the model, referred to as the ‘Projection Model’, projects the population into the future to examine the impacts of different management options on the population. The projection model is based on the same equations as the fitting model, but uses the parameter values estimated for M and K in the projections.

MODEL STRUCTURE

Initial population

$$P = \sum_{i=1}^{26} (\alpha \times l_i) \tag{1}$$

Survival

For age 1:

$$n_{1,t} = ((n_{0,t-1} \times w) - c_{0,t-1}) \times e^{-Mo} \times (1 - (N_t / K)^{\theta}) \tag{2}$$

with $M_0 = \gamma \times M$

For age a, with 1<a<A:

$$n_{a,t} = (n_{a-1,t-1} \times e^{-M/2} - c_{a-1,t-1}) \times e^{-M/2} \tag{3}$$

For age A

$$n_{A,t} = [(n_{A-1,t-1} + n_{A,t-1}) \times e^{-M/2} - (c_{A-1,t-1} + c_{A,t-1})] \times e^{-M/2} \tag{4}$$

Reproduction

$$n_{0,t} = \sum_{a=1}^{A} n_{a,t} \times P_{a,t} \tag{5}$$

For age a, with 1<a<8

$$P_{a,t} \sim CorBin(n_{a.reprod,t}, p_{a.preg,t}) \tag{6}$$

For age a, with a ≥ 8 (i.e. 8+)

$$P_{a,t} = P_{8,t} \sim CorBin(n_{8+.reprod,t}, p_{8+.preg,t}) \quad (7)$$

also $$Psim_{8+,t} = 0.88 \times (1 - N_t / K)^{\theta} \quad (8)$$

where

P_{init} = size of the total initial population,

α = multiplying factor,

l_i = initial population size for the i^{th} age class,

$n_{a,t}$ = population numbers-at-age *a* in year *t*,

$c_{a,t}$ = the numbers caught at age *a* in year *t*,

$P_{a,t}$ = per capita pregnancy rate of age *a* parents in year *t*, assuming a 1:1 sex ratio,

$CorBin$ = multivariate distribution composed of binomial distributions which degree of correlation is controlled via an 8-dimension Gaussian copula (Sklar 1959; Joe 1997; Trivedi and Zimmer 2005). Note: this function is used during the fitting to establish a correlation between age-classes in pregnancy rates, assuming that if the mature animals (8+ years) have a better year, then younger age classes will also have better years.

$n_{a.reprod,t}$ = sample size used to obtain the observed pregnancy rate in year t,

$p_{a.reprod,t}$ = proportion of pregnancy in the observed group in year t,

$Psim_{8+,t}$ = per capita pregnancy rate of age 8+ parents estimated by its relation with the carrying capacity. The value of 0.88 corresponds to the maximum pregnancy rate observed when the population was low (i.e. far from the carrying capacity). This estimation is used to fit the model with observed pregnancy rates obtained during the same period.

M = the instantaneous rate of natural mortality of animals aged 1+ years,

M_0 = the instantaneous rate of natural mortality of animals in their first year,

γ = a multiplier to allow for higher mortality of first year seals. Assumed to equal 3, for consistency with previous studies,

w = the proportion of pups surviving an unusual mortality event arising from poor ice conditions or weather prior to the start of harvesting,

A = the 'plus' age class (i.e., older ages are lumped into this age class and accounted for separately, taken as age 25 in this analysis),

N_t = total population size,

K = carrying capacity

θ = theta, set at 2.4 (Trzcinski et al. 2006).

MONTE CARLO RESAMPLING AND PARAMETER ESTIMATION

The model creates a population matrix with 26 age classes from 1952 until the current year. The initial population vector (26 × 1) was created as an initial population age structure which size is adjusted by a multiplying factor (α). We included the uncertainty in the pregnancy rates and the pup production estimates in the fitting model by resampling the parameters using Monte Carlo techniques. At each iteration of the model, pregnancy rates are resampled for each year assuming a binomial distribution (correlated among age classes), and pup production estimates are resampled assuming a normal distribution (with variance based on estimates of the survey errors). For each iteration, the model then minimizes (1) the weighted sum-of-square differences between the pup production estimated by the model ($n_{0,t}$) and the resampled production estimates from the surveys, (2) the weighted sum-of-square differences between the 8+ pregnancy rate estimated ($P_{sim8+,t}$) and the resampled pregnancy rates, by estimating three parameters; the initial population factor (α), the instantaneous mortality rate (*M*), and the carrying capacity (*K*). The three parameters (α, *M* and *K)* are optimized by iterative methods. For each Monte Carlo iteration, new *M, K* and α are estimated and stored. The model runs in the programming language R.

DATA INPUT

Pup production estimates

The model was fitted to 12 independent estimates of pup production (Table 2) obtained in 1978, 1979, 1980 and 1983 based on mark-recapture experiments (Bowen and Sergeant 1983, 1985; revised in Roff and Bowen 1986), and aerial survey estimates for 1952, 1960, 1990, 1994, 1999, 2004, 2008 and 2012 (Sergeant and Fisher 1960; Stenson et al. 1993, 2002, 2003, 2005, 2010, 2014a). The 1952 and 1960 surveys did not cover the entire area and included estimates of pupping based upon visual estimates for concentrations seen, but not surveyed. Also, they did not correct for births occurring after the surveys. These two surveys are thought to provide useful information, but there is greater uncertainty surrounding their estimates. To reflect this, these surveys were assigned a coefficient of variation of 40%.

Reproductive rates

Estimates of late term pregnancy rates are available from sampling programs maintained by the Department of Fisheries and Oceans since 1954 (Sjare and Stenson 2010, Stenson and Wells 2010; Stenson et al. 2014b). Samples represent late-term pregnancy rates since they are collected only a few months (October to February) prior to pupping in March. It is assumed that there would have been no mortality after the samples were taken and animals are into the model at the age they would have had at the time of pupping. Data included in the model were available from 1954 to 2013 (Table 3). Seals 3 years old and younger were considered immature while seals 8 years and older were considered to be fully recruited into the population.

There are gaps in the time series of the data, and in some years sample sizes are small (Table 3). For this reason, we smoothed the data by applying local logistic regression (Loader 1999) to the binary data (pregnant or non-pregnant) (Tibshirani and Hastie 1987). This smoother yields errors around predictions and allows weighting by sample size to take into account the local density of data. Thus, there is no need to reject data points for which sample size is below an arbitrary threshold. Smoothing was performed using the R package LocFit (Loader 2010). Since we expected substantial curvature in the trajectory of pregnancy rates, we used a 2nd degree polynomial to further reduce bias (Sun and Loader 1994). The degree of smoothing was controlled with an adaptive bandwidth: for each fitting point, the bandwidth was chosen so that the local neighbourhood always contained a specified proportion (β) of the dataset. We determined β for each age class by testing a range of values and selecting the β that yielded the best fit (lowest AIC, Loader 1999). To compute confidence intervals, variance in the smoothed data was estimated using log-likelihood in the framework of normal approximations (Loader 1999. Using the binomial family kept pregnancy rates in the [0,1] interval and resulted in non-symmetric errors around the mean.

The smoothed reproductive rates were extrapolated backwards from 1954 to 1952. If the sample size for the reproductive tracts for a given year was below the threshold, then the model replaced the actual observed value with a smoothed value derived from the smoothing model for that year and age class. When the smoothed rates were used, uncertainty was incorporated by resampling pregnancy rates from a normal distribution in logit space, with a mean equal to the smoothed value and the standard error equal to the square root of the estimated variance. If the number of samples in that year and age class exceeded the threshold, then the reproductive rate from the data was used to estimate total abundance (Hammill et al 2012).

To identify an appropriate threshold, individual pregnancy rates were drawn, without replacement from samples where a large number of animals had been collected and the mean and variance were plotted against sample sizes of 5 to 100 animals. From this it was concluded that the variance stabilized at sample sizes of around 40 animals (Stenson et al. 2014b), which was used as the threshold in the model.

Catches

Catch data are available since 1952 and have been summarized by Stenson (2014) (Table 4). Briefly, there are five different types of catch input: the Canadian commercial harvest (Department of Fisheries and Oceans Statistics Branch); the Canadian Arctic subsistence hunt; animals caught incidentally in Canadian and American commercial fisheries (Sjare et al. 2005; Stenson 2014); and the Greenland subsistence hunt. Data were updated to include the most recent data to 2012 (Table 4). Reported catch levels from the Canadian and Greenland hunts were divided into numbers of animals aged 0 and numbers of animals aged 1+ years. For example, the Canadian hunt consists of 99% of young of the year while the Greenland hunt is limited to 14% young of the year (Stenson 2009). Consequently, 2% of the Canadian commercial harvest and 86% of the Greenland harvest are considered to be 1+ seals, which are distributed proportionally among the 1+ age classes. All harvests were corrected for seals struck and killed, but not landed or reported, and were incorporated into the model along with estimates of bycatch (Stenson 2005; Sjare et al. 2005). Since 1983, it was assumed that 95% of the YOY and 50% of the 1+ animals in the Canadian commercial hunt (Front and Gulf) were recovered while 50% of all animals killed in Greenland and the Canadian Arctic were assumed not to have been recovered and/or reported (Stenson 2014).

Ice-related mortality of YOY

Poor ice conditions result in increased mortality (M_{ice}) that affects animals prior to the hunt. This is incorporated into the model as a survival term. In previous assessments, M_{ice} was a qualitative measure based upon ice conditions, storm frequency and reports of mortality and/or dead seals washing ashore. In this assessment, a quantitative index based upon changes in ice cover in the Gulf and at the Front was used (Hammill and Stenson 2014) (Table 5).

PROJECTION MODEL

The projection model predicts the impact of future catch scenarios based upon estimates of current population (abundance at age), carrying capacity and natural mortality assuming:

1. mortality from bycatch: the proportion of seals struck and loss, and catches in the Canadian Arctic remain constant;
2. Greenland catches: for the forward projections it was assumed that the levels, and age structure, and proportion of struck and lost and bycatch were the same as used in the fitting model. We also assumed that the Greenland catch could be described by a uniform distribution with a minimum catch of 66,000 (from 2003) and a maximum catch of 92,000 (from 2006), which results in an average of 79,000 animals;
3. ice-related mortality (actually, expressed as survival in model), was assumed to vary with values of 0.77, 0.77, 0.35, 0.71 and 1 (average =0..73, SE=0.12);
4. based on estimate mortality over the last 5 years, In previous assessments, reproductive rates for 8+ animals were assumed to be fixed in the projection model to the values of the last 5 years, with each year having an equal probability of being selected. This approach was used again as well as an alternative approach that drew from a sample of reproductive rates that were observed over the last 10 years, with each year having an equal probability of being selected, and
5. the basic pup mortality (M_0) is fixed at three times 1+ mortality (M) and remains unchanged; the dynamics of the population can be described assuming density-dependent mortality acting on juvenile survival by the relationship:

$$n_{1,t} = ((n_{0,t-1} \times w) - c_{0,t-1}) \times e^{-M0} \times (1 - (N_t / K)^{\theta})$$

The model is projected forward to determine what level of catches will respect the management plan (i.e. 80% likelihood of population remaining above the Precautionary Reference Level) for the next 15 years. Ten thousand runs were completed for both the fitting and projection model.

RESULTS

Sampling for reproductive rate data was not undertaken prior to 1954, from 1955 to 1963, 1971 to 1977, 1983 and 1984. There are additional years where data are not available for specific age classes or sample sizes are very small (Table 3). The smoother fitted to the reproductive data provided a means of interpolating for missing years and captured the variability in the data fairly well over the years from 1952 – 2013 (Fig. 1). The greatest number of samples is available for the 8+ year class (Table 3). For this group, the overall trend was for reproductive rates to be high from the 1950s to the 1980s and then declined throughout the 1990s and 2000s. This trend has continued over the last two years. However, unusually high reproductive rates among 8+ females were noted in 2007 (rpd rate=0.76, n=84) and 2008 (rpd rate=0.74, n=61), 2012 (rpd rate=0.75, n=28) and 2013 (rpd rate=0.83, n=6)(Table 3). However, given the small number of samples available in 2012 and 2013, it is not clear if these estimates are accurate.

First, to estimate the predicted value for 2012 pup production, we fit the model to the aerial survey data and the reproductive rate data up to 2011. For this initial run the impacts of ice-related mortality are included, but the estimates are based on the qualitative index presented in previous assessments. This run resulted in estimates of alpha the initial population vector multiplier of 0.18 (SE=0.008), K =10.0 million (SE=1,252,000), M_{1+} =0.02 (SE=0.006), and an estimated pup production of 840,000 (SE=269,000)) for the year 2012 (Fig. 2).

In a second run, we fitted the population model to the pup survey data up to, and including 2012 (Table 2), the reproductive rates up until 2013 (Table 3) and including information on catches (Table 4) and the new, quantitative index of ice-related mortality M_{ice} (Table 5). This second run resulted in estimates of alpha of 0.19 (SE=0.007), M_{1+}=0.025 (SE=0.007), K=10.8 million (SE=564,000), a 2012 estimated pup production of 929,000 (SE=148,000), and a total population of 7,445,000 (SE=698,000) (Fig. 3, 4). The estimated pup production for 2014 is 853,000 (SE=202,000). The estimated 2014 population is 7,411,000 (SE=656,000) animals.

The largest population estimated, from the second run was in 2009, with an estimated population of 7,824,000 (SE=806,000) animals. Thus, Nmax was 7.8 million, N_{70}=5.5million, N_{50}=3.9 million and N_{30}=2.3 million animals.

This second run was used to evaluate the impact of different harvest scenarios on the population.

HARVEST SCENARIOS

Currently the harvest is almost entirely beaters (i.e. YOY that have moulted their white lanugo fur). Science was asked to examine harvest scenarios over the next 5 years (2014-2018) with an 80% confidence of remaining in the healthy zone (i.e. > N_{70}). Also, what is the risk that the Harp seal population will drop below 50% and 70% of Nmax catch levels of 300,000, 400,000, 500,000 and 600,000 animals assuming that the harvest comprised 95%, 90% or 70% young of the Year (YOY), with the remainder of the harvest comprised of animals aged 1+ year. We assumed that the TAC was taken in full each year.

An important factor affecting future harvests is herd productivity. Over the last 5 years the productivity of the herd has declined, particularly among animals aged 8 years and older, which account for 70% or more of the pup production. The mean reproductive rate of animals aged 8+ years was 0.34 between 2009-2013, compared to an average of 0.48 between 2004-2013. The change in reproductive rates does not appear to be affected by density dependent factors alone, complicating projections into the future. We examined the possibility of using the reproductive rates from the last 5 years (2009-2013), and the last 10 years (2004-2013).

If the future productivity of the herd is similar to that observed over the last 5 years (2008-13), then a harvest of 125,000, 100,000, and 75,000 animals would have an 80% probability of the population remaining above N70 for an age composition of the harvest of 95%, 90% and 70% YOY respectively (Table 6). The probability of remaining above the critical reference level (ie N_{30}) would be 0.99, 0.99 and 0.99 for age compositions of the harvest of 95%, 90% and 70% YOY respectively. Harvests of 250,000, 225,000 and 150,000 animals would have an 80% probability of respecting N_{50} assuming age compositions of the harvest of 95%, 90% and 70% YOY. At these harvest levels, the probability that the population would respect the critical reference limit of N_{30} would be 0.96, for the three different age compositions of the harvest.

If the future productivity of the herd is similar to that observed over the last 10 years (2004-13), then a harvest of 325,000, 275,000, and 175,000 animals would have an 80% probability of the population remaining above N_{70} for an age composition of the harvest of 95%, 90% and 70% YOY respectively (Table 7). The probability of remaining above the critical reference level would be 0.99, for the three different age compositions of the harvest. Harvests of 450,000, 375,000 and 225,000 animals would have an 80% probability of respecting N50 assuming age compositions of the harvest of 95%, 90% and 70% YOY. At these harvest levels, the probability that the population would respect the critical reference limit of N_{30} would be 0.95, 0.95 and 0.96, for harvests comprised of 95%, 90% and 70% YOY.

If the future productivity of the herd is similar to that observed over the last 5 years (2008-13), then a harvest of 300,000, 400,000, 500,000 and 600,000 animals would have a probability of 0.68, 0.91, 0.98 and 1 of falling below N_{70} assuming an age composition of the harvest of 95% YOY (Table 8). The probability of falling below N50 for similar harvests was 0.29, 0.6, 0.85, and 0.96 respectively. The probability of falling below the Critical Reference Level (N_{30}) was 0.07, 0.21, 0.43, and 0.68 respectively (Table 8). If the harvest is comprised of 90% YOY, then the probability of falling below N_{70} for harvests of 300,000, 400,000, 500,000 and 600,000 animals was 0.82, 0.97, 1, and 1 respectively. The probability of falling below N_{50} would be 0.45, 0.81, 0.97, and 1 respectively. The probability of falling below N30 would be 0.14, 0.42, 0.76, and 0.94 respectively. If the harvest is comprised of 70% YOY, then harvests of 300,000, 400,000, 500,000 and 600,000 would have a probability of falling below N_{70} of 1 for all harvests. The probability of falling below N_{50} would be 0.94, 1, 1, and 1 respectively. The probability of falling below N_{30} would be 0.72, 0.99, 1 and 1 respectively.

If the future productivity of the herd is similar to that observed over the last 10 years (2004-13), then a harvest of 300,000, 400,000, 500,000 and 600,000 animals would have a probability of 0.16, 0.35, 0.59 and 0.8 of falling below N_{70} assuming an age composition of the harvest of 95% YOY (Table 9). The probability of falling below N_{50} for similar harvests was 0.04, 0.11, 0.28, and 0.49 respectively. The probability of falling below the Critical Reference Level (N_{30}) was 0.01, 0.03, 0.28, and 0.49 respectively (Table 9). If the harvest is comprised of 90% YOY, then the probability of falling below N_{70} for harvests of 300,000, 400,000, 500,000 and 600,000 animals was 0.25, 0.53, .81, and 0.95 respectively. The probability of falling below N_{50} would be 0.07, 0.23, 0.52, and 0.80 respectively. The probability of falling below N_{30} would be 0.02, 0.07, 0.22, and 0.51 respectively. If the harvest is comprised of 70% YOY, then harvests of 300,000, 400,000, 500,000 and 600,000 would have a probability of falling below N_{70} of 0.76, 0.98, 1, and 1 respectively. The probability of falling below N_{50} would be 0.45, 1, 1, and 1 respectively. The probability of falling below N_{30} would be 0.2, 0.71, 0.98 and 1 respectively.

DISCUSSION

The population model used for northwest Atlantic harp seals is very sensitive to changes in the reproductive rates. There is a long time series of available data for this population, and observed reproductive rates have varied considerably (Sjare and Stenson 2010, Stenson and Wells 2011). Some of this variability can be attributed to sampling error, but other changes reflect real changes rates due to density dependent processes or environmental conditions (Stenson et al. 2014b). The very high estimate of pup production in 2008, was the result of unusually high reproductive rates observed in that year (Fig 1, 2). Our understanding of changes in reproductive rates is hampered because, for some years, sample numbers have been limited, while in others they are totally lacking. Therefore, some method is needed to allow for the natural inter-annual variability to be captured while interpolating for years where data were missing or too few. Previous analyses have utilized a variety of methods to estimate annual pregnancy rates from the available reproductive samples. Bowen et al. (1981) used annual smoothing (as opposed to smoothing by age used in this analysis) to ensure that for any given year the proportion mature increased with age in the event that the sampling predicted otherwise. An analysis by Shelton et al. (1992) explored the use of multi-linear regression, analysis of covariance, analysis of variance, and auto-regression models, and concluded that all methods were inadequate to predict the unknown pregnancy rates. More recent efforts to estimate pregnancy rates were based upon the method described in Shelton et al. (1996; presented with some modifications in Warren et al. 1997). For each age, successive contingency table analysis tested successive pregnancy rate data for significant changes in pregnancy rates (referred to as ‘harmonized’ rates.). However, this approach resulted in significant jumps in pregnancy rates, and if pregnancy data are ‘pooled' over an extended time period in the contingency analysis, an extreme change in sampled rates is needed before the change is considered statistically significant.

In recent assessments, a non-parametric smoother had been applied to the reproductive rate data (Stenson et al. 2009). However, this smoother, which estimated variance based upon refitting to the samples assuming a normal distribution, appears to have underestimated the uncertainty associated with the reproductive rate data. Since the 2011 assessment, the data have been considered to be binomially distributed and a new smoother has been applied (Hammill et al 2011a). This smoother appears to better account for the uncertainty in the data, as well as changes occurring in reproductive rates (Fig. 2). Results from Stenson et al (2014b) indicate that the variance around the mean begins to stabilize with sample sizes of 40 or more animals. Therefore, when more than 40 samples are available for an age class in a year, then the model uses the raw data as part of the model fitting process, but in years where fewer samples are obtained, the model uses the smoother generated reproductive rates estimates.

Changes observed in size at age (Chabot and Stenson unpublished data) and in reproductive rates (fecundity and mean age of sexual maturity; Sjare and Stenson 2010, Stenson and Wells 2010; Stenson et al. 2014b), have roughly mirrored changes in pup production (i.e. increasing pup production, declining reproductive rates) in a manner that is consistent with density-dependent changes in the dynamics of the population. For this assessment, instead of using a fixed K, the model was modified to fit to both the survey estimates of pup production as well as the reproductive rate data to estimate K. The resulting estimate of 10.8 million animals is identical to historical estimates of K of 10.8 million (range =7.6-15.4 million) obtained from back-calculation methods using historical catch data (Hammill et al 2011b). The similarities between the two approaches provide some confidence that estimates of K may be reasonable. However, they also are based on the assumption that current environmental conditions are similar to those experienced by harp seals over 200 years ago In reality, the exact form of the density-dependent relationship is poorly understood and attempts to understand this relationship further are complicated by the impacts of highly variable harvests on individual cohorts as they work their way through the population, an absence of data on mortality rates and the fact that surveys are only flown every 4-5 years.

Harp seals require stable pack ice for pupping and early development of the young. The mid-1980’s until the late 1990s were characterized by a period of heavier than normal ice conditions, which would have favoured pup survival (Bajzak et al. 2011, Johnston et al. 2005). This has been followed by a period of lighter than normal ice-conditions, and the winters of 2010 and 2011 are notable as the poorest winters on record for ice cover in the Atlantic. This is thought to have resulted in high mortality among YOY, but unfortunately we do not have any measure of mortality for harp seals. Although ice-related mortality among the YOY has been incorporated into the assessment since 2003, this estimate has been based on expert opinion only. Incorporating the quantitative estimates based upon anomalies in ice cover at the Front and in the Gulf provides a clearer basis for this estimate of ice mortality, although a direct measure of M remains elusive. Poor ice conditions in 1981, combined with a very large hunt resulted in the 1981 cohort disappearing from the population (Sergeant 1991). The poor conditions observed in 2010 and 2011, may have had a similar effect, and if so, this would provide some insights into the relationship between ice conditions and ice related mortality.

The Northwest Atlantic harp seal population is currently near the highest levels observed since monitoring began almost 60 years ago. Modifications to the current assessment model provide a means of estimating environmental carrying capacity assuming a certain functional relationship between total population size and juvenile survival, and between population size and reproductive rates. This has resulted in a significant change in our understanding of the population, from one that was estimated to be 8.1 million animals in 2008, growing exponentially and expected to number 9.1 million (95% CI=7.5 to 10.7 million) animals in 2010, to our current understanding of a population, whose dynamics are described by density-dependent factors, that reached a maximum (N_{max}) of 7.8 million animals in 2009 (95%CI =6.5 to 8.9 million) and currently numbers around 7.4 million animals (95% CI=6.6 to 8.2 million). As more information is obtained, our understanding of this functional relationship may also change which could result in changes to estimates of total population size and trends. Currently, the population appears to have stabilized, with little change in abundance over the last decade owing to the effects of the large harvests during 1996-2006 as they work themselves through the population and a decline in productivity of the herd. This decline in productivity likely results from density-dependent effects through resource limitation acting on females, as well as short-term fluctuations in environmental conditions (Stenson et al. 2014b). These conditions are expected to continue, at least in the near term, consequently productivity will likely remain relatively low.

The future trajectory of the herd will depend upon changes in reproductive rates, commercial harvest levels in Canada, and harvests in the unregulated Greenland subsistence hunt, as well the response of animals to changes in ice conditions. In 2012, we explored alternative approaches to model future harvests in Greenland as well as changes in reproductive rates (Hammill et al. 2012). In this assessment we refined our approach to modelling ice related mortality. However, trying to understand factors that affect reproduction and trying to model changes in the Greenland catch over the next 5-20 years is highly uncertain. Consequently, we used a conservative approach, where future changes in reproductive rates and Greenland harvests are based on sampling from a range of values of each parameter that have been observed over the last 5-10 years.

Scientists provide regular advice to managers based on biological assessments of an exploited resource. These assessments attempt to predict changes in the resource by incorporating information on catches, estimates of recruitment, and indices of abundance into a population model (Cooke 1995). Because the information is often incomplete and estimated model parameters are subject to natural variability, the resulting advice has considerable uncertainty.

In the past, failure to appreciate the risk associated with this uncertainty has led managers to be more aggressive when setting exploitation levels, often with catastrophic results. The collapse of northwest Atlantic cod (*Gadus morhua*) stocks and many large whale populations are examples where traditional management approaches have failed (Rice and Rivard 2003; Baker and Clapham 2004).

The Precautionary Approach aims to outline clear rules for management actions in response to changes of the resource with respect to different thresholds. The main objective is to be more prudent in the face of uncertainty, and to minimize the risk of causing serious harm (Hammill and Stenson 2007, 2014). Different methods of setting the precautionary and limit reference points have been identified and reviewed (Stenson et al. 2012; Hammill and Stenson 2014). Methods based on previous minima that have allowed recovery or on fixed levels are not recommended because environmental conditions that allowed recovery at previous low levels may no longer apply. The lack of recovery among groundfish stocks in Atlantic Canada is a very good example of the problems associated with this assumption.

In Atlantic Canada, estimates of total harp, grey and hooded seal population size are determined using population models fitted to aerial survey estimates of pup production flown every 4-5 years. Since harvests target YOY, and animals are not recruited to the breeding population before the age of 4-5 years, there is considerable uncertainty associated with population abundance, which may be exaggerated if model formulation is incorrect, or if input parameters such as the reproductive rates vary in unpredictable ways. Therefore, it is conceivable that significant declines in the population could occur, but would not be detected until 10-15 years later (Hammill and Stenson 2009). Model simulations have indicated that a management framework that attempts to manage the resource with an 80% probability that the population remains above N_{70} significantly reduces the likelihood that the population will fall into the critical zone, particularly under conditions where some model assumptions were not satisfied (Hammill and Stenson 2009). This is also evident in our analyses of different harvest scenarios to provide TAC advice. If we assume that future reproductive rates are similar to rates that have been observed over the last decade, then harvests (comprising 95% YOY) of 325,000, seals would have a likelihood of 0.8 or greater of remaining above N_{70} and a likelihood of remaining above N_{30} of 0.99. Harvests of 450,000 animals with the same age composition of the harvest would that have a likelihood of 0.8 of keeping the population above N_{50}, but the likelihood of remaining above N_{30} would decline to 0.95. However, if harvest rates are set based on the expectation that future reproductive rates were similar to those observed between 2004 and 2013, when in fact reproductive rates were actually more similar to conditions observed between 2009 and 2013, then an annual harvest of 325,000 seals would reduce the likelihood that the population will remain above N_{70} to 0.24, while the likelihood that the population remains above N_{30} declines to 0.90. A harvest of 450,000 animals would only have a probability of 0.26 of remaining above N_{50}, and the probability of the population not suffering serious harm ie remaining above N_{30} would be reduced to 0.69 (Tables 6, 7). Although monitoring of reproductive rates will provide insights into changes in herd productivity, the detection of actual changes in pup production will not be evident for a decade, by which time the probability that the herd could suffer serious harm would increase markedly.

Several factors should be monitored to determine if a multiyear TAC should be re-evaluated. In general, significant changes in any of the major assumptions used in the projections should trigger a new analysis. The most important is annual monitoring of reproductive rates. As indicated several times above, changes in reproductive rates, either leading to an increase in productivity or to a decrease, will have an important impact on the trajectory of the population. Catches of harp seals in Greenland appear to be relatively stable, but this harvest is not regulated, and any major change will require that this advice be re-examined. Significant changes in mortality, particularly pup mortality associated with poor ice conditions, will also influence the reliability of any projections.

There has been an increase in the frequency of lighter ice cover winters, particularly in the Gulf over the last decade (Soulen et al. 2013 Stenson and Hammill 2011). If this trend continues, the contribution of the Gulf to the Northwest Atlantic herd will decline and this herd may disappear as a significant component of the Northwest Atlantic harp seal population. This is not expected to occur before a new assessment in five years, but the current allocation of 70:30 Front:Gulf may need to be examined if poor ice conditions continue. In the past decade, declines in ice conditions in the Gulf have been obvious while changes in the ice at the Front have been less obvious. However, climate change model predict that the area off southern Labrador will be the next area of major change. Since the majority of the population pups at the Front, increases in YOY mortality in this area will have a significant impact on the ability of the population to withstand any given level of harvest. Therefore, ice conditions should be monitored, and if a series of 3 or more years of extremely poor ice conditions are identified, then the population should be reassessed.

In summary, abundance of northwest Atlantic harp seas was estimated using a population model that incorporates information on removals, and unusual mortality related to poor environmental conditions and is fitted to independent survey estimates of pup production and data on reproductive rates. From the model, 2012 pup production and total population size are estimated to be 929,000 (SE=148,000) and 7,445,000 (SE=698,000) respectively. The outlook for 2014, is an estimated pup production of 853,000 (SE=202,000) and a total population size of 7,411,000 (SE=656,000). The population appears to be relatively stable, showing little change in total abundance since the 2000 survey. Pup production reached a maximum in 2008, but has declined since then owing to a combination of a decade of large harvests (1996-2006) that are now working themselves through the population as well as a decline in reproductive rates. The decline in reproductive rates is likely related to the large size of the population as well as current environmental conditions. These conditions are expected to continue and reproductive rates are likely to remain relatively low.

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TABLES

Table 1. Summary of changes to harp seal model. Exponential model=exp, density dependent model=dd, carrying capacity in millions=K, mortality =M.

Year	Population Model type	Reproductive rates	Population (million)	Significant changes
2000	Exp	Contingency table harmonized rates		90% beater
2003	Exp	Healey smoother non-parametric (Healey et al. 2003) , Extended 1997 rates to 2003 and future	2002 = 5.5 2003 = 5.3	92% beater, ice related M approximately 15% EXCEL model ,
2005	Exp	Healey smoother non-parametric , (Healey et al. 2003) Extended 1997 rates to 2005 and future	2004=5.7 2005=5.8	95% beater, ice M=0.1 in projections
2008	Exp	Healey smoother non-parametric , (Healey et al. 2003), to 1999, averaged 2000-2005 and extrapolated forward	2005=5.7 2008=5.6 2009=5.6	95% beater, Model reprogrammed from EXCEL to R, projected ice M=average 12%
2009	Exp	Healey smoother non-parametric , (Healey et al. 2003) Rpd rates updated to 2007, projected	2008 (lo)=6.9 2008 (hi)=8.2	Uncertainty in pup survey estimate (low count accepted), smoothed rates until 2007. poor fit to data in 2008 using high pup count
2010	DD K=12 set, Exp examined	Annual reproductive rates for 8+ ages, average last 5 years used in projections, Reproductive rates were correlated so if one year class had a poor year, other year classes also had poor years.	2004=7.4 2008 (exp)=8.7 2010 (exp) =9.6 2008 (dd)=8.1 2010 (dd)=8.6	ice mortality updated to average 30%, transition from exponential growth to density-dependent (DD) growth of population. K was set.
2011	DD, K=12, estimated/set	updated to 2010, new binomial smoother, annual rpd rates for 8+, projection used uniform distribution for reproduction from last 5 years in projections	2008=8.4 2010=7.8	

Year	Population Model type	Reproductive rates	Population (million)	Significant changes
current	DD, K=10, estimated	updated to 2013, binomial smoother, annual rpd rates for 8+, correlation in rpd rates re-established. Projection can be DD prediction for rpd rates or some other function eg uniform distribution among observed rates from last 5 years	2008=7.5 2010=7.1 2012=6.9	Model fitted to reproductive rates (in addition to existing fitting to pup production estimates) Future Greenland harvest expressed as a function of population size

Table 2. Pup production estimates used as input into the population model.

Year	Estimate	Standard Error	Reference
1951	645,000	322,500[1]	Sergeant and Fisher 1960
1960	235,000	117,500[1]	Sergeant and Fisher 1960
1978	497,000	34,000	Roff and Bowen 1986
1979	478,000	35,000	Roff and Bowen 1986
1980	475,000	47,000	Roff and Bowen 1986
1983	534,000	33,000	Bowen and Sergeant 1985
1990	577,900	38,800	Stenson et al. 1993
1994	702,900	63,600	Stenson et al. 2002
1999	997,900	102,100	Stenson et al. 2003
2004	991,400	58,200	Stenson et al. 2005
2008	1,630,000	110,400	Stenson et al. 2010
2012	791,043	69,685	Stenson et al. 2014a

[1] Assumed a coefficient of variation of 40%.

Table 3. Year, sample size (n), number pregnant (#preg) and late term age-specific reproductive rates of Northwest Atlantic harp seals.

Age	4		5		6		7		8+	
Year	*n*	#Preg	*n*	#Preg	*n*	#Preg	*n*	#Preg	*n*	#Preg
1954	4	0	3	1	3	2	16	12	33	29
1964	11	0	9	1	2	1	4	3	25	22
1965	30	1	44	5	37	20	38	27	109	96
1966	7	0	9	1	17	6	11	8	49	43
1967	10	0	19	4	33	20	29	28	123	109
1968	27	0	19	6	20	14	12	11	55	48
1969	25	1	25	4	16	7	28	23	165	146
1970	13	0	13	3	12	6	10	9	107	92
1978	40	1	38	23	20	18	9	6		
1979	21	5	15	8	5	5	9	8	21	20
1980	2	0	2	1	1	1	0		12	9
1981	5	1	4	3	2	1	7	6	17	14
1982	4	0	5	2	1	1	4	3	3	1
1985	4	0	3	1	5	2	3	3	1	1
1986	1	1	0		2	1	1	0	7	7
1987	12	2	8	3	9	7	4	4	24	15
1988	17	2	6	1	3	3	0		19	14
1989	8	0	9	0	6	2	3	2	22	22
1990	8	0	7	1	3	1	1	0	10	6
1991	10	0	11	2	7	4	3	1	29	18
1992	10	2	11	3	9	4	8	6	32	21
1993	11	1	17	2	7	0	5	4	35	17
1994	23	1	16	2	14	6	7	3	41	34
1995	10	0	13	6	4	2	5	2	24	14
1996	8	0	6	0	4	1	1	1	35	24

Age	4		5		6		7		8+	
Year	*n*	#Preg	*n*	#Preg	*n*	#Preg	*n*	#Preg	*n*	#Preg
1997	6	0	4	0	10	3	2	2	36	27
1998	6	0	10	3	9	2	4	2	36	22
1999	6	0	7	0	18	4	15	6	59	37
2000	1	0	9	3	6	4	5	2	43	29
2001	2	0	0		2	2	3	0	39	26
2002	2	0	4	1	5	3	17	10	72	40
2003	1	0	3	2	2	1	3	2	91	59
2004	2	0	5	0	5	1	1	0	76	31
2005	9	1	9	0	13	2	7	0	86	55
2006	2	0	0		0		0		119	67
2007	1	0	5	0	3	1	2	2	84	64
2008	6	0	3	0	2	0	0		61	45
2009	1	0	1	0	1	0	1	1	103	57
2010	3	0	0		0		1	0	116	34
2011	3	0	2	1	0		0		147	30
2012	0		1	0	0		0		20	15
2013									6	5

Table 4. Removals of Northwest Atlantic harp seals from different sources taken from Stenson 2014.

Year	Arctic	Greenland	Commercial (Age =0)	Commercial (Age=1+)	Bycatch (Age=1+)	Bycatch (Age=0)
1952	1,784	16,400	198,063	109,045	0	0
1953	1,784	16,400	197,975	74,911	0	0
1954	1,784	19,150	175,034	89,382	0	0
1955	1,784	15,534	252,297	81,072	0	0
1956	1,784	10,973	341,397	48,013	0	0
1957	1,784	12,884	165,438	80,042	0	0
1958	1,784	16,885	140,996	156,790	0	0
1959	1,784	8,928	238,832	81,302	0	0
1960	1,784	16,154	156,168	121,182	0	0
1961	1,784	11,996	168,819	19,047	0	0
1962	1,784	8,500	207,088	112,901	0	0
1963	1,784	10,111	270,419	71,623	0	0
1964	1,784	9,203	266,382	75,281	0	0
1965	1,784	9,289	182,758	51,495	0	0
1966	1,784	7,057	251,135	72,004	0	0
1967	1,784	4,242	277,750	56,606	0	0
1968	1,784	7,116	156,458	36,238	0	0
1969	1,784	6,438	233,340	55,472	0	0
1970	1,784	6,269	217,431	40,064	15	53
1971	1,784	5,572	210,579	20,387	99	391
1972	1,784	5,994	116,810	13,073	141	480
1973	1,784	9,212	98,335	25,497	107	358
1974	1,784	7,145	114,825	32,810	41	141
1975	1,784	6,752	140,638	33,725	66	219
1976	1,784	1,1956	132,085	32,917	169	923
1977	1,784	1,2866	126,982	28,161	296	1,281
1978	2,129	1,6638	116,190	45,533	538	2,381
1979	3,620	17,544	132,458	28,083	511	2,799
1980	6,350	15,255	132,421	37,105	263	2,454
1981	4,672	22,974	178,394	23,775	382	3,539
1982	4,881	26,926	145,274	21,465	343	3,442
1983	4,881	24,784	50,058	7,831	458	4,504
1984	4,881	25,828	23,922	7,622	425	3,683
1985	4,881	20,785	13,334	5,701	632	4,225
1986	4,881	26,098	21,888	4,046	1,042	7,136
1987	4,881	37,859	36,350	10,446	1,978	11,118
1988	4,881	40,415	66,972	27,074	1,391	7,154
1989	4,881	42,970	56,346	8,958	799	9,457
1990	4,881	45,526	34,402	25,760	921	2,700
1991	4,881	48,082	42,382	10,206	615	9,074
1992	4,881	50,638	43,866	24,802	6,507	18,969
1993	4,881	56,319	16,401	10,602	7,596	18,876
1994	4,881	57,373	25,223	36,156	10,513	35,881
1995	4,881	62,749	34,106	31,661	6,060	13,641
1996	4,881	73,947	184,856	58,050	18,347	10,765
1997	2,500	68,815	220,476	43,734	5,059	13,541

Year	Arctic	Greenland	Commercial (Age =0)	Commercial (Age=1+)	Bycatch (Age=1+)	Bycatch (Age=0)
1998	1,000	81,272	251,403	31,221	975	3,571
1999	500	93117	237644	6908	6312	9799
2000	400	98458.5	85035	7020	1611	9736
2001	600	85427.5	214754	11739	4847	14628
2002	1000	66734.5	297764	14603	3837	5492
2003	1000	66149	280174	9338	1881	3486
2004	1000	70585.5	353553	12418	3890	8703
2005	1000	91695.5	323800	6029	3807	8518
2006	1000	92210	346426	8441	3816	8539
2007	1000	82836	221488	3257	3845	8602
2008	1000	80556	217565	285	3924	8780
2009	1000	72142	76688	0	3946	8829
2010	1000	90014	68654	447	3884	8691
2011	1000	74013	40371	18	3883	8688
2012	1000	79912[1]	71319	141	3883	8688
2013	1000	79912[1]	90703	0	3883	8688

[1] average of last 5 years.

Table 5. Years when unusual ice mortality is assumed to have occurred, and values input to the model to account for this mortality. Survival was assumed to be normal (i.e. 1.0) in all other years. 2013 estimates were taken from Hammill and Stenson (2014). Data are missing from the ice charts for 1970. This value was set to 1.

Year	Survival (prior to 2012)	2012 survival estimates (updated)	2013 survival estimates
1969	0.75	0.43	0.35
1970			1
1978			0.92
1981	0.75	0.19	0.32
1996			0.93
1998	0.94	0.91	0.83
1999			0.94
2000	0.88	0.87	0.8
2002	0.75	0.83	0.88
2005	0.75	0.76	1.0
2006	0.90	0.99	0.86
2007	0.78	0.91	0.85
2010	0.55	0.41	0.71
2011		0.3	0.35
2012		0.83	0.77
2013		0.90	0.77

Table 6. Probability of respecting N70, N50 and N30 at different harvest levels and age compositions of 95% YOY, 90%YOY and 70% YOY, assuming that the reproductive rates over the next 5 years are more similar to those observed between 2008-2013.

Age composition	Harvest	Probability of respecting N70	N50	N30	Age composition	Probability of respecting N70	N50	N30
95%YOY	100000	0.87	0.98	0.99	90%YOY	**0.85**	0.97	0.99
95%YOY	125000	**0.83**	0.97	0.99	90%YOY	0.78	0.96	0.99
95%YOY	150000	0.76	0.95	0.99	90%YOY	0.71	0.94	0.99
95%YOY	175000	0.71	0.93	0.99	90%YOY	0.63	0.90	0.98
95%YOY	200000	0.63	0.90	0.98	90%YOY	0.53	0.86	0.97
95%YOY	225000	0.55	0.86	0.98	90%YOY	0.43	**0.80**	0.96
95%YOY	250000	0.47	**0.83**	0.96	90%YOY	0.34	0.73	0.93
95%YOY	275000	0.39	0.76	0.95	90%YOY	0.26	0.65	0.91
95%YOY	300000	0.32	0.71	0.93	90%YOY	0.18	0.55	0.86
95%YOY	325000	0.24	0.64	0.90	90%YOY	0.12	0.45	0.81
95%YOY	350000	0.18	0.55	0.88	90%YOY	0.08	0.35	0.74
95%YOY	375000	0.13	0.48	0.84	90%YOY	0.05	0.27	0.67
95%YOY	400000	0.09	0.40	0.79	90%YOY	0.03	0.19	0.58
95%YOY	425000	0.07	0.32	0.74	90%YOY	0.02	0.13	0.49
95%YOY	450000	0.04	0.26	0.69	90%YOY	0.01	0.08	0.39
95%YOY	475000	0.03	0.20	0.63	90%YOY	0.00	0.06	0.31
95%YOY	500000	0.02	0.15	0.57	90%YOY	0.00	0.03	0.24
95%YOY	550000	0.01	0.09	0.43	90%YOY	0.00	0.01	0.12
95%YOY	600000	0.00	0.04	0.32	90%YOY	0.00	0.00	0.06
70%YOY	100000	0.73	0.94	0.99				
70%YOY	125000	0.59	0.89	0.98				
70%YOY	150000	0.44	**0.81**	0.96				
70%YOY	175000	0.29	0.69	0.92				
70%YOY	200000	0.17	0.54	0.85				
70%YOY	225000	0.09	0.38	0.74				
70%YOY	250000	0.04	0.23	0.61				
70%YOY	275000	0.02	0.12	0.44				
70%YOY	300000	0.00	0.06	0.28				
70%YOY	325000	0.00	0.03	0.15				
70%YOY	350000	0.00	0.01	0.08				
70%YOY	375000	0.00	0.00	0.03				
70%YOY	400000	0.00	0.00	0.01				
70%YOY	425000	0.00	0.00	0.00				
70%YOY	450000	0.00	0.00	0.00				
70%YOY	475000	0.00	0.00	0.00				
70%YOY	500000	0.00	0.00	0.00				
70%YOY	550000	0.00	0.00	0.00				
70%YOY	600000	0.00	0.00	0.00				

Table 7. Probability of respecting N70, N50 and N30 at different harvest levels and age compositions of 95% YOY, 90% YOY and 70% YOY, assuming that the reproductive rates over the next 5 years are more similar to those observed between 2003-2013.

Age composition	Harvest	Probability of respecting N70	N50	N30	Age composition	Probability of respecting N70	N50	N30
95%YOY	100000	0.98	0.99	1.00	90%YOY	0.98	0.99	1.00
95%YOY	125000	0.98	0.99	1.00	90%YOY	0.97	0.99	1.00
95%YOY	150000	0.97	0.99	1.00	90%YOY	0.96	0.99	0.99
95%YOY	175000	0.96	0.99	1.00	90%YOY	0.94	0.99	0.99
95%YOY	200000	0.95	0.99	0.99	90%YOY	0.92	0.98	0.99
95%YOY	225000	0.92	0.98	0.99	90%YOY	0.89	0.98	0.99
95%YOY	250000	0.90	0.98	0.99	90%YOY	0.86	0.96	0.99
95%YOY	275000	0.87	0.97	0.99	90%YOY	**0.81**	0.94	0.99
95%YOY	300000	0.84	0.96	0.99	90%YOY	0.75	0.93	0.98
95%YOY	325000	**0.81**	0.95	0.99	90%YOY	0.69	0.90	0.98
95%YOY	350000	0.76	0.93	0.98	90%YOY	0.61	0.86	0.96
95%YOY	375000	0.70	0.91	0.98	90%YOY	0.54	**0.82**	0.95
95%YOY	400000	0.65	0.89	0.97	90%YOY	0.47	0.77	0.93
95%YOY	425000	0.59	0.85	0.96	90%YOY	0.39	0.69	0.90
95%YOY	450000	0.53	**0.81**	0.95	90%YOY	0.31	0.63	0.87
95%YOY	475000	0.47	0.77	0.93	90%YOY	0.24	0.56	0.82
95%YOY	500000	0.41	0.72	0.92	90%YOY	0.19	0.48	0.78
95%YOY	550000	0.29	0.62	0.87	90%YOY	0.10	0.32	0.64
95%YOY	600000	0.20	0.51	0.81	90%YOY	0.05	0.20	0.49
70%YOY	100000	0.96	0.99	1.00				
70%YOY	125000	0.94	0.99	0.99				
70%YOY	150000	0.89	0.98	0.99				
70%YOY	175000	**0.83**	0.96	0.99				
70%YOY	200000	0.74	0.92	0.98				
70%YOY	225000	0.62	**0.87**	0.96				
70%YOY	250000	0.49	0.79	0.93				
70%YOY	275000	0.36	0.68	0.88				
70%YOY	300000	0.24	0.55	0.80				
70%YOY	325000	0.14	0.41	0.69				
70%YOY	350000	0.08	0.28	0.56				
70%YOY	375000	0.04	0.17	0.42				
70%YOY	400000	0.02	0.10	0.29				
70%YOY	425000	0.01	0.05	0.18				
70%YOY	450000	0.00	0.02	0.10				
70%YOY	475000	0.00	0.01	0.05				
70%YOY	500000	0.00	0.00	0.02				
70%YOY	550000	0.00	0.00	0.00				
70%YOY	600000	0.00	0.00	0.00				

Table 8. Probability of falling below N70, N50 and N30 at different harvest levels and age compositions of 95% YOY, 90% YOY and 70% YOY, assuming that the reproductive rates over the next 5 years are more similar to those observed between 2008-2013.

Age composition	Harvest	Probability of not respecting N70	N50	N30	Age composition	Harvest	Probability of not respecting N70	N50	N30
95%YOY	100000	0.13	0.02	0.01	90%YOY	100000	0.15	0.03	0.01
95%YOY	125000	0.17	0.03	0.01	90%YOY	125000	0.22	0.04	0.01
95%YOY	150000	0.24	0.05	0.01	90%YOY	150000	0.29	0.06	0.01
95%YOY	175000	0.29	0.07	0.01	90%YOY	175000	0.37	0.10	0.02
95%YOY	200000	0.37	0.10	0.02	90%YOY	200000	0.47	0.14	0.03
95%YOY	225000	0.45	0.14	0.02	90%YOY	225000	0.57	0.20	0.04
95%YOY	250000	0.53	0.17	0.04	90%YOY	250000	0.66	0.27	0.07
95%YOY	275000	0.61	0.24	0.05	90%YOY	275000	0.74	0.35	0.09
95%YOY	300000	0.68	0.29	0.07	90%YOY	300000	0.82	0.45	0.14
95%YOY	325000	0.76	0.36	0.10	90%YOY	325000	0.88	0.55	0.19
95%YOY	350000	0.82	0.45	0.12	90%YOY	350000	0.92	0.65	0.26
95%YOY	375000	0.87	0.52	0.16	90%YOY	375000	0.95	0.73	0.33
95%YOY	400000	0.91	0.60	0.21	90%YOY	400000	0.97	0.81	0.42
95%YOY	425000	0.93	0.68	0.26	90%YOY	425000	0.98	0.87	0.51
95%YOY	450000	0.96	0.74	0.31	90%YOY	450000	0.99	0.92	0.61
95%YOY	475000	0.97	0.80	0.37	90%YOY	475000	1.00	0.94	0.69
95%YOY	500000	0.98	0.85	0.43	90%YOY	500000	1.00	0.97	0.76
95%YOY	550000	0.99	0.91	0.57	90%YOY	550000	1.00	0.99	0.88
95%YOY	600000	1.00	0.96	0.68	90%YOY	600000	1.00	1.00	0.94
70%YOY	100000	0.27	0.06	0.01					
70%YOY	125000	0.41	0.11	0.02					
70%YOY	150000	0.56	0.19	0.04					
70%YOY	175000	0.71	0.31	0.08					
70%YOY	200000	0.83	0.46	0.15					
70%YOY	225000	0.91	0.62	0.26					
70%YOY	250000	0.96	0.77	0.39					
70%YOY	275000	0.98	0.88	0.56					
70%YOY	300000	1.00	0.94	0.72					
70%YOY	325000	1.00	0.97	0.85					
70%YOY	350000	1.00	0.99	0.92					
70%YOY	375000	1.00	1.00	0.97					
70%YOY	400000	1.00	1.00	0.99					
70%YOY	425000	1.00	1.00	1.00					
70%YOY	450000	1.00	1.00	1.00					
70%YOY	475000	1.00	1.00	1.00					
70%YOY	500000	1.00	1.00	1.00					
70%YOY	550000	1.00	1.00	1.00					
70%YOY	600000	1.00	1.00	1.00					

Table 9. Probability of falling below N70, N50 and N30 at different harvest levels and age compositions of 95% YOY, 90% YOY and 70% YOY, assuming that the reproductive rates over the next 5 years are more similar to those observed between 2004-2013.

Age composition	Harvest	Probability of not respecting N70	N50	N30	Age composition	Probability of not respecting N70	N50	N30
95%YOY	100000	0.02	0.01	0.00	90%YOY	0.02	0.01	0.00
95%YOY	125000	0.02	0.01	0.00	90%YOY	0.03	0.01	0.00
95%YOY	150000	0.03	0.01	0.00	90%YOY	0.04	0.01	0.01
95%YOY	175000	0.04	0.01	0.01	90%YOY	0.06	0.01	0.01
95%YOY	200000	0.05	0.01	0.01	90%YOY	0.08	0.02	0.01
95%YOY	225000	0.08	0.02	0.01	90%YOY	0.11	0.02	0.01
95%YOY	250000	0.10	0.02	0.01	90%YOY	0.14	0.04	0.01
95%YOY	275000	0.13	0.03	0.01	90%YOY	0.19	0.06	0.01
95%YOY	300000	0.16	0.04	0.01	90%YOY	0.25	0.07	0.02
95%YOY	325000	0.19	0.05	0.01	90%YOY	0.31	0.10	0.02
95%YOY	350000	0.24	0.07	0.02	90%YOY	0.39	0.14	0.04
95%YOY	375000	0.30	0.09	0.02	90%YOY	0.46	0.18	0.05
95%YOY	400000	0.35	0.11	0.03	90%YOY	0.53	0.23	0.07
95%YOY	425000	0.41	0.15	0.04	90%YOY	0.61	0.31	0.10
95%YOY	450000	0.47	0.19	0.05	90%YOY	0.69	0.37	0.13
95%YOY	475000	0.53	0.23	0.07	90%YOY	0.76	0.44	0.18
95%YOY	500000	0.59	0.28	0.08	90%YOY	0.81	0.52	0.22
95%YOY	550000	0.71	0.38	0.13	90%YOY	0.90	0.68	0.36
95%YOY	600000	0.80	0.49	0.19	90%YOY	0.95	0.80	0.51
70%YOY	100000	0.04	0.01	0.00				
70%YOY	125000	0.06	0.01	0.01				
70%YOY	150000	0.11	0.02	0.01				
70%YOY	175000	0.17	0.05	0.01				
70%YOY	200000	0.26	0.08	0.02				
70%YOY	225000	0.38	0.13	0.04				
70%YOY	250000	0.51	0.21	0.07				
70%YOY	275000	0.64	0.32	0.12				
70%YOY	300000	0.76	0.45	0.20				
70%YOY	325000	0.86	0.59	0.31				
70%YOY	350000	0.92	0.72	0.44				
70%YOY	375000	0.96	0.83	0.58				
70%YOY	400000	0.98	0.90	0.71				
70%YOY	425000	0.99	0.95	0.82				
70%YOY	450000	1.00	0.98	0.90				
70%YOY	475000	1.00	0.99	0.95				
70%YOY	500000	1.00	1.00	0.98				
70%YOY	550000	1.00	1.00	1.00				
70%YOY	600000	1.00	1.00	1.00				

FIGURES

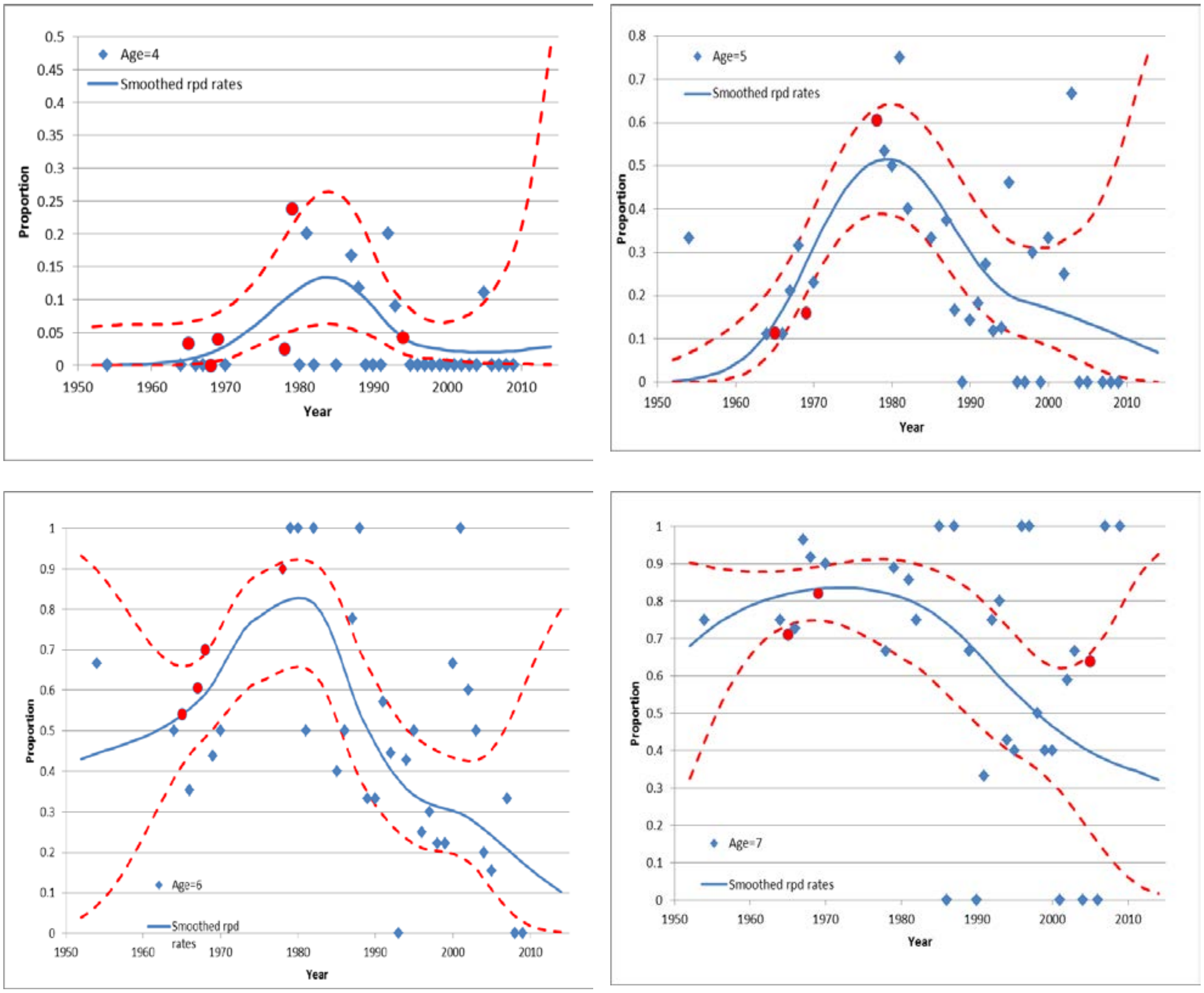


Figure 1. Age specific reproductive rates and non-parametric smoothed rates for ages 4 to 7 years. Diamond (blue) symbols represent data points based on less than 20 samples, round (red) symbols represent samples where there were 20 or more samples

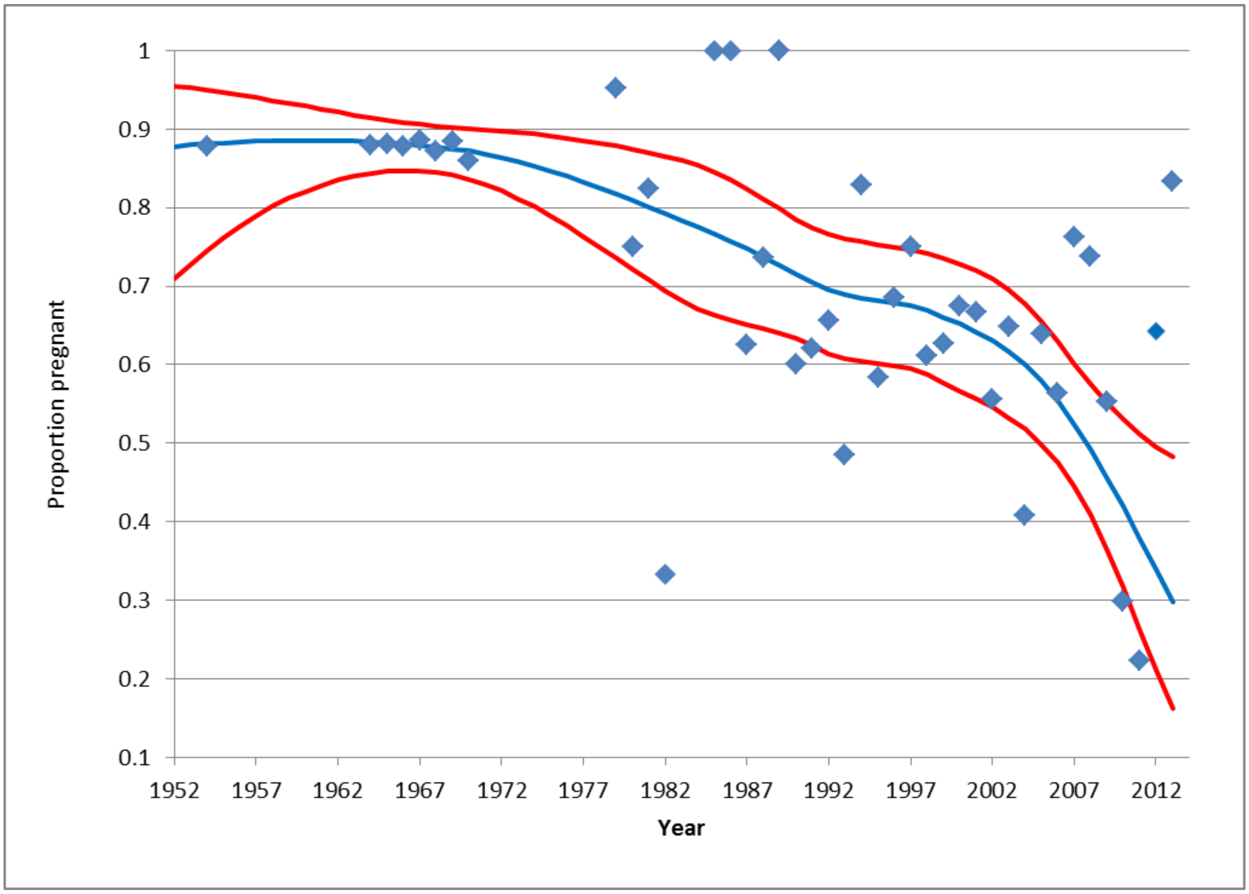


Figure 1 (continued). Age specific reproductive rates, non-parametric smoothed rates and predicted reproductive rates if determined by density-dependent factors only for animals aged 8+ years.

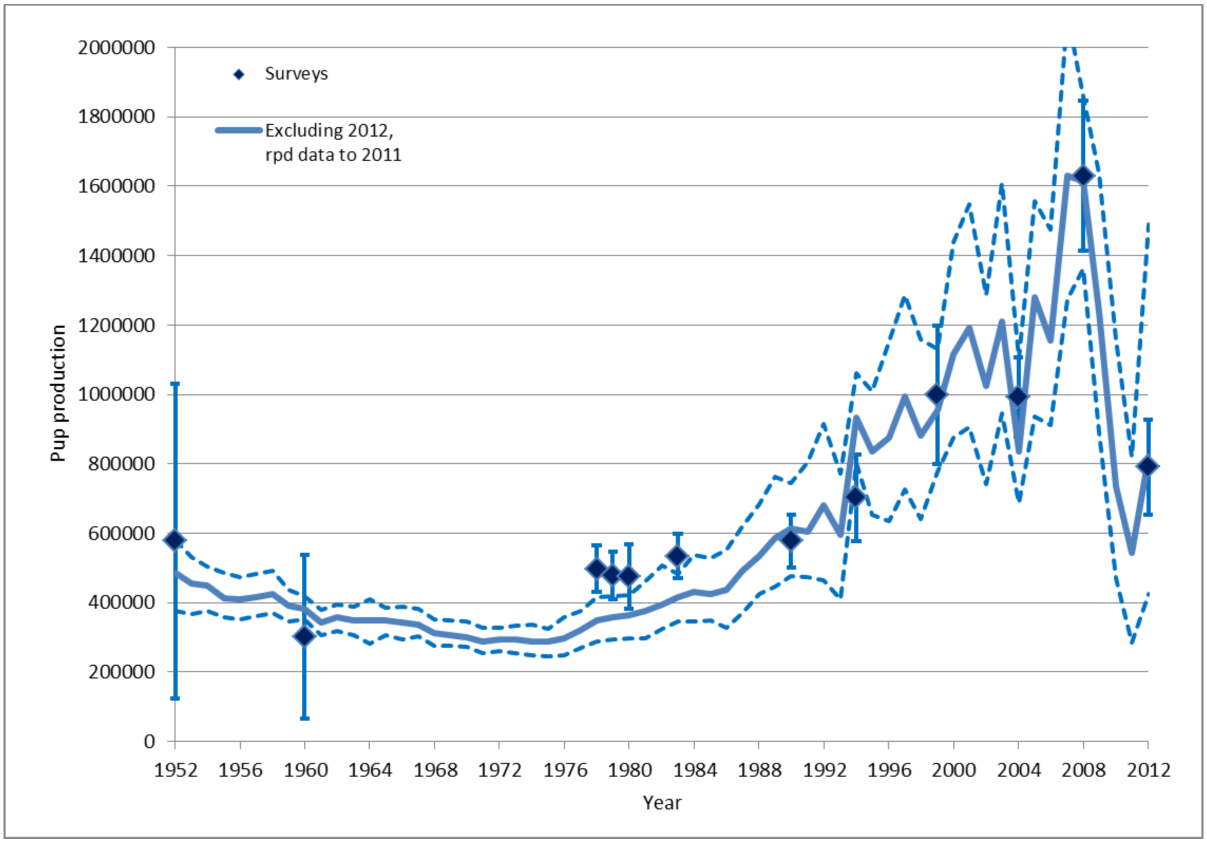
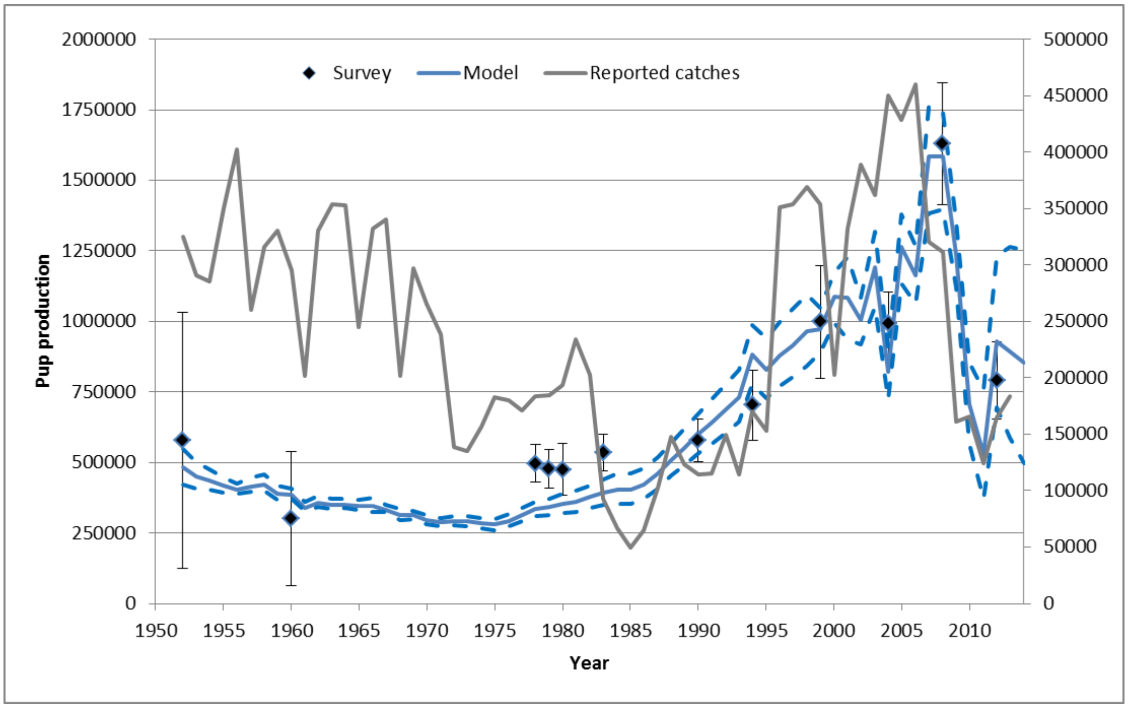


Figure 2. Estimated pup production from the model fitted to pup survey estimates (mean ± 95% CI) (excluding the 2012 estimate) and reproductive data up to and including 2011.



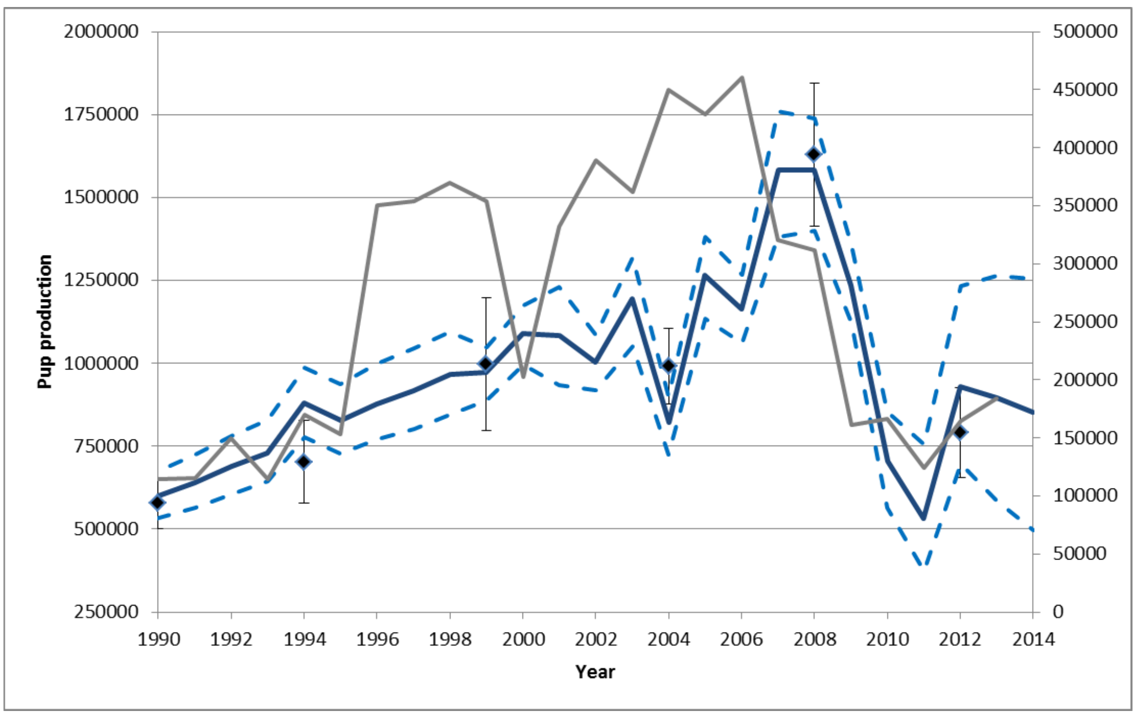
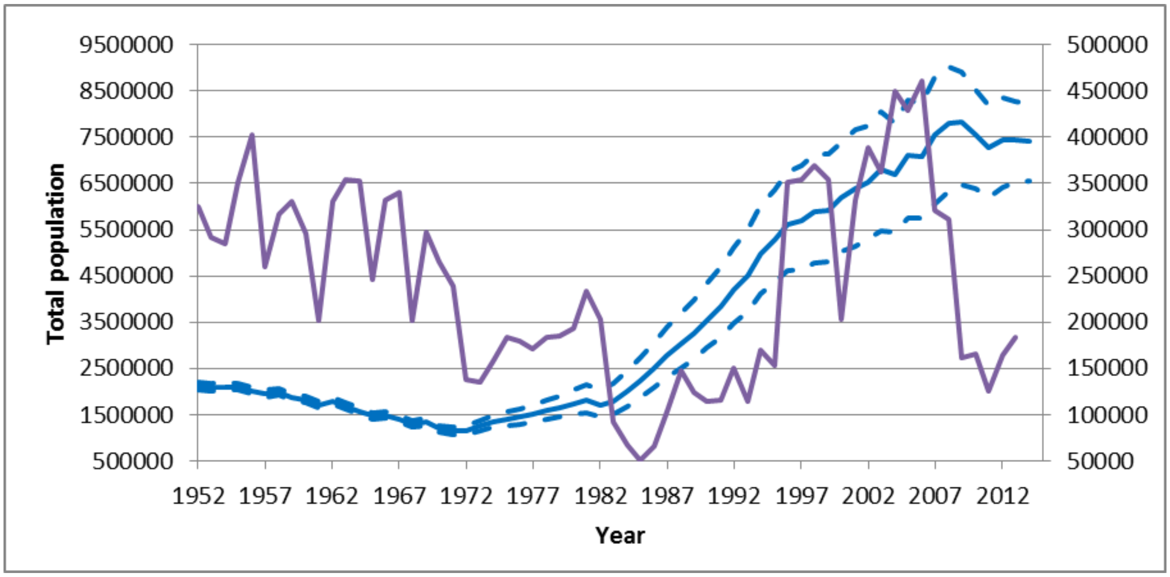


Figure 3. Estimated annual pup production for model fitted to pup survey estimates (mean ± 95% CI) and reproductive data up to and including 2013 (left Y-axis). Also presented are reported catches (right Y-axis).



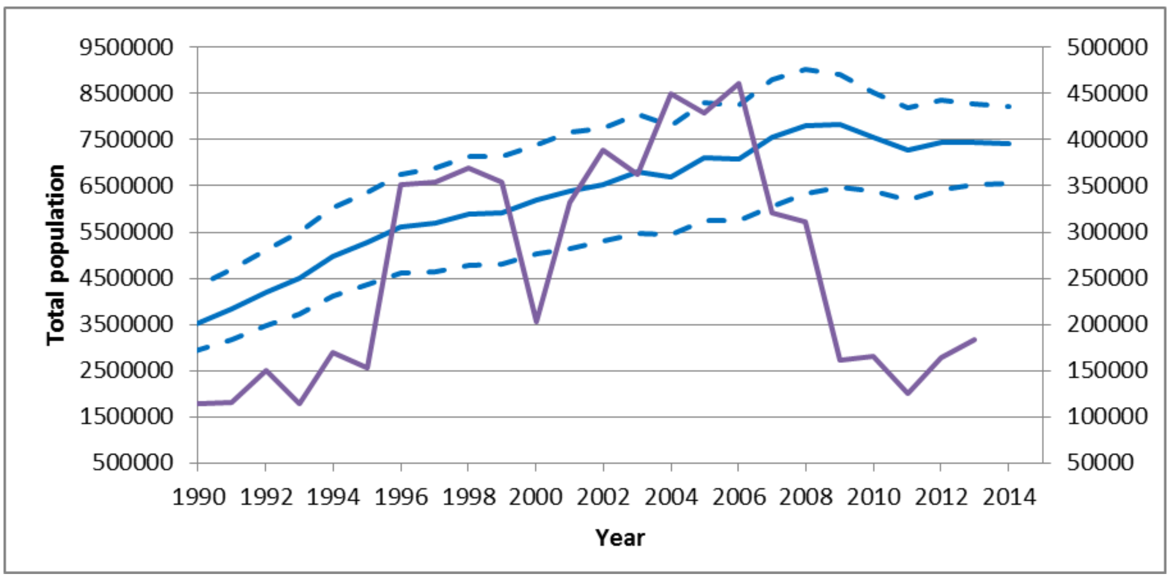


Figure 4. Estimated population trajectory for model fitted to pup survey estimates (mean ± 95% CI) (including the 2012 estimate) and reproductive data up to and including 2013 (left Y-axis). Annual reported catches are also included (right Y-axis).