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Northwest Atlantic Harp Seals Population Trends, 1952-2012

Tendances de la population de phoques du Groenland de l'Atlantique Nord-Ouest, 1952-2012

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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 2012. 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. Reproduction rates have continued to decline. Samples collected up to 2011, indicate that adult reproductive rates have declined to as low as 0.22, which is much lower than the estimate of 0.74 observed for 2008, the last year data were available for the 2010 assessment. The model was fit to eleven estimates of pup production from 1952 to 2008, using two different methods of smoothing the reproductive data and assuming carrying capacity can be either 10.8 million or 12 million seals. Estimated pup production in 1952 was 500,000 (95% CI=500,000-600,000) animals. Pup production declined throughout the 1960s reaching a minimum 1971, and then increased to a maximum of 1,600,000 (95% CI=1,400,000-1,800,000) in 2008. Estimated pup production declined to 600,000 (95% CI=500,000-700,000) in 2011 due to the low pregnancy rates observed. The total population size in 1952 was 2,300,000 (95% CI=2,200,000 -2,400,000) declining to a minimum in 1971 and then increasing to 7.9 to 8.3 million (95% CI=7,300,000-9,000,000) in 2008, depending upon the assumptions. The 2008 estimate is also N_{Max}. The 2012 population is estimated to be 7.3 to 7.7 million. Although the previous assessment indicated that a harvest of 400,000 could be sustained for the remainder of the management period, the maximum harvest that would respect the management plan under this assessment is 300,000 animals, assuming that beaters comprise 97% of the harvest. The difference is due to the significant decline in reproductive rates observed in samples collected since 2008. Increasing catches on one component of the population through a transfer of quota will adversely impact that component unless it is offset by an equal reduction in subsequent years.

RÉSUMÉ

Un modèle de population a été utilisé pour examiner les changements dans la taille de la population de phoques du Groenland entre 1952 et 2012. 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. Les taux de reproduction ont continué de diminuer. Des échantillons prélevés jusqu'en 2011 indiquent que les taux de reproduction des adultes ont baissé à pas plus de 0,22, taux beaucoup plus faible que l'estimation de 0.74 observée en 2008, dernière année pendant laquelle des données étaient disponibles pour l'évaluation de 2010. Le modèle a été ajusté à onze estimations périodiques de production de petits de 1952 à 2008, en utilisant deux méthodes différentes de lissage de données de reproduction et en supposant que la capacité de support peut être de 10,8 millions ou de 12 millions de phoques. La production estimée de petits en 1952 était de 500 000 (95 % IC = 500 000 à 600 000) animaux. La production de petits a diminué pendant les années 1960, pour atteindre un minimum en 1971, et a ensuite augmenté à un maximum de 1 600 000 (95 % IC = 1 400 000 à 1 800 000) en 2008. La production estimée de petits a diminué à 600 000 (95 % IC = 500 000 à 700 000) en 2011 en raison des faibles taux de gestation observés. La taille de la population totale en 1952 était de 2 300 000 (95 % IC = 2 200 000 à 2 400 000), elle a diminué à un minimum en 1971 pour ensuite augmenter de 7,9 à 8,3 millions (95 % IC = 7 300 000 à 9 000 000) en 2008, selon les hypothèses. L'estimation de 2008 est également N_{Max}. La population de 2012 est estimée entre 7,3 et 7,8 millions. Bien que l'évaluation précédente ait indiqué qu'il serait possible de maintenir une récolte de 400 000 animaux pour le reste de la période de gestion, la récolte maximale qui respecterait le plan de gestion dans le cadre de la présente évaluation est de 300 000 animaux, en supposant que les brasseurs représentent 97 % de la récolte. La différence est attribuable au déclin important des taux de reproduction observés dans les échantillons prélevés depuis 2008. Augmenter le nombre de prises dans une composante de la population en transférant un quota nuira à cette composante, à moins d'être compensée par une réduction égale au cours des années ultérieures.

INTRODUCTION

Information on abundance of natural resources is required for setting appropriate harvest limits, building ecosystem models or evaluating the impacts of environmental change or industrial activities upon a resource. Phocid life–histories 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 at sea over a very wide range, where they are often below the surface and hence difficult to count. During the breeding season, mature animals are often concentrated, and although adults may not always be hauled-out, the young are often available on land, or on the ice, to be counted using visual or photographic surveys (Bowen et al. 1987; Stenson et al. 1993, 2002, 2003). An estimate of total population size is then 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*) is a medium sized, migratory phocid distributed over continental shelf regions of the north Atlantic. Three populations are recognized; the White Sea, Northeast Atlantic and the Northwest Atlantic. The Northwest Atlantic population summers in the Arctic, but migrates south along the Canadian continental shelf in the autumn to overwinter and reproduce off northeastern Newfoundland and in the Gulf of St. Lawrence. Harp seals require pack ice as a platform for hauling out on, to give birth and nurse their young. After weaning the YOY remain with the ice, using it as a resting platform, for several weeks. The harp seal is the most abundant pinniped in the North Atlantic. They are an important predator and play an important role in structuring the North Atlantic ecosystem (Morissette et al. 2006; Bundy 2001). The Northwest Atlantic harp seal is harvested commercially in Atlantic Canada, with reported catches as high as 366,00 animals in 2004, making it the largest marine mammal harvest in the world. Harp seals are also hunted for subsistence purposes in Arctic Canada, and Greenland and are taken as bycatch in commercial fisheries.

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 (Tynan and DeMaster 1997). 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. In years, where there is very little ice-cover, mortality (M_{ice}) of nursing and weaned YOY is likely quite high. For example, there was very little ice cover in 1981 and M_{ice} 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 M_{ice} includes the reports of large numbers of carcasses on the beaches or large numbers of drifting carcasses in the water. Although these observations show that M_{ice} might be high at the whelping or at the post-weaning stages, it is difficult to quantify. Nonetheless, it suggests that unusual mortality should be considered when the dynamics of the population are being described.

Pregnancy rates are of vital importance for assessing the dynamics of a population, as they provide insights into productivity and the ability of the female component in the population to secure resources. In Northwest Atlantic harp seals, pregnancy rates are determined by sampling females during the latter part of pregnancy and calculating the proportion pregnant (Sjare and Stenson 2010). Data are available from as early as the 1950's, but collections were irregular. Since 1979, annual pregnancy rate data have been collected, but in some years sample sizes are small (Sjare and Stenson 2010).

DFO Fisheries management has requested that DFO Science examine different catch scenarios and determine if they respect the management objective, that is for the next four years (2012-2015) there is an 80% probability that the harp seal population will remain above 70% of its maximum observed size over the long term. The scenarios we have been asked to examine are:

A) 400,000 for each year with 10% adults/ 90% beaters;
B) 400,000 for each year with 30% adults/ 70% beaters;
C) 500,000 for each year with 10% adults/ 90% beaters; and
D) 500,000 for each year with 30% adults/ 70% beaters.

In addition, poor ice conditions observed in recent years, have prevented the Gulf fleet from obtaining their allocation in some years and industry has asked to take their quota at the Front. Therefore, Science was also asked to provide advice on the impact of a transfer of the Gulf quota to the Front on the population given the following scenarios:

A) one year of Gulf sealers taking approximately 50K, and 100K seals from the Front quota;
B) two years of Gulf Sealers taking approximately 50K, and 100K seals from the Front quota;
C) five years of Gulf Sealers taking approximately 50K, and 100K seals from the Front quota.

The objective of this study is to estimate current abundance of Northwest Atlantic harp seals incorporating recent removals, ice conditions and reproductive data, and to estimate the impact of proposed removals and a transfer of quotas between areas.

MATERIALS AND METHODS

Modelling the dynamics of the Northwest Atlantic harp seal population occurs in two steps. In the first, using Monte Carlo sampling, the model is fitted to independent estimates of pup production by adjusting initial population size (α) and adult (i.e. seals one year of age and older referred to as '1+') mortality rates (*M*). It is assumed that the dynamics of the population can be described by assuming density dependent mortality acting on juvenile survival. 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 (Hammill and Stenson 2009).

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

1. reproductive rates (and variance) remain constant over the period of the projection;
2. mortality from bycatch, the proportion of seals struck and loss, and catches in the Canadian Arctic remain constant;
3. Greenland catches may vary between 70,000 and 100,000 (uniform distribution), with an average of 85,000 animals;

4. ice-related mortality was assumed to follow a uniform distribution based on estimate mortality over the last 5 years;
5. pup mortality is fixed at three times 1+ mortality (M) and remains unchanged;
6. the dynamics of the population can be described assuming density-dependent mortality acting on juvenile survival.

The model is projected forward to determine if the catches will respect the management plan (i.e. 80% likelihood of population remaining above the Precautionary Reference Level) for the next 15 years.

Model structure

The basic model has the form: $n_{a,t} = ((n_{a-1,t-1*} w) - c_{a-1,t-1})\, e^{-(\gamma)m}$ (1)

for age a = 1

$$n_{a,t} = (n_{a-1,t-1} e^{-m/2} - c_{a-1,t-1}) e^{-m/2} \quad (2)$$

for 1 < a < A,

$$n_{A,t} = [(n_{a-1,t-1} + n_{A,t-1}) e^{-M/2} - c_{a-1,t-1}] e^{-M/2} \quad (3)$$

for a = A, where A-1 is taken as ages A-1 and greater, and for a = 0;

$$n_{0,t} = \sum_{a=1}^{A} n_{a,t} P_{a,t} \quad (4)$$

$$n_{1,t} = ((n_{a-1,t-1*} w) - c_{a-1,t-1})\, e^{-(\gamma)m} * [1-(N_t/K)^{\Theta}] \quad (5)$$

where
$n_{a,1}$ = 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. P is expressed as a Normally distributed variable, with mean and standard error taken from the reproductive data
m = the instantaneous rate of natural mortality,
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, assumed a Normal distribution (mean=12 million, SE=240,000 or mean=10.8 million, SE=196,000) (Hammill et al. 2011)
Θ= theta, set at 2.4 (Trczinski et al. 2006).

The model creates a population matrix with 26 age classes from 1952 until the current year. It is created using data on pregnancy rates, removals and ice-related mortality. The model minimizes the weighted sum-of-square differences between the pup production estimated by the model and the observed production from surveys, by estimating two parameters; the instantaneous mortality rate (*M*) and the initial population factor (α). The latter parameter is used to estimate the initial population in 1952. An initial population vector (26 × 1) was created to which α is multiplied. This initial population vector can be interpreted as an initial population age structure and the initial population size is calculated using:

$$P = \sum_{i=1}^{26} \left(\alpha \cdot l_i \right) \qquad (6)$$

Where *P* is the total population, α the initial population parameter and l_i the initial population size for the i^{th} age class.

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. The model is adjusted using the weighted sum-of-square difference between the pup production estimated by the model and the observed production from the surveys. The two parameters (*M* and α) are optimized to minimize the weighted sum-of-square difference by iterative methods. For each Monte Carlo simulation, a new *M* and α were estimated and stored. The model functions within the programming language R.

<u>Data Input</u>

Pup production estimates

The model was fit to 11 independent estimates of pup production (Table 1) 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 and 2008 (Sergeant and Fisher 1960; Stenson et al. 1993, 2002, 2003, 2005, 2009). 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. They are thought to provide useful information, but there is greater uncertainty surrounding these estimates. To reflect this, these surveys were assigned a coefficient of variation of 40%.

Reproductive rates

Late term pregnancy data are available from sampling programs maintained by the Department of Fisheries and Oceans since 1954 (Sjare and Stenson 2010). 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 incorporated into the model at the age they would have had at the time of pupping. There are gaps in the time series of the data, and in some years sample sizes are small (Table 2). Thus an approach is needed to interpolate age specific reproductive rates during years where there are no data or where samples are limited (N<5).

Two methods were used to smooth the reproductive rate data. The first approach used the smoother outlined in Stenson et al. (2009). The data are assumed to follow a binomial distribution, are smoothed then are incorporated into the model assuming that the smoothed data approximate a Normal distribution with known mean and SE. A Gaussian weight function is applied to the data depending on the distance between neighbouring points. Bandwidths were selected using Generalized Cross Validation. This approach has been termed the ‘old smoother’. In 2010, we applied the Old Smoother where smoothed values for ages 4-7 were incorporated into the model. For animals aged 8+ years, actual reproductive rates for animals

8+ were incorporated into the model, except in years where data were lacking for the 8+ animals , in which case smoothed values were included. In this paper, we also use a slightly different approach which smoothes the data using local likelihood estimation (Loader 1999). We call this approach the 'New Smoother' where, a local logistic regression, is applied to the binary data (pregnant or non-pregnant) for which an additive Gaussian model would not be appropriate (Tibshirani and Hastie 1987). It also 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. Using this technique, smoothing was performed using the LocFit package in R (Loader, 2010), which provides diagnostic measures to evaluate model fit. Since we expected substantial curvature in the trajectory of pregnancy rates, we used a 2^{nd} 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).

Variance in the data was estimated using log-likelihood in the framework of normal approximations (Loader 1999). This variance estimate was used to compute confidence intervals. When using the binomial family, prediction and errors are calculated on a logit scale. Values are then back-transformed using the inverse logit function, resulting in non symmetric errors around the mean. The harp seal fitting model incorporates uncertainty 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. Data included in the model were available from 1954 to 2008.

Seals 3 years old and younger were considered immature while seals 8 years and older were considered to be fully recruited into the population. The smoothed reproductive rates were extrapolated backwards from 1954 to 1952. For all years and age classes, the smoothed rates were used if less than 5 samples were available, otherwise the observed rate was used.

In previous years, the reproductive rate (mean and Standard Error) estimated by the smoother for the last year was used for the population projections into the future. In this paper the reproductive rates used to project into the future were randomly sampled, from the reproductive rates observed over the last 5 years (2007-2010) for which sample sizes were greater than 5. These were treated as a binomial sample with mean and sample size=N. If there were fewer than 5 samples per year, the model sampled from the rates estimated by the smoother for the past 5 years in the projections.

Catches

Catch data are available since 1952 and have been summarized by Stenson (2009). 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; Waring et al. 2005, 2007); and the Greenland subsistence hunt. Data were updated to include the most recent data to 2008 (Table 3). 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 98% 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 2009; 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 2009).

For the forward projections, it was assumed that the levels, and age structure, of struck and lost and bycatch were the same as used in the last years of the fitting model. Greenland harvest was assumed to vary uniformly between 70,000 and 100,000.

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 (Table 4). Currently, M_{ice} is a qualitative measure based upon ice conditions, storm frequency and reports of mortality and/or dead seals washing ashore. In this assessment, M_{ice} was recalculated for the Gulf and the Front herds separately, with M_{ice} for the total herd being estimated based on a ratio of 0.7 Front to 0.3 Gulf. The total estimate is presented in Table 4. In projections into the future, the model selected M_{ice} from a sample of values assigned to the last 5 years. Each value had an equal probability of being selected.

RESULTS

Sampling for reproductive rate data were 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 samples are very small (<5) (Table 2) The smoother fitted to the reproductive data provide a means of interpolating for missing years and captured the variability in the data fairly well (Fig. 1). For the age classes 4-6 years, age specific pregnancy rates were relatively low during the 1960s, increased during the 1970s to reach a peak value in the 1980s and then generally declined. For the 7 year old age class, a similar pattern was observed, but the increase during the 1970s was less evident than for the younger animals. The greatest number of samples was available for the 8+ year class (Table 2). For this group, reproductive rates remained high from the 1950s to the 1980s then declined throughout the 1990s and 2000s. This trend has continued over the last two years.

Little difference was observed between the two smoothers, with the exception of the 8+ age class. Generally, the old smoother had a narrower, less variable 95% CI band, whereas the new smoother showed more variability in the width of the 95% CI band and seemed more able to incorporate the variability observed among the samples. The new smoother also fit the recent declines observed among 8+ animals better than the old smoother (Fig. 1).

The population model was fitted to 11 independent estimates of pup production (Table 1) under four scenarios: using the old smoother to smooth reproductive rates and K=12 million animals or K=10.8 million animals; using the new smoother and K=12 million or K=10.8 million. All scenarios provided similar estimates of pup production and total population size throughout the fitting period, 1952-2012. The new smoother appeared to be associated with slightly higher mortality rates and provide a better fit to the survey data, (Fig. 2).

Using the old smoother and K=12 million (SE=196,000) animals adult mortality was 0.033 (SE=0.003). Pup production in 1952 was 523,000 (95% CI=477,000 to 574,000)(Fig. 2). Pup production declined throughout the 1960s, reaching a minimum 1971, and then increasing to 1,600,000 (95% CI=1,400,000-1,800,000) in 2008. Estimated pup production declined to a minimum of 600,000 (95% CI=500,000-700,000) in 2011, but could increase to 1,100,000 (95% CI=900,000-1,300,000) in 2012 depending on reproductive rates. The total population size in

1952 was 2,300,000 (95% CI=2,200,000 -2,400,000) declining to a minimum in 1971, then increasing to 8,300,000 (95% CI=7,600,000-9,000,000) in 2008. The 2008 estimate is also N_{Max}. The population has declined since then and the estimated 2012 population is 7,800,000 (95% CI=7,000,000-8,500,000) (Fig. 3).

Using the old smoother and K=10.8 million (SE=196,000) (Hammill et al. 2011) animals adult mortality was 0.031 (SE=0.003). Pup production in 1952 was 500,000 (95% CI=470,000 to 600,000)(Fig. 2). Pup production declined throughout the 1960s, reaching a minimum 1971, and then increasing to 1,600,000 (95% CI=1,400,000-1,800,000) in 2008. Estimated pup production declined to a minimum of 600,000 (95% CI=400,000-700,000) in 2011, but could increase to 1,100,000 (95% CI=900,000-1,200,000) in 2012. The total population size in 1952 was 2,300,000 (95% CI=2,200,000 -2,400,000) declining to a minimum in 1971, then increasing to 8,100,000 (95% CI=7,500,000-8,900,000) in 2008. The 2008 estimate is also N_{Max}. The population has declined since then and the estimated 2012 population is 7,600,000 (95% CI=6,900,000-8,300,000) (Fig. 3).

Using the new smoother and K=12 million (SE=240,000) animals adult mortality was 0.038 (SE=0.003). Pup production in 1952 was 500,000 (95% CI=490,000 to 570,000)(Fig.2). Pup production declined throughout the 1960s, reaching a minimum 1971, and then increasing to 1,600,000 (95% CI=1,400,000-1,800,000) in 2008. Estimated pup production declined to a minimum of 600,000 (95% CI=400,000-700,000) in 2011, but could increase to 1,200,000 (95% CI=1,000,000-1,400,000) in 2012. The total population size in 1952 was 2,300,000 (95% CI=2,200,000 -2,400,000) declining to a minimum in 1971, then increasing to 8,300,000 (95% CI=7,500,000-8,900,000) in 2008. The 2008 estimate is also N_{Max}. The population has declined since then and the estimated 2012 population is 7,700,000 (95% CI=6,900,000-8,400,000) (Fig. 3).

Using the new smoother and K=10.8 million (SE=196,000) animals adult mortality was 0.035 (SE=0.003). Pup production in 1952 was 500,000 (95% CI=480,000 to 600,000)(Fig.2). Pup production declined throughout the 1960s, reaching a minimum 1971, and then increasing to 1,600,000 (95% CI=1,400,000-1,800,000) in 2008. Estimated pup production declined to a minimum of 500,000 (95% CI=400,000-700,000) in 2011, but could increase to 1,100,000 (95% CI=1,000,000-1,300,000) in 2012. The total population size in 1952 was 2,300,000 (95% CI=2,200,000 -2,400,000) declining to a minimum in 1971, then increasing to7,900,000 (95% CI=7,300,000-8,500,000) in 2008. The 2008 estimate is also N_{Max}. The population has declined since then and the estimated 2012 population is 7,300,000 (95% CI=6,600,000-7,900,000) (Fig. 3).

Although the fitted populations were similar, slight differences were observed among projections, with runs incorporating the Old smoother and K=12M, allowing for slightly higher harvests than runs assuming K=10.8M and the New Smoother. This is likely due to the lower estimated mortality rates obtained using K=12M and the Old Smoother.

Scenarios where the hunt consists of 90% and 70% beaters were examined. However, currently the harvest is >97% beaters and this scenario was examined as well. For a harvest consisting of 97% beaters, and 3% 1+ animals a TAC of up to 300,000 animals would respect the management objective to maintain an 80% probability that the population remains above an N70 level of 5,500,000 (Fig. 4, 5). If the harvest is comprised of 90% beaters, 10% animals aged 1+ years, a harvest of up to 250,000 would continue to respect the plan. For a harvest comprising 70% beaters and 30% 1+ animals a TAC of 170,000 animals would respect the management objective (Fig. 5).

DISCUSSION

Previous analyses have attempted to provide annual pregnancy rates from the available sampling data. Bowen et al. (1981) used annual smoothing (as opposed to smoothing by age as 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) attempted multi-linear regression, analysis of covariance, analysis of variance, and auto-regression models, and discovered that all methods were inadequate to predict the unknown pregnancy rates. More recent efforts to estimate pregnancy rates are 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 tests successive pregnancy sample data for significant changes in pregnancy rates, and the resulting rates are referred to as `harmonized' rates. However, this approach results 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.

Some of this variability may be due to sampling. Therefore, some type of smoothing on the available data would allow us to account for the inter-annual variability and allow for some interpolation for years where data were missing. In recent assessments, a non-parametric smoother was applied to the reproductive rate data (Stenson et al. 2009). This allowed us to interpolate for years with missing data and to reduce some of the inter-annual variability in the data which were attributed to small sample sizes. 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. For this assessment, the data were considered to be binomially distributed and the smoother appeared to account better for the uncertainty in the data (Fig. 1).

Changes observed over the last 60 years 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), 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. However, the impacts of highly variable harvests as individual cohorts 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 complicates attempts to determine the underlying density-dependent mechanisms required to incorporate a density-dependent function into the model fitting and reliably estimate the environmental carrying capacity (K). At the last assessment a range of values for K were examined and it was concluded that K probably lay between 12 and 16 million animals (Hammill and Stenson 2011). Hammill et al. (2011) attempted to reconstruct the population back to the 18th century to obtain an estimate of K. They obtained an estimated K of approximately 11,000,000 (10.8 m, range = 7,551,320-15,444,476), suggesting that the carry capacity is near the lower end of the range. Therefore, in the current assessment, the model was fitted to two values of K (10.8 million and 12 million) to evaluate the impact of different catches on the population. The two values are not significantly different, but the data appear to provide a slightly better fit to K=12 million, which is well within the range of potential values and this value of K is recommended for the advice.

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. In press, 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. Mortality among young of the year (YOY) was high in both years, particularly in 2011, when good ice started to form, providing a platform for animals to pup on, but rapidly disintegrated resulting in high mortality (Stenson and Hammill 2011). Reproductive rates in 2011 were the lowest on record (fecundity < 25%), resulting in an estimated pup production of only 600,000 animals or only 38% of pup production in 2008 (1.6 million). If only 21% of these animals survived due to poor ice conditions, this would have left only 120,000 animals available to harvesters. The commercial hunt removed 40,000 animals leaving approximately 80,000 YOY (excluding struck & loss) to migrate north during the spring. We would expect very few animals from this cohort to have survived.

At the 2010 assessment, reproductive data up to 2008 were incorporated into the model and used to provide harvest advice. The most significant change since then is the decline in reproductive rates observed. Reproductive rates were high in 2008 (~70% of 8+ being pregnant) and were used to project the population forward and to evaluate impacts of different harvest levels. In this assessment, we were able to update the reproductive rate data to 2011. These data show that there has been a significant decline in rates since 2008, with adult (8+ years) rates declining to a low of 22% in 2011 (Table 2). The reproductive data are an important input into the population model and drive the future predictions; slight changes in assumed fecundity will have significant implications for the population trajectory. The challenge is how to decide on suitable rates to use in forward projections. In previous assessments, the smoothed reproductive rate estimates from the most recent year were used to project forward. If rates remain below the smoothed estimates, we will overestimate pup production, whereas if the estimates rates increase we will underestimate pup production. In this assessment, we sampled from the vector of observed rates between 2007-2011. Using this approach, we may still underestimate or overestimate future reproductive rates, but rather than use a single value, the intent was to capture the range of recent rates and some of the uncertainty in the reproductive rate data in the forward projections

In 2010, the assessment indicated that a harvest of 400,000 could be sustained for the remainder of the management period. As a result, we were asked to evaluate possible catches of 400,000 and 500,000 with different ratios of young in the catch for the 2012 harvest. None of these scenarios respected the management plan. In this assessment, the maximum harvest that would respect the management plan is 300,000 animals, assuming that beaters comprise 97% of the harvest. If the proportion of beaters in the harvest is lower, then much lower harvests will be needed to continue to respect the management plan. This is because harvests of older animals will have a direct impact on the breeding population, because seals that have a lower natural mortality than YOY are taken and these are associated with much higher loss rates (50% vs 5%) as well. The major reason for this change from the 2010 assessment is the sharp decline in herd productivity since 2008. Over the longer term, the large mortality of YOY that appeared to occur in 2010 and 2011 will have some impact on future recruitment, as well as the expected continued poor ice conditions over the next few years.

In addition to estimating the impact of various catch levels, we were asked to explore the consequences of transferring part of the Gulf quota to the Front. The northwest Atlantic harp seal population is generally considered as a single stock for management purposes and this was supported by genetic studies and analyses of tag returns (Lavigne et al. 1978; Sergeant 1991; Diaz Gómez 2010). Aerial survey results indicate that on average 29% (SE=7, CV=24%), are born in the Gulf and 71% (SE=7, CV=10%) of the pups are born at the Front although there is variability among years, occasionally due to an influx of ice from the Front via the Strait of Belle Isle. Generally, animals tagged as young of the year show increasing homing to their natal area as they mature, although some movement may occur, particularly in years of extremely poor ice such as occurred in 1969 and 2010. In these years the lack of ice in the Gulf is thought to have resulted in a shift in distribution of some females who were unable to find suitable ice in the Gulf to the Front where they pupped (Sergeant 1991; Stenson and Hammill 2011). However, the number of females that may have moved cannot be estimated and it is unknown if these animals or their offspring returned to the Gulf in subsequent years. Current harvest allocations to the Front and Gulf fleets (70:30) are consistent with the relative size of each component of the population and therefore maintains the integrity of each group. The impact of transferring catches among years has been explored previously (Hammill and Stenson 2009). They found that a carryover of up to 20% of the TAC would still respect the management objectives, as long as the overall number of animals removed over the life of the management period remained unchanged. Therefore, years when the number of animals removed was higher, would be accompanied by a reduction in allowable catch of an equal amount in subsequent years. If the total quota is set at the highest level that is consistent with the management objective, a transfer without subsequent reduction to compensate would result in overharvesting. The same principle would apply to a transfer from the Gulf to the Front; increasing the allocation from the Front to allow hunting by the Gulf fleet would not result in long-term conservation concerns for the Front herd only if this increase in catch is offset in subsequent years by an equal reduction in the allocation so that over the term of the management plan, the number of animals removed from each herd does not exceed the total allocation for that component. The impact of a transfer among herds when the overall quota is not set at the maximum, would depend upon the difference between the TAC and the maximum and the amount of transfer proposed.

The Northwest Atlantic harp seal population is currently near the highest levels observed since monitoring began almost 60 years ago. Pup production in 2008 was on the order of 1.63 million animals with a total population size of around 8.0 million animals. Since then the population has likely declined to about 7.7 million animals. Recent declines in productivity, an increase in the frequency of poor ice conditions and a largely unregulated harvest of harp seals in Greenland will have a major impact on future trends in the population.

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Table 1: Pup production estimates used as input into the population model. [1] Assumed a coefficient of variation of 40%.

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

Table 2. Year , sample size (n), number pregnant (#preg) and late term age-specific reproductive rates of Northwest Atlantic harp seals. [1] Rates for 2012 are assumed values taken as the average of the last 5 years.

Year	Age = 4			Age = 5			Age = 6			Age = 7			Age=8+		
	n	#Preg	rate	n	#Preg	rate	n	#Preg	rate	n	#Preg	rate	n	#Preg	rate
1954	4	0	0.00	3	1	0.33	3	2	0.67	16	12	0.75	33	29	0.88
1964	11	0	0.00	9	1	0.11	2	1	0.50	4	3	0.75	25	22	0.88
1965	30	1	0.03	44	5	0.11	37	20	0.54	38	27	0.71	109	96	0.88
1966	7	0	0.00	9	1	0.11	17	6	0.35	11	8	0.73	49	43	0.88
1967	10	0	0.00	19	4	0.21	33	20	0.61	29	28	0.97	123	109	0.89
1968	27	0	0.00	19	6	0.32	20	14	0.70	12	11	0.92	55	48	0.87
1969	25	1	0.04	25	4	0.16	16	7	0.44	28	23	0.82	165	146	0.88
1970	13	0	0.00	13	3	0.23	12	6	0.50	10	9	0.90	107	92	0.86
1978	40	1	0.03	38	23	0.61	20	18	0.90	9	6	0.67			
1979	21	5	0.24	15	8	0.53	5	5	1.00	9	8	0.89	21	20	0.95
1980	2	0	0.00	2	1	0.50	1	1	1.00	0			12	9	0.75
1981	5	1	0.20	4	3	0.75	2	1	0.50	7	6	0.86	17	14	0.82
1982	4	0	0.00	5	2	0.40	1	1	1.00	4	3	0.75	3	1	0.33
1985	4	0	0.00	3	1	0.33	5	2	0.40	3	3	1.00	1	1	1.00
1986	1	1	1.00	0			2	1	0.50	1	0	0.00	7	7	1.00
1987	12	2	0.17	8	3	0.38	9	7	0.78	4	4	1.00	24	15	0.63
1988	17	2	0.12	6	1	0.17	3	3	1.00	0			19	14	0.74
1989	8	0	0.00	9	0	0.00	6	2	0.33	3	2	0.67	22	22	1.00
1990	8	0	0.00	7	1	0.14	3	1	0.33	1	0	0.00	10	6	0.60
1991	10	0	0.00	11	2	0.18	7	4	0.57	3	1	0.33	29	18	0.62
1992	10	2	0.20	11	3	0.27	9	4	0.44	8	6	0.75	32	21	0.66

1993	11	1	0.09	17	2	0.12	7	0	0.00	5	4	0.80	35	17	0.49
1994	23	1	0.04	16	2	0.13	14	6	0.43	7	3	0.43	41	34	0.83
1995	10	0	0.00	13	6	0.46	4	2	0.50	5	2	0.40	24	14	0.58
1996	8	0	0.00	6	0	0.00	4	1	0.25	1	1	1.00	35	24	0.69
1997	6	0	0.00	4	0	0.00	10	3	0.30	2	2	1.00	36	27	0.75
1998	6	0	0.00	10	3	0.30	9	2	0.22	4	2	0.50	36	22	0.61
1999	6	0	0.00	7	0	0.00	18	4	0.22	15	6	0.40	59	37	0.63
2000	1	0	0.00	9	3	0.33	6	4	0.67	5	2	0.40	43	29	0.67
2001	2	0	0.00	0			2	2	1.00	3	0	0.00	39	26	0.67
2002	2	0	0.00	4	1	0.25	5	3	0.60	17	10	0.59	72	40	0.56
2003	1	0	0.00	3	2	0.67	2	1	0.50	3	2	0.67	91	59	0.65
2004	2	0	0.00	5	0	0.00	5	1	0.20	1	0	0.00	76	31	0.41
2005	9	1	0.11	9	0	0.00	13	2	0.15	7	0	0.00	86	55	0.64
2006	2	0	0.00	0			0			0			119	67	0.56
2007	1	0	0.00	5	0	0.00	3	1	0.33	2	2	1.00	84	64	0.76
2008	6	0	0.00	3	0	0.00	2	0	0.00	0			61	45	.74
2009	1	0	0.00	1	1	0.20	1	0	0.00	1	1	1.00	103	57	0.55
2010	-	-		-	-		-	-		-	-		117	35	0.30
2011	-	-		-	-		-	-		-	-		94	21	0.22
2012[1]	3	0	0	3	0	0	2	0	0				90	45	0.50

Table 3. Catches of Northwest Atlantic harp seals from different sources (see Stenson 2009)

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	93,117	237,644	6,908	6,280	9,750
2000	400	98,458	85,035	7,020	1,608	9,715
2001	600	85,427	214,754	11,739	4,828	14,572
2002	1,000	66,734	297,764	14,603	3,837	5,492
2003	1,000	66,149	280,174	9,338	1,881	3,486
2004	1,000	70,585	353,553	12,418	3,796	8,494
2005	1,000	91,695	319,127	4,699	3,796	8,494
2006	1,000	92,210	346,426	8,441	3,796	8,494
2007	1,000	82,836	221,488	3,257	3,796	8,494
2008	1,000	80,554	217,565	285	3,796	8,494
2009	1,000	82,843	76,688	0	3,796	8,494
2010	1,000	82,843	68,654	447	3,796	8,494
2011	1,000	82,843	40,238	132	3,796	8,494

Table 4. 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.

Year	Survival (previous assessments)	Updated survival estimates
1969	0.75	0.60
1981	0.75	0.43
1998	0.94	0.94
2000	0.88	0.91
2002	0.75	0.88
2005	0.75	0.83
2006	0.90	0.99
2007	0.78	0.94
2010	0.55	0.59
2011		0.21

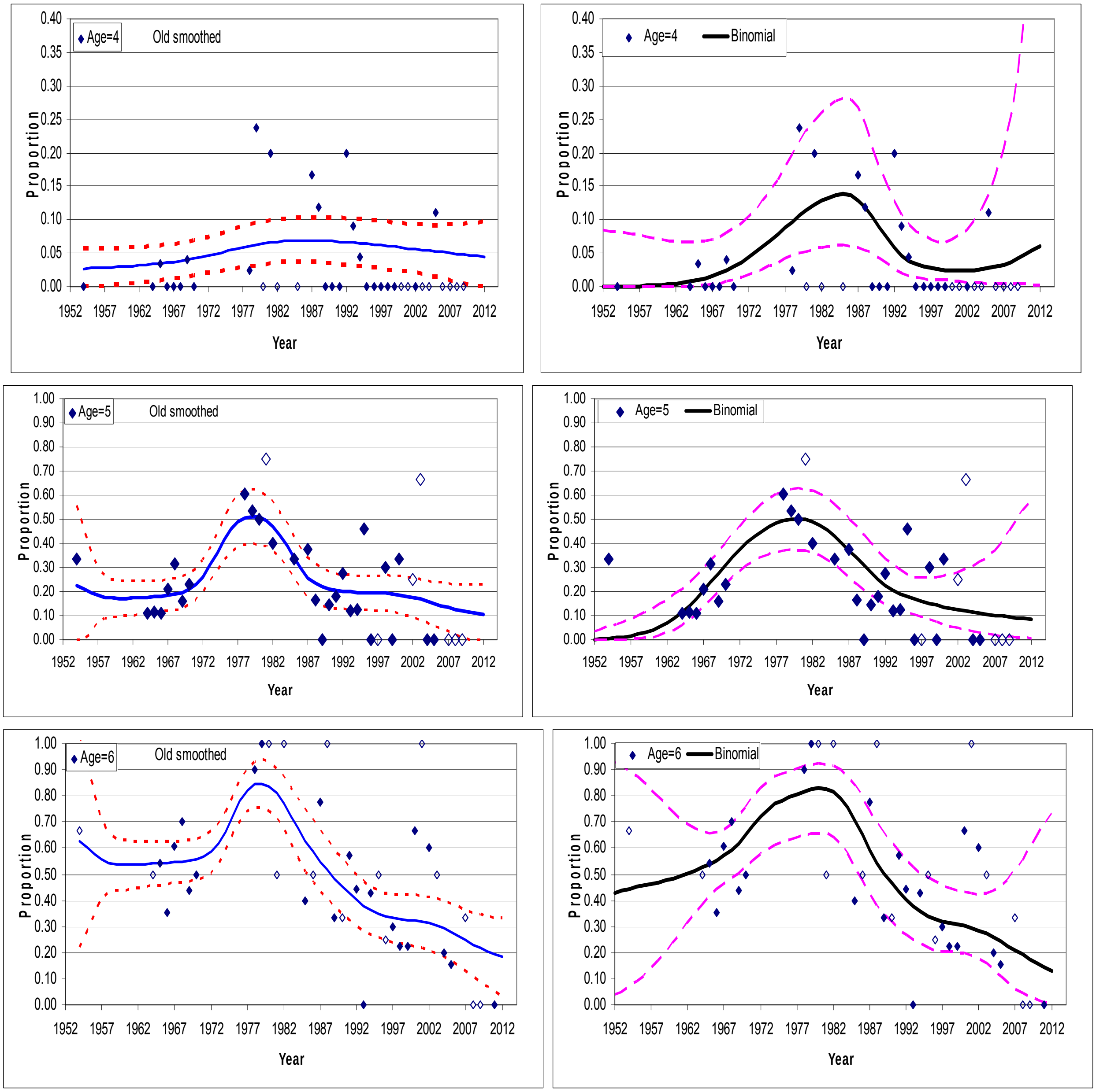


Figure 1. Age specific reproductive rates and non-parametric smoothed rates. Open symbols represents N<5 samples.

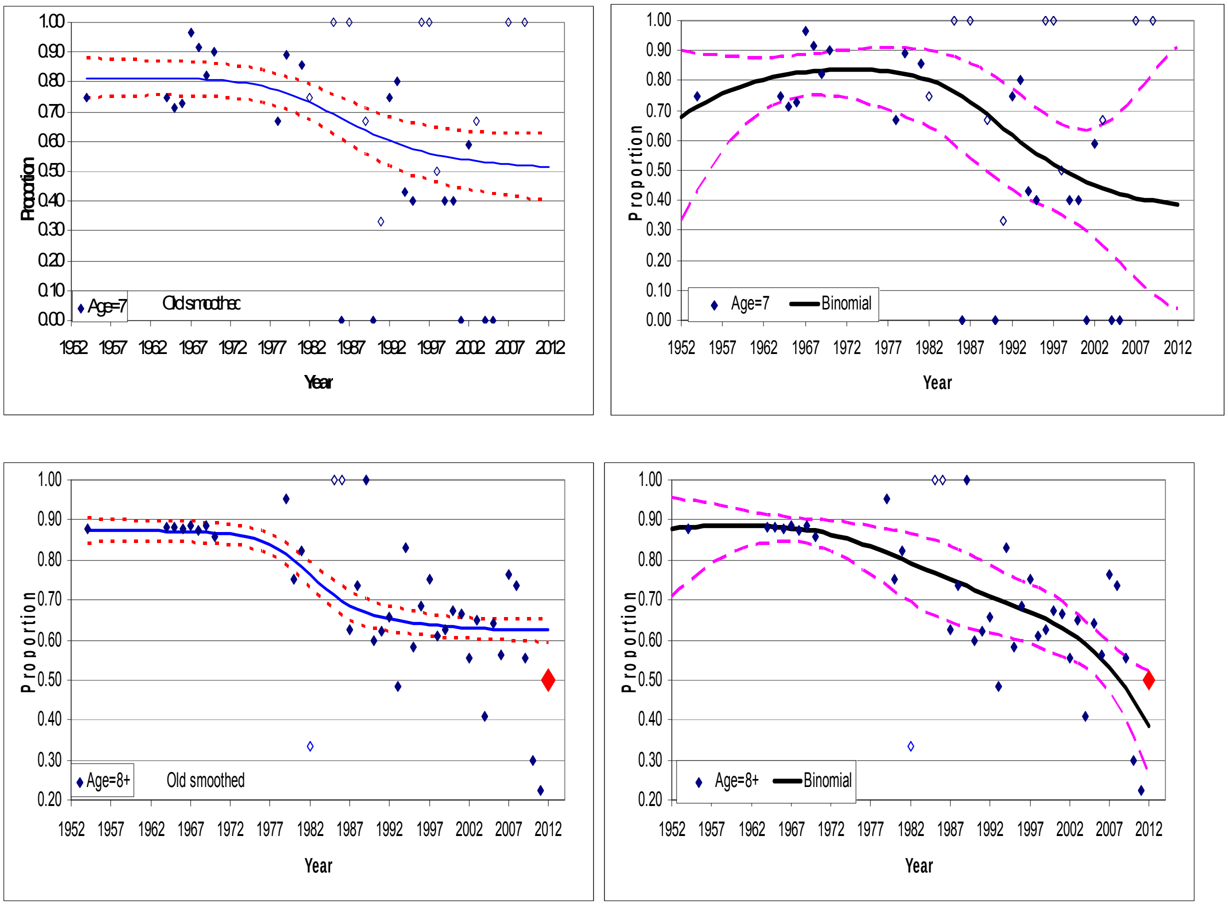
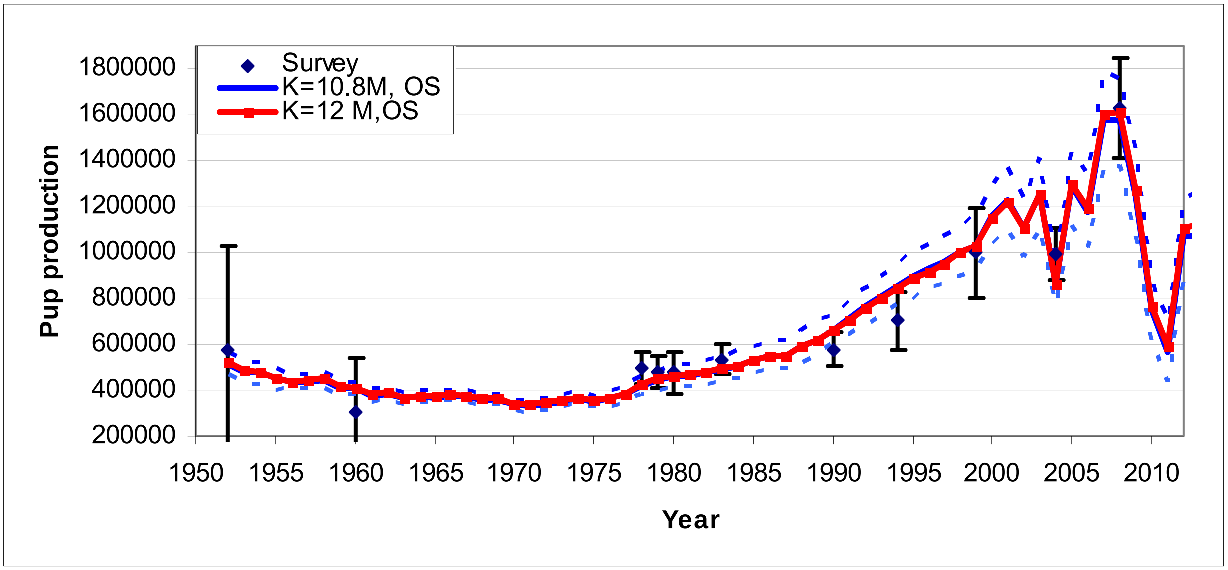


Figure 1. Age specific reproductive rates and non-parametric smoothed rates. The smoother used in previous assessments is on the left while the smoother used in this study are on the right. Open symbols represents N<5 samples.



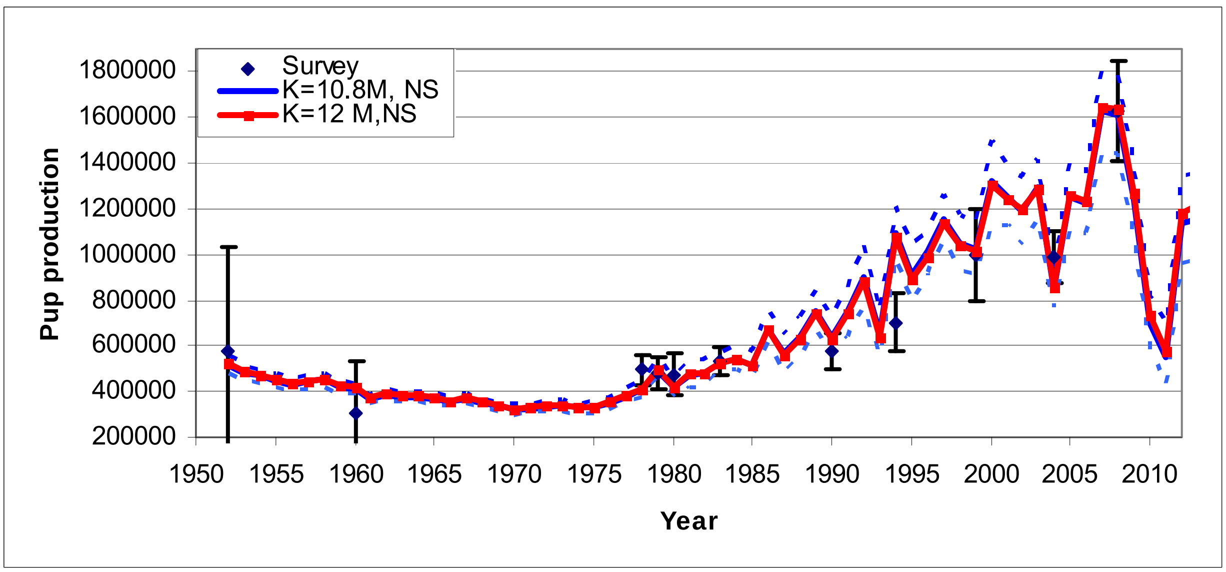
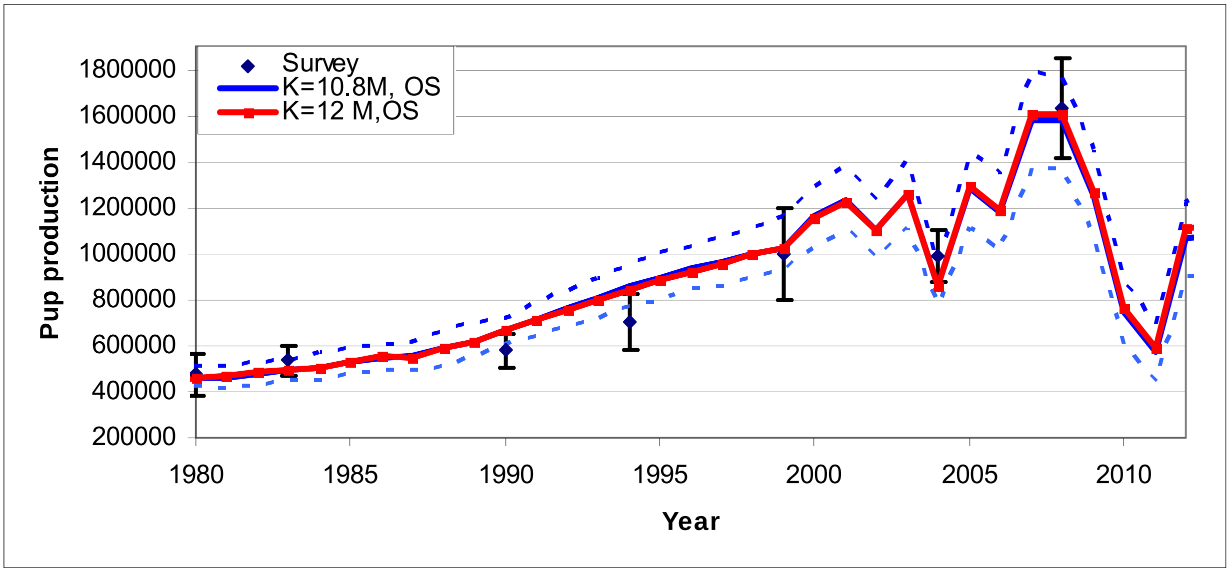


Figure 2a. Changes in estimated pup production (mean±95% C.I.) and survey estimates (mean±95% C.I.) from 1952 to 2012, using the old smoother (OS) and the new smoother (NS) and assuming K=10.8 million or 12 million.



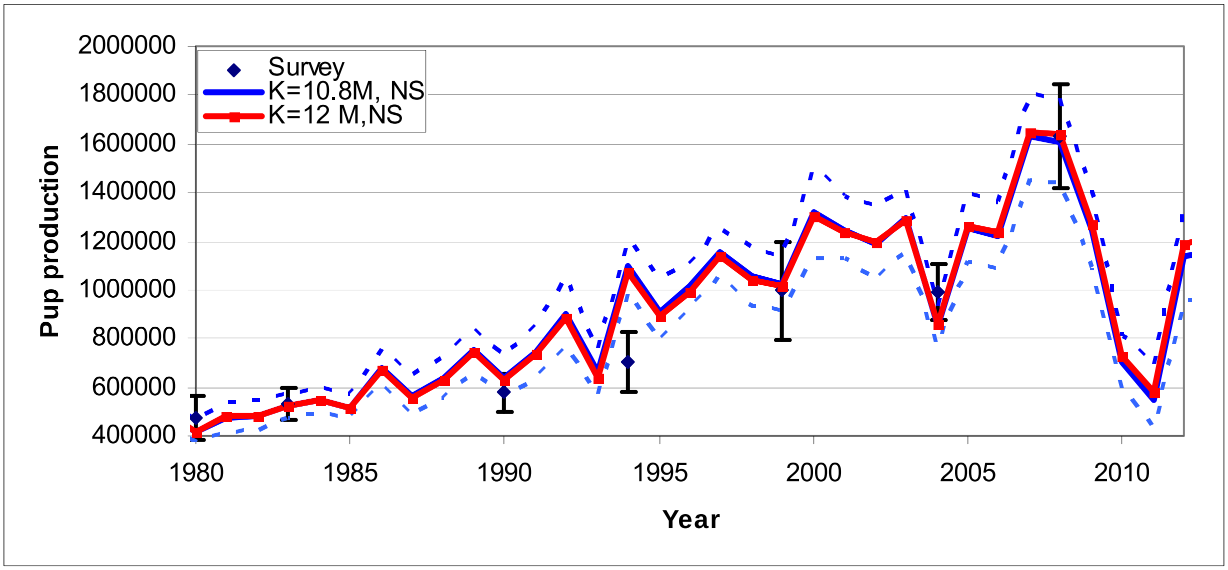
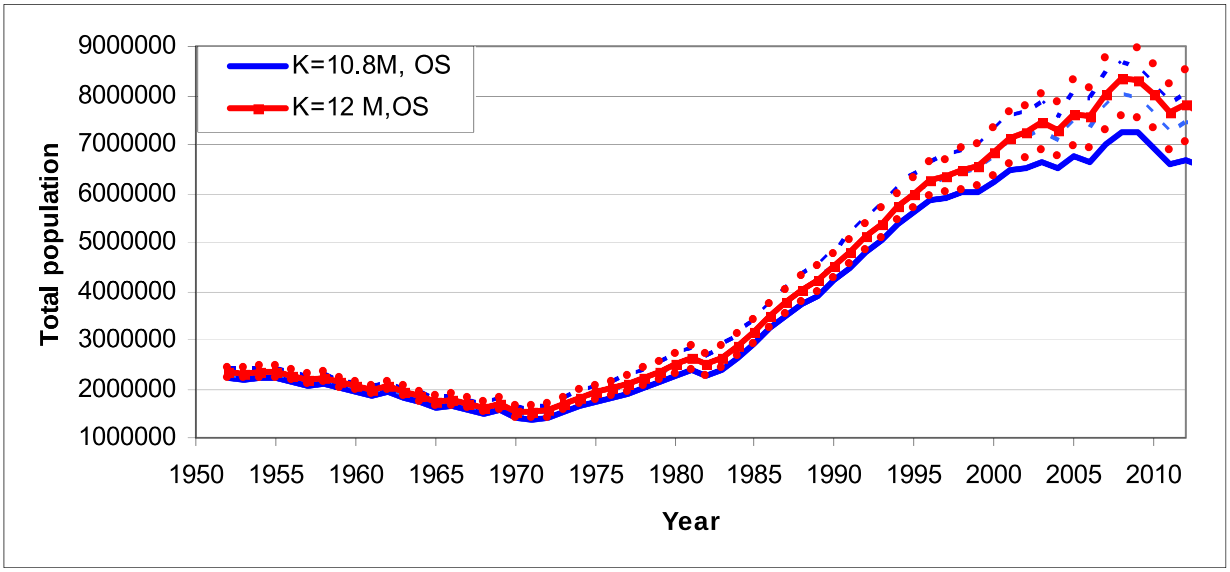


Figure 2b. Changes in estimated pup production (mean±95% C.I.) and survey estimates (mean±95% C.I.) from 1980 to 2012, using the old smoother (OS) and the new smoother (NS) and assuming K=10.8 million or 12 million.



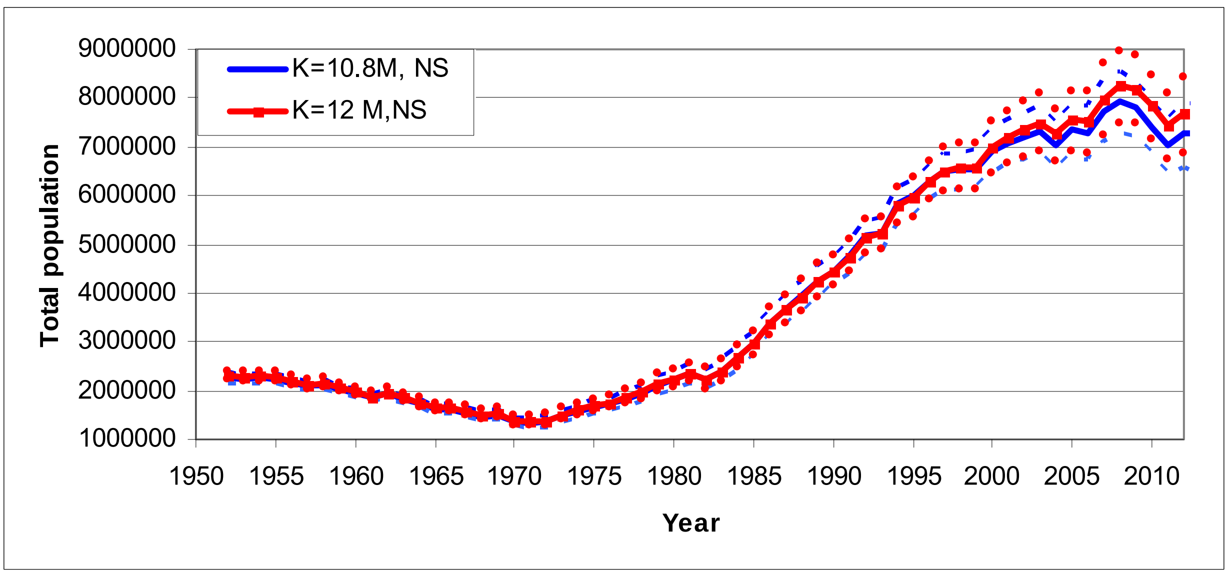


Figure 3a. Changes in estimated population size (mean±95% C.I.) from 1952 to 2012, using the old smoother (OS) and the new smoother (NS) and assuming K=10.8 million or 12 million.

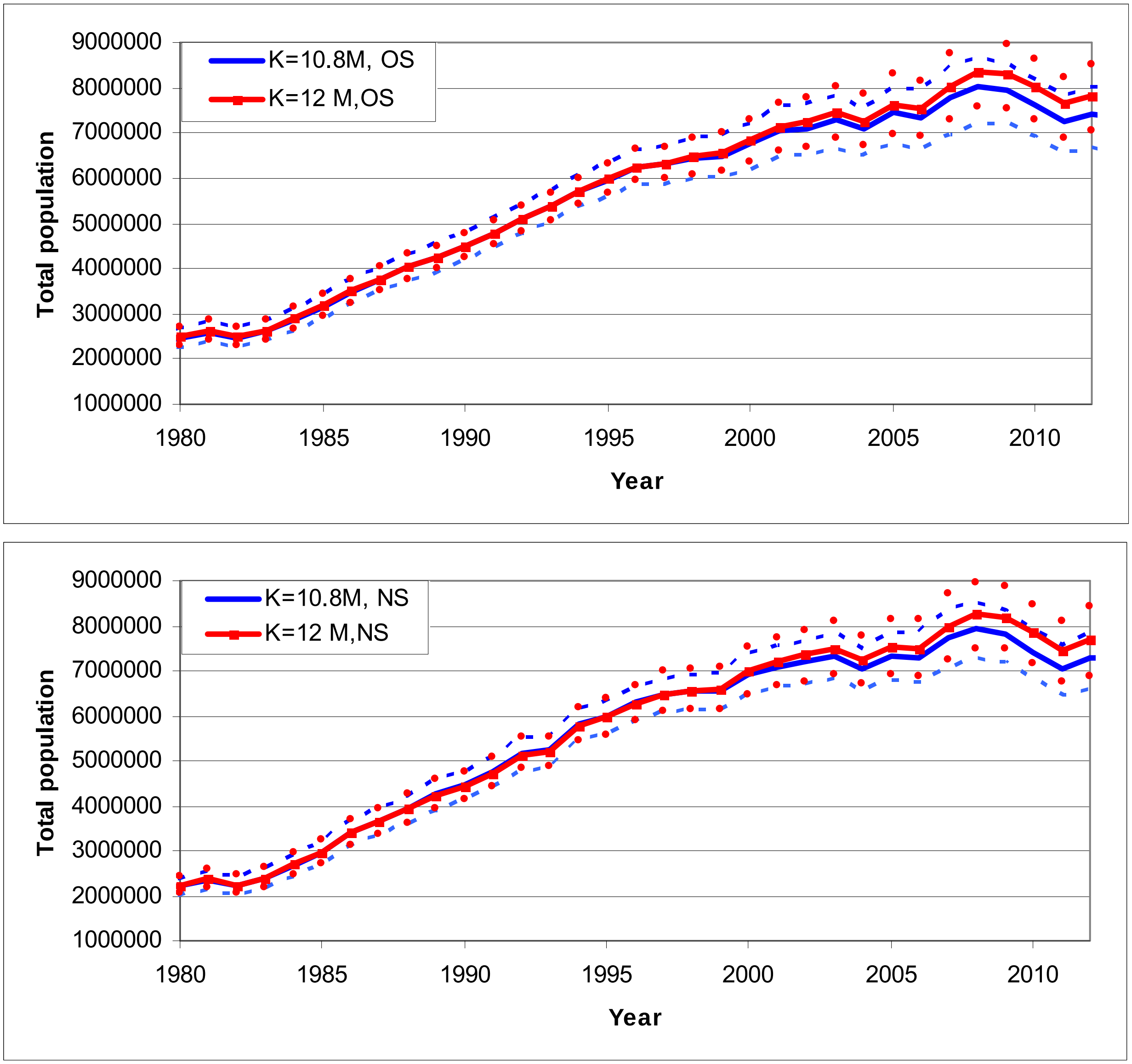


Figure 3b. Changes in estimated population size (mean±95% C.I.) from 1980 to 2012, using the old smoother (OS) and the new smoother (NS) and assuming K=10.8 million or 12 million.

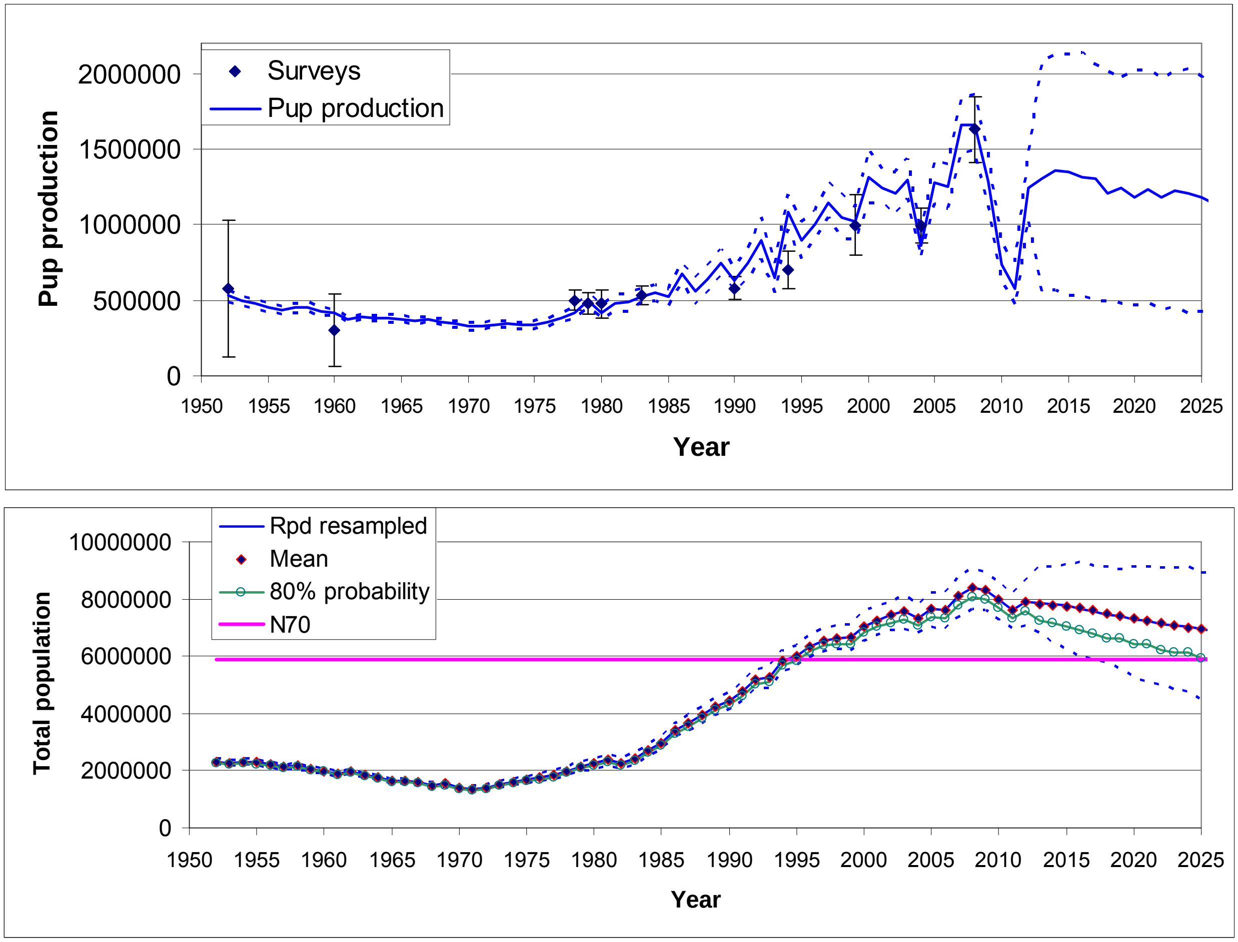


Figure 4. Expected trajectory (± 95% C.I.) of the northwest Atlantic harp seal population subject to a harvest of 300,000 animals annually and assuming that 97% of the harvest is comprised of YOY.N70 is set at 70% of the largest population observed. The management objective is to maintain an 80% probability that the population will remain above N70.

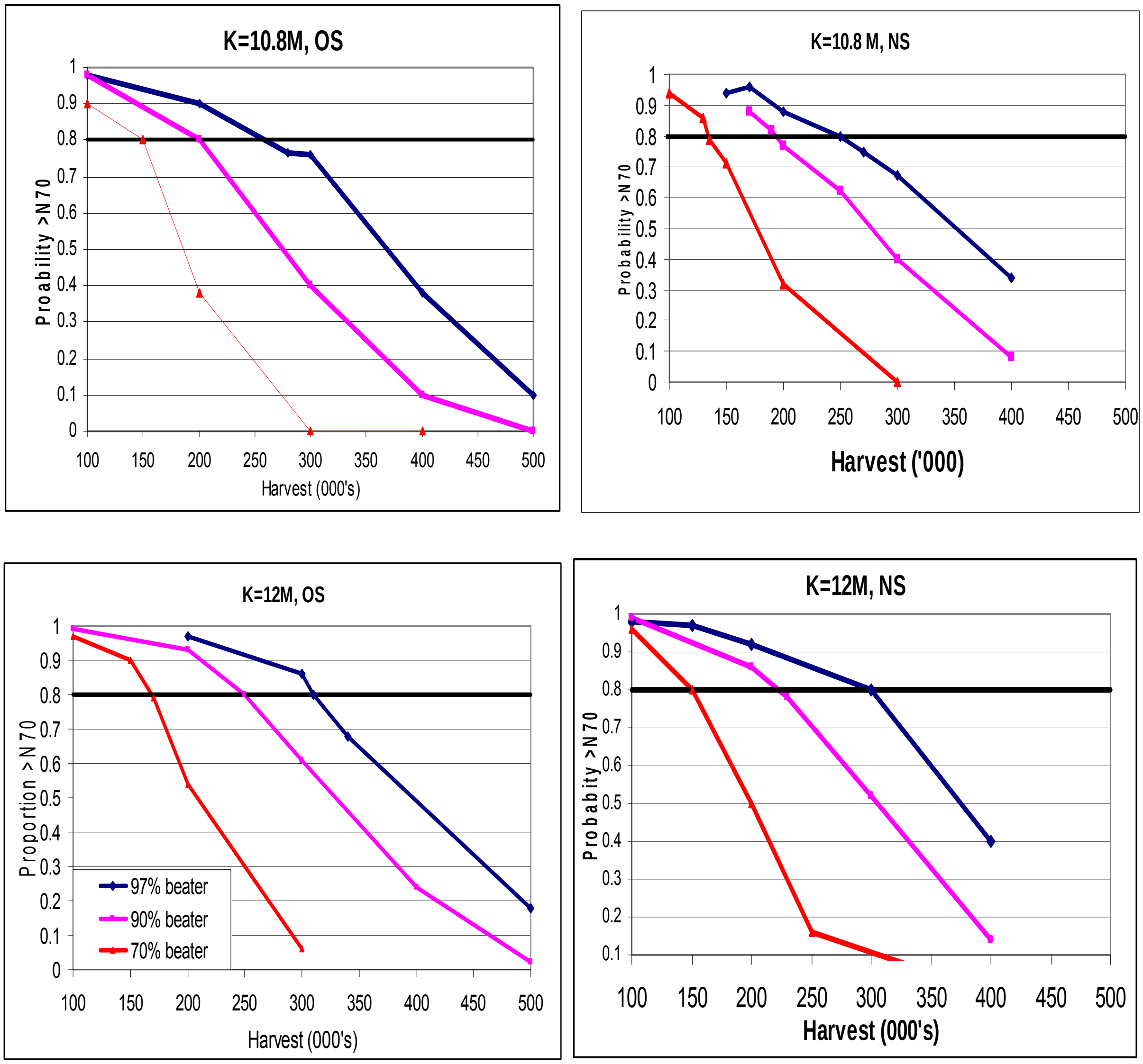


Figure 5. Probability of different harvest composition (% Beaters in harvest) and different harvest levels maintaining the population above N70 for 15 years