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Grey Seal Population Trends in Canadian Waters, 1960-2014

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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 model of grey seal population dynamics was fitted to pup production estimates for the Sable Island, Coastal Nova Scotia (CNS) and Gulf of St. Lawrence (Gulf) seal herds to provide estimates of the Canadian component of the Northwest Atlantic grey seal population from 1960-2014. As with the 2012 assessment, the model was fit to each of the three herds separately, resulting in separate predictions of pup production and total population size by estimating initial population size (α), adult mortality (M) and environmental carrying capacity (K). Grey seal pup production in 2014 is estimated to be 93,000 (95% CI=48,000 to 137,000) animals, with a total population of 505,000 (95% CI=329,000 to 682,000). Sable Island production is estimated to account for about 77% of the estimated total number of pups born in 2014. The estimated 2014 total population of each herd was 394,000 (95% CI 238,000 to 546,000), 13,800 (95% CI=9,300 to 27,300), and 98,000 (95% CI=54,000-179,000), for the Sable, Coastal Nova Scotia and Gulf of St. Lawrence herds respectively. The model predicts that the overall population has continued to increase. To assess the impact of potential future removals on the population, the 2014 population was projected forward for 30 years under different harvest scenarios. To maintain an 80% probability of staying above the precautionary reference level (N70) and assuming that young of the year (YOY) comprise 95% of the catch, then harvests of 39,200 animals (Sable:33,000; CNS:1,200; Gulf:5,000) could be taken. If YOY comprise 90% of the catch then the total harvest would be 36,600 (Sable=31,000; CNS: 1,100; Gulf: 4,500). If YOY comprise 70% of the catch, then the total harvest would be 28,200 (Sable: 24,000; CNS: 700; Gulf: 3,500). Higher harvests are associated with increased risk of falling below the limit reference level and subsequent population collapse. Based on this assessment of the population, harvest levels at 50,000 grey seals or more, even with a harvest comprising 95% pups, have a moderate to high probability of resulting in a population decline below N70 and N50. The risk increases with the level of harvest and with the percentage of the harvest of seal age 1 and older. Further work is needed to estimate age and sex-specific adult mortality and reproductive rates and to incorporate change in these rates into the herd-specific models, to determine the strength and nature of density-dependent changes in vital rates. Density-dependent changes in vital rates have a large impact on estimates of carrying capacity and the sustainability of future removals. Estimates of population size and trends will become increasingly uncertain until there is new information on pup production for each of the herds. A reassessment of the stock should be completed when new pup production estimates are available or be triggered by evidence of considerable changes in vital rates, including mass mortality of adult seals.

Tendances de la population de phoques gris de l'Atlantique Nord-Ouest, 1960-2014.

RÉSUMÉ

Un modèle de dynamique de population pour le phoque gris a été adapté aux estimations de production de petits pour les troupeaux de l'Île de Sable, de la zone côtière de la Nouvelle-Écosse (CNE) et du golfe du Saint-Laurent (Golfe) afin de fournir une estimation de la composante canadienne de la population de phoques gris de l'Atlantique Nord-Ouest pour la période 1960-2014. Comme dans l'évaluation de 2012, le modèle a été ajusté à chacune des trois colonies séparément, ce qui entraîne des estimations distinctes de la production de petits et de la taille de la population totale en estimant la taille de la population initiale (α), la mortalité adulte (M) et la capacité de charge environnementale (K). En 2014, la production totale de petits a été estimée à 93 000 animaux (IC 95 %, 48 000 – 137 000), avec une population totale de 505 000 (IC 95 %, 329 000 – 682 000). On estime que la production de l'Île de Sable représente 77 % du nombre total de petits nés en 2014. La population totale de chaque colonie en 2014 était de 394 000 (IC 95 %, 238 000 – 546 000), 13 800 (IC 95 %, 9 300 – 27 300) et 98 000 (IC 95 %, 54 000 – 179 000), pour les colonies de l'île de Sable, de la zone côtière de Nouvelle-Écosse et du golfe du Saint-Laurent respectivement. Le modèle prédit que la population globale a continué d'augmenter. Pour évaluer l'impact des prélèvements potentiels futurs sur la population, la population de 2014 a été projetée vers l'avant sur une période de 30 ans selon différents scénarios de récolte. Pour maintenir une probabilité de 80 % de rester au-dessus du seuil de précaution de référence (N70) et en supposant que les jeunes de l'année constituent 95 % de la capture, on pourrait récolter 39 200 phoques (Île de Sable : 33 000 ; CNE : 1 200 ; Golfe : 5 000). Si les jeunes de l'année constituent 90 % de la capture, la récolte totale pourrait être de 36 600 individus (Île de Sable = 31 000 ; CNE: 1 100 ; Golfe : 4 500). Si les jeunes de l'année constituent 70 % de la capture, la récolte totale pourrait être de 28 200 (Île de Sable : 24 000 ; CNE : 700 ; Golfe : 3 500). Des niveaux de récoltes supérieurs sont associés à un risque accru de tomber en dessous du niveau de référence limite et ultérieurement, à un effondrement de la population. Sur la base de cette évaluation de la population, des niveaux de récolte de 50 000 phoques gris ou plus, même avec une récolte constituée de 95 % de petits, produisent une probabilité de modérée à forte d'aboutir à une baisse de la population en dessous du N70 et N50. Le risque augmente avec le niveau de récolte et le pourcentage de la récolte de phoques âgés d'un an et plus. D'autres travaux sont nécessaires pour estimer la mortalité à l'âge et selon le sexe des adultes et le taux de reproduction et pour incorporer le changement de ces taux dans les modèles spécifiques à la colonie, afin de déterminer la force et la nature des changements dépendant de la densité dans les taux de survie. Les changements de densité - dépendante des taux de survie ont une grande incidence sur les estimations de la capacité de charge et la durabilité des prélèvements futurs. Les estimations de la taille et les tendances des populations deviendront de plus en plus incertaines jusqu'à ce que de nouvelles informations sur la production de petits pour chacune des colonies soient disponibles. Une réévaluation du stock devrait être faite lorsque de nouvelles estimations de la production de petits seront disponibles ou pourrait être déclenchée par des preuves de changements considérables dans les taux de survie, incluant la mortalité massive de phoques adultes.

INTRODUCTION

Little is known of historical abundance or harvests of grey seals (*Halichoerus grypus*) in Atlantic Canada. Grey seals appear to have been abundant throughout Atlantic Canada during the 16th and 17th Centuries, but by the 18th Century, their numbers had declined markedly due to high levels of harvesting for oil. In the late 1800s, Gilpin (1874) speaks of herds of only 20 or 30 seals on Sable Island, and in the early 1950s, they were considered to be rare throughout eastern Canada (Lavigueur and Hammill 1993; Fisher 1955; Bowen 2011). Government sponsored culls and a bounty program may have slowed grey seal recovery in the 20th Century (Bowen and Lidgard 2012), but over the last five decades the Canadian grey seal population has increased from approximately 15,000 animals in the 1960s to over 350,000 in 2007 (Mohn and Bowen 1996; Thomas et al. 2007).

Within Canadian waters the grey seal population is subdivided into three groups for management considerations based on the locations of main breeding colonies: Sable Island (Sable), Gulf of St. Lawrence (Gulf), and Coastal Nova Scotia (CNS) components (Fig. 1). Nevertheless, these three herds represent a single population based on the lack of genetic differences (Boskovic et al. 1996; Wood et al. 2011). Sable Island, Nova Scotia, Canada, is located approximately 300 km east of Halifax (44.8 N, 60.8 W). It is home to the largest breeding colony of grey seals in the world (Bowen et al. 2007). The second largest breeding colony in Atlantic Canada occurs in the Gulf of St. Lawrence (Gulf), where grey seals have their young on the pack-ice in the southern Gulf or on small islands (Fig. 1). A relatively small number of animals breed on isolated islands along coastal Nova Scotia. These have traditionally been in the area known as the Eastern Shore (Mansfield and Beck 1977). In the last few years, small colonies have also appeared along the southwestern shore of Nova Scotia on Flat and Noddy Islands. Outside of the breeding season, there is overlap in the distribution of animals from the different colonies (e.g. Lavigueur and Hammill 1993; Harvey et al. 2008; Breed et al. 2006). Grey seal pupping also occurs in the northeastern United States, and has been increasing, with pup production of around 1,000 animals in 2002 (Anonymous 2014; Wood et al. 2007).

The herds in the three regions have had different population trajectories. Prior to 1997, pup production increased at a rate of 13% a year on Sable Island (Bowen et al. 2011). Between 2007 and 2010, the rate of increase slowed to about 4%, suggesting that the population may be facing resource limitation. Pup production in the Gulf has been much more variable than on Sable Island due to higher bounty, culling and scientific harvests (Hammill et al. 1998), and higher mortality rates associated with pupping on the pack-ice (Hammill and Stenson 2011; Thomas et al. 2007). Along the CNS shore, significant culling efforts, particularly in the Basque Island area limited pup production to the low 100's during the 1970s, and commercial hunting has occurred on Hay Island over the last decade.

McLaren et al. (2001) identified a need to manage seals under a framework that incorporated benchmarks and harvest control rules. In 2003, the Department implemented a management approach, referred to as the Atlantic Seal Management Strategy (ASMS), which incorporated the precautionary approach into the management of Atlantic seals. Grey seals are currently classified as being 'Data Rich'. For such species, the framework identifies a precautionary reference level at 70% (N70) of the largest population size. A secondary reference level is set at 50% (N50) while the critical reference limit has been identified at 30% (N30) of the largest estimated population (Hammill and Stenson 2007). The primary goal of management framework is to ensure that the population does not decline to levels where it falls below the critical reference level (N30) and as such is considered to have suffered serious harm. To minimize the risk of falling below the critical reference level the population is normally managed around the precautionary reference level.

Here we use three-parameter models, similar to that developed for harp seals (*Pagophilus groenlandicus*; Hammill et al. 2013b), fitted separately to a time series of pup production estimate for each grey seal herd. The model also includes information on age-specific reproductive rates, ice-related mortality of young of the year (YOY) seals (Gulf only) and human removals (Hammill et al. 2013a). The models are fitted separately to independent estimates of pup production for each herd by adjusting the starting population size, adult mortality and carrying capacity. New data on reproductive rates and removals have been used to provide estimate total population size in Atlantic Canada as well as harvest advice. Estimates of juvenile and adult survival from mark-recapture analysis of Sable Island data have been used to refine the model. In addition to advice on the risk associated with different harvest levels and age compositions, we also consider what changes in population status might trigger a review of the multi-year population assessment.

MATERIALS AND METHODS

Modelling the dynamics of the Northwest Atlantic grey seal population occurs in two steps. In the first, using Monte Carlo sampling, the model is fitted to independent estimates of the total pup production 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 was developed to consider density-dependent changes in mortality acting on first year survival as well as acting on reproduction. Over the last 3 decades, little change in reproductive rates has been observed. Therefore, for all herds it is assumed that the dynamics of the population can be described by density-dependent changes in mortality acting on first year survival only. It is also assumed that the sex ratio is 1:1, that removals of pups occurs at the beginning of the year and that removals of animals 1-year and older occurs mid-way through the year. A gamma parameter specifies the relationship between adult female survival and juvenile survival. In the Sable model gamma is set to 3 whereas for the Gulf and CNS models gamma is set to 6, under the assumption that pup mortality in the Gulf and CNS areas is much higher due to loss from breaking ice and storm surges.

A second component of the model, referred to as the ‘Projection Model’, projects the estimated current population into the future to examine the impacts of different management options on population size and trends. The projection model is based on the same equations as the fitting model.

MODEL STRUCTURE

Initial population size

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

Survival

For age 1:

$$n_{1,t} = ((n_{0,t-1} \times w) - c_{0,t-1}) \times e^{-M_1} \times (1 - (N_t / K)^{\theta})$$

with $M_1 = \gamma \times M$

For age a, with 1<a<A:

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

For age A

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

Reproduction

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

For age a, with 1<a<8

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

For age a, with a ≥ 8 (i.e. 8+)

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

also $Psim_{8+,t} = 0.9 \times (1 - N_t / K)^{\theta}$

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 (Hammill et al. 2013b). Note: this function is only used during the fitting part (see below the point 4 of the projection part specifications),

$n_{a.reprod,t}$ = 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 0.9 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_1 = the instantaneous rate of natural mortality,

γ = a multiplier to allow for higher mortality of first year seals. This was set to 3 for Sable Island (den Heyer et al. 2013), but to 6 for CNS and the Gulf. This was based on the ratio between juvenile mortality and adult mortality at a time when the Sable Island herd was much smaller than it is currently (Hammill et al. 2013a; den Heyer et al. 2013)

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 the objective function by estimating three parameters; the initial population factor (α), the instantaneous mortality rate (*M*), and the carrying capacity (*K*). For the Gulf herd the objective function includes both (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, and (2) the weighted sum-of-square differences between the 8+ pregnancy rate estimated ($P_{sim8+,t}$) and the resampled pregnancy rates. For Sable and the Gulf the model is fit to the pup production estimates only. The three parameters (α, *M* and *K)* are optimized by iterative methods (n=5000). For each Monte Carlo iteration, new *M, K* and α are estimated and stored. The model runs in the programming language R.

DATA INPUT

Initial population

The initial population vector (26×1) was created as an initial population age structure. In the early 1960s there was little information on grey seal abundance, but the majority of animals were believed to be in the Gulf, followed by CNS and then Sable Island with the smallest herd. For the starting vector pup production in 1960 was assumed to be 5000, 800, and 500 for the Gulf, CNS and Sable herds. Subsequent age classes were created assuming that adult mortality (M) was approximately 6% and first year mortality was 3 times adult mortality. This adult mortality rate arose from some early simulations (Hammill unpublished data) and was similar to the 5% rate estimated by Mohn and Bowen (1996).

Pup production

The model was fit to independent estimates of pup production (Table 1) obtained for each herd. Not all herds have been assessed in the same year(s) and not all estimates have used the same methods. Nevertheless, for each herd there is a consistent time series of estimates.

Pregnancy rates

Gulf of St. Lawrence

Late-term pregnancy data are available from sampling programs conducted in the Gulf of St. Lawrence (Hammill and Gosselin 1995). Samples were collected between late May and November. Fall samples represent late-term pregnancy rates since they were collected only a few months prior to pupping in December. It is assumed that there were no abortions after the samples were taken. These late-term rates are likely to over-estimate birth rates, but they are the best data that are available for this purpose at this time. The mean birthdate is assumed to be 1 January, and all animals age one year on this date. Females enter the model at the age that they turn on 1 January of each year. There are gaps in the time series of reproductive data, and in some years sample sizes are small (Table 2). When sample sizes were <25, reproductive rates were estimated by smoothing the data using a local likelihood estimator (Hammill et al. 2013b).

Sable Island

Since 1969, more than 7000 grey seals have been branded on Sable Island. An analysis of sightings of individually branded females on the Sable Island breeding colony during two time periods, 1987-1999 and 1998-2002, was used to estimate i) juvenile survival (weaning to age 4), ii) adult survival, iii) age at first birth, and iv) sighting probabilities (ages 4 to 14), which can be used as a proxy for average birth rate (den Heyer et al. 2013). Estimated apparent survival rates of adult females averaged 0.95 between 1987 and 1999, and 0.97 between 1998 and 2002. Estimated probabilities of average age of first birth (over ages 4 to 14 yr) for cohorts brandied in mid-80s and those branded between 1998 and 2002, increased from 5.6 to 6.5. However, the change in apparent juvenile survival was most notable with a decrease from 0.78 for the 1980s cohorts to 0.33 for the recently branded cohorts. As non-breeding female grey seals are not sighted, the capture probability in this mark-recapture analysis is the product of probability of breeding and the probability of being sighted in a given year, and thus provides a lower bound for average birth rates at 53 to 78 %.

Mansfield (1977) estimated pregnancy rates on Sable Island to be 0.85, which is close to the overall rate of 0.89 from the sampling program. Schwarz and Stobo (1997) developed an open robust mark-recapture analysis to estimate the proportion of females breeding on Sable Island. The open robust design uses the sightings within a breeding season to estimate the capture probability for those animals on the breeding colony, and thus estimate the proportion of animals that have returned to the breeding. Schwarz and Stobo (1997) analysed the sightings of females born and branded in 1973 between 1978 and 1994. They estimated capture probabilities for a breeding season between 0.110 and 0.868, with a marked improvement over time. Throughout this period the estimated return rate, or proportion of females on the breeding colony, was high, ranging from of 0.804 to 1.09. Since 1989, the sightings effort during the breeding season on Sable Island has become more standardized. A mark-recapture analysis of sightings during each breeding season between 1989 and 2013 has been used to estimate probability of capture for females during a season between from 0.81 to 0.96, with an average of 0.89 (unpublished data). Application of the full open robust analysis will allow us to estimate the proportion of females breeding. For this assessment, the reproductive rates from the Gulf were used.

Coastal Nova Scotia

There are no data on the pregnancy rates of grey seals at the Coastal Nova Scotia breeding colonies, so the reproductive rates from the Gulf were applied to these colonies.

Removals

Data on removals from the herds are available since 1960. There are four types of removals: the Canadian commercial harvest (Department of Fisheries and Oceans, Statistics Branch); those from nuisance seal licences, those from bounty kills and culls, and those from science sampling programs. The Canadian commercial hunt consists of 99% young of the year. All harvests were corrected for estimates of seals struck and killed, but not landed or reported. The commercial hunts and culls occur on land or on the ice. For these hunts all animals were assumed to have been recovered. For the scientific collections, animals are shot in the water. It was assumed that struck and loss rates would be similar to shooting adult harp seals where the struck and loss is 50% (Sjare and Stenson 2002). Our own data suggest that this rate is closer to 30% but we do not have information on struck and loss rates from contract hunters. We did not correct reports of nuisance seal harvests for struck and loss, since there is no requirement to recover the animal. There is uncertainty about the reporting of animals shot as nuisance seals, but no correction was made for this.

New data on the number of grey seals taken through nuisance seal licenses on the Scotian Shelf between 2008 and 2012 were included. At present, there is no estimate for 2013 nuisance seal removals, so the most recent 5-year mean was used.

Ice-related mortality of YOY in the Gulf

Grey seals in the Gulf give birth on the ice as well as on islands. In heavy ice years, the majority of animals are born on the ice, whereas in years of light ice more pups are born on the islands (Hammill and Stenson 2011). Pup mortality appears to be higher in the Gulf herd than on Sable and in poor ice years we have observed that pups are being lost during the surveys (e.g., 1997, 2010), although the numbers lost have been difficult to quantify. Hammill and Stenson (2011) used an index based on the late January Northumberland Strait ice cover, where the index = 1/(mean ice cover-ice cover in year t). In years when ice cover was greater than the mean, the index was set to 1 (Hammill and Stenson 2011). In 2011 and 2012, there was very little ice-cover in the traditional whelping areas, and survey flights indicated that seals were not using what ice was available. Poor ice conditions continued in 2013, therefore it was assumed seals responded in a similar manner to that observed in 2011 and 2012 and the index was set to 1 (Table 3).

Survival on Sable Island

The mark-recapture estimates of juvenile and adult survival for the Sable Island herd provide can also be used to parameterize the model. An alternate formulation of the model, did not assume a ratio of adult to juvenile mortality. Instead adult survival (*M*) was fixed at the long-term average (0.045) and the age 1 mortality (M_1) was estimated as part of the model fitting procedure.

For age 1:

$$n_{1,t} = ((n_{0,t-1} \times w) - c_{0,t-1}) \times e^{-M_1} \times (1 - (N_t / K)^{\theta})$$

For age a, with 1<a<A:

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

For age A

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

where M = 0.045.

Projection model

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

1. mortality from nuisance seal removals, culls, and science harvests remain constant. For the Sable Island herd, nuisance seal removals were assumed to follow a uniform distribution with limits of 3,000 to 6,000 animals. This was increased from last year's projections (limits 3,000 to 5,000) based on new data on removals. In the Gulf, a uniform distribution allowed removals to vary between 100 and 400 animals. Along the CNS, a uniform distribution allowed removals 10-100 seals,
2. ice-related mortality was set at 0 for all three herds,
3. age-specific rates for each of the last 5 years were included in a vector of reproductive rates and each had had an equal probability of being selected for a projection run, and
4. the dynamics of the population can be described assuming density-dependent mortality acting on first year survival by the relationship:

$$n_{1,t} = ((n_{0,t-1} \times w) - c_{0,t-1}) \times e^{-M_1} \times (1 - (N_t / K)^{\theta}) .$$

The model was projected forward to 2044 to determine if the catches will respect the management objective (i.e. 80% likelihood of population remaining above the Precautionary Reference Level, N70, and 95% likelihood of population above Limit Reference Level, N30). Grey seals are not fully recruited into the breeding population until age 8-10, and assessments are often spaced 5 years apart. This means that it is not possible to detect any impact of harvest activity for 15 or more years (Hammill and Stenson 2008). Therefore, for a 5 year management plan, the projection period has been increased to 30 years to assess the full impact of harvest strategies.

RESULTS

REPRODUCTIVE DATA

In the 2012 assessment, the Gulf reproductive rate data showed a sharp decline over the last few years. Observations from Sable Island did not indicate that any rapid decline in numbers of pups born on Sable Island had occurred. Therefore, for the 2012 assessment, reproductive rates from the Gulf dataset up to 2008 were projected forward assuming no change. Re-examination of the dataset revealed that several animals collected during December to April had been included. These data included animals collected at the whelping site, i.e., were accompanied by pups, but this was not noted, or animals that had been collected prior to implantation. These samples were excluded from this assessment, consequently the reported reproductive rates are higher than in the previous assessment. The smoother fitted to the reproductive data provided a means of interpolating for missing years and captured the variability in the data fairly well (Fig. 2). Overall, reproductive rates for age 8 years and older were high throughout most of the time-series. There appears to have been a decline in the reproductive rates for age classes 5-7 year olds since the early 2000s, but samples sizes are very small for these age classes (Table 2).

Model estimates

Sable Island

We ran two versions of the model for Sable Island. Fitting the accepted (gamma=3) model to the pup production data, using updated age-specific reproductive rate and nuisance removals data, generated parameter estimates of α = 0.15 (SE =0.04), M=0.068 (SE=0.006), K=815,000 (SE=260,000). The model predicts that the rate of increase in pup production has slowed (Fig. 3), with pup production in 2014 predicted to be 71,000 (95% CI=39,000 to 123,000) and total population to be 394,000 (95% CI 238,000 to 546,000) (Fig. 3).

Fitting the model with fixed adult female mortality (M=0.045 from den Heyer et al. 2013) to the pup production data, using updated age-specific reproductive rate and nuisance removals data, generated parameter estimates of α = 0.15 (SE =0.02), M_1=0.36 (SE=0. 05) and K=804,000 (SE=260,000). Again, the model predicts that the rate of increase in pup production has slowed (Fig. 4), with pup production in 2014 predicted to be 72,000 (95% CI=51,000-103,000) and total population to be 392,000 (95% CI 266,000 to 500,000).

Coastal Nova Scotia

Fitting the model to the CNS estimates of pup production using the updated age specific reproductive rates from the Gulf results in a 2014 pup production estimate of 3,400 (95% CI =1,900-6,000), and a total population of 13,500 (95% CI=9,000-26,500), with α = 0.10 (SE =0.02), M=0.04 (SE=.01) and K=16,700 (SE=9,000) (Fig. 5).

Gulf of St. Lawrence

Fitting the model to the Gulf pup estimates of pup production with the updated reproductive data generated parameter estimates of α = 0.08 (SE =0.03), M=0.075 (SE=0.012), K=545,000 (SE=326,000) resulted in a 2014 pup production estimate of 18,000 (95%CI=8,000-33,000) and a total population of 98,000 (95% CI=54,000-179,000), M=0.08 (SE=0.01), K=298,000 (SE=138,000) (Fig. 6).

Combining all three herds, grey seal pup production in 2014 is estimated to be 93,000 (95% CI=48,000-137,000) animals, with an associated total population of 505,000 (95% CI=329,000-682,000) (Fig. 7). Sable Island pup production is estimated to account for 77% of the estimated total number of pups born in 2014.

SUSTAINABLE HARVEST LEVELS

To estimate the impact of a harvest on the dynamics of a long-lived animal such as the grey seal, population projections need to be long enough to allow the full effects of the harvest to move through the age-structure of the population. In the case of grey seals, we have used a period of 30 years. For the Sable Island herd, assuming that future reproductive rates continue to vary around a recent mean value, a TAC with an annual harvest of up to 29,000 animals assuming YOY comprise 95% of the catch, would respect the management objective of having an 80% probability of remaining above N70. The probability of remaining above N30 would be 95% (Table 4, Fig. 8). If YOY comprised only 90% of the catch, then a harvest of 26,000 would continue to respect the N70 management objectives, while a harvest of 21,000, comprised of 70% YOY, would have slightly more than an 80% chance of remaining above N70 and a 95% probability of remaining above N30.

For the CNS herd, assuming that future reproductive rates continue to vary around the recent mean value and a catch consisting of 95% YOY, a TAC with an annual harvest of up to 1,200 animals would respect both the management objective of having an 80% probability of remaining above N70. The probability of remaining above N30 would be 95%. If YOY comprised 90% of the catch, then a harvest of 1,100 would continue to respect the N70 management objectives, while a harvest of 700 animals comprised of 70% YOY would respect the management objectives (Table 5, Fig. 9).

For the Gulf herd, assuming that future reproductive rates continue to vary around a recent mean value, a TAC with an annual harvest of up to 5,000 animals assuming YOY comprise 95% of the catch, would respect the management objective of having an 80 % probability of remaining above N70 and a greater than 95% probability of remaining above N30 (Table 6, Fig. 10). If YOY comprised only 90% of the catch, then a harvest of 4,500 would continue to respect the N70 and N30 management objectives, while a harvest of 3,500 animals comprised of 70% YOY would have a 95% probability of remaining above N30 and more than an 80% chance of remaining above N70.

Fisheries management requested Science to evaluate the risk of falling below N70 and N50 for harvests of 50,000, 60,000, 70,000, 90,000 and 100,000 seals per year, assuming age compositions of 95%, 90% and 70% young of the year. Although Canadian grey seals form a single population, the dynamics of the three herds differ. Consequently, each herd is assessed separately and it was assumed that all animals were in their resident areas. To evaluate the risk of an overall harvest of 50,000 to 100,000 animals causing the population to decline below N70 and N50, harvest effort was allocated to each herd assuming that they are proportional to pup production in each herd (0.04 CNS, 0.19 Gulf, 0.77 Sable) (Table 8). For all harvest levels and age compositions examined, the risk of the population falling below N70 and N50 was greater than 0.2, the limit identified in Atlantic Seal Management Strategy. The risk increases as the level of harvest increases and the proportion of pups in the harvest decreases (Table 8).

DISCUSSION

Since the 2012 grey seal assessment, there are only two sources of new input data to the model. The first is an update of removals from the population. These removals are primarily associated with grey seals killed under permit through the issuance of nuisance seal licenses.

These removals are poorly reported and therefore there is a large degree of uncertainty about the level of removals. The second source are new data on age-specific, late-term pregnancy rates of females sampled in the Gulf of St. Lawrence in 2012 and a reanalysis of samples taken from 2009-2011. Both the new data and the re-analysis of collections back to 2009 indicate that reproductive rates have remained high contrary to the conclusion in the 2012 assessment.

Using the new reproductive rates, the model predicts a continued increase in the size of the Sable Island and Gulf herds. An increase in Sable Island population size is predicted under both versions of the model, i.e., with a fixed ratio of adult to YOY mortality rates or where adult mortality is fixed to the rates estimated from mark-recapture data on Sable (den Heyer et al. 2013). The model also predicts a modest increase in the CNS herd. As indicated by the rapidly increasing confidence limits, there is growing uncertainty about the trajectory of all three herds, which is to be expected since the last pup survey was in 2010.

Although the predicted increase is consistent with last year's assessment, this year's model predicts a larger population size. The new time series of reproductive rate data provide no evidence of density dependence changes in reproductive rates. This results in a higher estimate of carrying capacity (K) being produced by the model, and correspondingly a higher estimate of total population size. We have little empirical data with which to estimate carrying capacity for Sable Island, or the other two grey seal herds. Nevertheless, there has been a large reduction in estimated juvenile survival of seals born at Sable Island between cohorts born between 1985-89 and 1998-2002, which indicates that the population is likely experiencing some resource limitation as the population grows (den Heyer et al. 2013). In 2012, we assumed that a range of priors that lay between 10,000 and 500,000, with the model fitting to K=332,000 (SE=58,000). However, in this model, which incorporates larger variability in reproductive rates, the parameter estimate for K in Sable is at the boundary in the range of values examined, indicating that the carrying capacity is poorly estimated. Increasing the range of the prior also increases the level of K, thereby reducing the effect of density dependence and increasing population size. This underscores how little we know about K for the Sable Island herd.

We also examined an alternative scenario for Sable Island, where adult mortality was set (M=0.045 from den Heyer et al. 2013). This model also resulted in pup production and total population estimates that continue to increase. However, model estimates for M_1 (0.36) were high compared to $M_{juvenile}$ (ages 1-4 = 0.26) estimates during the period of high population growth from the mark-recapture analysis (den Heyer et al. 2013). Several factors might partially account for this discrepancy. Pregnancy rates estimated from shot samples in the Gulf may overestimate true birth rates. Further our model may not adequately capture the strength of density-dependence on juvenile survival (i.e., theta may be too small). Unfortunately, until we have further estimates of pup production, or juvenile survival, we have no data to refine the theta chosen.

Population size and trends for the coastal Nova Scotia herd are particularly uncertain as vital rates for this component are unavailable and therefore rates from the other herds are assumed to apply here. Also, the population may not be closed to movement of females. Grey seals along CNS have received less attention than in the Gulf and on Sable. This is because the main CNS colony, Hay Island (discovered in 1994), is relatively new and all coastal colonies combined still contribute little to the overall Canadian grey seal population. Historically, small colonies have persisted in spite of repeated harvesting activity, particularly around Basque Island off the east coast of Cape Breton Island. Erosion has altered the island so that currently little remains of it to serve as a pupping site, but small numbers are still observed (approximately 12 pups in 2012; M. O. Hammill, personal observation), and based on bounty and science collections during the 1960s-1970s the Gaborus/Fourchu area appears to have been an area where grey seals were locally abundant.

The model does not fit well to the CNS trend in pup production even when the early, less reliable (those from 1984 to 1989), estimates of production are not used to fit the model. The 'best' fit generates an adult mortality estimate that is low compared to empirical estimates from Sable Island. This estimate lies against the lower boundary of the prior indicating that the model fits the data poorly. At present the CNS component is the smallest of the three, and it's location and small size mean that it is likely influenced by immigration from the larger herds, and particularly from the Sable Island herd. To the extent that this is the case, a fundamental assumption that the CNS is a closed population is violated. Although we have no data to test this assumption, the poor fit to the pup production data, and the estimate of adult *M* at the lower bound, suggest that immigration of females may be a serious source of bias.

Variable ice conditions, particularly since the early 1990s have complicated attempts to assess grey seals in the Gulf. Correcting estimates for variable pup mortality at birth provide a better fit overall to the survey data. However, in recent years another shift appears to be underway. In some years, when some ice forms, limiting access to the islands, animals pup on the ice and mortality can be high if this ice breaks up before animals are weaned. In recent years, suitable ice has not formed in the Gulf, which has allowed access to islands that were not available for pupping when there was ice, e.g., Brion Island, Pictou Island, and Anticosti Island (Hammill and Stenson 2011). These conditions are likely more favourable to survival of grey seal pups, although human disturbance and storm surges may offset the advantages of pupping on these islands. Therefore, in heavy ice years, a factor to correct for ice-related mortality does not appear to be needed. In years, where there is sufficient ice for pupping, but this ice is of poor quality and access to islands is limited, a factor does appear to be needed to take into account ice-related mortality. However, in years when there is very little ice, and animals can access the larger islands in the southern Gulf, no correction for ice-related mortality is required as females will shift to a terrestrial site for pupping. Continued high levels of removal in the Gulf have also had an impact on the dynamics of this herd.

Another area of uncertainly that will result in an overestimation of population size, is the assumed 1:1 adult sex ratio. There are several reasons to expect that there are fewer males in the population than females. First, juvenile males have higher mortality rates than females (Hall et al. 2001) and second, longevity of males is less than females based on resighting histories of known individuals at Sable Island. Although the degree to which females outnumber males in the population is unknown, the current model likely over-estimates population size and therefore the harvest that can be sustained. This will be true for each of the three herds, although the ratio of males to females in the population could differ among the three herds.

Population projections are based on assumptions about the birth and survival rates experienced by the population in the future. We have assumed that rates will either be similar to the recent past or that changes are governed by density-dependence in first year mortality. Our understanding of these density-dependent relationships is still at an early stage as we have little data with which to estimate either the form or strength of density effects on pregnancy rates or survival. Thus population projections of more than a few years and the associated effects of harvest should be interpreted with caution.

We have presented these harvest levels as annual harvests for a five-year management plan. Harvest levels are presented within the context of respecting N70, but also within the context of having a very high probability (<95%) of not falling below the critical reference level of N30. This is particularly important given that population models only represent a perception of the population, which can change markedly as model formulation and new data are included. Failure to consider this uncertainty has resulted in population collapses in several fisheries. The harvest levels estimated from this year's assessment are smaller than those presented in the last assessment despite an increase in the estimated population size. This is due to several factors: 1) our level of uncertainty about the population has increased because it has now been four years since the last survey was completed in 2010; 2) because of a delay of approximately 4-8 years between birth and recruitment to the adult population, and the 5 year span between surveys there is considerable uncertainty surrounding the population trajectory; 3) demographic inertia will ensure that harvest effects will persist for a long time in the population. We have attempted to fully account for these effects by projecting harvests over a longer period of time.

Based on this assessment of the population, harvest levels at 50,000 grey seals or more, even with a harvest comprising 95% pups, have a moderate to high probability of resulting in a population decline below N70 and N50. The risk increases with the level of harvest and with the proportion of the harvest that consists of seal age 1 and older. New estimates of pup production for each herd are needed to increase confidence in the risk associated with particular harvest levels.

Management actions focus around the Precautionary level, to minimize the chances that the resource may decline to a level where serious harm may occur, a level referred to as the critical reference limit. A resource falling below the Precautionary Reference level, but remaining above the critical reference limit falls into what is referred to as the cautious zone, where harvesting should be reduced to encourage the resource to return to the healthy zone. A stock falling below the critical reference level is considered to have suffered serious harm and falls into what is referred to as the critical zone. In many jurisdictions, the likelihood of the resource declining to the critical reference limit should be less than 3-5%.

This can be a challenge for managing seals because estimates of total seal population size for harp, grey and hooded seals 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 4-8 years, there is considerable uncertainty associated with population abundance that may be exaggerated if model formulation is incorrect, or if input parameters 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).

A new pup survey is needed to increase our understanding of Canadian grey seal population size. Without such an assessment, projecting future trends of this population is highly uncertain. A new survey could result in significant changes to our advice. Other factors that would trigger changes to the science advice include significant changes in age specific reproductive rates and in juvenile mortality rates. A mass mortality event could also trigger changes to our advice.

LITERATURE CITED

Boskovic, R., Kovacs, K.M. and Hammill, M.O. 1996. Geographic distribution of mitochondrial DNA haplotypes in grey seals *Halichoerus grypus*. Can. J. Zool. 74:1787-1796.

Bowen, W.D. 2011. Historical Grey Seal Abundance and Changes in the Abundance of Grey Seal Predators in the Northwest Atlantic. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/026.

Bowen, W. D. and Lidgard, D. C. 2012. Vertebrate predator control: effects on prey populations in terrestrial and aquatic ecosystems. Mammal Review. DOI:10.1111/j.1365-2907.2012.00217.x

Bowen, W.D., McMillan, J.I. and Blanchard, W. 2007. Reduced population growth of gray seals at Sable Island: evidence from pup production and age of primiparity. Marine Mammal Science 23: 48-64.

Bowen, W.D., den Heyer, C., McMillan, J.I., and Hammill, M.O. 2011. Pup Production at Scotian Shelf Grey Seal (Halichoerus grypus) Colonies in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/066.

Breed, G.A., W. D. Bowen, J. I. McMillan and M. L. Leonard. 2006. Sexual segregation of seasonal foraging habitats in a non-migratory marine mammal. Proc. R. Soc. B (2006) 273, 2319–2326, doi:10.1098/rspb.2006.3581

den Heyer, W. Bowen, D. and McMillan, J. I. 2013. Long-term changes in grey seal vital rates at Sable Island estimated from POPAN mark-resighting analysis of branded seals. DFO Can. Sci. Advis. Sec. Res. Doc. 2013/021.

Fisher, H. D. 1955. The grey seal (*Halichoerus grypus* (Fabricius)) in the western Atlantic. Unpubl. Ms 17p.

Gilpin, J. B. 1874. On the seals of Nova Scotia. Proceedings and transactions of the Nova Scotian Institute of Natural Science 3(4): 377-384.

Hall, A. J., B. McConnell and Barker, R. J. 2001. Factors affecting first-year survival in grey seals and their implications for life history strategy. Journal of Animal Ecology 70: 138-149.

Hammill, M.O. and Gosselin, J.F. 1995. Grey seal (*Halichoerus grypus*) from the Northwest Atlantic: Female reproductive rates, age of maturity and age at first birth in Northwest Atlantic grey seals *(Halichoerus grypus*). Can. J. Fish. Aquat. Sci. 52:2757-2761.

Hammill, M.O. and G.B. Stenson. 2007. Application of the Precautionary Approach and Conservation Reference Points to the management of Atlantic seals. ICES Journal of Marine Science, 64: 702–706.

Hammill, M.O. and Stenson, G.B. 2008. Abundance of Northwest Atlantic harp seals (1960 – 2008). DFO Can. Sci. Advis. Sec. Res. Doc. 2008/077.

Hammill, M.O. and Stenson, G.B. 2009. A preliminary evaluation of the performance of the Canadian management approach for harp seals using simulation studies. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/093.

Hammill, M.O. and Stenson, G.B. 2011. Pup production of grey seals, in the Gulf of St. Lawrence in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/122.

Hammill, M.O. and G.B. Stenson. 2013. A Discussion of the Precautionary Approach and its Application to Atlantic Seals. DFO Can. Sci. Advis. Sec.Res. Doc. 2013/030. v + 25 p.

Hammill, M.O., Stenson, G.B. Myers, R.A. and Stobo, W.T. 1998. Pup production and population trends of the grey seal (*Halichoerus grypus*) in the Gulf of St Lawrence. Can. J. Fish. Aquat. Sci. 55:423-430.

Hammill, M.O, Bowen, W.D. den Heyer, C. 2013a. Northwest Atlantic Grey Seal Population Trends, 1960-2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/169. vi + 35 p.

Hammill, M.O., Stenson, G.B., Doniol-Valcroze, T., and Mosnier, A. 2013b. Estimating carrying capacity and population trends of Northwest Atlantic harp seals, 1952-2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/148. iii + 31 p.

Harvey, V., S. D. Côté and M.O. Hammill.2008. The Ecology Of 3-D Space Use In A Sexually Dimorphic Mammal. Ecography 31: 371-380.

Lavigueur, L., and Hammill, M.O. 1993. Distribution and seasonal movements of grey seals, *Halichoerus grypus*, in the Gulf of St. Lawrence. Can. Field Naturalist 107:329-340.

Mansfield, A. W. 1977. Growth and longevity of the grey seal (*Halichoerus grypus*) in eastern Canada. ICES C.M. 1977/N:6.

Mansfield, A.W. and Beck, B. 1977. The grey seal in eastern Canada. Dept. Environ., Fish. And Mar. Serv. Tech. Rep. No. 704. 81 pp.

McLaren, I.A., S. Brault, J. Harwodd and D. Vardy. 2001. The eminent panel on seal management. 165 p.

Mohn, R. and Bowen, W.D. 1996. Grey seal predation on the eastern Scotian Shelf: modelling the impact on Atlantic cod. Can. J. Fish. Aquat. Sci. 53:2722-2738.

National Oceanic and Atmospheric Administration (NOAA Fisheries). Marine Mammal Stock Assessment Reports (SARs) by Species/Stock. [Online]. Updated May 13, 2014.

Schwarz, C.J., and W.T. Stobo, 1997. Estimating temporary migration using robust design. Biometrics 53:178-194.

Sjare, B. and Stenson, G. B. 2002. Estimating struck and loss rates for harp seals (*Pagophilus groenlandicus*) in the Northwest Atlantic. Mar. Mamm. Sci. 18:710-720.

Thomas, L, Hammill, M.O. and Bowen, W.D. 2007. Estimated size of the Northwest Atlantic grey seal population 1977-2007. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/082.

Trzcinski, M.K., R. Mohn, and W.D. Bowen. 2006. Continued Decline Of An Atlantic Cod Population: How Important Is Gray Seal Predation? Ecological Applications, 16(6), 2006, Pp. 2276–2292.

Wood, S.A., Brault, S. and Gilbert, J.R. 2007. 2007. Aerial Surveys of Grey Seals in the Northeastern United States. NAMMCO Sci. Publ. 6:117-121.

Wood, S.A., T.R. Frasier, B.A. McLeod, J.R. Gilbert, B.N. White, W.D. Bowen, M.O. Hammill, G.T. Waring, and S. Brault. 2011. The genetics of recolonization: an analysis of the stock structure of grey seals (*Halichoerus grypus*) in the northwest Atlantic. Can. J. Zool. 89. 490-497.

Table 1. Pup production estimates used as input into the population model.

Year	Sable Island		Coastal Nova Scotia		Gulf	
	Estimate	SE	Estimate	SE	Estimate	SE
1960						
1961						
1962			130	400		
1963	400	400	180	400		
1964	550	550	190	400		
1965	660	660	230	400		
1966			180	400	900	500
1967	580	580	270	400		
1968	700	700				
1969	800	800				
1970	800	800	100	400		
1971	1000	1000	130	400		
1972	950	950				
1973	1200	1200				
1974	1250	1250	135	400		
1975			180	400	3800	3800
1976	2000	2000	130	400		
1977	2181	173			3900	3900
1978	2687	192				
1979	2933	201				
1980	3344	214				
1981	3143	208				
1982	4489	248				

Year	Sable Island		Coastal Nova Scotia		Gulf	
	Estimate	SE	Estimate	SE	Estimate	SE
1983	5435	273				
1984	5856	283	142	400	7169	911
1985	5606	277	135	400	6706	795
1986	6301	294	151	400	5588	679
1987	7391	318	179	400		
1988	8593	343				
1989	9712	365	179	400	9352	1756
1990	10451	575			9176	649
1991						
1992						
1993	15500	463				
1994			900			
1995						
1996			395	148	10717	1306
1997	25400	750	1061	242	6839	800
1998						
1999						
2000			799	210	5260	910
2001						
2002						
2003						
2004	41500	4381	2469	152	14210	1200
2005						

Year	Sable Island		Coastal Nova Scotia		Gulf	
	Estimate	SE	Estimate	SE	Estimate	SE
2006						
2007	54482	1288	3017	80	11413	1077
2008						
2009						
2010	62054	587	2960	272	11228	6442

Table 2. Year, age (years), number of females collected between 1969 and 2012 (N) and number of females pregnant (Preg). Note age 8 refers to females 8 years of age and older.

Year	Age	N	Preg rate	Age	N	Preg rate	Age	N	Preg rate	Age	N	Preg rate	Age	N	Preg rate
1969	4	12	0.25	5	7	0.71	6	9	1	7	6	1	8	36	0.81
1982	4	4	0.00	5	4	0.75	6	8	0.88	7	1	1	8	48	0.90
1986	4	4	0.25	5	2	1.00	6	4	0.75	7	7	0.86	8	34	0.94
1987	4	7	0.14	5	10	0.50	6	8	0.63	7	9	0.67	8	71	0.94
1988	4	7	0.29	5	14	0.71	6	10	0.90	7	5	0.80	8	57	0.89
1992	4	16	0.06	5	16	0.75	6	15	0.87	7	7	0.86	8	36	0.89
1994	4	1	0.00	5	3	0.00	6	1	1.00	7	2	1.00	8	0	
1998	4			5			6	1	0.00	7	1	1.00	8	10	0.80
1999	4			5	2	0.00	6	2	1.00	7	2	1.00	8	12	1.00
2000	4	5	0.40	5	3	0.67	6	6	0.83	7	2	1.00	8	18	0.89
2001	4	1	0.00	5	0		6	1	1.00	7			8	6	0.83
2002	4	7	0.29	5	3	0.33	6	3	1.00	7	7	0.86	8	22	0.86
2003	4	2	0.00	5	4	0.50	6	3	1.00	7	0		8	9	0.67
2004	4	5	0.00	5	6	0.83	6	3	0.33	7	4	0.75	8	28	0.93
2005	4	1	0.00	5	3	1.00	6	1	0.00	7			8	1	1.00
2006	4	1	0.00	5	0		6			7			8		
2007	4	1	0.00	5	3	0.67	6	3	1.00	7	0		8	10	0.90
2008	4			5			6	5	1.00	7	2	1	8	9	0.78
2009	4			5			6			7	0		8		
2010	4	4	0	5	1	1	6	2	1.00	7	1	1	8	11	1.00
2011	4	1	1	5	2	0	6			7	1	1	8	16	0.75
2012	4	0		5	3	0	6	2	0.50	7	4	0	8	13	0.92

Table 3. Survival coefficient used to account for pups drowning before surveys were completed in the Gulf.

Year	Survival	Year	Survival	Year	Survival
1960	1.0	1980	0.8	2000	0.7
1961	1.0	1981	1.0	2001	0.7
1962	1.0	1982	1.0	2002	0.4
1963	1.0	1983	0.5	2003	1.0
1964	1.0	1984	1.0	2004	1.0
1965	1.0	1985	1.0	2005	0.7
1966	1.0	1986	1.0	2006	0.1
1967	1.0	1987	1.0	2007	0.5
1968	1.0	1988	1.0	2008	0.6
1969	0.8	1989	1.0	2009	1.0
1970	1.0	1990	1.0	2010	0.6
1971	1.0	1991	0.9	2011	1.0
1972	0.9	1992	1.0	2012	1.0
1973	1.0	1993	0.8		
1974	1.0	1994	1.0		
1975	0.4	1995	0.2		
1976	0.8	1996	1.0		
1977	1.0	1997	0.7		
1978	0.6	1998	0.7		
1979	1.0	1999	0.2		

Table 4. Removals of grey seals.

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
Sable						
1960	0	0	0	0	0	0
1961	0	0	0	0	0	0
1962	0	0	0	0	0	0
1963	0	0	0	0	0	0
1964	0	0	0	0	0	0
1965	0	0	0	0	0	0
1966	0	0	0	0	0	0
1967	0	0	0	0	0	0
1968	0	0	0	0	0	0
1969	0	0	0	0	0	0
1970	43	2	0	0	0	0
1971	1	12	0	0	0	0
1972	0	0	0	0	0	0
1973	0	0	0	0	0	0
1974	0	2	0	0	0	0
1975	22	0	0	0	0	0
1976	0	9	0	0	0	0
1977	0	69	0	0	0	0
1978	0	0	0	0	0	0
1979	0	0	0	0	0	0
1980	0	0	0	0	0	0
1981	0	69	0	0	0	0

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
1982	0	0	0	0	0	0
1983	0	214	0	0	0	0
1984	0	20	0	0	0	0
1985	0	0	0	0	0	0
1986	0	0	0	0	0	0
1987	0	0	0	0	0	0
1988	0	46	0	0	0	0
1989	0	477	0	0	0	0
1990	0	197	0	0	0	0
1991	0	0	0	0	0	0
1992	0	6	0	0	0	0
1993	0	0	0	0	0	0
1994	0	0	0	0	0	0
1995	0	0	0	0	0	0
1996	0	24	0	0	0	0
1997	0	7	0	0	0	0
1998	0	0	0	0	0	0
1999	1638	0	0	0	0	0
2000	1743	0	0	0	0	0
2001	1820	0	0	0	0	0
2002	1953	0	0	0	0	0
2003	2079	0	0	0	0	0
2004	2660	0	0	0	0	0
2005	2751	0	0	0	0	0

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
2006	3437	0	0	0	0	0
2007	3373	0	0	0	0	0
2008	3018	0	0	0	0	0
2009	5218	0	0	0	0	0
2010	1853	0	0	0	0	0
2011	1722	0	0	0	0	0
2012	5428	0	0	0	0	0
2013	3500	0	0	0	0	0
Coastal Nova Scotia						
1960	0	0	0	0	0	0
1961	0	0	0	0	0	0
1962	0	0	0	0	0	0
1963	0	293	0	0	0	0
1964	0	6	0	0	0	0
1965	0	1	0	0	0	0
1966	0	0	0	0	0	0
1967	0	0	0	0	17	212
1968	0	104	0	0	18	134
1969	0	1	0	0	31	104
1970	0	0	0	0	125	450
1971	0	0	0	0	97	382
1972	0	0	0	0	32	408
1973	0	0	0	0	36	431
1974	0	0	0	0	51	482

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
1975	0	0	0	0	87	512
1976	0	0	0	0	80	466
1977	0	0	0	0	34	373
1978	0	0	0	0	90	290
1979	0	0	0	0	45	269
1980	0	0	0	0	211	115
1981	0	46	0	0	35	197
1982	0	69	0	0	42	276
1983	0	197	0	0	45	152
1984	0	0	0	0	34	80
1985	0	0	0	0	0	0
1986	0	0	0	0	0	0
1987	0	0	0	0	0	0
1988	0	0	0	0	0	0
1989	0	24	0	0	0	0
1990	0	9	0	0	0	0
1991	0	0	0	0	0	0
1992	0	0	0	0	0	0
1993	0	0	0	0	0	0
1994	0	0	0	0	0	0
1995	0	0	0	0	0	0
1996	0	0	6	0	0	0
1997	0	0	0	0	0	0
1998	0	0	0	0	0	0

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
1999	0	0	0	0	0	0
2000	0	0	82	0	0	0
2001	0	0	1301	0	0	0
2002	0	0	0	0	0	0
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	0	0	494	0	0	0
2006	0	0	830	0	0	0
2007	0	0	868	0	0	0
2008	0	0	1261	0	0	0
2009	0	0	263	0	0	0
2010	0	0	50	0	0	0
2011	0	0	0	0	0	0
2012	0	0	0	0	0	0
Gulf						
1960	0	0	0	0	0	0
1961	0	0	0	0	0	0
1962	0	0	0	0	0	0
1963	0	0	0	0	0	0
1964	0	0	0	0	0	0
1965	0	0	0	0	0	0
1966	0	0	0	0	0	0
1967	0	0	0	0	0	0
1968	0	0	0	0	0	0

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
1969	0	0	0	0	159	485
1970	0	22	0	0	0	70
1971	0	0	0	0	45	361
1972	0	0	0	0	80	191
1973	0	0	0	0	39	127
1974	0	1	0	0	75	560
1975	0	1	0	0	447	1238
1976	0	1	0	0	16	79
1977	0	0	0	0	308	673
1978	0	0	0	0	57	267
1979	0	9	0	0	190	215
1980	0	0	0	0	336	994
1981	0	0	0	0	552	1242
1982	0	199	0	0	880	961
1983	0	12	0	0	814	1721
1984	0	12	0	0	135	96
1985	0	0	0	0	141	113
1986	0	230	0	0	402	180
1987	0	249	0	0	456	593
1988	0	298	0	0	379	90
1989	0	45	0	0	138	1700
1990	0	16	50	0	48	38
1991	0	0	50	0	0	0
1992	0	260	50	0	0	0

YEAR	Nuisance	Science	YOY	1 plus	Cull 1+	Cull YOY
1993	0	6	50	0	0	0
1994	0	39	50	0	0	0
1995	0	5	50	0	0	0
1996	0	33	50	0	0	0
1997	0	25	50	0	0	0
1998	0	20	50	0	0	0
1999	0	69	50	0	0	0
2000	0	89	50	0	0	0
2001	0	39	50	0	0	0
2002	0	100	50	0	0	0
2003	0	13	50	0	0	0
2004	0	93	50	0	0	0
2005	0	12	579	0	0	0
2006	0	28	1027	0	0	0
2007	0	87	879	0	0	0
2008	0	0	210	0	0	0
2009	0	0	0	0	0	0
2010	0	0	58	25	0	0
2011	0	200	200	18	0	0
2012	0	200	200	18	0	0
2013	25	0	200	18	0	0

Table 4. Decision table for the probability of respecting N70, N50 and N30 under harvest levels with different proportions of young of the year (YOY) in the harvest for the Sable Island grey seals.

Sable	**95%YOY**			**90%YOY**			**70%YOY**		
Harvest	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**
10000	0.97	1.00	1.00	0.97	1.00	1.00	0.95	1.00	1.00
11000	0.97	1.00	1.00	0.96	1.00	1.00	0.94	1.00	1.00
12000	0.96	1.00	1.00	0.96	1.00	1.00	0.94	1.00	1.00
13000	0.96	1.00	1.00	0.96	1.00	1.00	0.93	1.00	1.00
14000	0.96	1.00	1.00	0.95	1.00	1.00	0.92	1.00	1.00
15000	0.95	1.00	1.00	0.94	1.00	1.00	0.91	0.99	1.00
16000	0.95	1.00	1.00	0.94	1.00	1.00	0.90	0.98	1.00
17000	0.94	1.00	1.00	0.93	1.00	1.00	0.89	0.97	1.00
18000	0.94	1.00	1.00	0.93	1.00	1.00	0.87	0.96	0.99
19000	0.93	1.00	1.00	0.92	0.99	1.00	0.86	0.94	0.98
20000	0.93	1.00	1.00	0.91	0.99	1.00	0.85	0.92	0.96
21000	0.92	0.99	1.00	0.90	0.98	1.00	0.83	0.90	**0.95**
22000	0.91	0.99	1.00	0.89	0.97	1.00	0.82	0.88	0.92
23000	0.90	0.98	1.00	0.88	0.96	0.99	0.80	0.86	0.90
24000	0.89	0.97	1.00	0.87	0.95	0.98	**0.80**	0.84	0.88
25000	0.88	0.96	0.99	0.86	0.93	0.97	0.78	0.82	0.86
26000	0.88	0.95	0.98	0.85	0.92	**0.96**	0.77	**0.81**	0.84
27000	0.86	0.94	0.97	0.84	0.90	0.94	0.76	0.79	0.82
28000	0.85	0.92	0.96	0.83	0.89	0.93	0.75	0.78	0.80
29000	0.84	0.91	**0.95**	0.82	0.87	0.91	0.74	0.76	0.78
30000	0.83	0.89	0.93	0.81	0.85	0.89	0.73	0.75	0.77

Sable	95%YOY			90%YOY			70%YOY		
Harvest	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**
31000	0.82	0.87	0.92	**0.80**	0.84	0.87	0.72	0.74	0.76
32000	0.81	0.86	0.90	0.79	0.82	0.86	0.71	0.73	0.75
33000	**0.80**	0.84	0.88	0.78	0.81	0.84	0.70	0.72	0.73
34000	0.79	0.83	0.86	0.77	**0.80**	0.82	0.69	0.71	0.72
35000	0.78	0.82	0.85	0.76	0.79	0.81	0.68	0.70	0.71
36000	0.77	**0.81**	0.83	0.75	0.77	0.80	0.68	0.69	0.70
37000	0.77	0.79	0.82	0.74	0.76	0.78	0.67	0.68	0.69
38000	0.76	0.78	0.81	0.73	0.75	0.77	0.65	0.67	0.68
39000	0.75	0.77	0.80	0.72	0.74	0.76	0.63	0.65	0.66
40000	0.74	0.76	0.78	0.72	0.73	0.75	0.62	0.64	0.65

Table 5. Probability of respecting N70, N50 and N30 under harvest levels with different proportions of young of the year (YOY) in the harvest for the Coastal Nova Scotia grey seals.

CNS	**95%YOY**			**90%YOY**			**70%YOY**		
Harvest	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**
100	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
200	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
300	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
400	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99
500	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99
600	0.99	0.99	0.99	0.98	0.99	0.99	0.95	0.99	0.99
700	0.98	0.99	0.99	0.98	0.99	0.99	**0.89**	0.99	0.99
800	0.98	0.99	0.99	0.96	0.99	0.99	0.79	0.97	0.98
900	0.96	0.99	0.99	0.94	0.99	0.99	0.64	**0.88**	**0.95**
1000	0.94	0.99	0.99	0.89	0.98	0.99	0.49	0.69	0.81
1100	0.90	0.98	0.99	**0.80**	0.96	0.98	0.38	0.50	0.60
1200	**0.83**	0.96	0.98	0.69	**0.90**	**0.96**	0.30	0.37	0.43
1300	0.73	0.92	**0.96**	0.57	0.76	0.87	0.25	0.29	0.32
1400	0.62	**0.82**	0.92	0.47	0.62	0.73	0.21	0.24	0.26
1500	0.52	0.68	0.82	0.38	0.48	0.59	0.19	0.20	0.22
1600	0.43	0.56	0.69	0.32	0.39	0.46	0.17	0.18	0.19
1700	0.36	0.46	0.57	0.27	0.32	0.37	0.16	0.17	0.18
1800	0.31	0.37	0.46	0.24	0.27	0.31	0.15	0.16	0.16
1900	0.27	0.31	0.38	0.21	0.24	0.26	0.14	0.15	0.15
2000	0.24	0.27	0.32	0.20	0.21	0.23	0.14	0.14	0.14

Table 6. Decision table for the probability of respecting N70, N50 and N30 under harvest levels with different proportions of young of the year (YOY) in the harvest for the Gulf of St. Lawrence grey seals.

Gulf Harvest	95%YOY			90%YOY			70%YOY		
	N70	**N50**	**N30**	**N70**	**N50**	**N30**	**N70**	**N50**	**N30**
500	0.98	1	1	0.98	1	1	0.98	1	1
1000	0.98	1	1	0.975	1	1	0.97	1	1
1500	0.97	1	1	0.96	1	1	0.95	1	1
2000	0.96	1	1	0.95	1	1	0.92	0.99	1
2500	0.94	0.99	1	0.94	0.99	1	0.89	0.97	0.99
3000	0.93	0.98	1	0.91	0.98	1	0.85	0.94	0.98
3500	0.9	0.975	0.99	0.88	0.96	0.99	**0.8**	0.9	**0.96**
4000	0.88	0.96	0.98	0.85	0.95	0.97	0.75	**0.85**	0.92
4500	0.85	0.94	0.97	**0.81**	0.91	**0.96**	0.69	0.79	0.86
5000	**0.81**	0.9	**0.95**	0.77	0.88	0.93	0.63	0.71	0.79
5500	0.77	0.86	0.92	0.72	**0.83**	0.89	0.58	0.65	0.71
6000	0.72	**0.82**	0.89	0.68	0.77	0.85	0.54	0.59	0.64
7000	0.63	0.71	0.8	0.59	0.65	0.73	0.45	0.48	0.52
8000	0.56	0.62	0.69	0.5	0.55	0.61	0.38	0.4	0.42
9000	0.49	0.53	0.6	0.44	0.47	0.51	0.31	0.33	0.35
10000	0.42	0.45	0.5	0.38	0.41	0.44	0.25	0.26	0.28
11000	0.36	0.39	0.43	0.32	0.34	0.37	0.2	0.21	0.22
12000	0.31	0.34	0.37	0.27	0.29	0.31	0.16	0.17	0.18
14000	0.22	0.24	0.28	0.19	0.2	0.22	0.1	0.1	0.11
16000	0.16	0.17	0.2	0.13	0.14	0.15	0.06	0.07	0.07
18000	0.11	0.12	0.14	0.09	0.1	0.1	0.04	0.05	0.05
20000	0.09	0.09	0.11	0.07	0.07	0.08	0.03	0.03	0.03

Table 7. Decision table reporting the probability of falling below N70 and N50 based on regional allocations for different harvest levels, assuming that harvests are proportional to pup production (0.04 CNS, 0.19 Gulf, 0.77 Sable), under 3 harvest strategies (95, 90 and 70% YOY).

Total TAC	**CNS**			**Gulf**			**Sable**		
	TAC	**N70**	**N50**	**TAC**	**N70**	**N50**	**TAC**	**N70**	**N50**
A - Harvest 95% YOY									
50,000	2,000	0.76	0.73	9,500	0.56	0.52	38,500	0.25	0.22
60,000	2,400	0.83	0.81	11,400	0.64	0.62	46,200	0.31	0.3
70,000	2,800	0.85	0.85	13,300	0.69	0.67	53,900	0.41	0.39
90,000	3,600	0.89	0.88	17,100	0.78	0.76	69,300	0.69	0.66
100,000	4,000	0.92	0.91	19,000	0.83	0.8	77,000	0.83	0.81
B - Harvest 90% YOY									
50,000	2,000	0.8	0.79	9,500	0.6	0.57	38,500	0.27	0.26
60,000	2,400	0.85	0.84	11,400	0.69	0.67	46,200	0.34	0.33
70,000	2,800	0.87	0.86	13,300	0.73	0.71	53,900	0.46	0.44
90,000	3,600	0.92	0.91	17,100	0.81	0.8	69,300	0.78	0.76
100,000	4,000	0.94	0.94	19,000	0.87	0.86	77,000	0.9	0.89
C - Harvest 70% YOY									
50,000	2,000	0.86	0.86	9,500	0.73	0.71	38,500	0.36	0.34
60,000	2,400	0.88	0.88	11,400	0.79	0.78	46,200	0.5	0.48
70,000	2,800	0.92	0.92	13,300	0.84	0.83	53,900	0.71	0.69
90,000	3,600	0.98	0.97	17,100	0.9	0.9	69,300	0.97	0.96
100,000	4,000	0.99	0.99	19,000	0.93	0.92	77,000	0.99	0.99

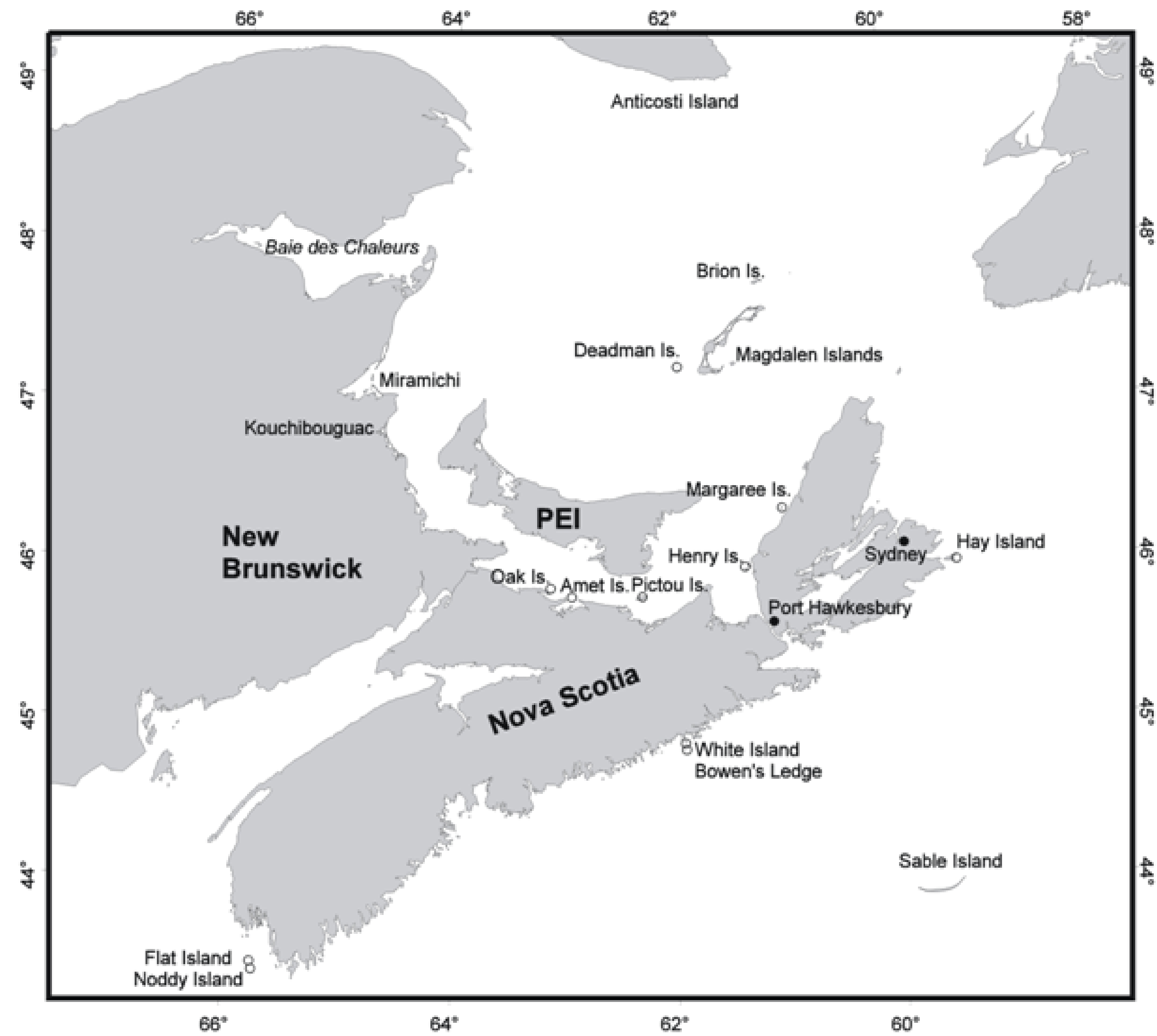


Figure 1. Map showing locations of main pupping colonies in Atlantic Canada.

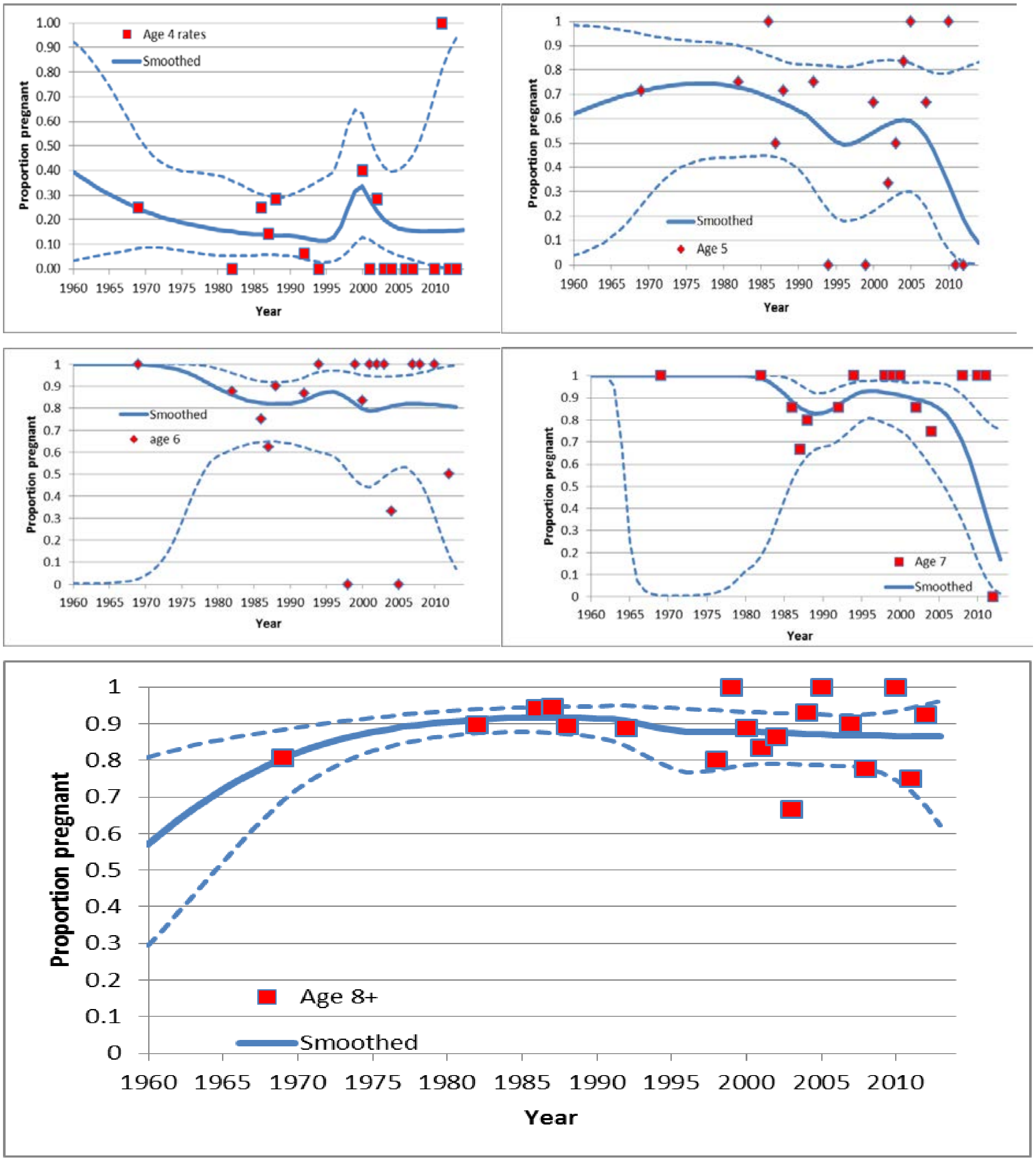


Figure 2. Age specific reproductive rates and non-parametric smoothed rates for the period 1969-2012 for ages 4-8+ years. Dotted lines represent 95% CI.

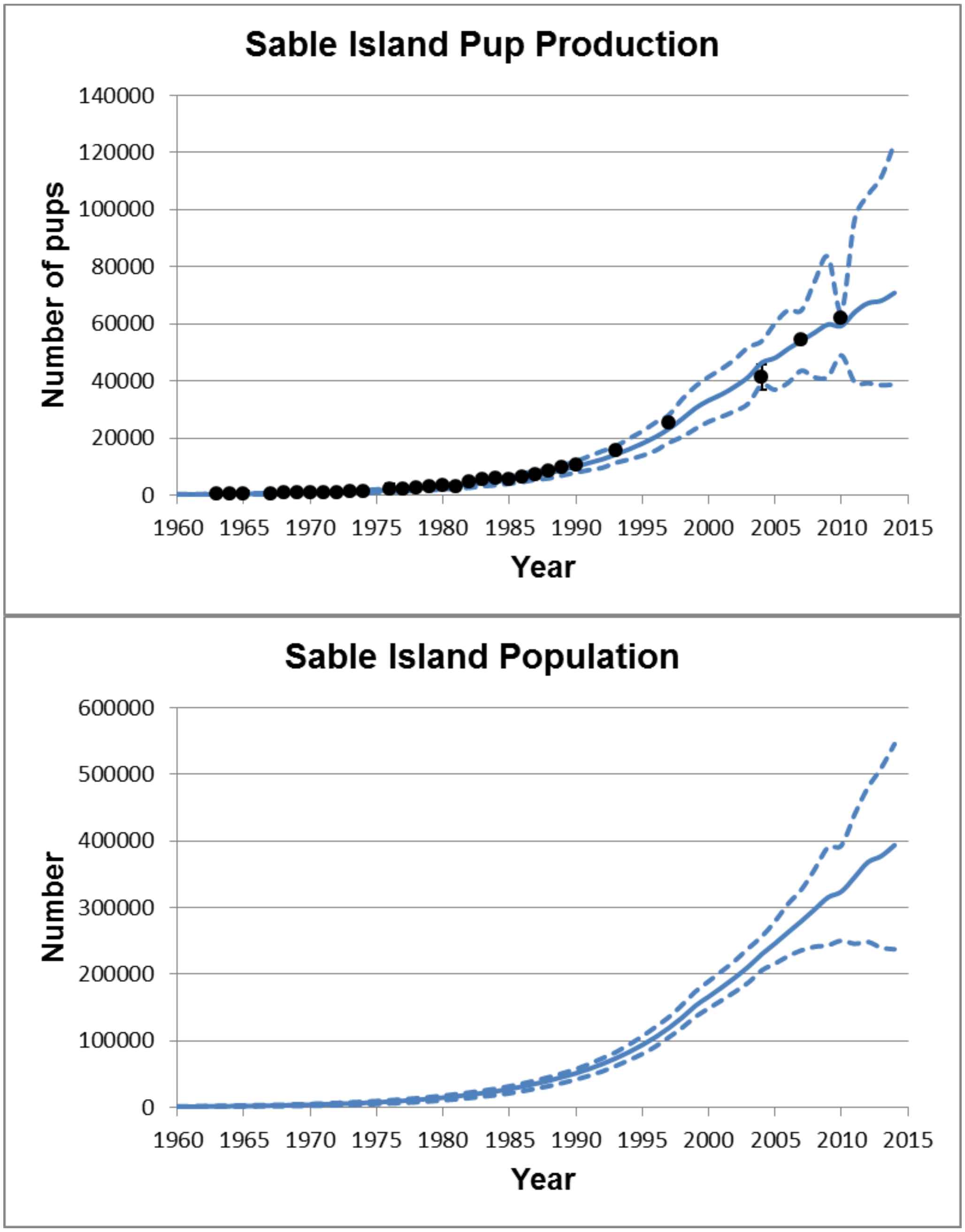


Figure 3. Sable Island pup production estimates in 2014 (solid black circles) and pup production (solid line) (top) and total population (bottom) predicted from the form of the assessment model that estimates M during fitting of the model to the pup survey, reproductive rate and removal data . Horizontal bars are standard errors on pup production estimates and dashed lines represent 95% CI for model predictions.

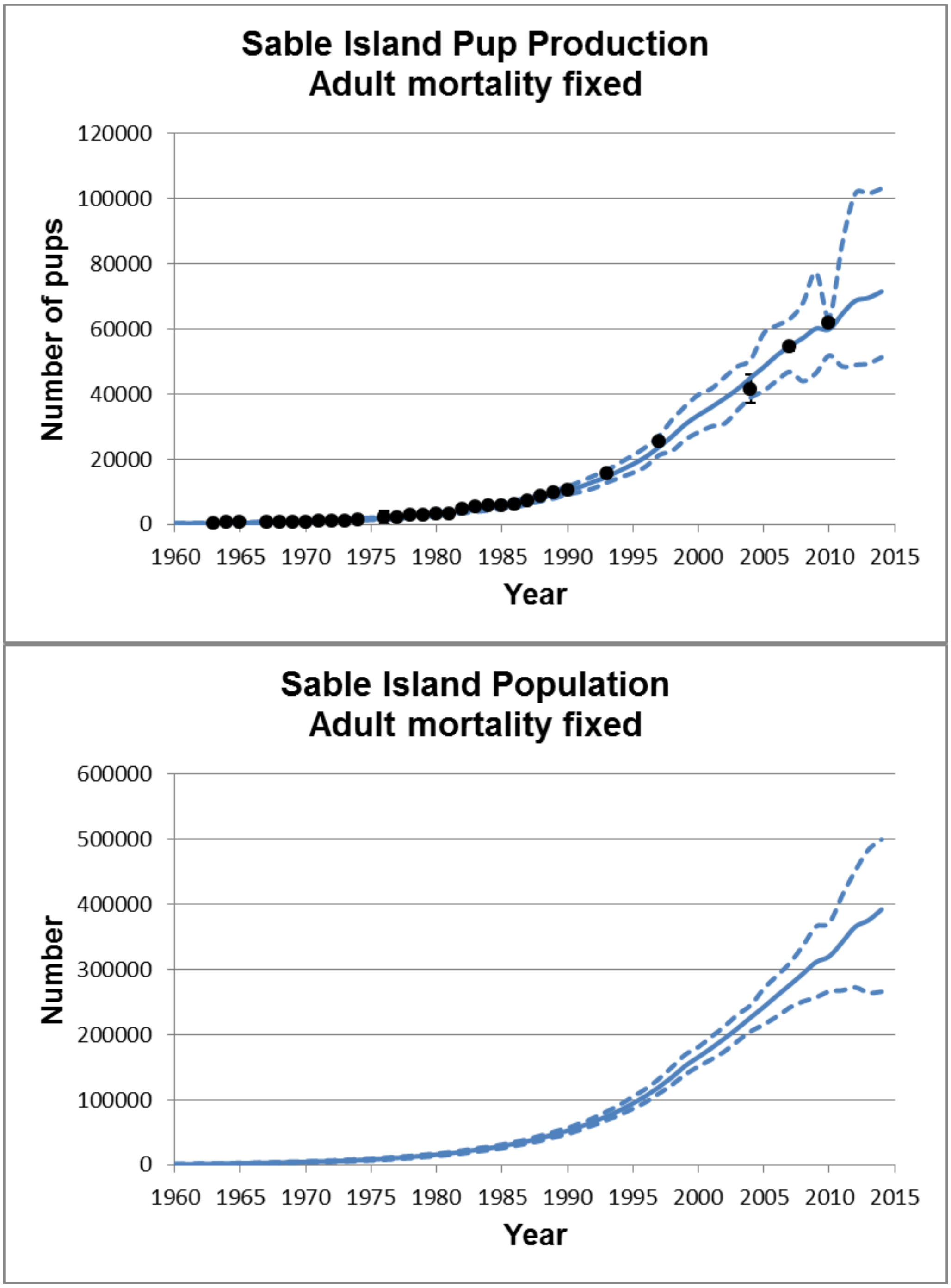


Figure 4. Sable Island pup production estimates (solid black circles) and pup production (solid line) (top) and total population through 2014 (bottom) predicted from the version of the model fixed adult mortality and estimated M_1.Horizontal bars are standard errors on pup production estimates and dashed lines represent 95% CI for model predictions.

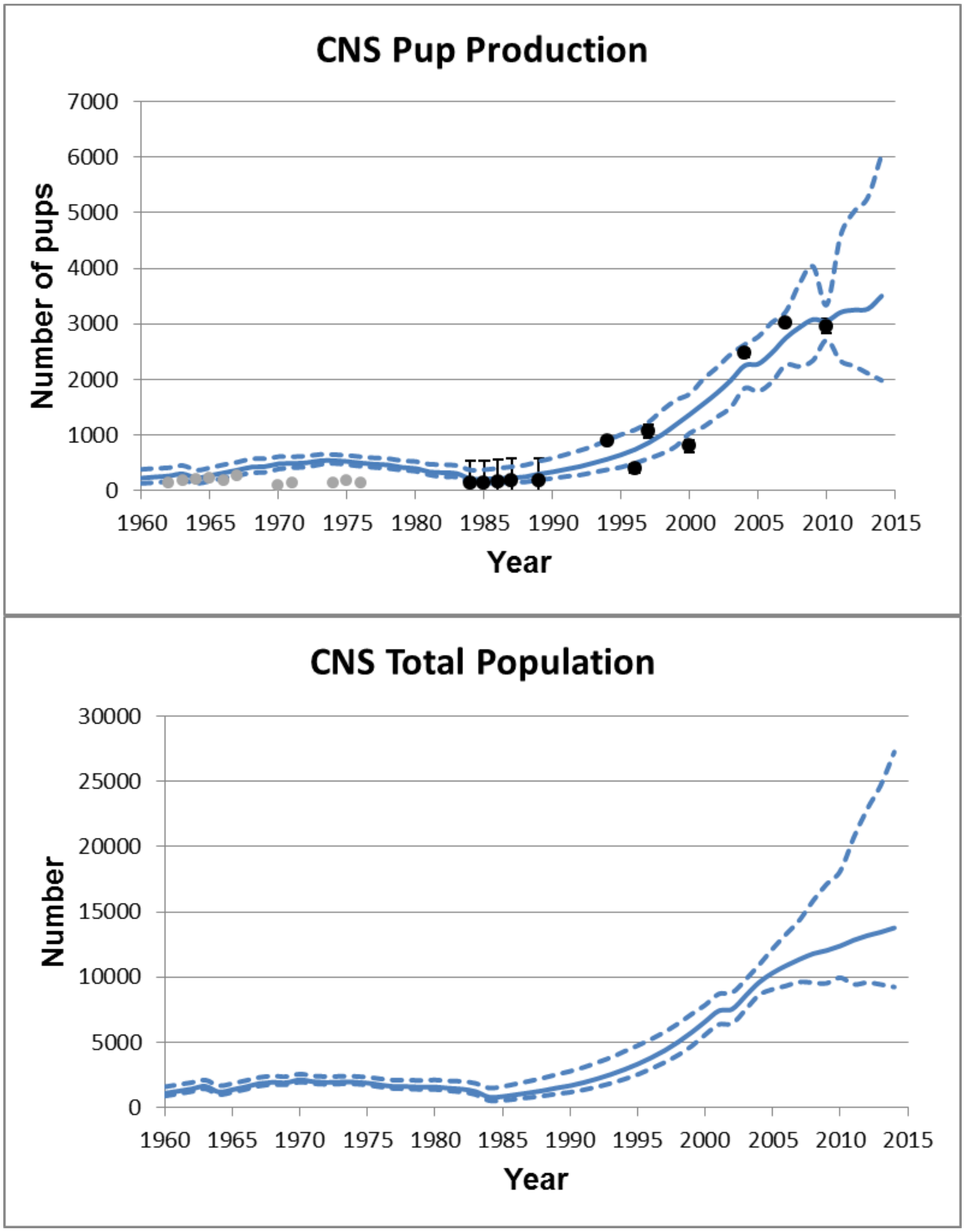


Figure 5. Coastal Nova Scotia pup production estimates (top) and total population size (bottom) through 2014. Horizontal bars are standard errors on pup production estimates and dashed lines represent 95% CI for model predictions. Light grey points indicate pup production estimates which were not used to fit the model.

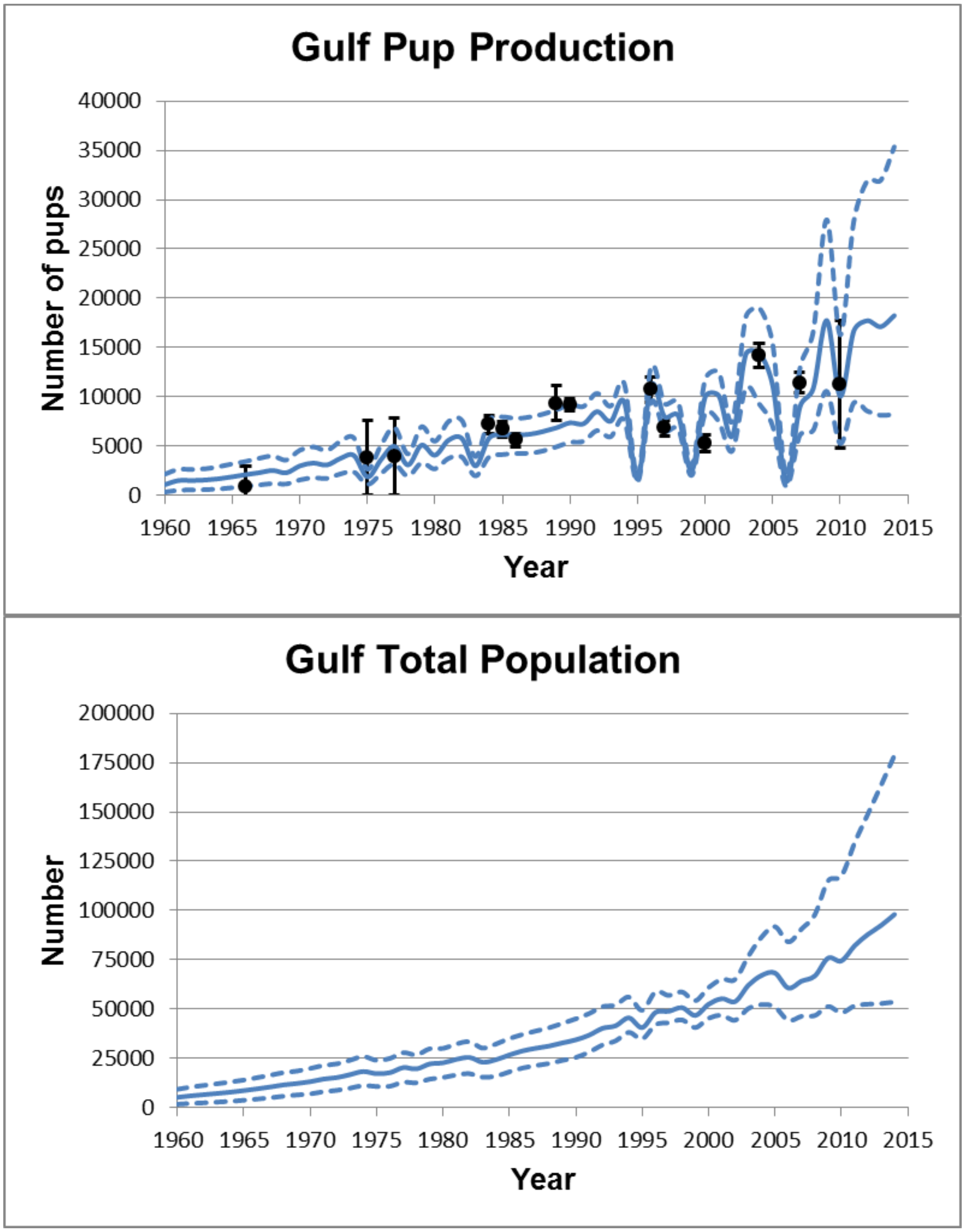


Figure 6. Gulf of St. Lawrence pup production estimates (top) and total population size (bottom) through 2014 using reproductive data from 1969-2012 and accounting for increased pup mortality due to poor ice conditions. Horizontal bars are standard errors on pup production estimates and dashed lines represent 95% CI for model predictions.

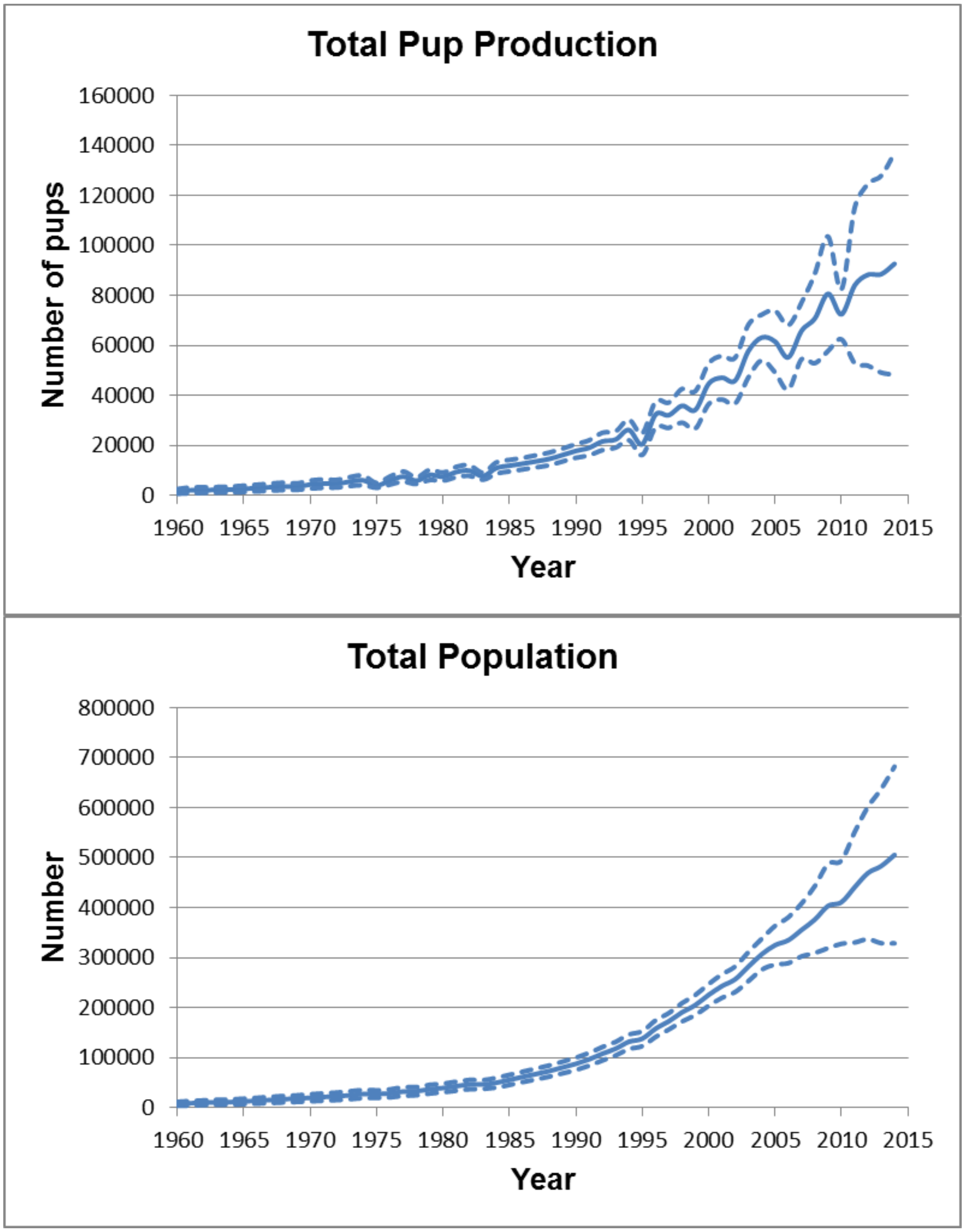


Figure 7. Total pup production estimates (top) and total population size (bottom) through 2014 using reproductive data from 1969-2012 and accounting for increased pup mortality in the Gulf due to poor ice conditions. Horizontal bars are standard errors on pup production estimates and dashed lines represent 95% CI for model predictions.

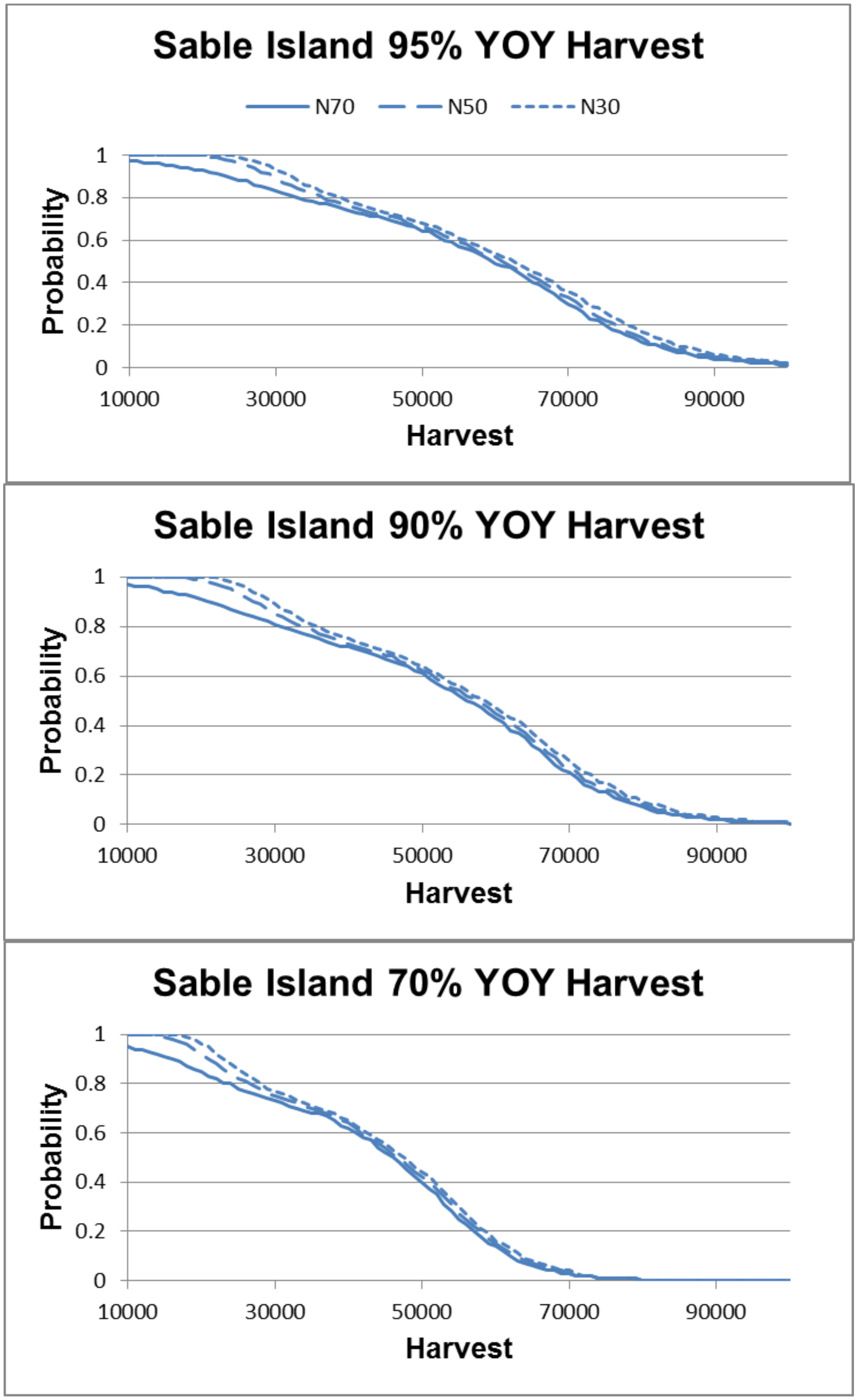


Figure 8. Probability of an annual harvest of the Sable Island herd with an age composition of 95% Young of the year (YOY) (top), 90% YOY (middle) and 70% YOY(bottom) remaining above N70, N50 or N30. The current management plan calls for an 80% probability that the management plan will remain above N70. The expectation is that the harvest will maintain a 95% probability of remaining above N30

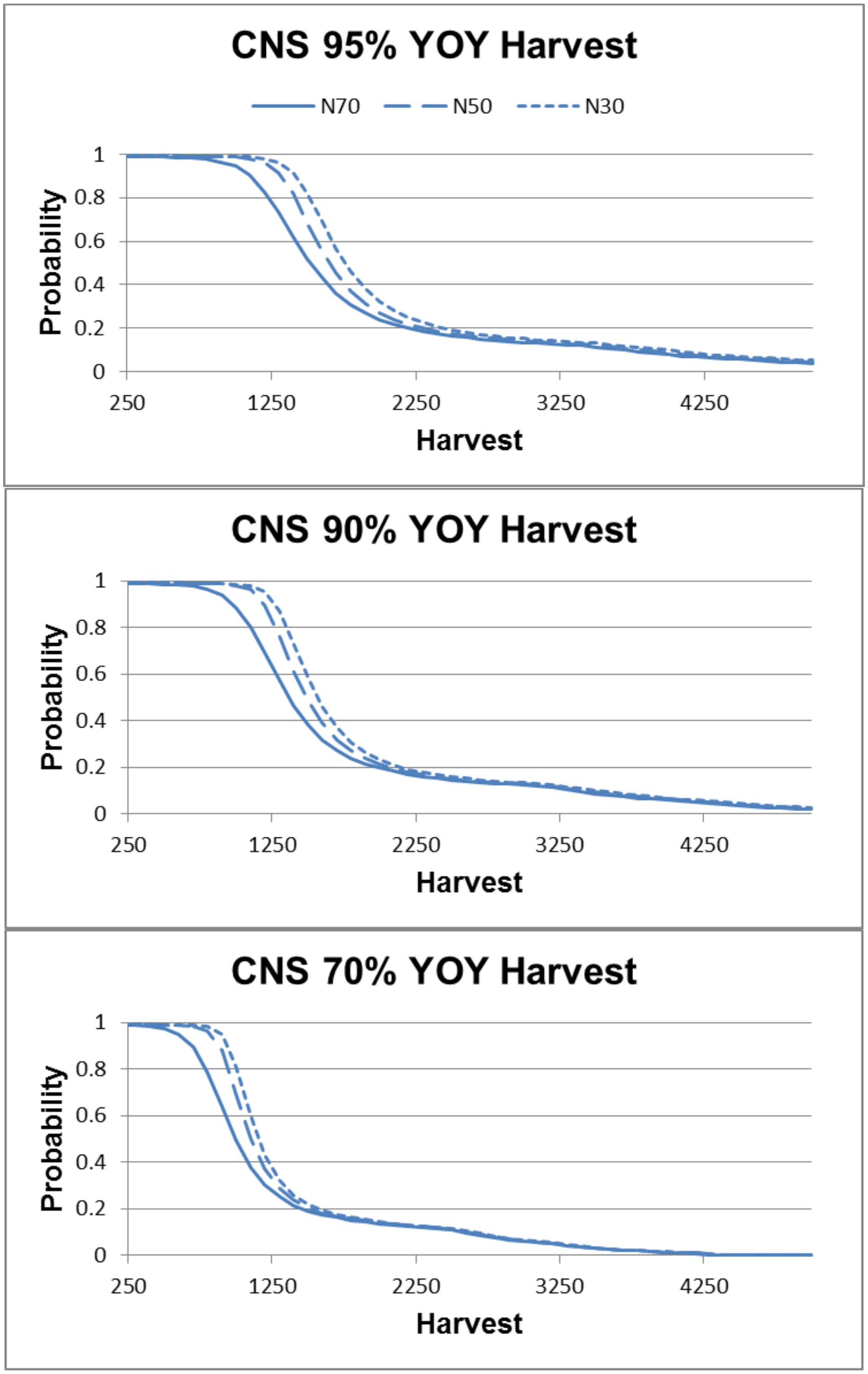


Figure 9. Probability of an annual harvest of the Coastal Nova Scotia herd with an age composition of 95% Young of the year (YOY) (top), 90% YOY (middle) and 70% YOY(bottom) remaining above N70, N50 or N30. The current management plan calls for an 80% probability that the management plan will remain above N70. The expectation is that the harvest will maintain a 95% probability of remaining above N30.

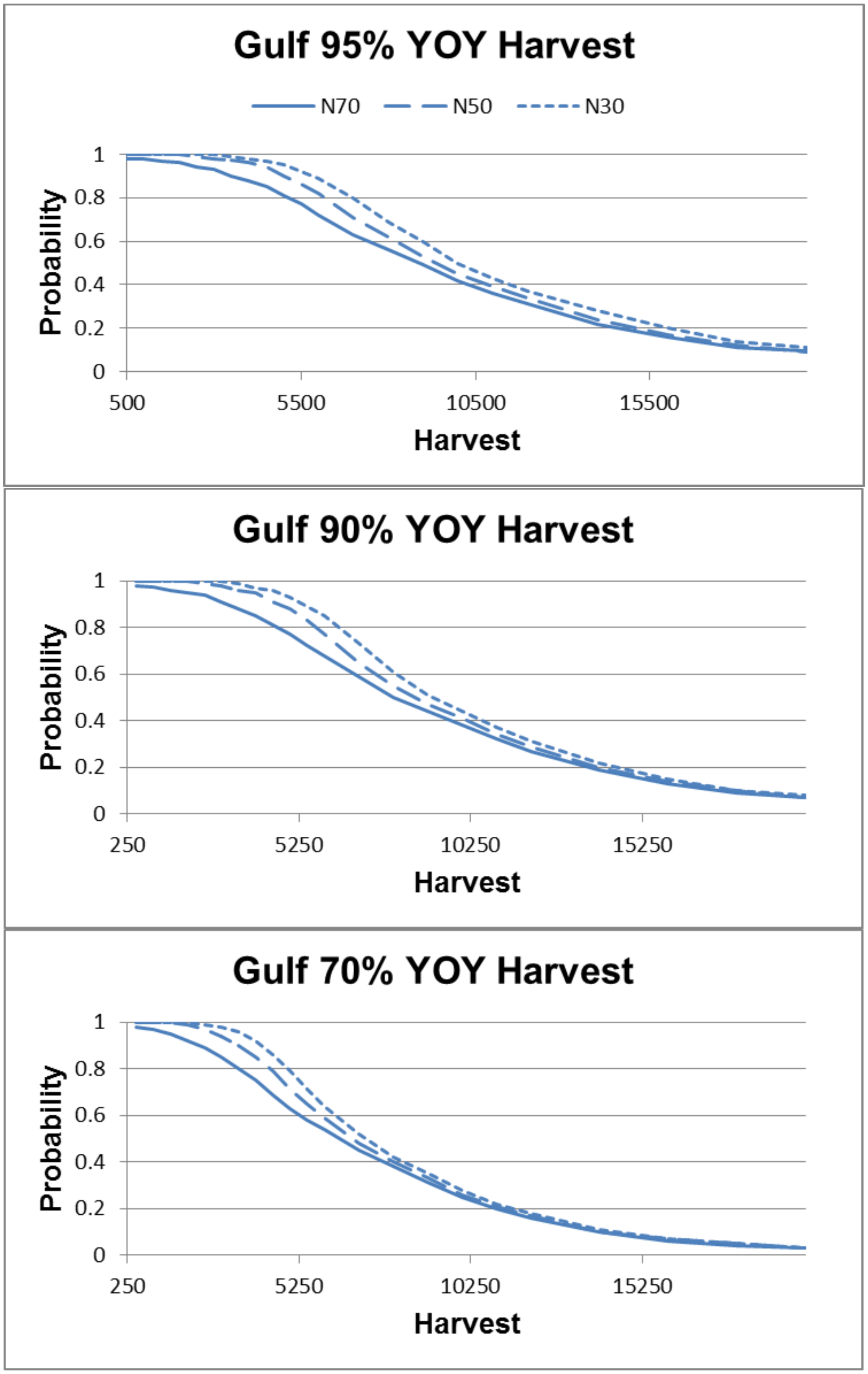
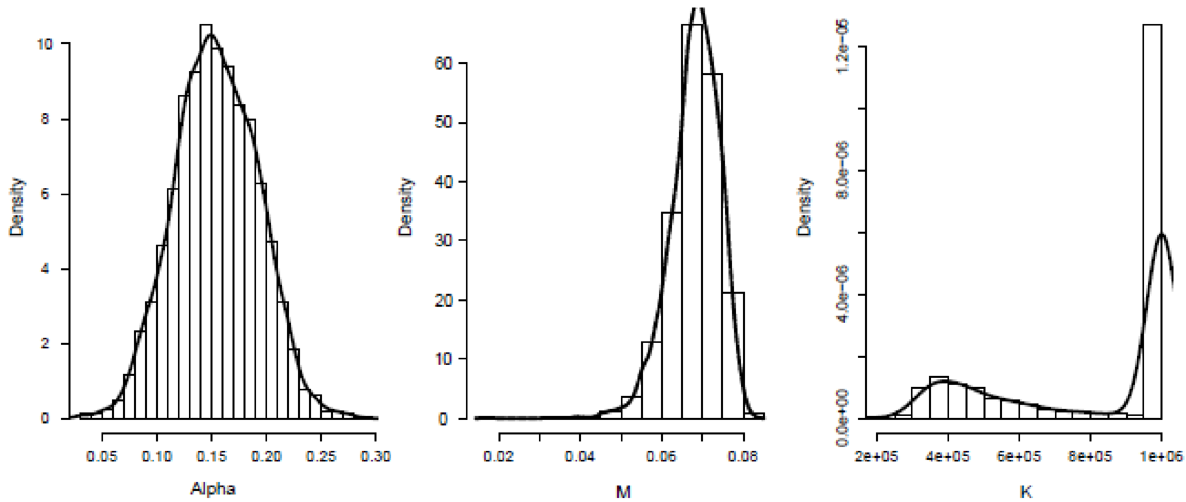
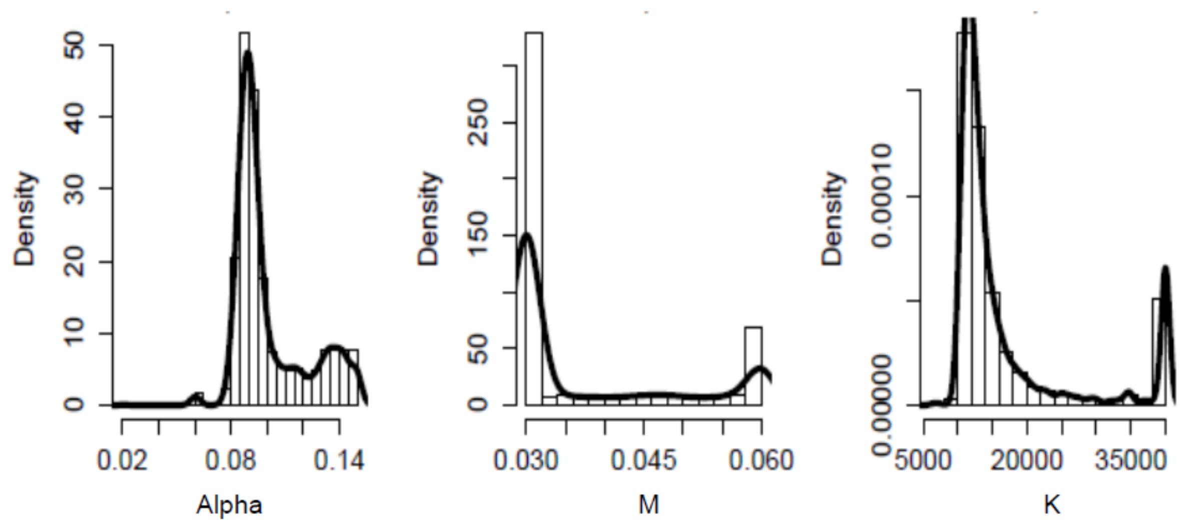


Figure 10. Probability of an annual harvest of the Gulf of St. Lawrence herd with an age composition of 95% Young of the year (YOY) (top), 90% YOY (middle) and 70% YOY(bottom) remaining above N70, N50 or N30. The current management plan calls for an 80% probability that the management plan will remain above N70. The expectation is that the harvest will maintain a 95% probability of remaining above N30.

Appendix A. Plots of the histogram and density distribution of the parameter estimates (n=5000) of the model (gamma=6, theta=2.4) fit to pup production estimates for Sable Island



Appendix B. Plots of the histogram and density distribution of the parameter estimates (n=5000) for the model (gamma=3, theta=2.4) fit to pup production estimates Coastal Nova Scotia.



Appendix C. Plots of the histogram and density distribution of the parameter estimates (n=5000) for the model (gamma=6, theta=2.4) fit to pup production estimates in the Gulf of St. Lawrence.