ADAPTIVE HARVEST MANAGEMENT FOR THE SVALBARD POPULATION OF PINK-FOOTED GEESE

2014 Progress Summary

Technical Report from DCE – Danish Centre for Environment and Energy No. 40 2014

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Astract: This document describes progress to date on the development of an adaptive harvest management strategy for maintaining the Svalbard population of pink-footed geese (*Anser brachyrhynchus*) near their agreed target level (60,000) by providing for sustainable harvests in Norway and Denmark. This report provides an assessment of the most recent monitoring information (1991-2013) and its implications for the harvest management strategy, and it is an update of an initial assessment for 2013-2015(see http://pinkfootedgoose.aewa.info/). By combining varying hypotheses about survival and reproduction, a suite of nine models have been developed that represent a wide range of possibilities concerning the extent to which demographic rates are density dependent or independent. These results suggest that the pink-footed goose population may have recently experienced a release from density-dependent mechanisms, corresponding to the period of most rapid growth in population size. The initial optimal harvest strategy for the 3-year period 2013–2015 suggested that the appropriate annual harvest quota is 15,000. The 1-year harvest strategy calculated to determine whether an emergency closure of the hunting season is required this year suggested an allowable harvest of 25,000; thus, a hunting-season closure is not warranted. If the harvest quota of 15,000 were met in the coming hunting season, the next population count would be expected to be 71,000. If only the most recent 4-year mean harvest were realized (11,300), a population size of 74,800 would be expected. Simulations suggest that it will take approximately seven years at current harvest levels to reduce population size to the goal of 60,000. However, it is possible that the extension of the forthcoming hunting season in Denmark could result in a total harvest approaching 15,000; in this case, simulations suggest it would only take about three years to reach the goal.

Keywords: adaptive management, density-dependence, harvest, population modelling

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Executive Summary

This document describes progress to date on the development of an adaptive harvest-management strategy for maintaining the Svalbard population of pink-footed geese (*Anser brachyrhynchus*) near their agreed target level (60 thousand) by providing for sustainable harvests in Norway and Denmark. Specifically, this report provides an assessment of the most recent monitoring information and its implications for the harvest management strategy.

The development of a passively adaptive harvest management strategy requires specification of four elements: (a) a set of alternative population models, describing the effects of harvest and other relevant environmental factors; (b) a set of probabilities describing the relative credibility of the alternative models, which are updated each year based on a comparison of model predictions and monitoring information; (c) a set of alternative harvest quotas, from which a 3-year quota is chosen; and (d) an objective function, by which alternative harvest strategies can be evaluated and an optimal strategy chosen.

By combining varying hypotheses about survival and reproduction, a suite of nine models have been developed that represent a wide range of possibilities concerning the extent to which demographic rates are density dependent or independent, and the extent to which spring temperatures are important. Five of the models incorporate density-dependent mechanisms that would maintain the population near a carrying capacity (i.e., in the absence of harvest) of 65k – 129k depending on the specific model. The remaining four models are density independent and predict an exponentially growing population even with moderate levels of harvest.

The most current set of monitoring information was used to update model weights for the period 1991 – 2013. Current model weights suggest little or no evidence for density-dependent survival and reproduction. These results suggest that the pink-footed goose population may have recently experienced a release from density-dependent mechanisms, corresponding to the period of most rapid growth in population size. There was equivocal evidence for the effect of May temperature days (number of days with temperatures above freezing: TempDays) on survival and on reproduction.

During the summer of 2013 we computed an optimal harvest strategy for the 3-year period 2013 – 2015. The strategy suggested that the appropriate annual harvest quota is 15 thousand. The 1-year harvest strategy calculated to determine whether an emergency closure of the hunting season is required this year suggested an allowable harvest of 25.0 thousand; thus, a hunting-season closure is not warranted. If the harvest quota of 15 thousand were met in the coming hunting season, the next population count would be expected to be 71.0 thousand. If only the most recent 4-year mean harvest were realized (11.3 thousand), a population size of 74.8 thousand would be expected. Simulations suggest that it will take approximately seven years at current harvest levels to reduce population size to the goal of 60 thousand. However, it is possible that the extension of the forthcoming hunting season in Denmark could result in a total harvest approaching 15 thousand; in this case, simulations suggest it would only take about three years to reach the goal.

1 Introduction

The Svalbard population of pink-footed geese has increased from about 10 thousand individuals in the early 1960's to roughly 80 thousand today. Although these geese are a highly valued resource, the growing numbers of geese are causing agricultural conflicts in wintering and staging areas, as well as tundra degradation in Svalbard. The African-Eurasian Waterbird Agreement (AEWA; http://www.unep-aewa.org/) calls for means to manage populations which cause conflicts with certain human economic activities. This document describes progress to date on the development of an adaptive harvest-management strategy for maintaining pink-footed goose (*Anser brachyrhynchus*) abundance near their target level (60 thousand) by providing for sustainable harvests in Norway and Denmark. Specifically, this report provides an update of relevant information for the first year following the harvest quota prescribed for the 2013-2015 hunting seasons.

Previous progress reports (http://pinkfootedgoose.aewa.info/) described the compilation of relevant demographic and weather data and specified an annual-cycle model for pink-footed geese. Dynamic models for survival and reproductive processes were parameterized using available data. By combining varying hypotheses about survival and reproduction, a suite of nine models were developed that represent a wide range of possibilities concerning the extent to which demographic rates are density dependent or independent, and the extent to which spring temperatures are important. These nine models vary significantly in their predictions of the harvest required to stabilize current population size, ranging from a low of about 500 to a high of about 17 thousand. For comparison, the harvest in Norway and Denmark has averaged 11.3 thousand per year during the last four years.

The passive form of adaptive management is being employed to formulate an optimal harvest strategy. In passive adaptive management, alternative population models and their associated probabilities are explicitly considered in the development of an optimal harvest strategy. Model-specific probabilities (or weights) represent the relative credibility of the alternative models, and are based on a comparison of predicted and observed population size. Models that are better predictors of observed population size gain probability mass according to Bayes' theorem. Models with higher probabilities have more influence on the optimal harvest strategy.

This report focuses on updates of population status and alternative model weights, given the prescription for an annual harvest quota of 15 thousand for the 3-year decision-making cycle starting with the 2013 hunting season. This annual update is part of the process agreed to by the AEWA Svalbard Pink-Footed Goose International Working Group in Copenhagen in April 2013. It uses the most recent data on harvest (autumn 2013), population size (autumn 2013 / spring 2014), and weather conditions on the breeding ground (May 2014). This report also describes the status of ongoing developments in pink-footed goose adaptive harvest management, as well as emerging technical issues.

2 Methods

The development of a passively adaptive harvest management strategy requires specification of four elements: (a) a set of alternative population models, describing the effects of harvest and other relevant environmental factors; (b) a set of probabilities describing the relative credibility of the alternative models, which are updated each year based on a comparison of model predictions and monitoring information; (c) a set of alternative harvest quotas, from which a 3-year quota is chosen; and (d) an objective function, by which alternative harvest strategies can be evaluated and an optimal strategy chosen. An optimal management strategy prescribes a 3-year harvest quota for each and every level of abundance (and environmental conditions) that may be observed at the time the decision is made. To allow for the possibility of unforeseen changes in population status, we also require criteria for 1-year emergency closure of the hunting season.

Alternative Models. – The nine alternative models of population dynamics suggest how reproductive and survival rates of pink-footed geese vary over time (Table 1, Appendix A). Five of the models incorporate density-dependent mechanisms that would maintain the population near a carrying capacity (i.e., in the absence of harvest) of 65k – 129k depending on the specific model. The remaining four models are density independent and predict an exponentially growing population even with moderate levels of harvest. Consideration of these density-independent models is not intended to suggest that population size is truly unregulated, but that density dependence may only manifest itself at abundances far exceeding those experienced thus far. All nine models fit the available data and at the time of their development it was not possible to say with any confidence which was more appropriate to describe the contemporary dynamics of pink-footed geese.

Table 1. Nine alternative models of pink-footed goose population dynamics and their associated carrying capacities (*K*, in thousands) for randomly varying days above freezing in May in Svalbard (TempDays). N and A are total population size and the number of sub-adults plus adults (in thousands), respectively, on November 1. The sub-models represented by (.) denote randomly varying demographic rates (i.e., no covariates). Models M3, M4, M6, and M7 are density-independent growth models and thus have no defined carrying capacity.

Model	**Survival sub-model**	**Reproduction sub-model**	***K* (sd)**
M0	(.)	(TempDays, A)	120 (8)
M1	(TempDays)	(TempDays, A)	129 (8)
M2	(TempDays, N)	(TempDays, A)	59 (4)
M3	(.)	(TempDays)	
M4	(TempDays)	(TempDays)	
M5	(TempDays, N)	(TempDays)	66 (3)
M6	(.)	(.)	
M7	(TempDays)	(.)	
M8	(TempDays, N)	(.)	65 (5)

Model Weights. – Bayesian posterior probabilities (or weights) can be used to express the relative ability of each model to accurately predict the changes in population size that actually occurred. We calculated posterior probabilities for each of the nine models for each of the years 1991-2013, assuming equal prior probabilities in 1991 (i.e., $p_i = 1/9$). Posterior model probabilities were calculated as:

$$p_i(t+1) = \frac{p_i(t)\mathcal{L}_i(t+1)}{\sum_i p_i(t)\mathcal{L}_i(t+1)}$$

where t denotes the year, and $\mathcal{L}_i$ denotes the likelihood of the observed population size, given model i. The likelihoods, in turn, were calculated from the normal density function:

$$\mathcal{L}_i(t+1) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{log(N_*(t+1)) - log(N_i(t+1))}{\sigma}\right)^2}$$

where N_* is the observed population size, N_i is a model-specific prediction of population size, and σ is a prediction error common to all models. This error was estimated by averaging the mean squared errors from all nine models:

$$\sigma = \sqrt{\sum_i^m \frac{\sum_t \left(log(N_*(t+1)) - log(N_i(t+1))\right)^2}{mn}} = 0.11116$$

where $m = 9$ models and sample size for yearly comparisons was $n = 12$.

Alternative Harvest Quotas. – We considered a set of harvest quotas of 0 to 30 thousand in increments of 2.5 thousand. This set seemed reasonable given the current harvest in Norway and Denmark of approximately 11 thousand and only coarse control over harvests. As explained in previous reports, calculation of an optimal strategy of absolute harvest (rather than harvest *rates*) requires that we first specify the number of young and adults in the total harvest. But this cannot be known *a priori* because it depends on the age composition of the pre-harvest population. Yet, the age composition of the pre-harvest population cannot be predicted from our models without knowing the age composition of the harvest. To resolve this dilemma requires the ability to specify the ratio:

$$z = \frac{1 - h_t}{1 - d \cdot h_t}$$

where h is the harvest rate of adults and d ≈ 2 is the differential vulnerability of young to adults. The problem is that z is not constant, but depends on the value of h (which is not known a priori). Therefore, we examined values of z for a range of realistic harvest rates (0.00 – 0.15) and chose a "typical" $z \approx 1.1$. We assumed this constant value for the purpose of calculating an optimal harvest strategy.

Objective Function. - Based on input from the International Working Group, the management objective is to maximize sustainable harvest, subject to maintaining the population size within acceptable limits. For computational purposes, the optimal value (V*) of a harvest-management strategy (A) conditional on resource status (x) at time t is a product of both harvest and a population utility:

$$V^*(A_t|x_t) = \max_{(A_t|x_t)} E\left[\sum_{\tau=t}^{T} H(a_\tau|x_\tau)u(a_\tau|x_\tau)|x_t\right]$$

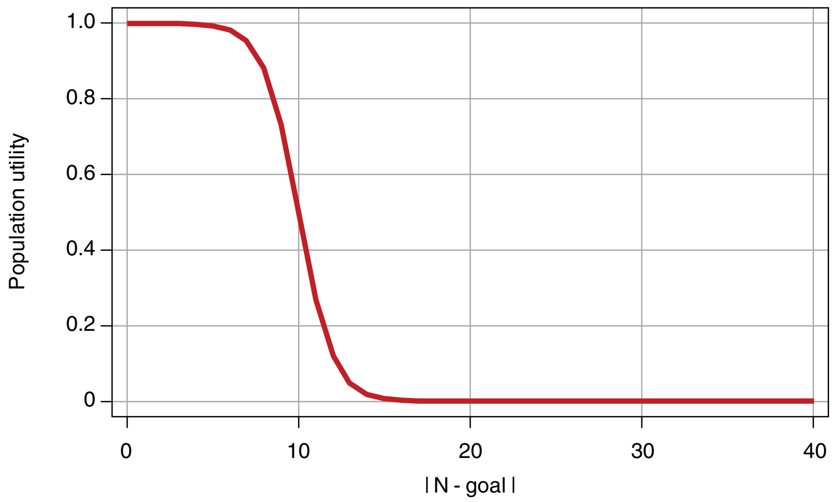
where $H(a_\tau|x_\tau)$ and utility $u(a_\tau|x_\tau)$ are action (a = harvest quota) and state-dependent harvest and population utility, respectively. Population utility is defined as:

$$u(a_\tau|x_\tau) = \frac{1}{1 + exp(|N_{t+1} - 60k| - 10k)}.$$

where N_{t+1} is the population size expected as a result of the current harvest quota and the population goal is 60 thousand (Fig. 1). Thus, the objective function devalues harvest-quota decisions that are expected to result in a subsequent population size different than the population goal, with the degree of devaluation increasing as the difference between population size and the goal increases.

Using the elements described above, we calculated a "quasi-optimal" harvest strategy based on updated model weights and a completely deterministic system using dynamic programming. With a 3-year decision-making cycle, environmental variation is compounded annually between quota decisions and a truly optimal solution is computationally intractable with available software. However, software that can compute an optimal, fully stochastic solution is currently being developed. We also calculated as optimal strategy (including stochasticity) for a 1-year decision making cycle. This strategy is used to determine whether an emergency closure of the hunting season is required in the midst of the 3-year quota.

Figure 1. Population utility expressed as a function of the absolute difference between expected population size and the population goal of 60 thousand. Population sizes between about 50 and 70 thousand are acceptable (and thus have high utility), while those outside that range are very undesirable (and thus have low utility).



3 Results and Discussion

We used the most up-to-date set of monitoring information (http://pinkfootedgoose.aewa.info/; Appendix B; also Madsen, J., F. Cottaar, O. Amstrup, T. Asferg, M. Bak, J. Bakken, T. K. Christensen, J. Hansen, G. H. Jensen, J. P. Kjeldsen, E. Kuijken, P. I. Nicolaisen, P. Shimmings, I. Tombre, and C. Verscheure. 2014. Svalbard Pink-footed Goose. Population Status Report 2013-14. Aarhus University and Danish Centre for Environment and Energy, 14 pp. Technical Report no. 39) to update model weights for the 1991 – 2013 period. We note that the model weights provided in the report for the 2013-2015 hunting seasons were incorrect due to a programming error, which has now been rectified. Discrimination among the nine alternative models became most pronounced after 2006 (Fig. 2, Appendix C). Current model weights (i.e., those based on population size after the 2013 harvest) suggest only slight evidence for density-dependent reproduction (p_{DD-R} = 0.1691, Fig. 3), and little evidence for density-dependent survival (p_{DD-S} = 0.0001, Fig. 4) (recall that probability or model weight is on a scale of 0.0 – 1.0, with 0.0 indicating no evidence and 1.0 indicating certainty). Taken at face value, these results suggest that the pink-footed goose population may have recently experienced a release from density-dependent mechanisms, corresponding to the period of most rapid growth in population size (Fig. 5). There was also little evidence for the effect of TempDays on survival (p_{DAYS-S} = 0.4481, 2 of 3 survival models) and on reproduction (p_{DAYS-R} = 0.3344, 2 of 3 reproductive models) (Fig. 6). We also calculated predictions of population size for each year based on each model, and then compared them with observed population sizes (Fig. 7). The predictive ability of most models has been relatively poor for population sizes exceeding 60 thousand, with a tendency towards predictions of population size that are less than those observed.

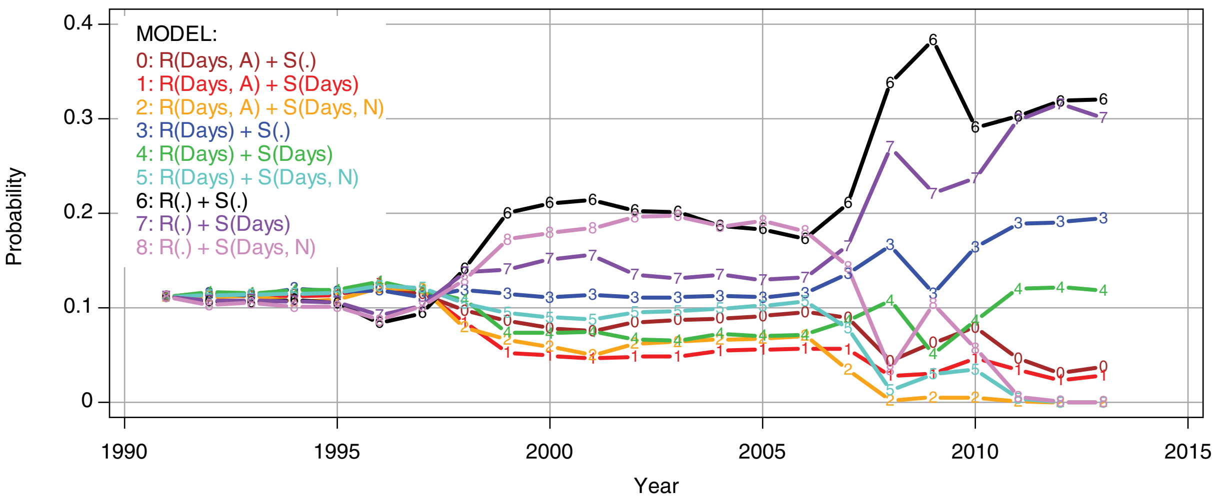


Figure 2. Posterior model weights for nine alternative models describing the annual dynamics of the pink-footed goose population, assuming equal prior model weights in 1991. See Table 1 and Appendix A for a description of the models.

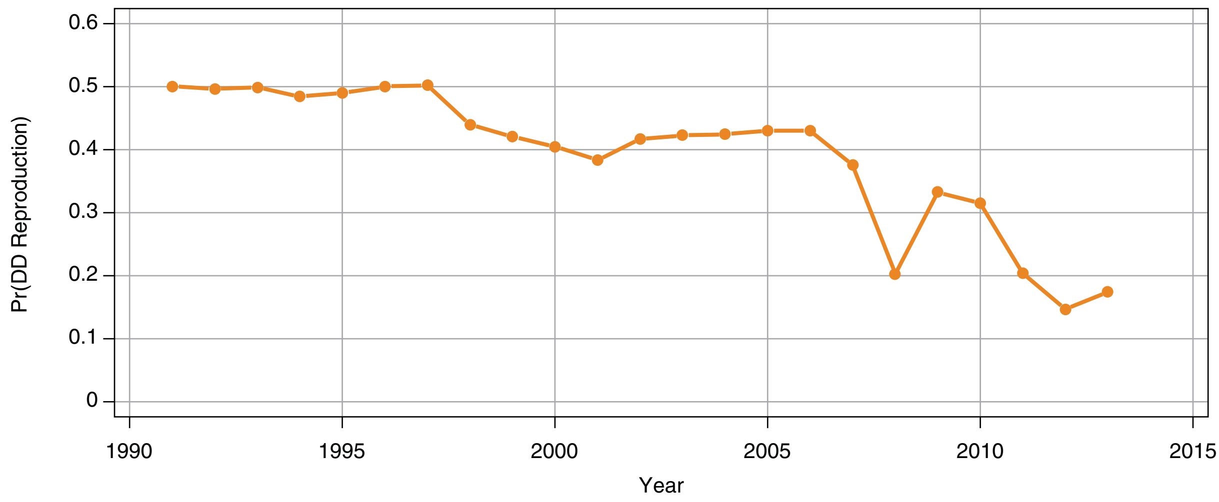


Figure 3. Aggregate weight on the models incorporating density-dependent reproduction for pink-footed geese.

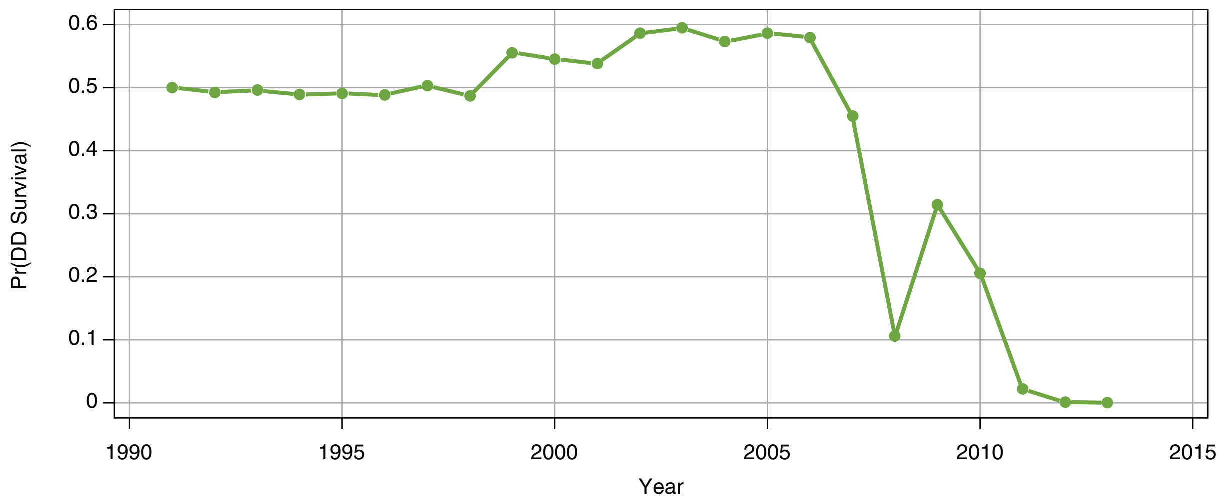


Figure 4. Aggregate weight on the models incorporating density-dependent survival for pink-footed geese.

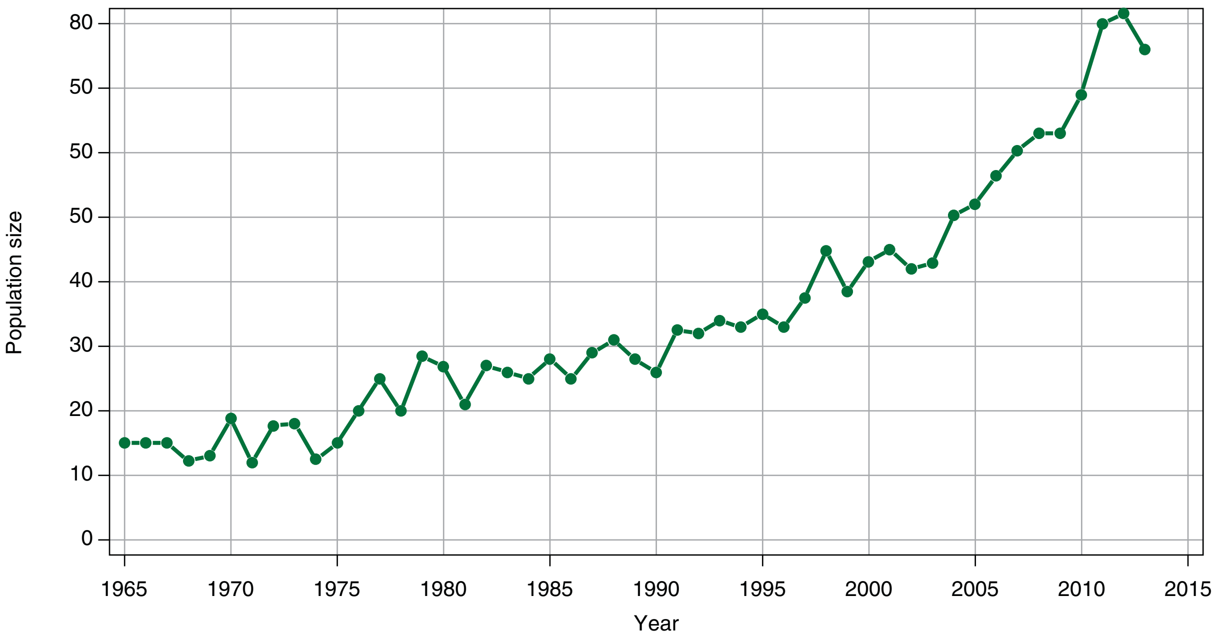


Figure 5. Counts of pink-footed geese (in thousands) during autumn/spring.

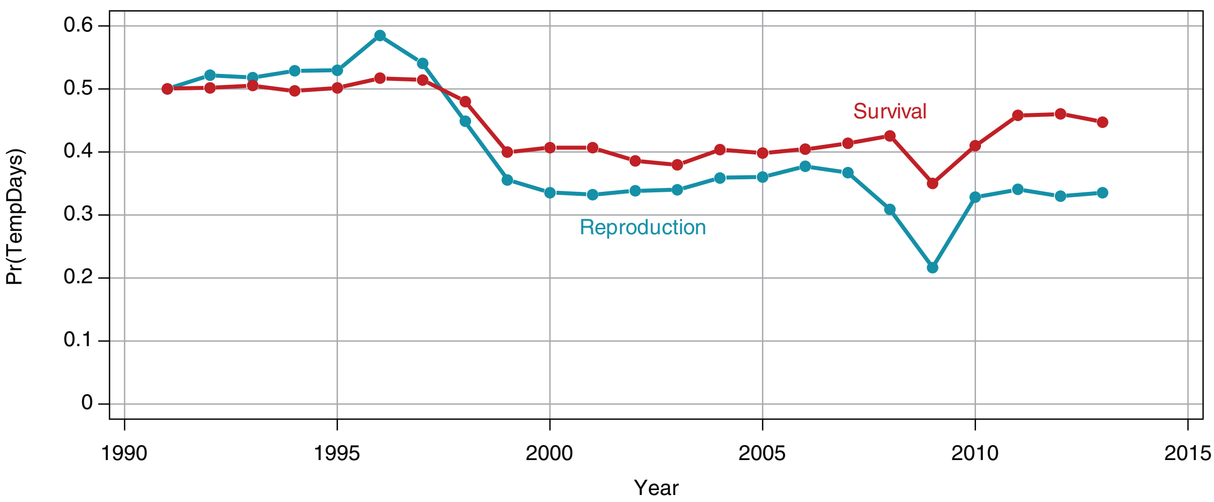


Figure 6. Aggregate weight on the models incorporating an effect of temperature days on survival and reproduction of pink-footed geese.

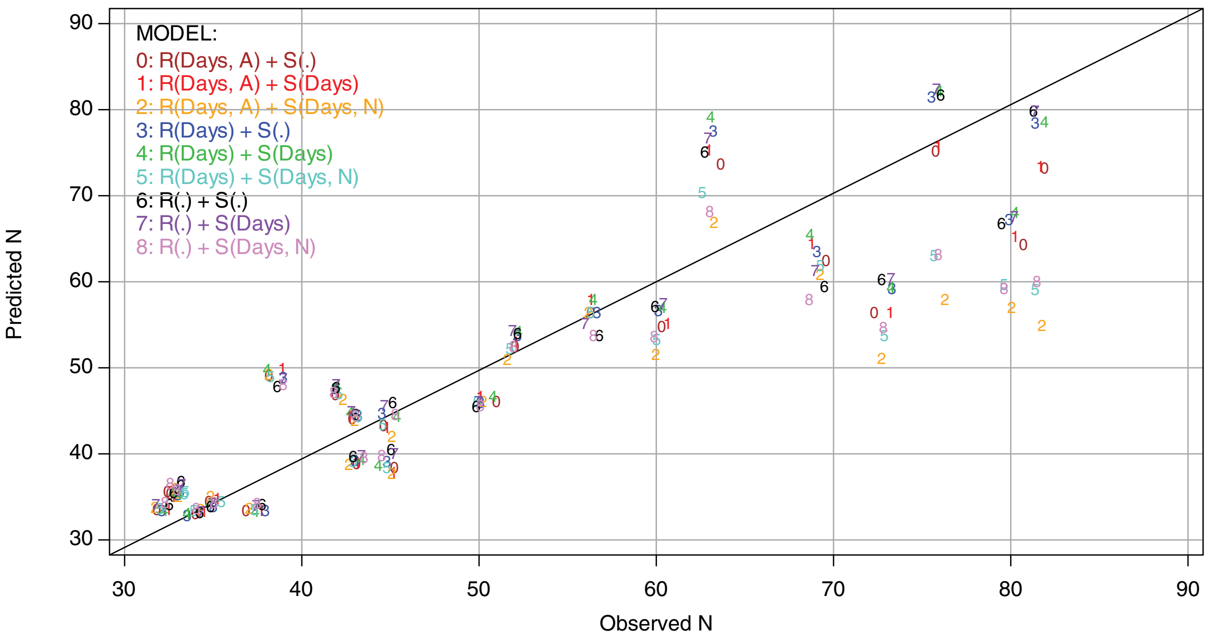
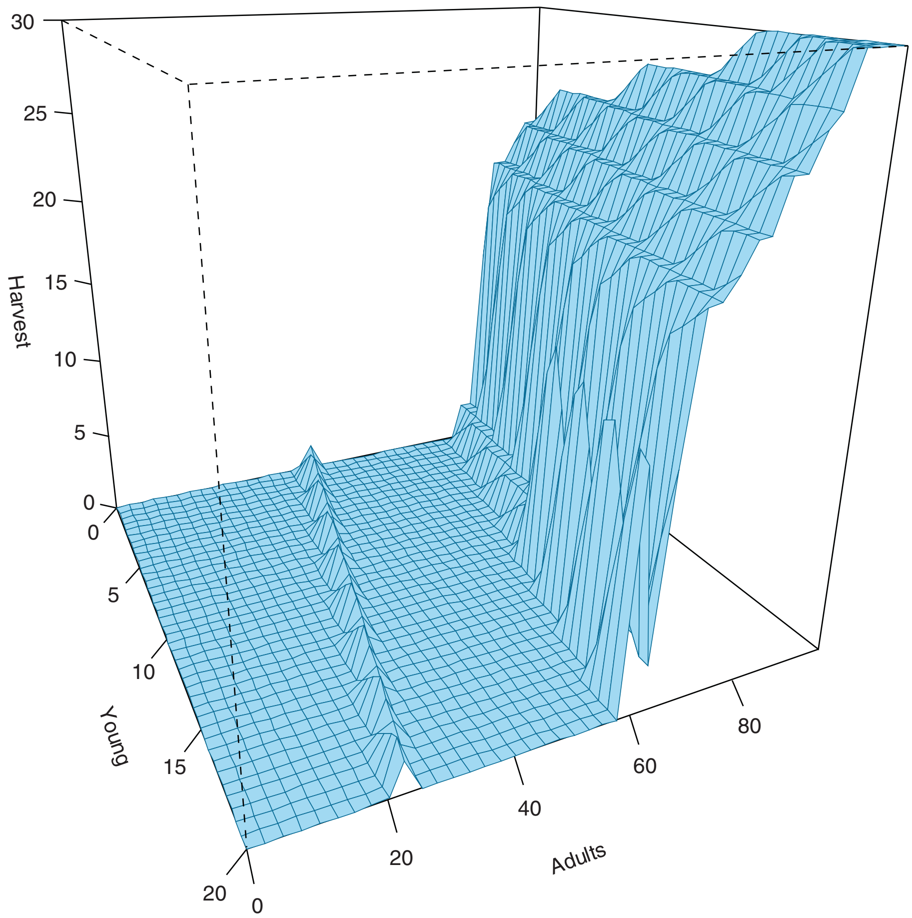


Figure 7. Comparison of observed population sizes and those predicted by nine alternative models describing the annual dynamics of the pink-footed goose population. See Table 1 and Appendix A for a description of the models. The diagonal line represents perfect correspondence between observations and predictions. Predictive ability declined as the population entered a rapid growth phase (i.e., observed population sizes in excess of 60 thousand).

Based on the corrected model weights for 2013, we re-computed a quasi-optimal harvest strategy for the 3-year period of 2013-2015. It is not practical to provide the full strategy here (it is a 5808 × 4 table), so we provide a figure displaying the prescribed harvest quotas for varying numbers of young and adults and based on average temperature days (Fig. 8). The prescribed, 3-year harvest quota for the 2013 – 2015 period remains 15 thousand, based on the observed numbers of young (8,064) and adults (73,536) in autumn 2012, and temperature days (8) in May 2013. We note, however, that the harvest strategy is extremely knife-edged, meaning that only small changes in population size (particularly around the goal of 60 thousand) are required to produce extreme changes in the harvest quota. This result can be primarily attributed to the lack of evidence for density dependence, such that the weighted or "average" model is essentially an exponential growth model. Exponential growth models can produce wide swings in population size with only small changes in harvest because there are no self-regulating mechanisms that would dampen changes in population size.

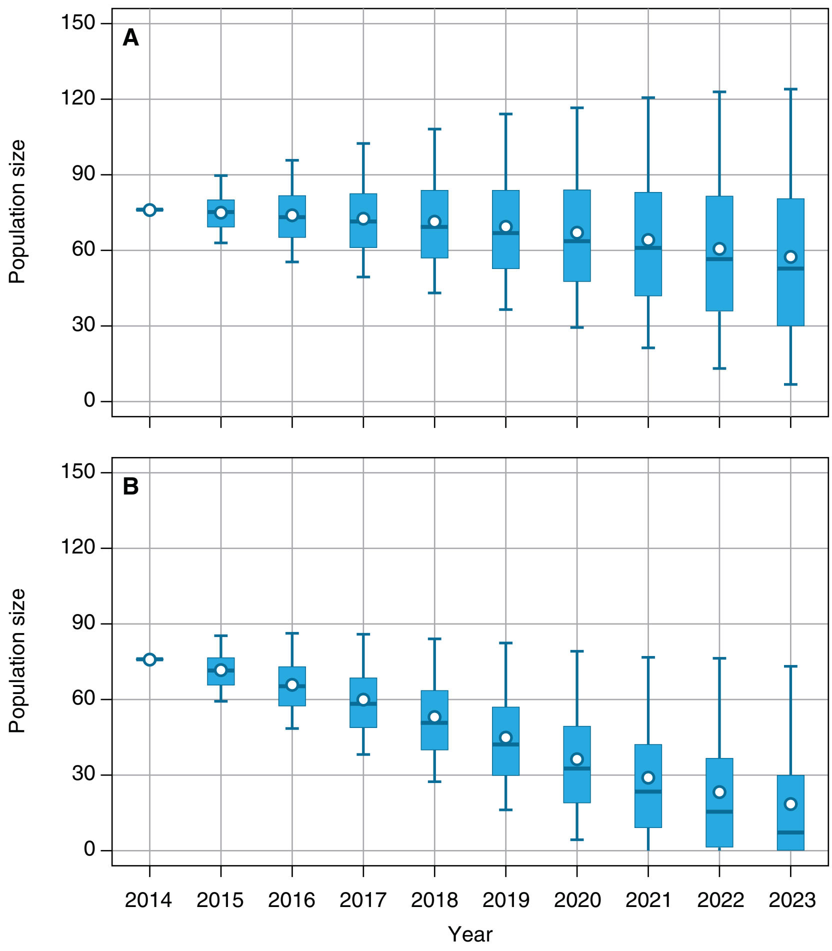
Figure 8. Three-year (2013-2015) harvest quotas for the Svalbard population of pink-footed geese, for eight days (near the average) above freezing in Svalbard in May. Harvest quotas and the number of young and adults are in thousands. The strategy is very knife-edged, meaning that extreme changes in harvest quota can accompany small changes in population size.



Using the most recent model weights, an observed population size of 76.0 thousand, 9 temperature days in May 2014, and an average harvest of 11.3 thousand for the upcoming hunting season, the weighted models predict a resulting population size of 74.8 thousand. If the quota of 15.0 thousand were achieved, we would expect a population size of 71.0 thousand. We also used Monte Carlo simulations to project population size over the next 10 years assuming an average harvest of 11.3 thousand or 15.0 thousand (Fig. 9). These simulations suggest that it would take approximately seven years to reduce the population size to 60 thousand given current levels of harvest. However, only about three years would be required if the harvest were to increase to 15.0 thousand.

Finally, managers have expressed a desire to know under what conditions a closure of the hunting season might be considered, in the event that the population falls below the target due to a combination of unforeseeable environmental conditions, e.g. extreme weather, and high harvest levels. To address this need, monitoring information and model weights are updated each year, followed by calculation of a one-year harvest strategy. Each year, this harvest strategy will prescribe the resource conditions (population size and temperature days) for which a closed season would be necessary. Based on guidance from the International Working Group, hunting season closures would be enacted for one year only, with a re-evaluation of resource conditions the following year. For the autumn 2014 hunting season, observed population size and temperature days prescribe a harvest of 25.0 thousand, well above the current quota of 15.0 thousand; thus, an emergency closure is not warranted.

Figure 9. Projection of pink-footed goose population size based on current model weights and assuming an average harvest of 11.3 thousand (top panel) and 15.0 thousand (bottom panel). Vertical lines represent 95% confidence limits, boxes are the interquartile ranges, horizontal lines are medians, and the diamond characters represent the means. Projections of population size were based on observed, post-harvest population size in 2013, random variation in temperature days, and model process error. Each time series was simulated five thousand times.



4 Ongoing Development of the Adaptive Harvest Management Process

Last year we reported on a number of modifications needed in the monitoring programs for pink-footed geese. Here we report the progress made in addressing those needs:

1. Regarding age composition of the harvest, Denmark has decided to move from wing surveys to direct reporting of pink-footed goose harvest; however, wing survey data will be retained to keep track of the age composition of the harvest. For the Norwegian case, we have six years of data on age composition of the harvest based on a collaboration with a group of hunters; hence, we do not yet have a full-reporting system but a voluntary contribution.
2. From the Danish wing surveys, annual data on the age composition (young vs older geese) are available; however, the sample size has been relatively small (usually <200 per year). Efforts are now being made to increase the numbers of wings from the Danish bag. Until recently, quantitative information was lacking about the age composition of the Norwegian harvest, but now a system has been implemented for collecting and aging wings in Nord-Trøndelag in mid-Norway.
3. Annual harvest estimates and predicted harvest do not include the crippled, non-retrieved geese which are likely to die due to their injuries before the end of the hunting season. At present we have no data concerning the level of non-retrieved geese are available. This should be addressed by field surveys and reporting by hunters in Norway and Denmark in order to derive an estimate of the total numbers shot annually. We are not aware of any progress on this issue since last year.
4. Until recently, population estimates were based on internationally coordinated counts in early November, which is in the middle of the hunting season. For modeling purposes, it would be advantageous to postpone the count to the spring, i.e., after the closure of hunting and as close to the migration to the breeding grounds as possible. During the last four seasons, spring counts in early May have been conducted with good results. Furthermore, autumn counts have become increasingly biased because the geese have been short-stopping in Norway, Denmark and Sweden and using new areas which are not fully covered. Therefore, we have found it necessary to use spring counts rather than those from autumn in recent years.
5. The most recent survival rate estimates are from 2002 and it is a high priority to update these estimates. Furthermore, effects of neckbands on survival and neckband loss rates should be estimated. Aarhus University has been conducting these analyses and has recently generated an up-to-date time series of survival rate estimates. Ideas for using these survival rate estimates to guide harvest management will be discussed at the autumn 2014 meeting of the International Working Group.

The other two principal needs concern the optimization process and the form of the model set. Because of software limitations, we currently are unable to account for sources of stochasticity in calculating optimal, 3-year harvest strategies. A new software program developed at North Carolina State University will allow us to overcome this limitation. Significant progress has been made in the application of this software, and implications for harvest management will be discussed at the 2014 meeting of the International Working Group.

Finally, we have noted that a Bayesian state-space model may be a more useful modeling approach than that originally used, as the Dutch review of previous work suggested
(http://pinkfootedgoose.aewa.info/node/149). The advantage of a Bayesian state-space model is that it can directly incorporate the harvest data in the modeling, as well as update all of the parameters of the model each year. With the current approach, a discrete set of models assumes that the parameters (e.g., regression coefficients) are fixed and the model weights are updated each year. With the Bayesian approach, the joint posterior distribution for all the parameters can be updated each year to account for uncertainty. It's a much more elegant way to use the available data, and we can discretize the joint posterior as finely as necessary to account for a wider array of parameter values. We plan to develop a Bayesian state-space model by the autumn of 2015 for consideration by the International Working Group.

Emerging Issues

The optimization of harvest strategies involves the interaction between models of population dynamics, decision alternatives (i.e., varying levels of harvest), and management objectives. As discussed, current model weights largely suggest density-independent population growth. In the absence of harvest, weighted models suggest a finite population growth rate of $\lambda = 1.133$ (or 13.3% per year); thus, the overall rate of hunting mortality needed to stabilize the population is $(\lambda - 1)/\lambda = 0.117$. Notably, small departures from this harvest rate will result in either rapid increases or declines in population size; yet the management objective tolerates only small departures from the goal of 60 thousand pink-footed geese. Combining exponential growth with this management objective, and accounting for the lagged effects of a 3-year harvest decision, produces a harvest strategy that is extremely knife-edged (Fig. 7). As a consequence, the optimal harvest quota may be quite high for populations only slightly higher than the goal of 60 thousand, and quite low or even zero for populations only slightly lower than the goal. We believe this form of management would be seen as unacceptable to most stakeholders, especially hunters and farmers. Thus, we believe it might be necessary to consider ways in which the variability in harvest quotas might be dampened; suggestions will be offered at the 2014 meeting of the International Working Group. We note, however, that moderating the variability in harvest quotas will mean increased variation in population size and this may be equally undesirable to some stakeholders. Because such tradeoffs are inevitable, we will endeavor to provide sufficient analyses to make an informed decision about addition of an objective that seeks to dampen variability in the harvest quota.

It has so far been unnecessary to determine how harvest levels could be manipulated in Norway and Denmark. The focus has been on increasing harvest to stabilize the population, and the observed harvest has been well below the current quota of 15 thousand. But even at current harvest levels, we expect the population size to decrease to the goal of 60 thousand over the next several years, at which time it will be necessary to reduce the harvest to the level necessary to maintain the population near the goal. Moreover, it is possible that the extension of the forthcoming hunting season in Denmark could result in an additional harvest of 1-2 thousand geese, such that the total harvest could approach 15 thousand; in this case, simulations suggest it would only take about three years to reach the population goal. We note that northern Europe does not have a strong tradition of regulating the level of harvest, such as is the case in North America. Thus, the International Working Group should begin to consider now possible ways of reducing the harvest if and when it becomes necessary. Possibilities include shortening the hunting season and/or imposing daily bag limits. Co-management agreements with hunters may also be a possibility if hunters are willing to voluntarily limit their take. In any case, extensive communication with stakeholders will be necessary to develop an efficient and acceptable approach.

Acknowledgements

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Appendix A

Models of survival and reproduction for the Svalbard population of pink-footed geese (Johnson, F. A., G. H. Jensen, J. Madsen, and B. K. Williams. 2014. Uncertainty, robustness, and the value of information in managing an expanding Arctic goose population. Ecological Modelling 273:186-199).

Survival. – We considered three alternative models to describe the dynamics of survival from non-hunting sources of mortality, θ_t: (1) survival varies randomly from year to year; (2) survival varies depending on weather conditions and population size at the start of the year (November 1); and (3) survival varies depending only on weather conditions.

The first model assumes that $\hat{\theta}_t$ has a mean of 0.951 and a standard deviation of 0.019. We used the method of moments to parameterize a beta distribution as $\hat{\theta}_t \sim Beta(125.16, 6.46)$.

For the other two models of survival, we used the logit of $\hat{\theta}_t$, total population size *N* on November 1, various weather variables *X* in the interval November 1 – October 31, and used least-squares regression to fit the model. The model including temperature days (days above freezing in Svalbard in May) and population size had the lowest AIC of all models examined:

$$ln\left(\frac{\hat{\theta}_t}{(1-\hat{\theta}_t)}\right) = 4.293 + 0.053X_t - 0.044N_t$$

where *X* is temperature days and population size *N* is in thousands. The regression coefficients for both covariates were of the expected sign and different from zero ($P < 0.05$).

Due to uncertainty about contemporary rates of survival and the degree of density dependence (especially given the recent growth in population size), we also considered a third model that included temperature days but not population size. This density-independent model had the form:

$$ln\left(\frac{\hat{\theta}_t}{(1-\hat{\theta}_t)}\right) = 2.738 + 0.049X_t$$

Reproduction. – We considered the counts of young during the autumn census, 1980-2011, as arising from binomial (or beta-binomial) trials of size N_t, and used a generalized linear model with a logit link to explain annual variability in the proportion of young (p_t). The best fitting models were based on a beta-binomial distribution of counts, which permits over-dispersion of the data relative to the binomial. The best model, as based on AIC, included population size and temperature days:

$$ln\left(\frac{\hat{p}_t}{(1-\hat{p}_t)}\right) = -1.687 + 0.048X_t + 0.014A_t$$

where *X* is May temperature days and *A* is the number of sub-adults and adults on November 1. The regression coefficients for both covariates were of the expected sign, but only the coefficient for temperature days was highly significant ($P = 0.01$). The coefficient for adult population size was only marginally significant ($P = 0.06$), and this appears to be because of a lack of evidence for density dependence post-2000.

To allow for the possibility that reproduction is not (or no longer is) density-dependent, we considered a model with only temperature days:

$$ln\left(\frac{\hat{p}_t}{(1-\hat{p}_t)}\right) = -1.989 + 0.027X_t$$

Finally, we considered a second density-independent reproduction model in which the number of young in autumn was described as rising from a beta-binomial distribution with no covariates. The parameters of this distribution were estimated by fitting an intercept-only model ($\bar{p} = 0.14, \theta = a/\bar{p} = b/(1-\bar{p}) = 43.77$).

Appendix B

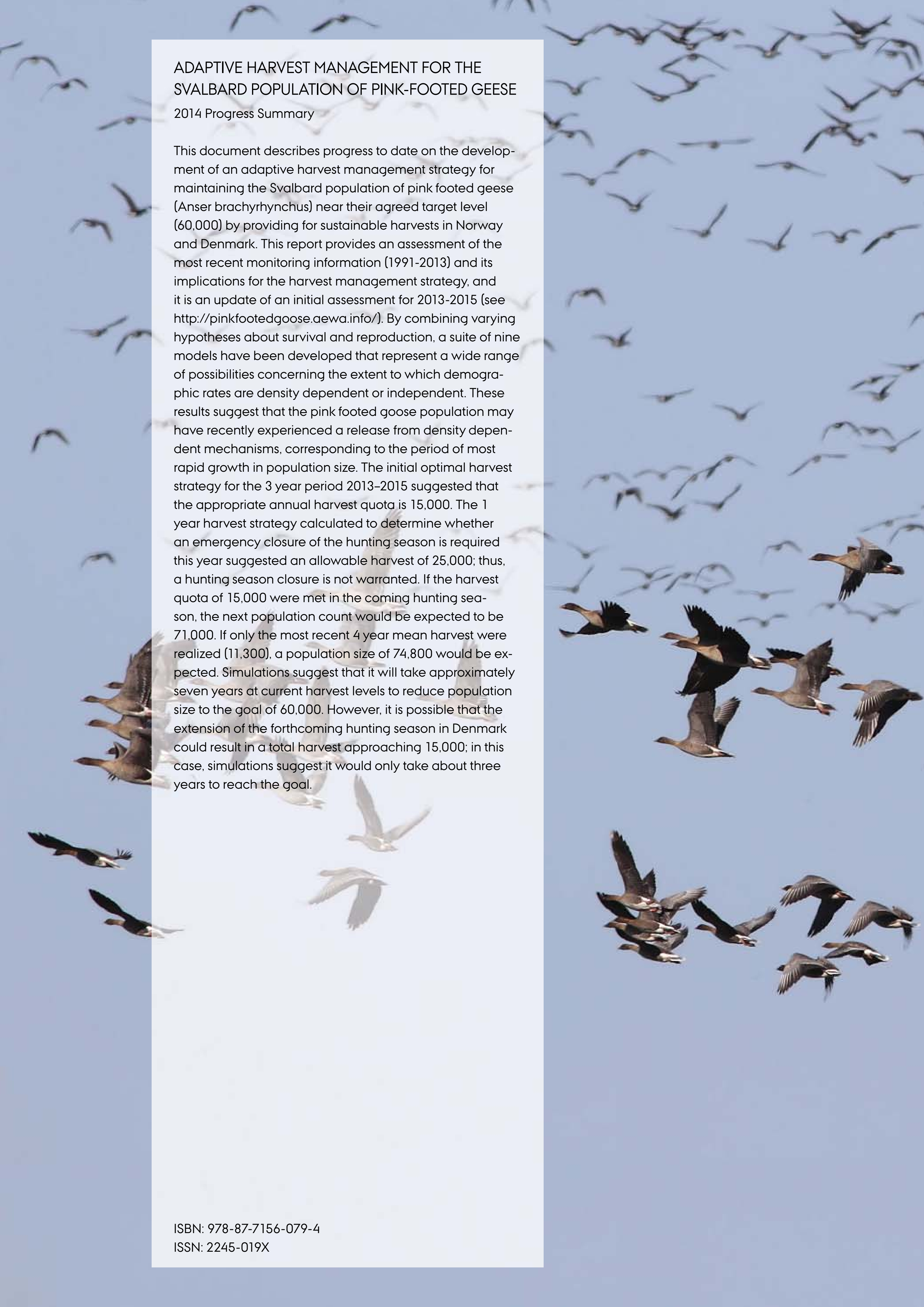
Monitoring information for the Svalbard population of pink-footed geese. N and Y represent total population size and the number of young, respectively, TempDays is the number of days above freezing in May in Svalbard, and HarvDen and HarvNor are the reported harvests from Denmark and Norway, respectively.

Year	N	Y	TempDays	HarvDen	HarvNor
1991	32500	7215	9	3000	NA
1992	32000	1984	4	2500	240
1993	34000	6154	7	2300	850
1994	33000	4092	7	2600	420
1995	35000	8260	9	2800	790
1996	33000	6072	1	2000	850
1997	37500	5400	4	2500	820
1998	44800	5466	0	1414	570
1999	38500	4736	13	1973	920
2000	43100	2112	6	2567	1400
2001	45000	4905	2	2353	548
2002	42000	4452	8	2611	655
2003	42900	5448	8	2299	684
2004	50300	5634	11	2056	1076
2005	52000	3796	8	1694	1347
2006	56400	9757	18	3518	1657
2007	60300	7658	7	4597	2221
2008	63000	8190	5	5416	2633
2009	63000	6867	15	4846	2600
2010	69000	15400	20	8841	3100
2011	80000	15600	10	8019	3410
2012	81600	8078	5	8580	2169
2013	76000	8968	8	9262	1819

Appendix C

Posterior model weights for nine alternative models describing the annual dynamics of the pink-footed goose population, assuming equal prior model weights in 1991. See Table 1 and Appendix A for a description of the models.

Year	M0	M1	M2	M3	M4	M5	M6	M7	M8
1991	0.11111	0.11111	0.11111	0.11111	0.11111	0.11111	0.11111	0.11111	0.11111
1992	0.11375	0.11438	0.11100	0.11554	0.11611	0.11300	0.10627	0.10706	0.10288
1993	0.11232	0.11453	0.11276	0.11275	0.11514	0.11400	0.10573	0.10785	0.10492
1994	0.11343	0.11146	0.10650	0.12010	0.11875	0.11451	0.10818	0.10646	0.10060
1995	0.11427	0.11367	0.10893	0.11693	0.11860	0.11561	0.10477	0.10594	0.10128
1996	0.12128	0.12691	0.12057	0.11855	0.12732	0.12288	0.08375	0.09203	0.08671
1997	0.11464	0.11820	0.11969	0.11119	0.11765	0.12109	0.09405	0.10209	0.10140
1998	0.09689	0.08423	0.07889	0.11906	0.10844	0.10417	0.14167	0.13731	0.12933
1999	0.08635	0.05249	0.06595	0.11474	0.07349	0.09427	0.19997	0.14039	0.17236
2000	0.07798	0.04887	0.05867	0.11061	0.07287	0.08962	0.21056	0.15151	0.17929
2001	0.07526	0.04600	0.04973	0.11371	0.07438	0.08712	0.21419	0.15544	0.18416
2002	0.08459	0.04805	0.06179	0.11058	0.06653	0.09509	0.20249	0.13493	0.19595
2003	0.08676	0.04836	0.06387	0.11079	0.06500	0.09634	0.20124	0.13052	0.19712
2004	0.08843	0.05427	0.06612	0.11211	0.07250	0.09902	0.18653	0.13508	0.18594
2005	0.09100	0.05544	0.06693	0.11085	0.07002	0.10205	0.18306	0.12925	0.19141
2006	0.09497	0.05639	0.06985	0.11568	0.07130	0.10650	0.17253	0.13178	0.18100
2007	0.08980	0.05591	0.03482	0.13602	0.08644	0.07810	0.21057	0.16520	0.14314
2008	0.04337	0.02766	0.00144	0.16605	0.10759	0.01229	0.33781	0.26979	0.03399
2009	0.06249	0.02967	0.00486	0.11480	0.05079	0.02941	0.38323	0.22091	0.10385
2010	0.07915	0.04667	0.00489	0.16396	0.08649	0.03445	0.29093	0.23712	0.05634
2011	0.04566	0.03399	0.00019	0.18892	0.11986	0.00405	0.30272	0.29905	0.00557
2012	0.03051	0.02295	0.00000	0.19058	0.12135	0.00006	0.31881	0.31561	0.00013
2013	0.03623	0.02750	0.00000	0.19480	0.11831	0.00002	0.32081	0.30229	0.00003



ADAPTIVE HARVEST MANAGEMENT FOR THE SVALBARD POPULATION OF PINK-FOOTED GEESE

2014 Progress Summary

This document describes progress to date on the development of an adaptive harvest management strategy for maintaining the Svalbard population of pink footed geese (Anser brachyrhynchus) near their agreed target level (60,000) by providing for sustainable harvests in Norway and Denmark. This report provides an assessment of the most recent monitoring information (1991-2013) and its implications for the harvest management strategy, and it is an update of an initial assessment for 2013-2015 (see http://pinkfootedgoose.aewa.info/). By combining varying hypotheses about survival and reproduction, a suite of nine models have been developed that represent a wide range of possibilities concerning the extent to which demographic rates are density dependent or independent. These results suggest that the pink footed goose population may have recently experienced a release from density dependent mechanisms, corresponding to the period of most rapid growth in population size. The initial optimal harvest strategy for the 3 year period 2013–2015 suggested that the appropriate annual harvest quota is 15,000. The 1 year harvest strategy calculated to determine whether an emergency closure of the hunting season is required this year suggested an allowable harvest of 25,000; thus, a hunting season closure is not warranted. If the harvest quota of 15,000 were met in the coming hunting season, the next population count would be expected to be 71,000. If only the most recent 4 year mean harvest were realized (11,300), a population size of 74,800 would be expected. Simulations suggest that it will take approximately seven years at current harvest levels to reduce population size to the goal of 60,000. However, it is possible that the extension of the forthcoming hunting season in Denmark could result in a total harvest approaching 15,000; in this case, simulations suggest it would only take about three years to reach the goal.

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