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ADAPTIVE HARVEST MANAGEMENT FOR THE SVALBARD POPULATION OF PINK-FOOTED GEESE 2016 PROGRESS SUMMARY

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Technical Report from DCE – Danish Centre for Environment and Energy No. 86 2016

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Fred A. Johnson[1]
Jesper Madsen[2]

[1]Wetland and Aquatic Research Center, U.S. Geological Survey, USA
[2]Aarhus University, Department of Bioscience

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Authors: Fred A. Johnson[1] & Jesper Madsen[2]
Institutions: [1]Wetland and Aquatic Research Center, U.S. Geological Survey, USA
[2]Aarhus University, Department of Bioscience

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Abstract: 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 (1991-2015) and its implications for the harvest management strategy. 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. Beginning with the 2016 hunting season, harvest quotas will be prescribed on an annual basis rather than every three years because of the potential to better meet population management objectives. Based on updated model weights, the recent observations of population size (74,800), the proportion of the population comprised of one-year-old birds (0.138), and temperature days in Svalbard (20), the optimal harvest quota for the 2016 hunting season is 25,000. The large increase in quota compared to that during first three years of AHM reflects stakeholders' desire to reduce population size to the goal of 60,000, recognizing that population size remains relatively high and above-average production is expected in 2016 due to a warm spring.

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

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Executive Summary

This document describes progress to date on the implementation of an adaptive harvest-management strategy designed to maintain the Svalbard population of pink-footed geese (*Anser brachyrhynchus*) near their target level (60,000) 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 2016 harvest management strategy.

The development of an adaptive harvest management (AHM) strategy requires specification of four elements: (a) a set of alternative population models, which bound the uncertainty about effects of harvest and other relevant environmental factors; (b) a set of probabilities (or weights) 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 to choose; and (d) a management 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 were developed. Those models represent a wide range of possibilities concerning the extent to which demographic rates are density dependent, and the extent to which spring temperatures influence survival and reproduction. 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 65,000 – 129,000 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 – 2015. Current model weights suggest little evidence for density-dependent survival and reproduction. These results suggest that the pink-footed goose population may have experienced a release from density-dependent mechanisms, corresponding to the period of most rapid growth in population size. There is equivocal evidence for the effect of May temperature days in Svalbard (number of days with temperatures above freezing) on survival and reproduction.

During the initial years of AHM (2013-2015), the optimal harvest strategy prescribed a harvest quota of 15,000 per year, to be shared by Norway and Denmark. The total harvest during the 2013-2015 hunting seasons was similar, but more variable (mean = 11,944, sd = 1,798), than during the preceding three years (mean = 11,380, sd = 588). Population size was similar, but less variable, during the three years of AHM (mean = 74,823, sd = 1,165) compared to the preceding years (mean = 76,867, sd = 6,859). Recent population counts confirm the suspicion that the count in May 2015 of 59,000 was biased low, and adjustments have been made. The percentage of young in autumn during the three-year period of AHM was lower and less variable (mean = 0.120, sd = 0.018) than during the preceding three years (mean = 0.171, sd = 0.064).

Beginning with the 2016 hunting season, harvest quotas will be prescribed on an annual basis rather than every three years because of the potential to better meet population management objectives. The optimal harvest strategy remains “knife-edged,” however, meaning that small changes in resource status can precipitate large changes in the annual harvest quota. This is likely to be of concern to hunters, and the International Working Group is actively investigating ways in which large swings in harvest quotas might be dampened. Based on updated model weights, the recent observations of population size (74,800), the proportion of the population comprised of one-year-old birds (0.138), and temperature days in Svalbard (20), the optimal harvest quota for the 2016 hunting season is 25,000. The large increase in quota compared to that during first three years of AHM reflects stakeholders’ desire to reduce population size to the goal of 60,000, recognizing that population size remains relatively high and above-average production is expected in 2016 due to a warm spring. The annual harvest quota is expected to average about 8,700 (sd = 9,600) over the long term. We stress again, however, that high annual variability in the annual quota can be expected unless the management objective is modified to dampen it and/or the pink-footed goose population exhibits more density dependence.

1 Introduction

The Svalbard population of pink-footed geese has increased from about 10,000 individuals in the early 1960's to roughly 75,000 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 development and implementation of an adaptive harvest-management strategy for maintaining pink-footed goose (*Anser brachyrhynchus*) abundance near their target level (60,000) by providing for sustainable harvests in Norway and Denmark. Specifically, this report provides an update of relevant information for the third year following the harvest quota prescribed for the 2013-2015 hunting seasons. It also provides the derived harvest strategy for the 2016 hunting season.

A previous progress report (Johnson & Madsen 2015) 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 17,000. For comparison, the harvest in Norway and Denmark has averaged about 12,000 per year during the last three years.

The passive form of adaptive management is being used 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 weights have more influence on the optimal harvest strategy.

This report focuses on updates of population status and alternative model weights, following the prescription for an annual harvest quota of 15,000 for the 3-year decision-making cycle beginning with the 2013 hunting season. It also provides an optimal harvest strategy and associated harvest-quota prescription for the 2016 hunting season. It uses the most recent data on harvest (autumn 2015), population size (autumn 2015/ spring 2016), and weather conditions on the breeding ground (May 2016)(Madsen et al. 2016). This report also describes the status of ongoing developments in adaptive harvest management for pink-footed geese, 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, which bound the uncertainty about effects of harvest and other relevant environmental factors; (b) a set of probabilities (or weights) 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 to choose; and (d) an objective function, by which alternative harvest strategies can be evaluated and an optimal strategy chosen. An optimal management strategy prescribes a harvest quota for each and every level of model weights, and for population abundance and environmental conditions that may be observed at the time a decision is made.

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 65,000 – 129,000 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 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 (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 1991-2015, 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 $n = 12$. This error reflects so-called process error, which is the variation in population size not explained by the models.

We also assessed the ability of the model set as a whole to predict population sizes by comparing the cumulative distribution of predictions with that of observations. The two distributions were compared visually and using a two-tailed Kolmogorov-Smirnov test (Marsaglia, G., W. W. Tsang, and J. Wang. 2003. Evaluating Kolmogorov's distribution. Journal of Statistical Software 8(18):4).

Alternative Harvest Quotas

We considered a set of possible harvest quotas of 0 to 30,000 in increments of 2,500. This set seemed reasonable given the current harvest in Norway and Denmark of approximately 12,000 and only coarse control over harvests. A quota of zero represents a closure of hunting seasons in Norway and Denmark. 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 (Appendix B). 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 maintain the population size within acceptable limits by regulating harvest in Norway and Denmark. 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, and where the expectation E is taken with respect to random environmental variation and model uncertainty. Population utility in turn is defined as a function of a time-dependent action conditioned on system state:

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

where N_{t+1} is the population size (in thousands) expected as a result of the harvest quota and the population goal is 60 (thousand) (Fig. 1). The 10 (thousand) in the equation for population utility represents the difference from the population goal when utility is reduced by one half. Thus, the objective function devalues harvest-quota choices 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 passively adaptive harvest strategy using stochastic dynamic programming. We used the open-source software MDPSolve© (https://sites.google.com/site/mdpsolve/) to compute an optimal solution. Based on a recent decision by the International Working Group, we calculated an optimal harvest strategy for a one-year decision making cycle (as opposed to a three-year cycle during initial implementation of adaptive harvest management). The optimal harvest strategy for the current model weights is a large table of four dimensions (all possible combinations of the number of young, adults, temperature days, and the corresponding harvest quota) and thus is difficult to display graphically. Therefore, we fit a classification tree to this optimal strategy (Ripley, B. 2016. tree: Classification and Regression Trees. R package version 1.0-37. https://CRAN.R-project.org/package=tree). The classification tree is a simplified representation of the optimal strategy and is provided to help discern significant patterns. The prescribed harvest quota is determined by the table of the optimal strategy.

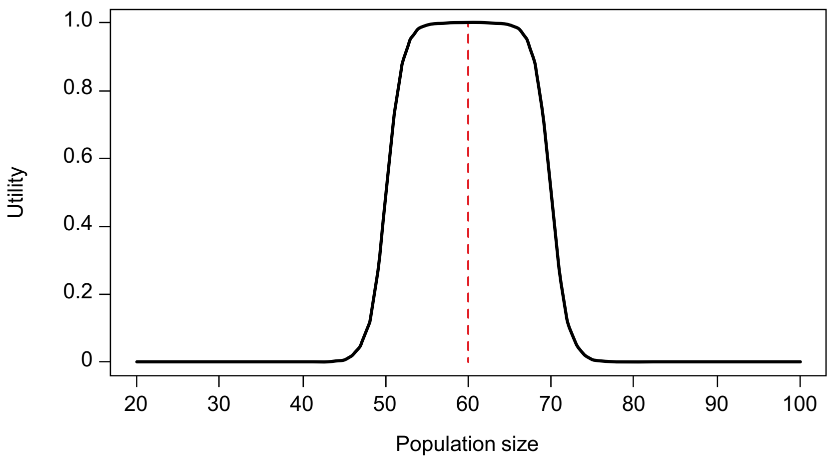


Figure 1. Utility (i.e., stakeholder satisfaction) expressed as a function of population size of pink-footed geese. Population sizes between about 50,000 and 70,000 are acceptable (and thus have high utility), while those outside that range are very undesirable (and thus have low utility).

3 Results and Discussion

Population status

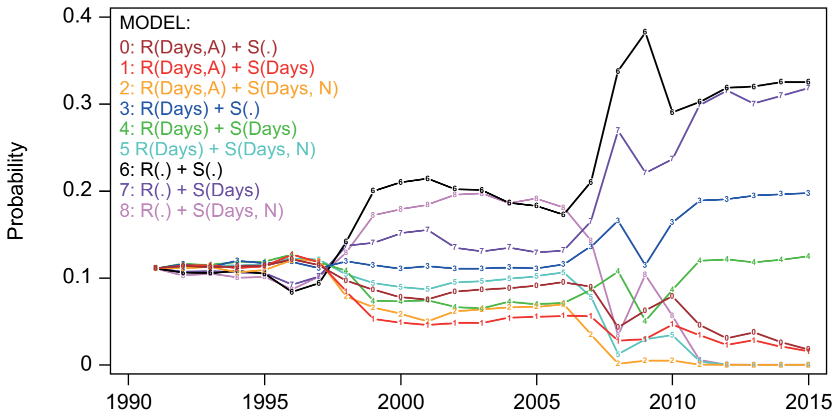
Pink-footed goose abundance traditionally has been determined in November, but counts in May have also been conducted for the last seven years because of concerns about negative bias in the November counts. Indeed, in five of those years, May counts have exceeded those in November, suggesting the likelihood that birds were missed during the November counts (because only population losses occur between November and May). In the past, we have used May counts when they were available for updating the harvest management strategy. During the last hunting season, however, Denmark eliminated hunting in January because of an unexpectedly low count in May 2015. Subsequent counts in November 2015 and May 2016 have assured us that the count in May 2015 was biased low (likely by a large amount). Obviously, differences in counts between November and May are problematic because one or both counts may be biased to an unknown degree, and because of differences in timing during the annual cycle. We will ask the International Working Group to discuss methods for addressing this issue at their December 2016 annual meeting. For the purpose of updating the harvest strategy this year, however, we have adopted an ad hoc solution, in which the maximum of the November or May count is used. We have made this adjustment retroactive for the period in which May counts are available (May 2010-2016), resulting in use of the November 2014 and 2015 counts rather than the subsequent May counts. We recognize the fact that the autumn and spring counts are separated by several months, and our approach omits the potential for significant mortality just prior to spring migration.

The population count in November 2015 was 74,800 and in May 2016 it was 74,000. The proportion of young-of-the-year in November 2015 was 0.138, which is close to the long-term average of 0.135 (sd = 0.050). Thus, the November population was comprised of about 10,300 young-of-the-year and about 64,500 adults. Svalbard has experienced a very warm spring, with 20 days above freezing in May 2016. This is far higher than the long-term average of 7.8 days (sd = 5.3) during 1990-2015.

Updating model weights

We used the most up-to-date set of monitoring information (Appendix C; Madsen et al. 2016) to update model weights for the 1991 – 2015 period. Discrimination among the nine alternative models became most pronounced after 2006 (Fig. 2, Appendix D). Current model weights (i.e., those based on population size after the 2015 harvest) suggest no evidence for density-dependent survival ($p_{DD-S} = 0.0000$, Fig. 3) (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). Similarly, the evidence for density-dependent reproduction is very low ($p_{DD-R} = 0.0938$, Fig. 3). Model weights thus far suggest that the pink-footed goose population may have experienced a release from density-dependent mechanisms, corresponding to the period of most rapid growth in population size (Fig. 4). There was equivocal evidence for the effect of TempDays on survival ($p_{DAYS-S} = 0.4591$, 2 of 3 survival models) and on reproduction ($p_{DAYS-R} = 0.3336$, 2 of 3 reproductive models) (Fig. 3). We also calculated predictions of population size for each year based on each model, and then compared them with observed population sizes (Fig. 5). The predictive ability of most models has been relatively poor for population sizes exceeding 60,000, with a tendency towards predictions of population size that are less than those observed. Nonetheless, the model set as a whole has produced a distribution of predictions that does not differ significantly from the distribution of observed population sizes ($D = 0.17, P = 0.59$, Fig. 6).

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.



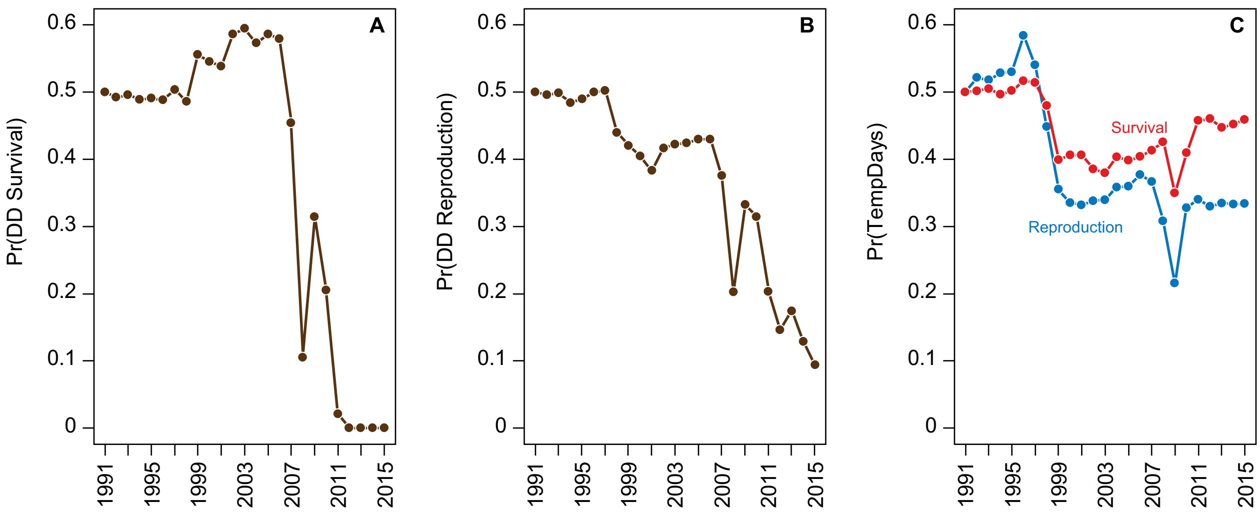
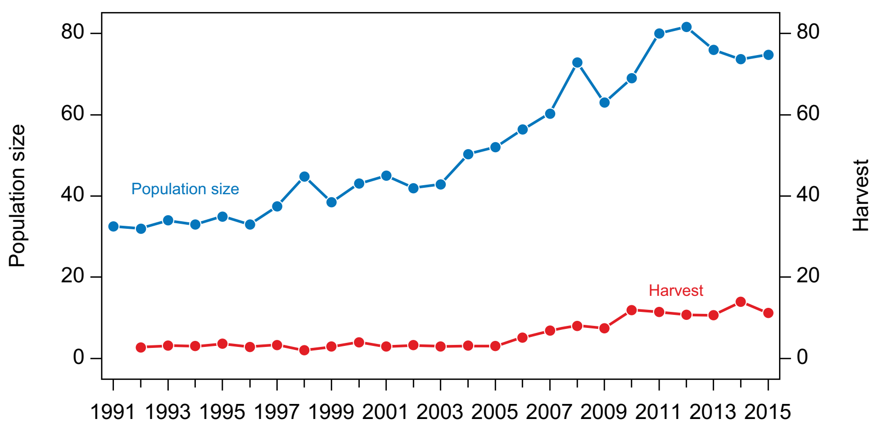


Figure 3. Aggregate weight on pink-footed goose population models that incorporate (A) density-dependent survival; (B) density-dependent reproduction; and (C) days above freezing in May in Svalbard in the reproductive and survival processes.

Figure 4. Counts of pink-footed geese during autumn/spring and total harvest (both in thousands) in Norway and Denmark.



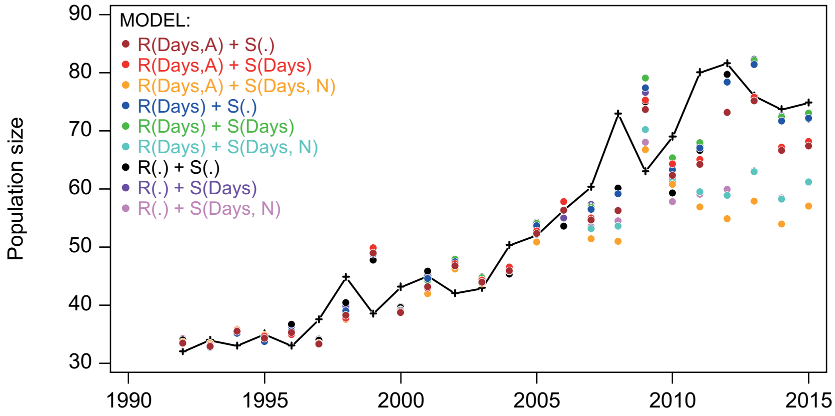
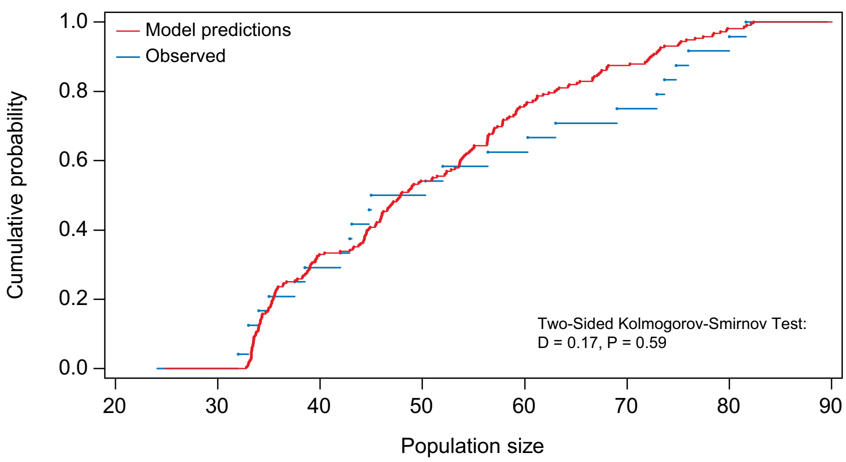


Figure 5. Comparison of observed population sizes (line) and those predicted by nine alternative models (filled circles) describing the annual dynamics of the pink-footed goose population. See Table 1 and Appendix A for a description of the models. Predictive ability declined as the population entered a rapid growth phase (i.e., observed population sizes in excess of about 55,000). Note that not all predictions are visible in the early years because model predictions were similar and thus filled circles overlap.

Figure 6. Cumulative distributions of predicted and observed population sizes (in thousands) of pink-footed geese. See Table 1 and Appendix A for a description of the predictive models. Predictive ability declined as the population entered a rapid growth phase (i.e., observed population sizes in excess of about 55,000). Based on the Kolmogorov-Smirnov test, however, there is no significant difference detectable (P = 0.59) in the two distributions overall.



Review of the 2013-2015 hunting seasons

During the initial years of AHM (2013-2015), the optimal harvest strategy prescribed a harvest quota of 15,000 per year, to be shared by Norway and Denmark. The total harvest during the 2013-2015 hunting seasons was similar, but more variable (mean = 11,944, sd = 1,798), than during the preceding three years (mean = 11,380, sd = 588). We note that the high variability in harvest during the 2013-2015 hunting seasons was due to the higher-than average harvest in Denmark in January 2015, which resulted from a one-year extension of the hunting season. Population size was also similar, but less variable, during the three years of AHM (mean = 74,823, sd = 1,165) compared to the preceding years (mean = 76,867, sd = 6,859). The percentage of young in autumn during the three-year period of AHM was lower and less variable (mean = 0.120, sd = 0.018) than during the preceding three years (mean = 0.171, sd = 0.064).

Harvest strategy for the 2016 season

Beginning with the 2016 hunting season, harvest quotas will be prescribed on an annual basis rather than every three years because of the potential to better meet population management objectives. The fitted classification tree suggests that the abundance of adults is the key criterion for determining the optimal harvest quota, followed by the abundance of young and temperature days (Fig. 7). The optimal harvest strategy, however, remains "knife-edged," meaning that only small changes in population size (particularly around the goal of 60,000) are required to produce large changes in the harvest quota (Fig. 8). 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.

Based on updated model probabilities, the recent observations of adult (64,500) and young (10,300) abundance, and 20 days above freezing in May in Svalbard, the optimal harvest quota for Norway and Denmark combined during the 2016 hunting season is 25,000 (7,500 for Norway and 17,500 for Denmark based on the agreed allocation of 30% and 70%, respectively). The large increase in quota compared to that during the first three years of AHM reflects stakeholders' desire to reduce population size to the goal of 60,000, recognizing current population size is relatively high and above-average production is expected in 2016 due to a warm spring. Based on updated model weights, the annual harvest quota is expected to average about 8,700 (sd = 9,600) over the long term. We stress again, however, that high annual variability in the annual quota can be expected unless the management objective is modified to dampen it and/or the pink-footed goose population exhibits more density dependence.

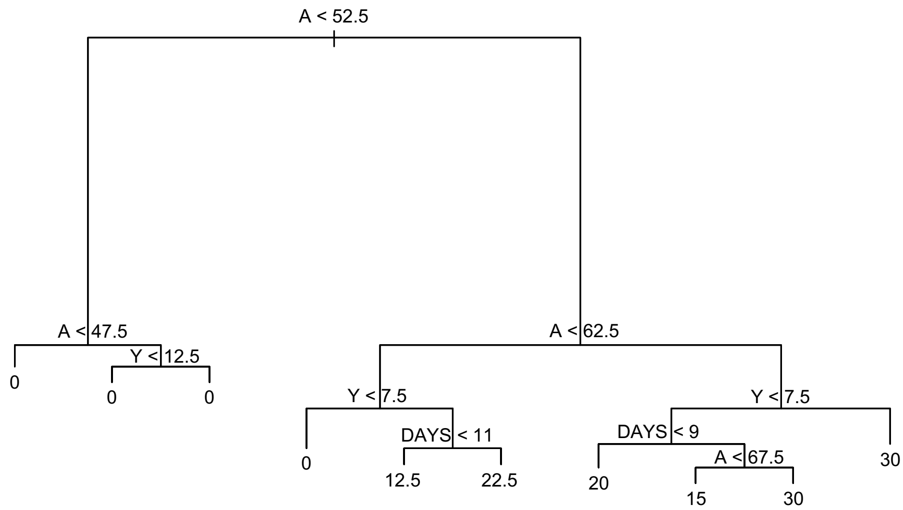
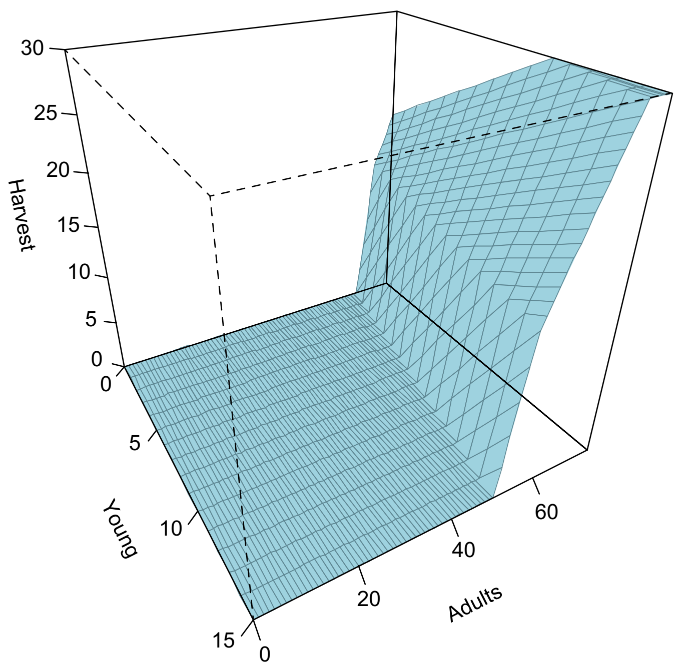


Figure 7. A statistical approximation of the optimal harvest strategy based on current model weights for pink-footed geese. The classification tree represents a series of yes-no questions (yes is the left branch; no is the right branch) for the abundance of adults and young (Y and A in thousands, respectively), and the number of days above freezing in May in Svalbard (DAYS). The approximate harvest quota (in thousands) is given at the ends of the branches. We stress that this is not the actual harvest strategy (which consists of a large table), but a statistical representation of the strategy designed to help discern important patterns. Because the classification tree represents an approximate harvest strategy, it depicts the 2016 harvest quota (rightmost branch) as 30,000, yet the prescribed quota based on the actual strategy is 25,000.

Figure 8. Harvest strategy for the Svalbard population of pink-footed geese, for the observed average of eight days above freezing in Svalbard in May, and as based on the most recent weights on the alternative population models (Appendix D). Harvest quotas and the number of young and adults are in thousands. The strategy is very knife-edged, meaning that large changes in harvest quota can accompany small changes in population size.



4 Ongoing Development of the Adaptive Harvest Management Process

Monitoring needs

There are a number of improvements being made in monitoring programs for pink-footed geese and we here report on recent progress.

Annual harvest estimates do not include the crippled, unretrieved geese which are likely to die due to their injuries before the end of the hunting season. Moreover, harvest quotas represent the total allowable kill, including both retrieved and unretrieved geese. Although the rate of crippling remains unknown, recent field work suggests that wounding of pink-footed geese is on the decline (http://pinkfootedgoose.aewa.info/node/201). Studies of this sort should be conducted periodically to help ensure that the actual harvest does not exceed the quota.

Because of concerns about the reliability of population counts, we suggest that independent population estimates should be derived based on capture-resightings of marked individuals. This has been done in the past, but the estimates need to be updated. Throughout the years, the proportion of marked individuals in goose flocks has been recorded in the field during autumn and spring. For precise estimates, however, it will be necessary to increase the proportion of marked individuals in the population, which has fallen in recent years due to difficulties catching a sufficiently large sample in Denmark. In each of the last two springs, however, over 350 pink-footed geese were caught by cannon-netting and neck-banded in Nord-Trøndelag, Norway, and it is planned to continue this effort in the coming years. Work on capture-recapture estimation of population size is in progress and will be presented in a separate report in 2016. This will also include recommendations for future monitoring and marking activities.

Reconsideration of management objective

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, the model-averaged finite population growth rate is $\lambda = 1.17$ (or 17% per year); thus, the overall rate of hunting mortality needed to stabilize population size is $(\lambda - 1)/\lambda = 0.15$. 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 60,000 pink-footed geese. Combining exponential growth with this management objective produces a harvest strategy that is extremely knife-edged. As a consequence, the optimal harvest quota may be quite high for populations only slightly higher than the goal of 60,000, 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. 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 are endeavoring to provide sufficient analyses to the International Working

Group so that they can make an informed decision about modification to the management objective to dampen variability in the harvest quota. Preliminary analyses suggest that smaller year-to-year changes in harvest quota could be achieved, with less risk of closed seasons, if hunters are willing to accept more frequent changes in the quota.

Revision of population models

Another principal need concerns the form of the model set. We believe a Bayesian state-space model may be a more useful 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 model development, 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 state-space 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 wide range of parameter values. Some progress has been made in the last year in terms of basic model structure, but much remains to be done to explore and fit environmental covariates that might explain observed changes in population size.

5 Acknowledgements

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Appendix A.

Models of survival and reproduction for the Svalbard population of pink-footed geese (Johnson et al. 2014).

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:

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

Annual survival is then the product of survival from natural causes $\hat{\theta}$ and hunting:

$$\hat{S}_t = \hat{\theta}_t(1-\hat{h}_t)$$

where $\hat{h}$ = estimated harvest rate (including retrieved and un-retrieved harvest) of birds that have survived at least one hunting season.

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.

The difficulties of specifying a harvest quota when population size is measured post-harvest.

To optimize a total harvest quota (or target), we must first be able to specify (for varying harvest quotas) the portion of the harvest that is expected to be young and the portion that is expected to be adults (actually sub-adults + adults). The expected age composition of the harvest, in turn, depends on the *pre-harvest age composition* of the population (i.e., prior to both the census and harvesting) and the *differential vulnerability of young*.

We can easily calculate the pre-harvest population of adults as:

$$A_t = (Y_{t-1} + A_{t-1})\,\theta_{t-1}$$

The pre-harvest population of young is:

$$Y_t = (Y_{t-1} + A_{t-1})\,\theta_{t-1}\left(\frac{1-h_t}{1-d\cdot h_t}\right)R_t$$

where both h and R are post-harvest and post-census. But h is not known (or specified) when total harvest is the control variable. However, this equation could provide the pre-harvest population of young (and therefore resolve our problem), if we could assume $\left(\frac{1-h_t}{1-d\cdot h_t}\right)$ is constant. But even if d is constant (which we do assume), $\left(\frac{1-h_t}{1-d\cdot h_t}\right)$ is not (it depends on the value of h).

Another possibility we explored was to assume that

$$\theta_{t-1}\left(\frac{1-h_t}{1-d\cdot h_t}\right) \approx 1 .$$

This was found to be a reasonable assumption, but only based on the assumptions used to partition survival into non-hunting and hunting components for the period in which we had survival rate estimates. If harvest rate varies from the approximately 4% assumed during the period of survival estimates, then the above equation is no longer a valid assumption. Of course, we are explicitly investigating the impacts of varying harvest rates.

Our conclusion is that a post-harvest assessment of population size and reproductive success imposes restrictions on the investigation of optimal harvest strategies that cannot be circumvented. This is part of the basis for recommending a pre-harvest population census and some measure of reproductive success prior to harvesting (which could be accomplished by assessing the age composition of the harvest). The problem could also be resolved if estimates of realized harvest rates of both young and adults were available.

Appendix C.

Monitoring information for the Svalbard population of pink-footed geese. N and Prop(Y) represent total population size and the proportion 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. All values pertain to the designated calendar year.

Year	N	Prop(Y)	TempDays	HarvDen	HarvNor
1991	32500	0.222	9	3000	NA
1992	32000	0.062	4	2500	240
1993	34000	0.181	7	2300	850
1994	33000	0.124	7	2600	420
1995	35000	0.236	9	2800	790
1996	33000	0.184	1	2000	850
1997	37500	0.144	4	2500	820
1998	44800	0.122	0	1414	570
1999	38500	0.123	13	1973	920
2000	43100	0.049	6	2567	1400
2001	45000	0.109	2	2353	548
2002	42000	0.106	8	2611	655
2003	42900	0.127	8	2299	684
2004	50300	0.112	11	2056	1076
2005	52000	0.073	8	1694	1347
2006	56400	0.173	18	3518	1657
2007	60300	0.127	7	4597	2221
2008	72900	0.130	5	5416	2633
2009	63000	0.109	15	4846	2600
2010	69000	0.220	20	8841	3100
2011	80000	0.195	10	8019	3410
2012	81600	0.099	5	8600	2169
2013	76000	0.118	8	8800	1819
2014	73700	0.103	8	12200	1791
2015	74800	0.138	9	8761	2460

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

2016 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 (1991-2015) and its implications for the harvest management strategy. 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. Beginning with the 2016 hunting season, harvest quotas will be prescribed on an annual basis rather than every three years because of the potential to better meet population management objectives. Based on updated model weights, the recent observations of population size (74,800), the proportion of the population comprised of one-year-old birds (0.138), and temperature days in Svalbard (20), the optimal harvest quota for the 2016 hunting season is 25,000. The large increase in quota compared to that during first three years of AHM reflects stakeholders' desire to reduce population size to the goal of 60,000, recognizing that population size remains relatively high and above-average production is expected in 2016 due to a warm spring.

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