Adaptive Harvest Management for the Svalbard Population of Pink-footed Geese (*Anser brachyrhynchus*)

AEWA European Goose Management Platform

EGMP Technical Report No.5

2017 Progress Summary

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EGMP Technical Report No. 5

Prepared by the AEWA European Goose Management Platform Data Centre

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1. Contents

2. 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 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 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 a mathematically optimal strategy identified.

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 – 2016. Current model weights suggest little 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 is equivocal evidence for the effect of May temperature days in Svalbard (number of days with temperatures above freezing) on survival and reproduction.

Beginning with the 2016 hunting season, harvest quotas are chosen on an annual basis rather than every three years because of the potential to better meet management objectives. The optimal harvest strategy, however, remains "knife-edged," meaning that small changes in resource status can precipitate large changes in the annual harvest quota. This potential outcome is likely to be of concern to hunters, and we are investigating ways in which large swings in harvest quotas might be dampened. Based on updated model probabilities, the recent observations of record-high population size (88,000), the above-average proportion of the population comprised of one-year-old birds (0.196), and temperature days in Svalbard (4), the suggested harvest quota for the 2017 hunting season is 36,000. Last year the quota was 25,000, yet a harvest of only 16,143 was realized. We are increasingly concerned that with the return of average spring temperatures in Svalbard, the population will continue to grow beyond managers' ability to control it, as is the case with many goose populations in Europe and North America.

3. Introduction

The Svalbard population of pink-footed geese has increased from about 10,000 individuals in the early 1960's to 88,000 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 the 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 relevant information for establishing the 2017 hunting seasons.

Johnson et al. (2013) described the compilation of relevant demographic and weather data and specified an annual-cycle model for pink-footed geese (http://pinkfootedgoose.aewa.info/sites/default/files/article_attachments/AHM%20Cooperator%20Report%201%20%281Feb2013%29%20FINAL.pdf). 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, and the extent to which spring temperatures influence survival and reproduction. These nine models vary significantly in their predictions of the harvests required to maintain the population near the goal of 60,000.

The passive form of adaptive management is used to formulate an optimal harvest strategy for pink-footed geese. 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. Model weights are updated each year based on the annual monitoring program; thus, the harvest strategy evolves over time as uncertainty about population dynamics is reduced.

This report focuses on updates of population status and alternative model weights, given the chosen harvest quota of 25,000 for the 2016 hunting season. It also provides an optimal harvest strategy and suggested harvest quota for the 2017 hunting season. It uses the most recent data on harvest (autumn 2016), population size (spring 2017), and weather conditions on the breeding ground (May 2017). This report also describes the status of ongoing developments in adaptive harvest management for pink-footed geese, as well as emerging technical and management issues.

4. 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 identified. An optimal management strategy identifies the most appropriate 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.

4.1. 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. 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)

4.2. 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 1991-2016, 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:

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

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:

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

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).

4.3. Alternative Harvest Quotas

We considered a set of possible harvest quotas of 0 to 50,000 in increments of 2,000. This set seemed reasonable given the recent average harvest of roughly 13,000 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.

4.4. Objective Function

The International Working Group established a management objective 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) at time t is a temporal sum of the product of harvest and 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 harvest $H(a_\tau|x_\tau)$ and population utility $u(a_\tau|x_\tau)$ are action $(a_\tau)$and resource-dependent (x_τ). Population utility 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 60,000 (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 (SDP). 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 (number of young and adults, temperature days, and corresponding harvest quota) and thus is difficult to display graphically and to interpret. Therefore, we depict a portion of the strategy with TempDays fixed near their average (8), as well as at those associated with late (TempDays = 0) and early (TempDays = 16) springs. We stress that the harvest strategy derived with SDP is mathematically optimal with respect to the stated management objectives, the alternative harvest quotas available, and the stochastic responses in population size. Of course, the decision maker is free to disregard the harvest strategy completely if any of these elements are subject to debate, or to choose a different harvest quota based on other considerations.

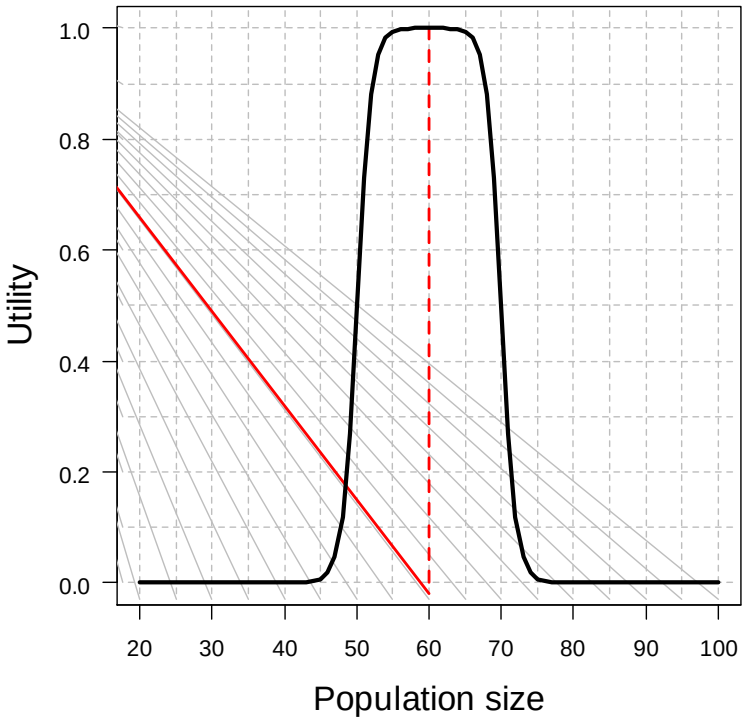

Figure 1. Utility (i.e., stakeholder satisfaction) expressed as a function of population size of pink-footed geese. Population sizes between about 50,000 and 70,000 are acceptable (and thus have high utility), while those outside that range are very undesirable (and thus have low utility).

5. Results and Discussion

5.1. Population status

Pink-footed goose abundance traditionally has been determined using raw counts in November, but counts in April or May have also been conducted for the last eight years because of concerns about increasing (negative) bias in the November counts. Indeed, in six of those years, May counts have exceeded those in November, suggesting the possibility that birds were missed during the November counts (because only population losses occur between November and May). Thus, spring counts have become the standard for updating the harvest management strategy. During the 2015 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 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 in any given year and because of differences in timing. Thus, we have adopted an admittedly *ad hoc* solution, in which the November or May count that is deemed most accurate by those conducting the censuses is used for the purpose of updating the harvest strategy.

The population count in November 2016 was 88,000 – 104,000, with the range of uncertainty a result of delayed timing of some counts (Madsen et al. 2017. Svalbard Pink-Footed Goose Population Status Report 2016-17. AEWA European Goose Management Platform Data Centre, Aarhus University). In April/May 2017 population size was estimated as 88,000, which we use for purposes of this report. The proportion of young-of-the-year in November 2016 was 0.196, which is much higher than the long-term average of 0.138 (sd = 0.050). Thus, the population was comprised of about 17,000 young-of-the-year and about 71,000 adults. This year, Svalbard has experienced a later than normal spring, with only 4 days above freezing in May 2017.

5.2. Updating model weights

We used the most up-to-date set of monitoring information (Appendix C) to update model weights for the 1991 – 2016 period. 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 2016 harvest) suggest little evidence of density dependence ($p_{DD} = 0.0357$) (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). There is no evidence for density-dependent survival $p_{DD-S} = 0.0000$ (Fig. 3). Similarly, the evidence for density-dependent reproduction is very low ($p_{DD-R} = 0.00483$, 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 ($p_{DAYS-S} = 0.6126$, 2 of 3 survival models), but an increase in evidence for its effect on reproduction ($p_{DAYS-R} = 0.7298$, 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 ($D = 0.17, P = 0.54$, Fig. 6).

5.3. Harvest strategy for the 2017season

Beginning with the 2016 hunting season, harvest quotas are chosen on an annual basis rather than every three years because of the potential to better meet population management objectives. The optimal harvest strategy is computed based on current model weights and identifies the most appropriate harvest quota for each possible combination of adult and young abundance and TempDays that might be observed in the monitoring program. This year, we encountered difficulties in getting the strategy to converge numerically, partly due to the continuing decline in evidence for density dependence, and partly due to the nature of the objective function. In the objective function used since 2013, goals for population size and sustainable harvest are strongly complimentary, meaning that meeting both goals is necessary to maximize stakeholder satisfaction. This produces a tension that is difficult to reconcile because in the absence of density dependence high harvest can be achieved only with high populations (those much higher than the goal). We tried a number of approaches to achieve convergence to the optimal strategy, but failed to do so. Although we were able to derive a strategy, we cannot be sure how close it is to the true optimum. With the current population comprised of 71,000 adults and 17,000 young, and with 4 TempDays in May 2017, the strategy prescribes a harvest quota for the 2017 season of 44,000. Yet a harvest of 44,000 would be expected to produce a subsequent population size of 53,900 (95% CL: 43,300 – 67,000), which is rather far below the goal of 60,000.

A possible solution for calculating an optimal strategy is to modify the objective function in such a way that meeting the population goal is the sole objective, to be attained by the regulation of harvest. Thus, harvest would have no explicit value, but would merely be a tool for achieving the population goal. The modified objective function is thus:

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

which is different from the original objective function in that it omits harvest, $H(a_\tau|x_\tau)$, from the summation term.

Using this objective function, the strategy converged quickly to the optimum. The associated strategy reflects some effect of TempDays, with harvest quotas quickly increasing as the number of adults exceed 60,000 (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 (71,000) and young

(17,000) abundance, and 4 days above freezing in May in Svalbard, the optimal modeled harvest quota for Norway and Denmark combined during the 2017 hunting season is 36,000. This represents an increase over the harvest quota for 2016 of 25,000, and is attributable to the record-high population size in spring of 2017. A harvest of 36,000 would be expected to result in a subsequent population size of 61,900 (95%CL: 49,700 – 76,900), which is very close to the goal. However, it seems unlikely that hunters could achieve this harvest. Last year the quota was 25,000, yet a total harvest of only 16,143 was realized. If we assume a similar harvest this year, the expected population next year is 81,900 (95%CL: 65,800 – 101,800), which represents a small decline. This expected decline is partly attributable to the late spring in Svalbard in 2017. We are increasingly concerned that with the return of more average spring temperatures in Svalbard, the population will continue to grow beyond managers' ability to control it, as is the case with many goose populations in Europe and North America.

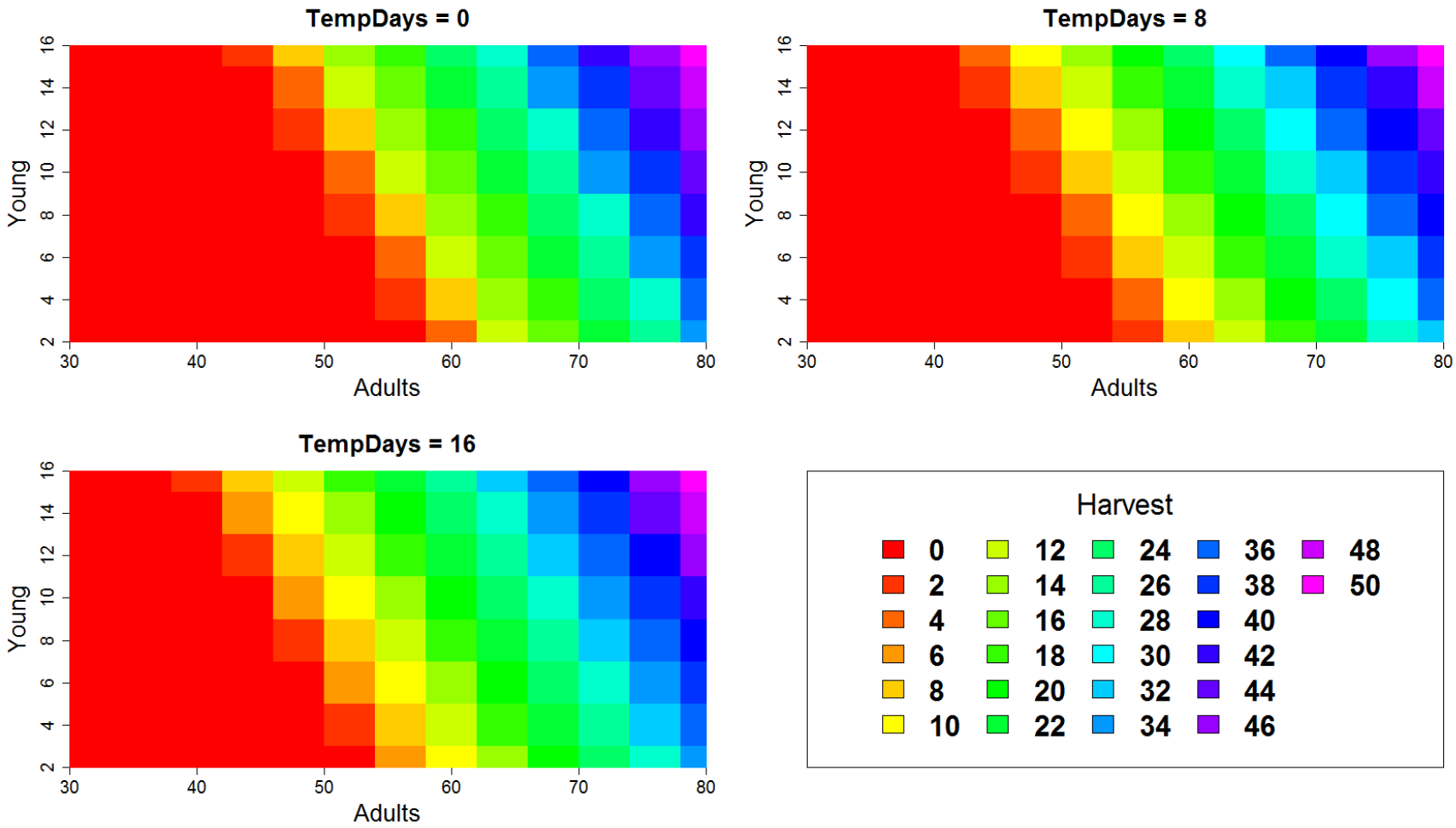

Figure 7. Optimal harvest quotas (in thousands) for pink-footed geese based on the number of adults and young (both in thousands) and the number of days above freezing in May in Svalbard (TempDays), as based on the most recent weights on the alternative population models (Appendix C).

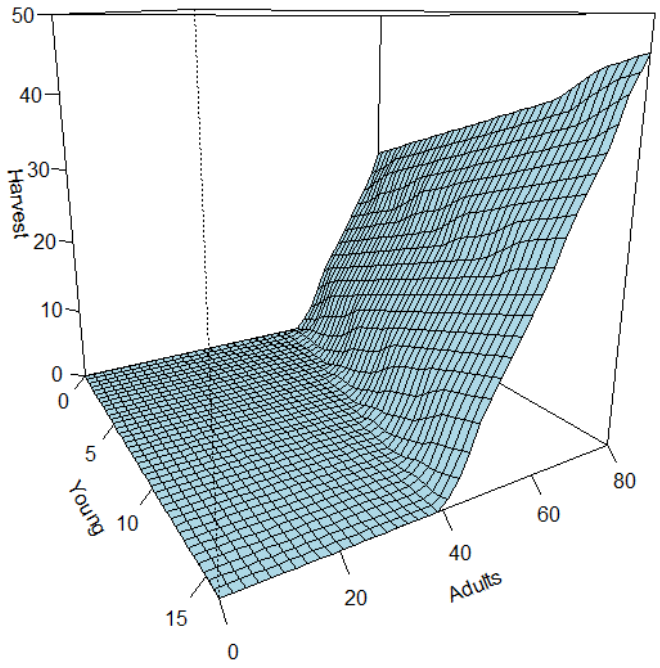

Figure 8. Harvest strategy for the Svalbard population of pink-footed geese, for the observed average of eight days above freezing in Svalbard in May, and as based on the most recent weights on the alternative population models (Appendix C). Harvest quotas and the number of young and adults are in thousands.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

6. Ongoing Development of the Adaptive Harvest Management Process

6.1. Monitoring needs

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

1. Annual harvest estimates do not include thewounded, 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. Recent work suggests that wounding of pink-footed geese is on the decline (Clausen, K. K., T. E. Holm, L. Haugaard, and J. Madsen. 2017. Crippling ratio: A novel approach to assess hunting-induced wounding of wild animals. Ecological indicators 80:242-246.). Studies of this sort, conducted periodically could help ensure that the actual harvest does not exceed the quota.
2. Because of concerns about the reliability of population counts, we suggest that independent population estimates be derived based on capture-resightings of marked individuals. There has been a renewed effort to derive these estimates in recent years (see Madsen et al. 2017. Svalbard Pink-Footed Goose Population Status Report 2016-17. AEWA European Goose

Management Platform Data Centre, Aarhus University), but we stress that this effort would require a continuing and sustained effort to mark and observe geese.

6.2. 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. This causes a tension between the objectives of maintaining the population near the goal of 60,000 and providing maximum, sustainable hunting opportunity in Denmark and Norway. This tension is causing numerical issues in deriving an optimal strategy. We have suggested a solution in this report that shifts the sole emphasis to maintaining the population near goal, while using harvest to accomplish that objective. This approach does not explicitly account for the value of harvest, but rather assumes harvest is merely a tool to maintain population abundance within acceptable limits. Yet we know that hunters value the hunting opportunity afforded by sustainable populations of waterbirds. Therefore, we could consider an objective function that accounts for both the desire to maintain a population near its goal and the desire to provide sustainable hunting opportunities:

$$V^*(A_t|x_t) = \max_{(A_t|x_t)} E\left[\sum_{\tau=t}^{T} w_p u(a_\tau|x_\tau) + \left(1 - w_p\right)H(a_\tau|x_\tau)|x_t\right]$$

where w_p is the relative degree of emphasis on maintaining the population near its goal (note that for $w_p = 1$ the objective function reduces to the one used in this report). The second term then is the relative value of harvest, scaled by the maximum harvest under consideration. Thus, $w_p = 1$ represents a sole objective related to population size and $w_p = 0$ represents a sole objective of maximizing sustainable harvest. Values of w_p intermediate between 0 and 1 represent a mix of both objectives. This additive objective function avoids the problem of strong complimentarity present in the original, multiplicative objective function. We emphasize that the assignment of weights is not the purview of scientists, but of decision makers who must judge how best to balance the desires of different stakeholder interests.

A second concern involves the size of the change in year-to-year harvest quotas. The absence of density dependence in the population contributes to a harvest strategy that is 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. Preliminary analyses suggest that smaller year-to-year changes in harvest quota could be achieved, with less risk of closed hunting seasons, if hunters are willing to accept more frequent changes in the quota.

6.3. 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 systematic 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 recently 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.

7. Acknowledgements

Funding for this research was provided by national and provincial statutory authorities in support of the AEWA European Goose Management Platform Data Centre (Finland, Norway, Sweden, Denmark, Schleswig-Holstein and Lower Saxony, Germany, the Netherlands, UK, Belgium), as well as Aarhus University and the U.S. Geological Survey. Any use of trade, product, or firm names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Government.

8. 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).

8.1. 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.

8.2. 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 ($\bar{p} = 0.14, \theta = a/\bar{p} = b/(1-\bar{p}) = 43.77$).

9. Appendix B

Monitoring information for the Svalbard population of pink-footed geese. N and Prop(Y) represent total population size and the proportion of young, respectively (i.e., raw counts), 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 calendar year (except those cases in recent years when the November count has been replaced by the count in the following spring; gray shading).

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	74000	0.138	9	8761	2460
2016	88000	0.196	20	13335	2808

10. 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	0.111111	0.111111	0.111111	0.111111	0.111111	0.111111	0.111111	0.111111	0.111111
1992	0.113752	0.114375	0.111004	0.115543	0.116112	0.113005	0.106269	0.107056	0.102884
1993	0.112324	0.114528	0.112755	0.112746	0.115141	0.114004	0.10573	0.107849	0.104923
1994	0.113429	0.111458	0.106501	0.120101	0.118749	0.114513	0.108183	0.106461	0.100604
1995	0.11427	0.113667	0.108931	0.116929	0.118602	0.115609	0.104772	0.105937	0.101284
1996	0.121283	0.12691	0.12057	0.118552	0.127316	0.122881	0.083752	0.092031	0.086705
1997	0.114636	0.118203	0.119692	0.111191	0.117655	0.121089	0.094049	0.10209	0.101395
1998	0.096892	0.084226	0.078895	0.119063	0.10844	0.104172	0.141667	0.137312	0.129332
1999	0.086348	0.052488	0.065952	0.114737	0.073493	0.094265	0.199969	0.14039	0.172359
2000	0.077986	0.048874	0.058675	0.110611	0.072874	0.089619	0.210563	0.15151	0.179288
2001	0.075261	0.046002	0.049735	0.113711	0.074377	0.087124	0.214187	0.155443	0.18416
2002	0.084595	0.048047	0.061795	0.110577	0.066529	0.095092	0.202489	0.134927	0.195948
2003	0.086759	0.048362	0.063869	0.110788	0.064999	0.096341	0.201242	0.130523	0.197115
2004	0.088436	0.054271	0.066116	0.11211	0.072495	0.099024	0.18653	0.135078	0.18594
2005	0.091001	0.05544	0.06693	0.110854	0.070015	0.102052	0.183057	0.129247	0.191404
2006	0.094969	0.05639	0.06985	0.115681	0.071296	0.106503	0.172529	0.131784	0.180997
2007	0.089805	0.055911	0.03482	0.136021	0.086436	0.0781	0.210566	0.165204	0.143138
2008	0.075198	0.047309	0.008014	0.161327	0.103115	0.038003	0.269057	0.211992	0.085985
2009	0.078369	0.047012	0.008109	0.156188	0.090275	0.039994	0.281304	0.212397	0.086353
2010	0.090782	0.06764	0.007455	0.204009	0.14061	0.042851	0.195306	0.208501	0.042848
2011	0.051996	0.048908	0.00028	0.23337	0.193438	0.005001	0.201747	0.261054	0.004206
2012	0.035197	0.033444	5.25E-07	0.238475	0.198397	7.53E-05	0.215229	0.279084	9.92E-05
2013	0.04167	0.039965	2.66E-08	0.24303	0.192843	1.92E-05	0.215935	0.26651	2.65E-05
2014	0.033597	0.033997	9.19E-10	0.247293	0.19568	3.22E-06	0.219681	0.269745	4.71E-06
2015	0.020015	0.022718	4.99E-11	0.24811	0.207491	6.45E-07	0.218118	0.283546	9.13E-07
2016	0.011785	0.023903	5.14E-12	0.30114	0.402636	1.80E-07	0.074436	0.1861	4.55E-08

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