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ADAPTIVE HARVEST MANAGEMENT FOR THE SVALBARD POPULATION OF PINK-FOOTED GEESE: 2020/2021 SEASON

Prepared by the AEWA European Goose Management Platform Data Centre

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Summary

The Svalbard population of Pink-footed Geese (*Anser brachyrhynchus*) breeds almost exclusively in Svalbard, and winters primarily in Sweden, Denmark, The Netherlands and Belgium with stopover sites (spring and autumn) in Norway. This report describes an Adaptive Harvest Management (AHM) program designed to maintain abundance of this population near a goal of 60,000 by providing sustainable harvests in Norway and Denmark. Specifically, this report provides recent monitoring and assessment results and their implications for the 2020/2021 hunting season. In 2019, the International Working Group of the European Goose Management Platform (EGM IWG) adopted the use of an integrated population model (IPM) to guide the setting of annual harvest quotas. IPM estimates of abundance in both May and November show a historic pattern of rapid increase, followed by a period of relative stability, and thereafter by a possible decline. The November 2019 estimate of abundance is 80,400 (71,700–89,200). The May 2020 estimate of population size is 68,400 (59,800–77,600) and is closer to the goal of 60,000 than it has been since 2006. Stabilization of population growth is in keeping with declining survival rates that have corresponded with an increase in kill rates. Most of the recent increase in kill rate is attributable to an increase of hunting pressure in Denmark, where the birds are staying longer in winter and where efforts have been made to increase the harvest to help bring abundance in line with the goal. In contrast, productivity as indicated by the post-breeding ratio of young to adults has generally been increasing over the period of record, apparently in response to a warming climate in Svalbard. The harvest quota for the 2020/2021 hunting season, based on estimated population size and on 18 days above freezing in Svalbard in May 2020, is 22,000. The quota this year is the same as the IPM-based quota for 2019/20. Although abundance of Pink-footed Geese appeared to decline from May of 2019 to 2020, the number of days above freezing increased from 9 to 18, suggesting production this year will be much higher than average. Using an agreed upon allocation of the total quota (30% for Norway, 70% for Denmark), harvest quotas for Norway and Denmark this year are 6,600 and 15,400, respectively. For comparison, the *realized* harvest has averaged about 13,600 (11,700–16,500) during the last five years (about 62% of this year's quota), with an average harvest of 3,200 (2,700–3,700) in Norway and 10,300 (8,600–13,000) in Denmark. If the realized harvest in 2020/2021 is similar to this 5-year average, we would expect a population size in May 2021 similar to what was observed this year.

The 5th Meeting of the AEWA European Goose Management International Working Group is taking place remotely in an online conference format.

Introduction

The Svalbard population of Pink-footed Geese breeds almost exclusively in Svalbard, and winters primarily in Sweden, Denmark, The Netherlands and Belgium with stopover sites (spring and autumn) in Norway. This population of Pink-footed Geese has increased from about 10,000 individuals in the early 1960's to around 80,000 today. Although these geese are highly valued by society, growing numbers of Pink-footed 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 that cause conflicts with certain human economic activities. This document describes progress on the implementation of an AHM program for maintaining abundance of Pink-footed Geese near a goal of 60,000 by providing sustainable harvests in Norway and Denmark (Madsen et al. 2017).

The AHM program for Svalbard Pink-footed Geese began in 2013 using a set of population models described by Johnson et al. (2014). Of growing concern, however, was the observation that the predictive ability of these original models declined over time. Therefore, in 2019 the EGM IWG adopted the use of an IPM (Johnson et al. 2020) to guide the setting of annual harvest quotas. IPMs represent an advanced approach to modeling, in which all available demographic data are incorporated into a single, unified analysis. IPMs have many advantages over traditional approaches to modeling, including the proper propagation of uncertainty, better precision of demographic rates and population size, and the ability to handle missing data and estimate latent (i.e., unobserved) variables (Schaub and Abadi 2011, Kéry and Schaub 2012). Moreover, use of a Bayesian estimation framework for IPMs provides a natural framework for adaptation, in which model parameters can be updated over time based on observations from operational monitoring programs.

In this report we provide inference concerning population dynamics of Svalbard Pink-footed Geese based on an IPM updated with the most current monitoring information. We also use the IPM to derive a state-dependent harvest strategy, which provides optimal harvest quotas for varying population sizes and spring weather conditions on the breeding grounds. Finally, harvest quotas are provided for Norway and Denmark for the 2020/2021 hunting season based on an estimate of population size in May 2020, predicted reproductive success during the current breeding season, and using the agreed upon allocation of the total harvest quota.

Methods

1. Population Dynamics

Annual change in population size in May is described by a difference equation:

$$\begin{aligned} N_{t+1}^{M} &= N_t^M \theta_t \left[(1-k_t) + r_t (1 - v k_t) \right] \\ &= N_t^M \theta_t \left[\left(1 - \frac{h_t}{(1-c_t)} \right) + r_t \left(1 - v \frac{h_t}{(1-c_t)} \right) \right] \\ &= N_t^M \theta_t \left[\left(1 - \frac{(h_t^n + h_t^d)}{(1-c_t)} \right) + r_t \left(1 - v \frac{(h_t^n + h_t^d)}{(1-c_t)} \right) \right] \end{aligned} ,$$

where N_t^M is May population size in year *t*, θ_t is the annual rate of survival from natural causes, k_t is an integrated parameter reflecting the total kill (i.e., retrieved plus un-retrieved harvest) rate of birds aged >1 year, h_t is the annual rate of retrieved harvest of birds aged >1 years, c_t is the rate of crippling loss (un-retrieved harvest divided by total un-retrieved and retrieved harvest), *v* is the constant differential vulnerability of young of the year to harvest (i.e., the ratio of the kill rates of young and older birds), and r_t is the ratio of young to older birds at the start of the hunting season (i.e., post-breeding age ratio). In the third expression, the total harvest rate, h_t, is subdivided into a harvest rate for Norway, h_t^n, and one for Denmark, h_t^d. The post-breeding age ratio was estimated as a logistic function of the number of days above freezing in May in Svalbard.

Population size in November is a function of population size in May, six months of natural mortality, harvest in Norway, and the portion of harvest in Denmark occurring prior to mid-November:

$$\begin{aligned} N_t^N &= N_t^M \theta_t^{6/12}\left(1-\frac{\left(h_t^n+h_t^{d'}\right)}{\left(1-c_t\right)}\right)+N_t^M \theta_t^{4/12} r_t\left(1-v\frac{\left(h_t^n+h_t^{d'}\right)}{\left(1-c_t\right)}\right)\theta_t^{2/12} \\ &= N_t^M \theta_t^{6/12}\left[\left(1-\frac{\left(h_t^n+h_t^{d'}\right)}{\left(1-c_t\right)}\right)+r_t\left(1-v\frac{\left(h_t^n+h_t^{d'}\right)}{\left(1-c_t\right)}\right)\right] \end{aligned},$$

where N_t^N is November population size and $h_t^{d'}$ is the harvest rate of adults in Denmark prior to mid-November.

The set of difference equations for May and November population size are based on the following assumptions:

- Natural mortality and reproduction are year-dependent;
- Natural mortality is evenly distributed throughout the year, in spite of evidence that there may be some minor seasonal differences (Madsen et al. 2002), and natural mortality is the same for all birds that have survived at least one hunting season (Francis et al. 1992);
- Hunting seasons in September and October in Norway and Denmark expose a common group of birds to harvest (i.e., harvest does not occur sequentially, but simultaneously);
- Young are more vulnerable to harvest than older birds and this rate of differential vulnerability is constant;
- The rate of crippling loss has declined exponentially over time, as reflected in the number of young carrying embedded shot (Clausen et al. 2017);
- Hunters report only retrieved harvest; and
- Harvest mortality is additive to natural mortality.

2. Data

To fit the IPM we used the following sources of monitoring data (Heldbjerg et al. 2020) from the 1991/92 – 2019/20 seasons:

- Population count in May;
- May population estimate based on capture-mark-recapture (CMR) data;
- Proportion of wings submitted by Danish hunters prior to mid-November;
- Proportion of young in the autumn population in late October;
- Total harvest in Norway, September – January;
- Total harvest in Denmark, September – January;
- Population count in November; and
- The number of days above freezing in May in Svalbard.

The data used to fit the IPM are provided in the Appendix, and more detail about how the data were collected is available in Johnson et al. (2020). We note that in some cases the data used in this report are preliminary, and therefore results and conclusions are subject to change pending the availability of final data. In addition, not all monitoring data reported by Heldbjerg et al. (2020) are used in the IPM, principally because of the need for spatial and temporal consistency in the data.

3. Model Fitting

We fit the IPM using JAGS 4.3.0 (Plummer 2003), run in the R computing environment (R Core Team 2018) using runjags (Denwood 2016). For each model we used three chains of 120,000 iterations each and retained the last 20,000 samples from each chain for analysis. We assessed parameter convergence using the potential scale reduction factor, psrf (Gelman and Rubin 1992), and assumed values of psrf < 1.1 indicated parameter convergence (Gelman and Hill 2006). Full details concerning model fitting are provided by Johnson et al. (2020). Data and R code for fitting the model are available from the senior author (fred.johnson@bios.au.dk). Posterior parameter estimates are provided in what follows as medians and 95% credible intervals. We caution the reader that posterior estimates of demographic parameters will typically be different than those in the raw data because an IPM maximizes the *joint* statistical likelihood of all the data (i.e., it provides posterior estimates that best describe all of the input data in a single, unified analysis). This is a compelling feature of IPMs, although we recognize that it can sometimes be a source of confusion among non-statisticians.

4. Derivation of the Harvest Strategy

The posterior distribution of model parameters from the IPM, along with candidate harvest quotas and an agreed upon management objective, were used to derive a harvest quota for the 2020/2021 hunting season.

Candidate harvest quotas. – We considered a set of possible harvest quotas of 0 to 50,000 in increments of 1,000. A quota of zero represents a closure of hunting seasons in both Norway and Denmark. Of the total harvest quota, 70% is allotted to Denmark and 30% to Norway per their agreement.

Objective function. – The EGM IWG uses a management objective intended to maintain the population size within agreed upon limits by regulating harvest in Norway and Denmark. For computational purposes, the optimal value (V*) of a management strategy (A) at time t is the maximum (max) of the expectation (E) of the temporal sum of population utilities:

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

where population utility $u(a_\tau|x_\tau)$ is action (a_τ) 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 due to the realized harvest quota and the population goal is 60,000 (Figure 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 quotas 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. We emphasize that the optimization process only recognizes Pink-footed Goose abundance as having value. Harvest is merely used as a tool, without any inherent value recognized.

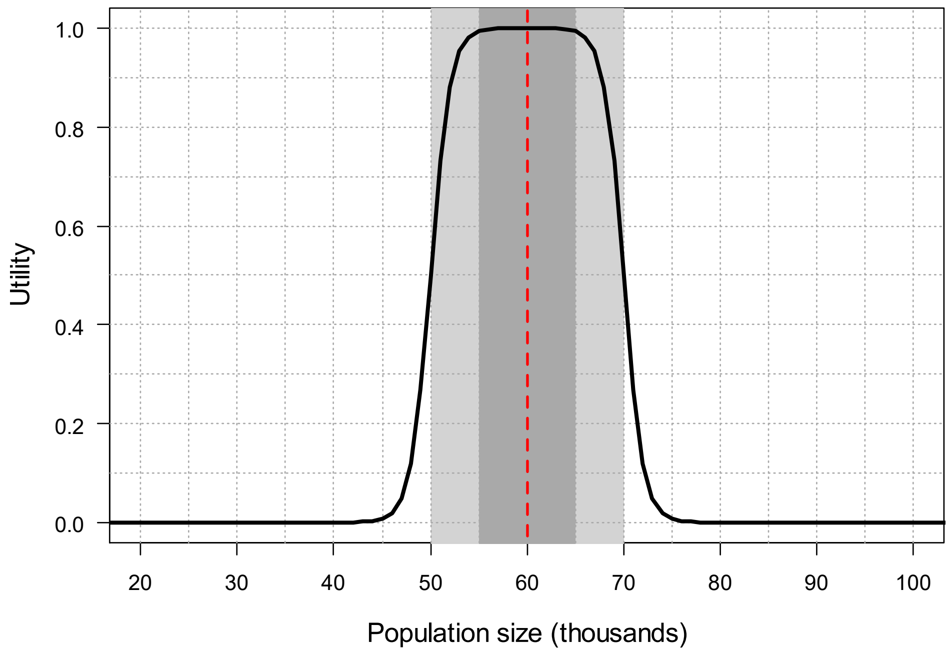

Figure 1. Utility (i.e., stakeholder satisfaction) expressed as a function of population size of Svalbard Pink-footed Geese. The population goal is 60,000 (red dashed line), but population sizes between about 55,000 and 65,000 (dark grey band) are acceptable (and thus have maximum utility), while those outside that range are less desirable (and thus have lower utility). The light grey bands represent population sizes that have ≥ ½ of maximum utility.

Calculation of the 2020 harvest strategy. – The harvest management process can be described as a Markov decision process (Marescot et al. 2013). A solution algorithm for a Markov decision process is stochastic dynamic programming, which we used to calculate a management strategy for the Svalbard population of Pink-footed Geese based on results of the IPM, the range of candidate harvest quotas, and the objective function described above. We used the open-source software MDPSolve© (https://github.com/PaulFackler/MDPSolve) for Matlab (https://www.mathworks.com/) to compute an optimal harvest strategy, which will evolve over time based on annual updates of the IPM. MDPSolve code to implement the optimization is available from the senior author upon request (fred.johnson@bios.au.dk).

The optimal management strategy based on the IPM explicitly recognizes annual variation in the number of days above freezing in May in Svalbard, as well as uncertainty in the relationship between days above freezing in May and subsequent productivity. It also explicitly recognizes annual variation in survival from natural causes. Differential vulnerability of young to harvest is currently treated as a deterministic value (median = 2.1) and a contemporary estimate of crippling loss of 2% (1–4%) is implicitly included in harvest quotas.

Results

May estimates of population size derived from the IPM correspond reasonably well with both the counts and the CMR estimates (Figure 2). The November estimates of abundance from the IPM are generally higher than the counts, suggesting that the November counts are negatively biased by an average of 18% (13–24%). IPM estimates of abundance exhibit less year-to-year variability than the raw data due to random error (e.g., under or over-counts) in the latter and the autoregressive nature of population abundance in the former. IPM estimates of abundance in both May and November show a historic pattern of rapid increase, followed by a period of relative stability, and thereafter by a possible decline; however, we caution the reader that credible intervals are wide enough to admit some ambiguity about recent trends (Figure 3). The November 2019 estimate of abundance is 80,400 (71,700–89,200). The May 2020 estimate of population size is 68,400 (59,800–77,600), and is closer to the goal of 60,000 than it has been since 2006.

Mortality rates are not observed directly, but nonetheless can be estimated by the IPM because of the inclusion of sufficient data on abundance, productivity, and harvests. As with most arctic-nesting geese, the rate of survival from natural causes is relatively high, with little annual variation (Figure 4A). In the last three years, however, IPM estimates suggest that there may have been an increase in natural mortality and this bears watching as additional years of data become available. Estimated harvest rates of adults (i.e., birds that have survived at least one hunting season) have increased over time (Figure 4B) and median estimates have remained >10% since the implementation of AHM in 2013. Harvest rates of young are higher than adults (i.e., birds that have survived at least one hunting season) by a factor of 2.1 (1.7–2.4), reflecting the higher vulnerability of young to hunting. Finally, annual survival from all causes reflects an historic pattern of relative stability followed by a period of decline, which coincides with increasing harvest rates (Figure 4C).

Increasing harvests and harvest rates are due mostly to increasing harvest pressure in Denmark since 2005, although harvests have increased substantially in Norway as well (Figures 5 & 6). The total harvest has averaged about 13,600 (11,700–16,500) during the last five years, with an average harvest of 10,300 (8,600–13,000) in Denmark and 3,200 (2,700–3,700) in Norway. The proportion of the harvest occurring before mid-November in Denmark has steadily declined over time, reflecting a change in migratory behavior that keeps the geese in Denmark for a longer period than historically (Figure 7).

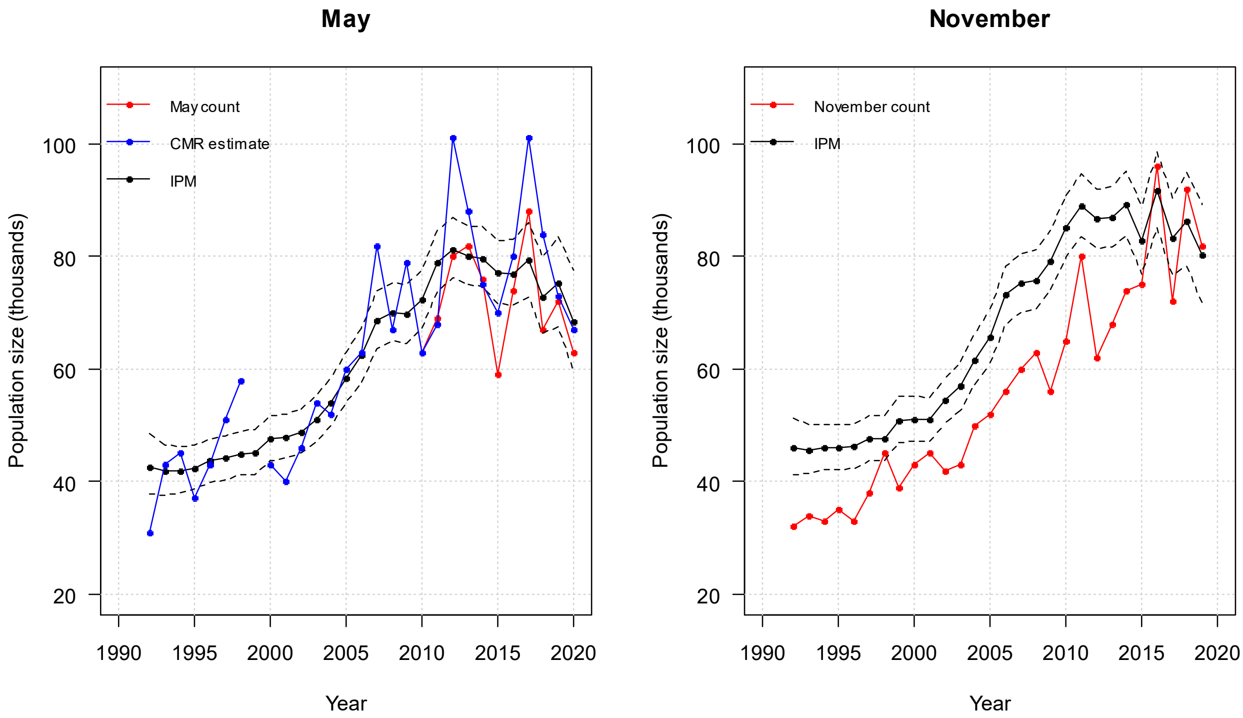

Figure 2. Estimate of abundance of Svalbard Pink-footed Geese in May and November based on raw counts (red), capture-mark-recapture (CMR) analyses (blue), and an IPM (black). 95% credible intervals of the IPM estimates are indicated by the black dashed lines.

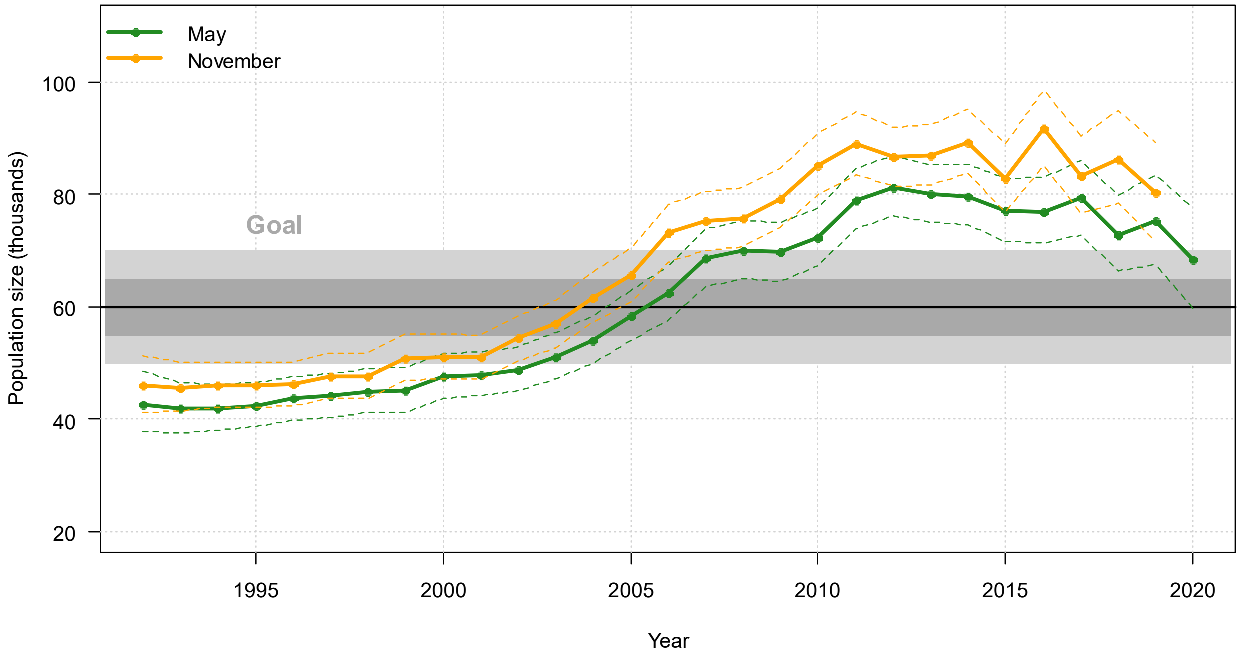

Figure 3. IPM-based estimates of abundance of Svalbard Pink-footed Geese in May and November, relative to the goal of 60,000. The dark grey band defines near-complete stakeholder satisfaction with population sizes, while the light grey band exhibits ≥ ½ of maximum satisfaction (see Figure 1). 95% credible intervals are indicated by the dashed lines.

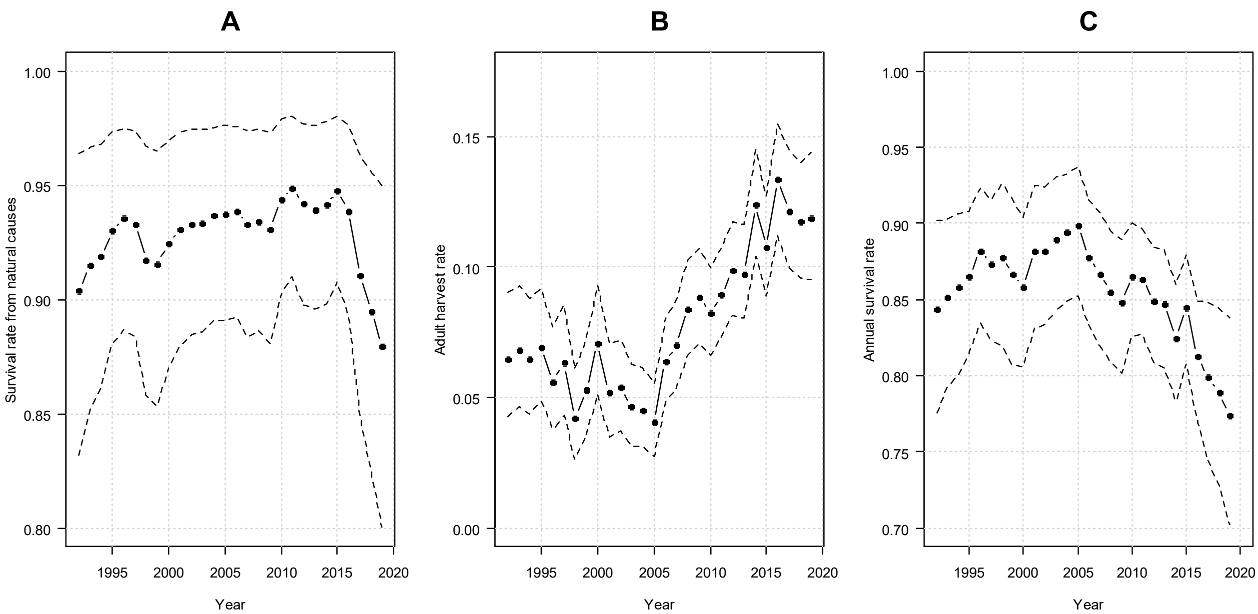

Figure 4. IPM-based estimates of survival and harvest rates of Svalbard Pink-footed Geese. (A) survival from natural causes (e.g., predation); (B) harvest rate of adults (i.e., birds that have survived at least one hunting season); and (C) annual survival from all causes. 95% credible intervals are indicated by the dashed lines.

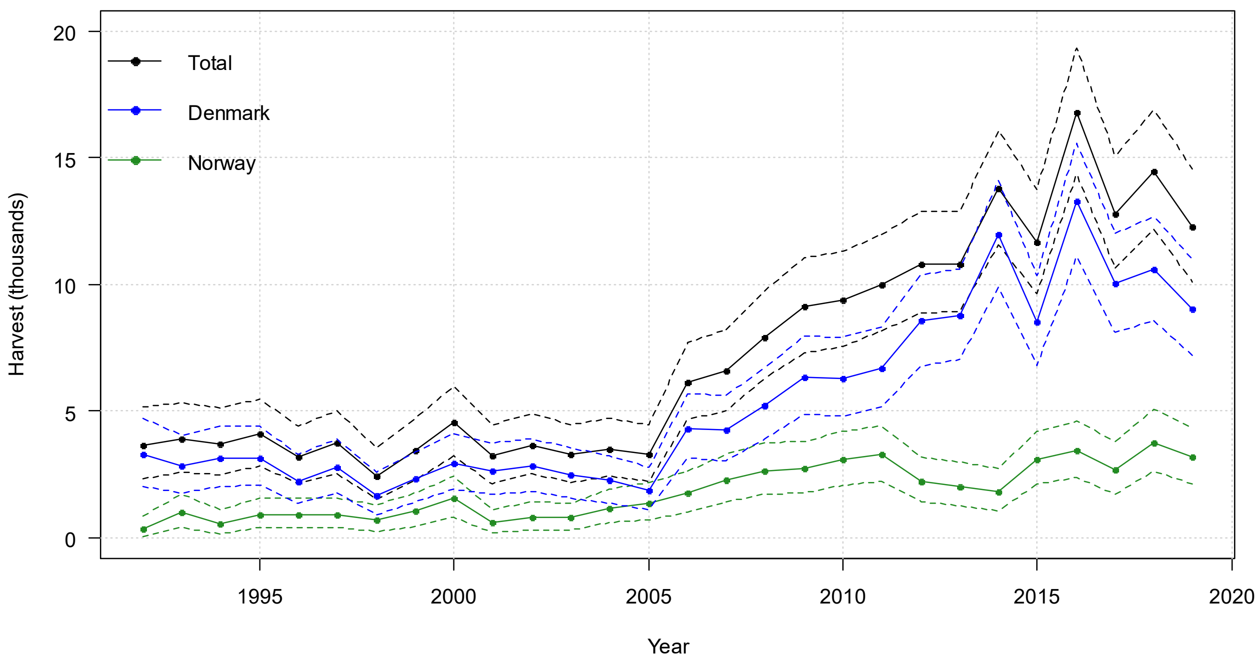

Figure 5. IPM-based estimates of harvests of Svalbard Pink-footed Geese. 95% credible intervals are indicated by the dashed lines.

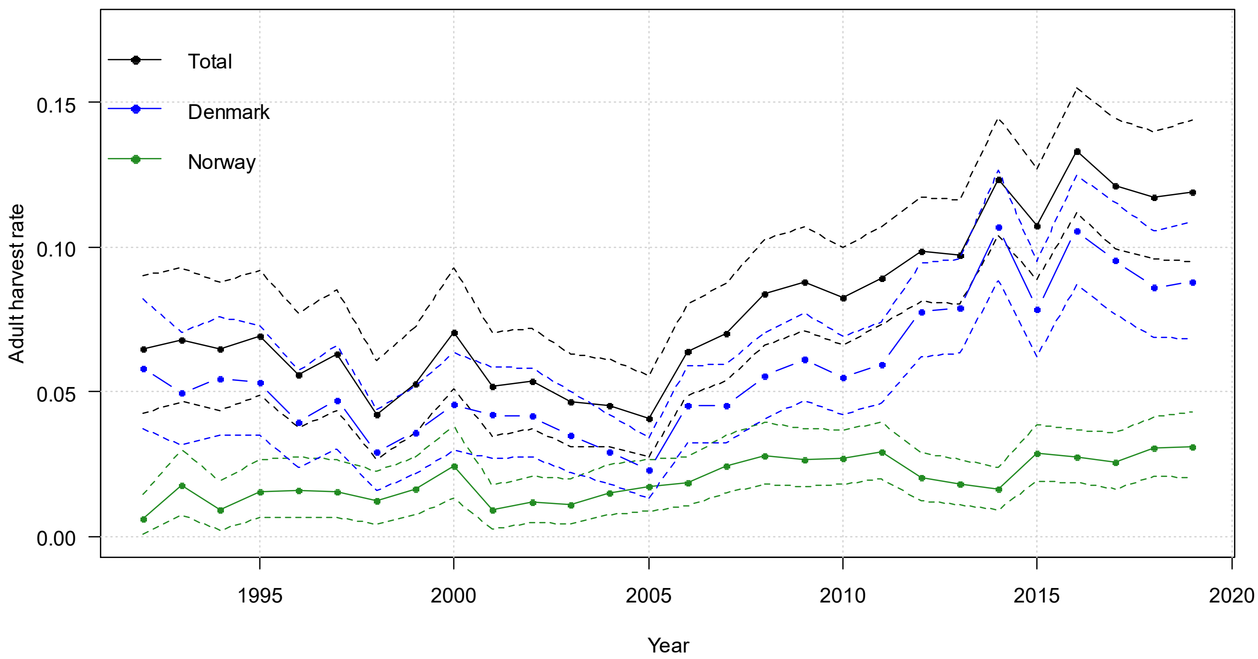

Figure 6. IPM-based estimates of adult harvest rate (i.e., birds that have survived at least one hunting season) for Svalbard Pink-footed Geese. 95% credible intervals are indicated by the dashed lines.

Estimates of productivity, as indicated by the post-breeding age ratio, have been variable over time, with an average of 0.21 (0.16–0.34) young per adult, or equivalently 17.6% (13.2–27.9%) young in the fall flight (Figure 8). Productivity has generally increased over time and is highly correlated with the number of days in which the mean air temperature is above freezing in May in Svalbard. For the period of record (1991–2019), the ratio of young to adults reached a maximum of 0.37 (0.30–0.43) in 2018 following 27 days above freezing in May in Svalbard. The next highest ratio of 0.32 (0.28–0.37) occurred in 2016, following 23 days above freezing. In contrast, the record low ratio of 0.16 (0.14–0.18) occurred in 1998, following 0 days above freezing in May in Svalbard.

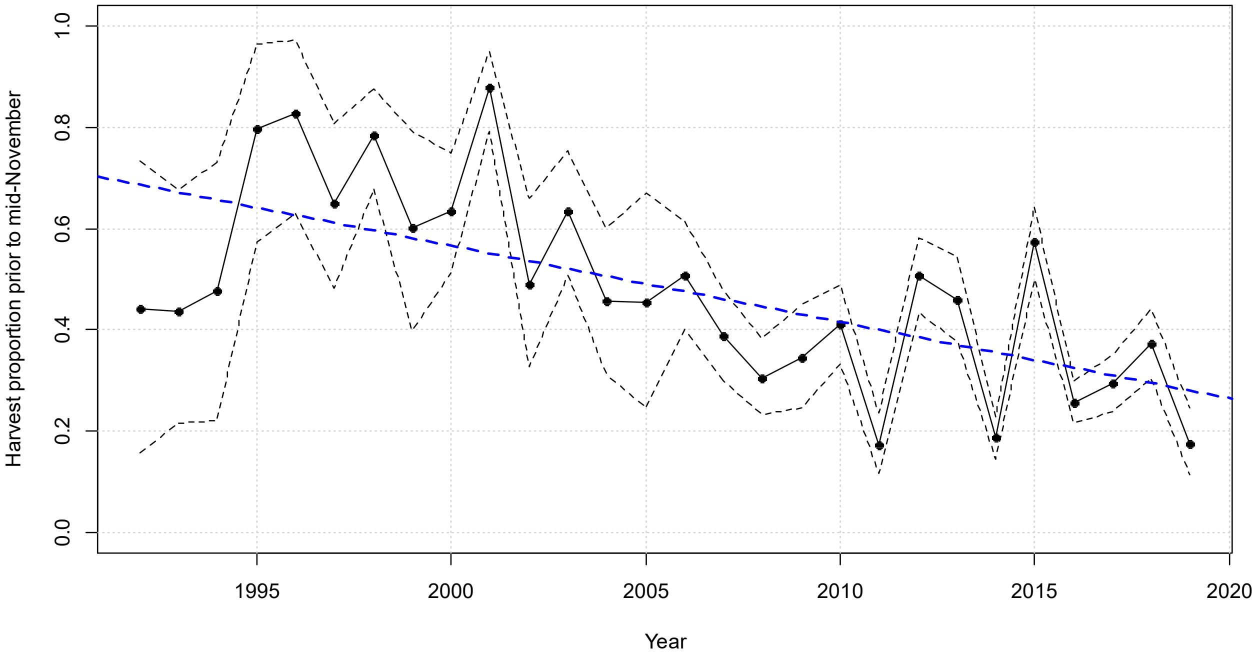

Figure 7. IPM-based estimates of the proportion of Svalbard Pink-footed Geese harvested in Denmark prior to mid-November. 95% credible intervals are indicated by the black dashed lines. The blue dashed line is the best fitting linear trend.

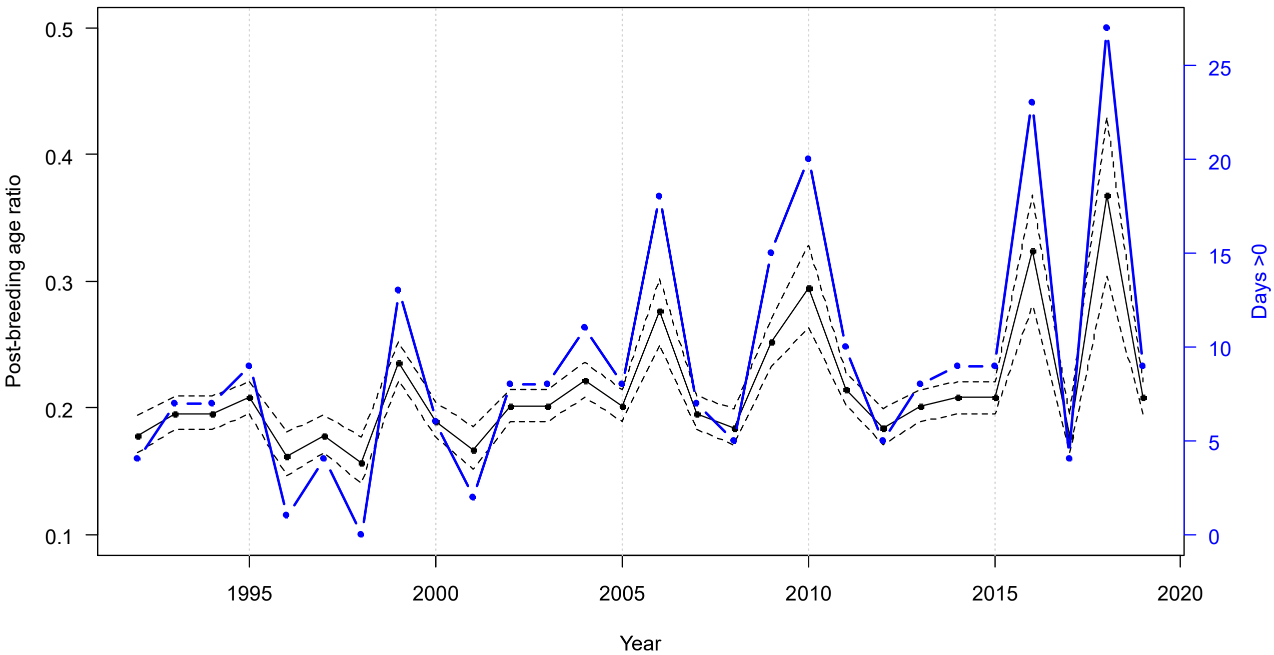

Figure 8. IPM-based estimates of the post-breeding season ratio of young to adults (i.e., birds that have survived at least one hunting season) for Svalbard Pink-footed Geese. 95% credible intervals are indicated by the dashed lines. In blue are the number of days above freezing in May in Svalbard.

The optimal management strategy based on results of the IPM, candidate harvest quotas, and the objective function expressing the level of satisfaction with various population sizes recommends harvest quotas ranging from 0 to 26,000 within the most desirable range of population sizes (i.e., 55,000–65,000) (Figure 9). Harvest quotas for population sizes <50,000 are 0 unless the number of days above freezing is very high. Harvest quotas for population sizes >65,000 increase rapidly with small increases in population size, regardless of the number of days above freezing in May. For a population at its goal of 60,000, and with a mean number of days above freezing (9), the harvest quota is about 7,500. The management strategy in Figure 9 also depicts the evolution of May population size, days above freezing in May, and harvest quotas since implementation of AHM in 2013. Following a record-high population size in 2012 of 81,200 (76,200–86,900), abundance has gradually declined toward the goal of 60,000.

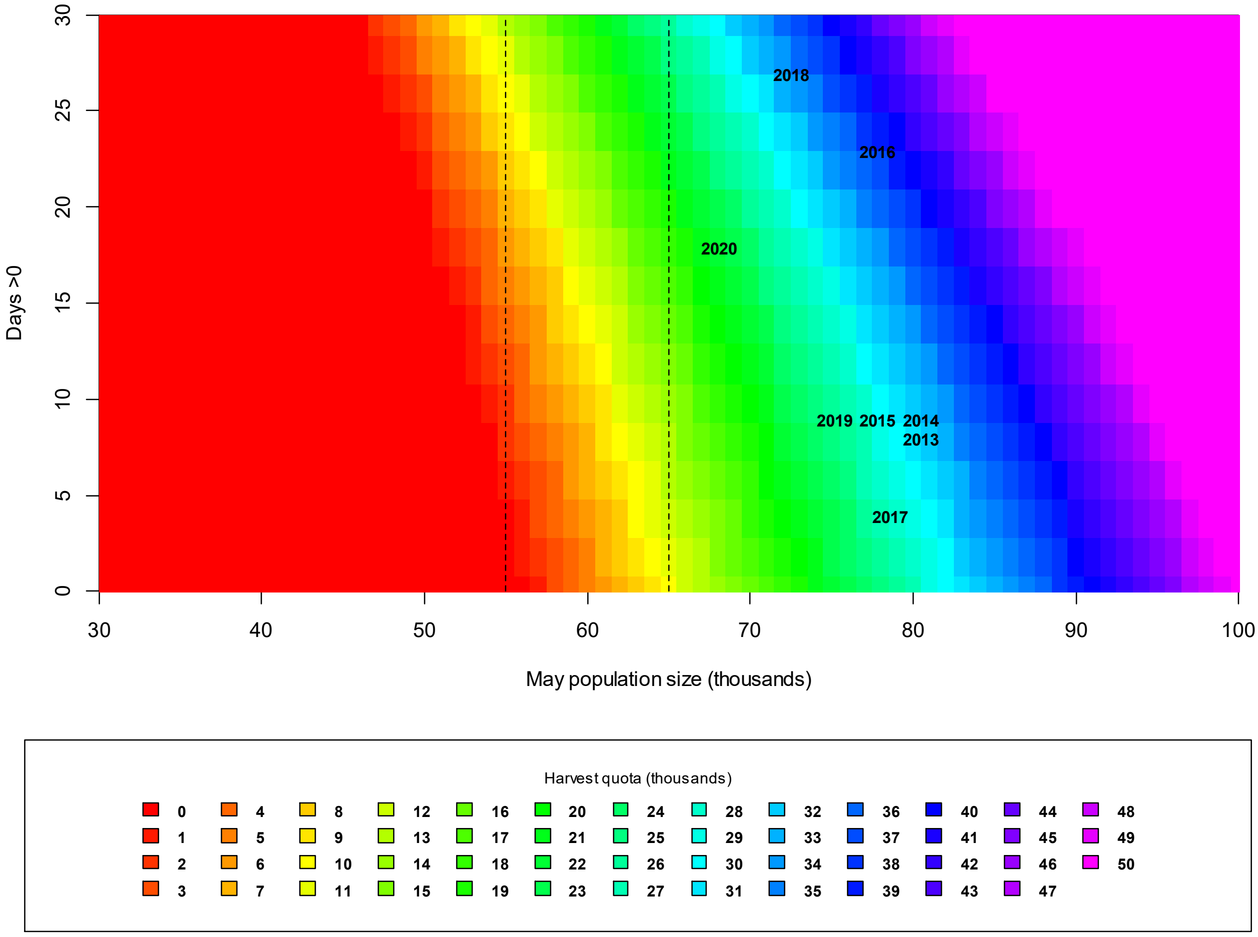

Figure 9. Optimal harvest quotas for Svalbard Pink-footed Geese based on an IPM and an objective to maintain population size near 60,000. Days >0 represents the number of days above freezing in May in Svalbard. The vertical dashed lines depict near-complete stakeholder satisfaction with population sizes. Also depicted are population sizes and days above freezing for the years in which AHM has been in place (2013–2020).

Discussion

Development of an IPM has contributed greatly to our understanding of Pink-footed Goose demography. The most recent results suggest that population size has stabilized, if not declined. This temporal pattern is in keeping with declining survival rates that have accompanied an increase in kill rates. Most of the recent increase in kill rate is attributable to an increase of hunting pressure in Denmark, where the birds are staying longer in winter and where efforts have been made to increase the harvest to slow population growth by extending the season into January (Madsen et al. 2016, Clausen et al. 2018). In contrast, productivity as indicated by the post-breeding age ratio has been increasing for much of the period of record, apparently in response to a warming climate in Svalbard (Piskozub 2017). Whether continued warming will further enhance productivity of Pink-footed Geese is unknown, as continued warming is likely to have ecological impacts far beyond decreasing snow cover, which is the principal benefit now because it provides an abundance of snow-free nesting sites (Madsen et al. 2007, Jensen et al. 2014).

We also note that the IPM uses all available demographic data to provide estimates of population size at two times during the annual cycle. The original AHM framework relied on a single count to set harvest quotas, and in May 2015 the count suggested that subsequent harvest restrictions were warranted (Madsen et al. 2017). Denmark restricted its hunting season despite a suspicion that the count was biased low, a suspicion confirmed by the following May count and our analyses here. An IPM is much more likely to provide a reliable estimate of abundance, which is accompanied by a measure of precision (unlike counts). By updating the IPM annually based on monitoring information, the associated management strategy can "evolve" over time in the spirit of adaptive management. Finally, IPMs can inform the design or redesign of monitoring programs because of their ability to integrate multiple sources of data, and to estimate parameters that may be occasionally missing from monitoring streams or else never observed (Schaub and Abadi 2011). For example, Johnson et al. (2020) used the IPM to suggest that both CMR estimates of survival rate and the observed proportion of young in the fall are negatively biased, and they offered several considerations for improving monitoring protocols.

The harvest quota for the 2020/2021 hunting season, based on estimated population size in May 2020 and on 18 days above freezing in Svalbard in May 2020, is 22,000. The quota this year is the same as the IPM-based quota for 2019/20. Although Pink-footed Goose abundance appeared to decline from 2019 to 2020, the number of days above freezing increased from 9 to 18, suggesting production this year will be much higher than average. Using an agreed upon allocation of the total quota (30% for Norway, 70% for Denmark), harvest quotas for Norway and Denmark this year are 6,600 and 15,400, respectively. For comparison, the *realized* harvest has averaged about 13,600 (11,700–16,500) during the last five years (about 62% of this year's quota), with an average harvest of 3,200 (2,700–3,700) in Norway and 10,300 (8,600–13,000) in Denmark.

With the May population size apparently approaching the goal, the relatively high harvest quota for 2020/2021 may seem counterintuitive. Recall, however, that the relationship between productivity and May temperatures is quite strong (see Fig. 8). In every year that the number of days above freezing has been above the average of nine days, we have seen strong population growth even after substantial harvests, often on the order of 5-10%. Moreover, the IPM has greatly improved our predictive power over the population models used in AHM from 2013 to 2018. In 2019, the prototype IPM predicted a May 2020 population size of 64,900 (50,300 – 83,700) *assuming* the 2019/20 quota of 22,000 was met. The realized harvest in 2019/20 was well short of the quota [12,300 (10,100–14,600)], although natural mortality may have been slightly higher than average. The best estimate for abundance in May 2020 based on the IPM updated with 2019/20 monitoring data is 68,400 (59,800–77,600). With the benefit of hindsight and based on the authors' >50 years of collective experience with population modelling, the 2019/20 prediction qualifies as surprisingly good. If the quota of 22,000 were met this year (which we believe to be highly unlikely based on past performance), we would expect a population size in May of 2021 of about 60,000 (46,400–77,600). However, if only 62% of the quota were achieved (the more likely scenario), we would expect the May 2021 population to be about 68,000 (52,600–88,000), which is similar to that observed this year.

Acknowledgements

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Literature Cited

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.

Clausen, K. K., J. Madsen, F. Cottaar, E. Kuijken, and C. Verscheure. 2018. Highly dynamic wintering strategies in migratory geese: Coping with environmental change. *Global Change Biology* 24(7):3214–3225.

Denwood, M. J. 2016. runjags : An R package providing interface utilities, model templates, parallel computing methods and additional distributions for MCMC models in JAGS. *Journal of Statistical Software* 71(9):1–25.

Francis, C. M., M. H. Richards, F. Cooke, and R. F. Rockwell. 1992. Changes in survival rates of Lesser Snow Geese with age and breeding Status. *The Auk* 109(4):731–747.

Gelman, A., and J. Hill. 2006. *Data Analysis Using Regression and Multilevel/Hierarchical Models*. Cambridge University Press.

Gelman, A., and D. B. Rubin. 1992. Inference from iterative simulation using multiple sequences. *Statistical Science* 7(4):457–472.

Heldbjerg, H., J. Madsen, O. Amstrup, J. Bakken, T. Balsby, T. Christensen, et al. 2020. Pink-footed Goose Population Status Report 2019-2020. AEWA EGMP document AEWA/EGMIWG/5.7.

Jensen, G. H., J. Madsen, F. A. Johnson, and M. Tamstorf. 2014. Snow conditions as an estimator of the breeding output in high-Arctic pink-footed geese Anser brachyrhynchus. *Polar Biology* 37:1–14.

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(0):186–199.

Johnson, F. A., G. S. Zimmerman, G. H. Jensen, K. K. Clausen, M. Frederiksen, and J. Madsen. 2020. Using integrated population models for insights into monitoring programs: An application using pink-footed geese. *Ecological Modelling* 415:108869.

Kéry, M., and M. Schaub. 2012. *Bayesian Population Analysis Using WinBUGS: A Hierarchical Perspective*. Academic Press.

Madsen, J., K. K. Clausen, T. K. Christensen, and F. A. Johnson. 2016. Regulation of the hunting season as a tool for adaptive harvest management — first results for pink-footed geese Anser brachyrhynchus. *Wildlife Biology* 22(5):204–208.

Madsen, J., M. Frederiksen, and B. Ganter. 2002. Trends in annual and seasonal survival of Pink-footed Geese Anser brachyrhynchus. *Ibis* 144(2):218–226.

Madsen, J., M. Tamstorf, M. Klaassen, N. Eide, C. Glahder, F. Rigét, H. Nyegaard, and F. Cottaar. 2007. Effects of snow cover on the timing and success of reproduction in high-Arctic pink-footed geese Anser brachyrhynchus. *Polar Biology* 30(11):1363–1372.

Madsen, J., J. H. Williams, F. A. Johnson, I. M. Tombre, S. Dereliev, and E. Kuijken. 2017. Implementation of the first adaptive management plan for a European migratory waterbird population: The case of the Svalbard pink-footed goose Anser brachyrhynchus. *Ambio* 46(S2):275–289.

Marescot, L., G. Chapron, I. Chadès, P. L. Fackler, C. Duchamp, E. Marboutin, and O. Gimenez. 2013. Complex decisions made simple: a primer on stochastic dynamic programming. *Methods in Ecology and Evolution* 4(9):872–884.

Piskozub, J. 2017. Svalbard as a study model of future High Arctic coastal environments in a warming world. *Oceanologia* 59(4):612–619.

Plummer, M. 2003. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. *Proceedings of the 3rd International Workshop on Distributed Statistical Computing; Vienna, Austria*.

R Core Team. 2018. R: A Language and Environment for Statistical Computing. Vienna, Austria.

Schaub, M., and F. Abadi. 2011. Integrated population models: a novel analysis framework for deeper insights into population dynamics. *Journal of Ornithology* 152(S1):227–237.

Appendix

Data used to fit an IPM for the Svalbard population of Pink-footed Geese. Labels are as follows:

- Year: self-explanatory
- May count: counts of geese in May
- CMR May: May abundance as based on a capture-mark-recapture analysis
- se(CMR May): standard error of CMR May
- Thaw days: days with mean temperature >0°C (an average of stations at Ny-Ålesund and Svalbard Lufthavn)
- Productivity: total # of geese observed and the # young, October 12 – November 4 in Jutland and Friesland
- Wing receipts: total number of wings submitted by Danish hunters and the number shot prior to November 15
- Nov counts: counts of geese in November
- Harvest: total harvests in Denmark and Norway

					Productivity		Wing receipts			Harvest	
Year	May count	CMR May	se(CMR May)	Thaw days	# birds	# young	Total	prior Nov 15	Nov count	Denmark	Norway
1991				9	343	76	60	48	33000	3000	NA
1992		31146	6782	4	6076	377	8	3	32000	2500	240
1993		43432	13249	7	4335	820	14	6	34000	2300	850
1994		44591	10372	7	8140	1028	11	5	33000	2600	420
1995		37007	11380	9	6747	1658	12	10	35000	2800	790
1996		43331	9186	1	4963	866	14	12	33000	2000	850
1997		51260	8886	4	3601	514	29	19	38000	2500	820
1998		58179	8950	0	7789	919	62	49	45000	1414	570
1999				13	7700	917	20	12	39000	1973	920
2000		42702	9601	6	6677	367	60	38	43000	2567	1400
2001		40363	9374	2	11692	1265	62	55	45000	2353	548
2002		45955	12687	8	13991	1495	31	15	42000	2611	655
2003		53552	14795	8	10495	1329	55	35	43000	2299	684
2004		52204	16918	11	9003	1034	42	19	50000	2056	1076
2005		59665	15480	8	12470	911	18	8	52000	1694	1347
2006		63442	19272	18	17606	3046	81	41	56000	4180	1657
2007		81555	22966	7	24489	2970	109	42	60000	4128	2221
2008		67115	18046	5	22100	2746	142	43	63000	5086	2633
2009		79469	23652	15	20240	2090	80	27	56000	6177	2600
2010	63000	62605	13440	20	11662	2522	147	60	65000	6264	3100
2011	69000	67636	36394	10	7546	1389	148	25	80000	6793	3410
2012	80000	100647	27681	5	20669	1991	172	87	62000	8580	2180
2013	82000	88362	6681	8	21321	2524	138	63	68000	8834	2010
2014	76000	74667	6296	9	19841	2128	325	60	74000	12172	1830
2015	59000	70479	4767	9	15150	1926	185	106	75000	8818	3170
2016	74000	80205	5283	23	18825	3981	424	109	96000	13526	3490
2017	88000	100583	7361	4	19992	1546	247	72	72000	9769	2590
2018	67000	84267	6475	27	19013	2498	194	72	92000	10236	3570
2019	72000	72607	5202	9	13453	831	128	22	82000	8621	3025
2020	63000	66521	5706	18							