An Integrated Population Model for the Central Management Unit of Taiga Bean Geese

AEWA European Goose Management Platform

Final Project Report

AEWA European Goose Management Platform
AEWA

AEWA European Goose Management Platform

An Integrated Population Model for the Central Management Unit of Taiga Bean Geese

Final Project Report

Prepared by the AEWA European Goose Management Platform Data Centre

Compiled by: Fred A. Johnson[1], Henning Heldbjerg[1], Samu Mäntyniemi[2]

[1] Aarhus University, Denmark
[2] Natural Resources Institute, Finland

Picture on the cover: © Marco Gola

DISCLAIMER

The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of UNEP/CMS and UNEP/AEWA concerning the legal status of any State, territory, city or area, or of its authorities, or concerning the delimitation of their frontiers and boundaries.

Table of Contents

Executive Summary

In 2019, Finland (Finnish Wildlife Agency and Natural Resources Institute) funded the development of an integrated population model (IPM) for the purpose of improving harvest management for the Central Management Unit (CMU) of Taiga Bean Goose (*Anser fabalis fabalis*). We relied heavily on previous work to specify model structure and for parameterizing prior distributions of model parameters. Observational data included population counts at three times during the year (January, March, and October) and estimates of harvest from Finland, Sweden, and Denmark. Both counts and harvest estimates contain varying numbers of the Tundra subspecies (*Anser fabalis rossicus*), and attempts to delineate the Taiga and Tundra subspecies in monitoring data have been sporadic and largely confined to recent years. While we have endeavored to eliminate the influence of Tundra Bean Geese in the IPM, we caution the reader that results and conclusions contained herein must be viewed in light of the limitations of the data and of our methods. Among key demographic parameters, only the posterior distribution for reproductive rate, differed markedly from its prior distribution. This was not unexpected due to extrinsic identifiability problems arising from the limited nature of the available data. Results suggest strong population growth in all three months in which counts are conducted, coincident with a sharp decrease in harvest pressure in 2014. Although harvests have generally been declining over the last decade for all three countries, the trend is most pronounced in Finland, where severe harvest restrictions were enacted. In contrast to the March 2020 population estimate of 75,200 (70,200 – 80,500) reported in the June 2020 harvest assessment, our estimate is 66,200 (61,300 – 72,000). The lower value was expected due to the exclusion of the Tundra subspecies. While the median population estimate is just shy of the target of 70,000 for Taiga Bean Geese, we note that the International Single Species Action Plan specifies a desired range of 60,000 – 80,000 birds in the CMU. Using the IPM, we project that March population size will approach 70,000 in five years (on the average) with a total annual harvest of 3,000. This is similar to the average realized harvest of 3,300 during 2014 – 2019. Finally, we note that while the average harvest has been at a level needed to help ensure population growth, the realized allocation of the harvest among countries has not been what has been agreed upon. Going forward, countries should consider bringing their harvests in line with the desired allocation of 58%, 30%, and 12% for Finland, Sweden, and Denmark, respectively.

Introduction

The International Single Species Action Plan (ISSAP) for the conservation of Taiga Bean Goose (*Anser fabalis fabalis*) (Marjakangas et al. 2015) recognized a dramatic and range-wide decline in population size and thus mandated a variety of conservation measures. Chief among these was the development and implementation of an international Adaptive Harvest Management (AHM) program to adjust harvest levels to reflect the status of the population, based on agreed upon objectives, management alternatives, predictive models, effective monitoring programs, and iterative learning. This report is concerned with the Central Management Unit (CMU) of Taiga Bean Goose, encompassing breeding areas in northernmost Sweden, Northern and Central Finland, Northeast Norway, and in Russian Karelia, the Kola Peninsula and Arkhangelsk district. Birds from the CMU mostly winter in Sweden, Denmark and Germany, and all stage in Sweden.

An initial assessment of harvest potential for the CMU was completed in 2016. In 2017, the European Goose Management Platform (EGMP) adopted a strategy consisting of a constant harvest rate of 3% to assist recovery of the population while providing limited hunting opportunities. In 2018, significant advances were made in harvest-assessment methods for species with sparse data, using Taiga Bean Geese as a case study (Johnson et al. 2018). In 2019, Finland (Finnish Wildlife Agency and Natural Resources Institute) funded the development of an integrated population model (IPM) for the purpose of further improving harvest management.

Integrated population models represent an advanced approach to modeling, in which all available demographic data are incorporated into a single analysis. IPMs have many advantages over traditional approaches to modeling, including the proper propagation of demographic uncertainty, better precision of demographic rates and population size, the ability to handle missing data and to estimate latent (i.e., unobserved) variables, and the capacity to guide the development of effective monitoring programs. 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.

Development of an IPM for Taiga Bean Geese took place over a year beginning in October 2019. A 6-month progress report is available from Johnson et al. (2020b). In addition, an annual harvest assessment was conducted in the spring of 2020 based on the preliminary IPM, and that report is available from Johnson et al. (2020a). It is critical to note, however, that these reports do not account for the presence of varying numbers of Tundra Bean Geese (*Anser fabalis rossicus*) in estimates of abundance and harvest. In this final report of IPM development, we have attempted to develop a model that is specific to Taiga Bean Geese in the CMU. This was challenging, however, as attempts to delineate the Taiga and Tundra subspecies in monitoring data have been sporadic and largely confined to recent years. Thus, we make no claim that the approach described herein is the best of all possible approaches, but we have endeavored to carefully document our methods and rationale so that they can be replicated and/or improved. We thus caution the reader that results and conclusions contained in this report must be viewed in light of the limitations of the data and of our methods.

Methods

1. Population Dynamics

We relied heavily on previous work to specify model structure and for parameterizing prior distributions of model parameters (Johnson et al. 2018). Most notably, we used a discrete theta-logistic model rather than an age-specific matrix model. The theta-logistic model requires less monitoring data to parameterize and appears capable of providing reasonable management guidance even if the population is age structured (Johnson et al. 2018). The following description of population dynamics has not changed from previous reports.

A key consideration in constructing an IPM is how to account for abundance that is observed at multiple times during the annual cycle. Counts of Taiga Bean Geese are available in January, March, and October (albeit with some level of contamination from Tundra Bean Geese). We consider March abundance as the start of the breeding season and the annual cycle. The challenge is to reframe the theta-logistic model, which only predicts annual changes in abundance, to one that will predict population size at other times during the year. In the following, we show how this can be done, initially assuming no density dependence in survival or production, and then accounting for density dependence. In this approach we make a limited number of assumptions: (1) all production occurs between March and October; (2) natural mortality is evenly distributed throughout the year; (3) density-dependence acts on both production and annual survival, and is based on abundance in March; and (4) the Finnish harvest represents the number of birds harvested prior to the October count (although we recognize that some small number of the Taiga subspecies are likely harvested in Finland during October and November, and some harvest of Bean Geese may occur in Sweden prior to October; Mikko Alhainen, pers. commun.).

To accommodate multiple counts during the year, we begin with the theta-logistic model with density dependence:

(Eq. 1)

$$\begin{aligned} N_{t+1} &= N_t + N_t r\left(1-\left(\frac{N_t}{K}\right)^{\theta}\right) - H_t \\ &= N_t\left(1 + r\left(1-\left(\frac{N_t}{K}\right)^{\theta}\right)\right) - H_t \end{aligned}$$

where *N* is population size, *r* is the intrinsic (or biological maximum) rate of growth, *K* is carrying capacity, θ is a parameter describing the type of density dependence (i.e., concave, linear, or convex), *H* is total harvest, and *t* is year. Now we omit harvest and density dependence:

(Eq. 2)

$$\begin{aligned} N_{t+1} &= N_t + N_t r \\ &= N_t(1+r) \end{aligned}$$

The expression $(1+r)$ is the intrinsic finite rate of population growth, which can also be expressed in terms of intrinsic survival from natural causes, ψ, and production, γ:

(Eq. 3)

$$\begin{aligned} N_{t+1} &= N_t\psi + N_t\psi\gamma \\ &= N_t(\psi + \psi\gamma) \end{aligned}$$

Therefore:

(Eq. 4)

$$\begin{aligned} 1 + r &= \psi + \psi\gamma \\ r &= \psi + \psi\gamma - 1 \end{aligned}$$

In the theta-logistic model, the realized rate of population growth results from a reduction in the intrinsic rate of growth based on the size of the population relative to carrying capacity:

(Eq. 5)

$$r' = r\left(1 - \left(\frac{N_t}{K}\right)^{\theta}\right)$$

Thus, to incorporate density dependence into a model with explicit survival and production rates, we simply multiply both sides of Eq. 4 by $\left(1 - \left(\frac{N_t}{K}\right)^{\theta}\right)$:

(Eq. 6)

$$r\left(1 - \left(\frac{N_t}{K}\right)^{\theta}\right) = (\psi + \psi\gamma - 1)\left(1 - \left(\frac{N_t}{K}\right)^{\theta}\right)$$

And now by substitution in our original theta-logistic model:

(Eq. 7)

$$N_{t+1} = N_t\left\{1 + \left[(\psi(1+\gamma) - 1)\left(1 - \left(\frac{N_t}{K}\right)^{\theta}\right)\right]\right\} - H_t$$

Having survival and production as explicit parameters allows us to implement our assumptions concerning timing of annual events. Thus, we predict abundance in October, N^O, as a function of March abundance, N^M:

(Eq. 8)

$$N_t^O = N_t^M + N_t^M\left[\left(\psi^{7/12}(1+\gamma^1) - 1\right)\left(1 - \left(\frac{N_t^M}{K}\right)^{\theta}\right)\right] - H_t^F$$

in which we assume seven months of natural mortality, all of the reproduction, and a portion of the total harvest occurring prior to October, where H^F represents the harvest in Finland.

Abundance in January is conditional on October abundance:

(Eq. 9)

$$N_t^J = (N_t^O - H_t^D - \alpha H_t^S)\psi^{3/12}$$

where H^D and H^S represent harvests in Denmark and Sweden, respectively, and where α represents the proportion of the Swedish harvest occurring prior to January (i.e., the regular hunting season).

Abundance in the following March is thus:

(Eq. 10)

$$N_{t+1}^M = \left(N_t^J - (1-\alpha)H_t^S\right)\psi^{2/12}$$

where $(1-\alpha)$ represents the proportion of the Swedish harvest that is taken after the regular season to help prevent crop damage (i.e., conditional hunting).

2. Prior Distributions of Model Parameters

We used the methods provided by Johnson et al. (2018) to develop informed priors for key demographic parameters. Using a combination of allometric relationships, fragmentary monitoring and research information, and expert judgment, we generated 100,000 replicate samples of survival in the absence of harvest and density dependence, ψ, reproductive rate in the absence of density dependence, γ, and spring carrying capacity, K. We then fit informative prior distributions using quantiles from these samples:

$$\psi \sim beta(58.17, 7.89)$$
$$\gamma \sim lognormal(-1.21, 0.26)$$
$$K \sim lognormal(11.38, 0.04)$$

We note that in the replicate samples used to fit these prior distributions, there was a negative correlation between ψ and γ. In future work, it may be advisable to specify a bivariate normal prior distribution for these parameters, using a logit and log transform, respectively.

With respect to the prior for θ, if we follow the methods of Johnson et al. (2018), a prior distribution for the form of density dependence is:

$$\theta \sim lognormal(0.85, 0.79)$$

which places 95% of the probability mass between 0.5 and 11.0. This prior, however, admits extreme (large) values of θ that we believe to be biologically implausible because they essentially admit no density dependence unless populations are very close to their carrying capacities. Because the difficulty in estimating the form of density dependence from a time series of population counts, when those counts are subject to observation error, is well established (Knape 2008), we use a slightly more informative prior for θ:

$$\theta \sim lognormal(0.85, 0.30)$$

This prior also has a median of 2.4, but places 95% of the probability mass between 1.3 and 4.2, which seems biologically more realistic given the intrinsic rate of growth estimated for this species of $r = 0.15$ (Johnson et al. 2012).

The parameter α represents the portion of the Swedish harvest occurring prior to the January population count. To develop an informative prior for this parameter, we relied on samples of geese that were shot during the course of the autumn and winter of 2017/2018 ($n = 233$) and of 2018/2019 ($n = 504$) (Niklas Liljebäck, pers. commun.). Using these data, we specified a prior for the proportion of harvest prior to January 15 as:

$$\alpha \sim beta(513, 224)$$

which has a mean of 0.70 and places 95% of the probability mass between 0.66 and 0.83. We assumed that α is fixed over time, although this assumption could be relaxed in future versions of the model.

Finally, we had to specify priors for initial population size in March 1996 and for country-specific harvests in each year. For initial population size, we specified:

$$N_{1996}^{M} \sim lognormal(10.80, 0.20)$$

which has a mean of about 55,000 and 95% of the probability mass between 33,000 and 73,000. Because March counts were not available prior to 2007, we specified a mean that is lower than the October count in the same year, and which is accompanied by a large variance.

For prior distributions of harvest, we specified uniform distributions on what we considered plausible ranges:

$$H_t^F \sim uniform(0, 10000)$$
$$H_t^S \sim uniform(0, 10000)$$
$$H_t^D \sim uniform(0, 5000)$$

In addition to estimating model parameters for the years in which data were available (1996 –2020), we used the fitted IPM to project population size (Kéry and Schaub 2012) five years into the future under a harvest scenario intended to produce a population size near the target of 70,000, using the agreed upon allocation among Range States. We note that the Russian harvest is unknown, and in the IPM it is implicitly included as natural mortality. We thus re-normalized the remaining Range States' desired harvest allocation as 58%, 30%, and 12% for Finland, Sweden, and Denmark, respectively. All priors for hypothetical future harvests for each Range State and for each year were specified as Poisson distributions with means based on the future harvest scenario.

3. Observation Models for Monitoring Data

We believe any effort to isolate Taiga Bean Geese in the CMU from existing monitoring data will be problematic. Attempts to delineate the Taiga and Tundra subspecies in monitoring data have been sporadic and largely confined to recent years. It also appears that counting protocols for Bean Geese have occasionally changed over time (e.g., in response to changing distributions of geese), usually with little or no documentation to help understand the effects of those changes on subspecies composition.

We also note that monitoring data for CMU Taiga Bean Geese occasionally include unknown numbers of Taiga Bean Geese from the Western Management Unit (WMU). Finally, we stress that available data are sometimes an unknown mix of preliminary and final estimates. In spite of these problems, we have attempted to extract Taiga Bean Geese from extant data because of the interest expressed by decision makers. Our methods involve a combination of pre-processing the data and using informative priors in the IPM to account for the potential number of Tundra Bean Geese occurring in count and harvest data. All count and harvest data used in the IPM were rounded to the nearest hundred in light of the imprecision in these estimates.

The anniversary date of the IPM is March of each year. March counts of Bean Geese in southern Sweden, Denmark, Norway, and Finland (Skyllberg 2015) were compiled for the years 2007 – 2020, with the exception of 2010 and 2013 when counting conditions were poor. It is likely that the March counts include some small number of Taiga Bean Geese from the WMU. In particular, counts from sites in Norway and Denmark likely represent WMU birds, and counts at those sites averaged about 400 during 2007 – 2015 (Skyllberg 2015). More critically, it is believed that about 4,000 of the birds in the March count are of the Tundra subspecies, and that the temporal variation in this value is about $\sigma = 1{,}000$ (Skyllberg 2015).

To account for the numbers of Tundra Bean Geese in the March count, we treated the proportion of the March count consisting of Taiga Bean Geese as a random-year effect, assuming that each year the proportion is drawn from a constant mean and temporal variance. To do so requires that we specify prior distributions for both this mean and variance. For the mean, we assumed the mean number of Taiga Bean Geese of 4,000 and calculated the resulting proportions of Taiga Bean Geese based on the total March counts for each year. These proportions have a mean of $\mu = 0.929$ and a standard error of $SE = 0.003$. Using the method of moments (Bolker 2008), an informative prior for the mean proportion of Taiga Bean Geese in the March count is:

$$p^{M,taiga} \sim beta(9230, 703)$$

We then specified a prior for each year's proportion using the logit of the mean:

$$\mu = log\left(\frac{p^{M,taiga}}{(1 - p^{M,taiga})}\right)$$

and a mildly informative prior whose median approximately replicates the reported temporal variability of 1,000 Tundra Bean Geese:

$$\sigma \sim \text{Uniform}(0, 1)$$

with:

$$e_t \sim \text{Normal}(0, \sigma)$$

such that:

$$\text{logit}\left(p_t^{M,taiga}\right) = \mu + e_t$$

The likelihood of the March count is therefore:

$$C_t^M \sim \text{lognormal}\left(\log\left(N_t^M / p_t^{M,taiga}\right) - 0.5s^2, s^2\right)$$

where N_t^M is the system prediction of Taiga Bean Geese in March and s is a residual standard deviation (Kéry and Schaub 2012:117).

For October counts, we used data exclusively from Sweden from 1996 – 2019. Although some observations of Taiga Bean Geese in October have been reported from Finland, Denmark, and the Netherlands, we are aware of data only for 2018 (n = 2,916) and 2019 (n = 6,317) (Heldbjerg et al. 2019, 2020), and at least some of these data are merely casual observations. For the years 2016 – 2019, October counts from Sweden are classified as Taiga, Tundra, and unidentified Bean Geese. For those years, we pre-processed the counts by adding to the Taiga counts a portion of the unidentified Bean Goose counts based on the observed proportions of known Taiga and Tundra Bean Geese in the October counts. This approach assumes that unidentified geese have the same subspecies composition as the identified geese.

For October counts in Sweden in years prior to 2016, we used an approach similar to that for March counts by assuming a random-year effect. We specified the mean proportion of the total Bean Geese that were Taiga Bean Geese using the mean ($\mu = 0.891$) and standard error ($SE = 0.025$) of the observed proportion of known Taiga Bean Geese among known Taiga Bean Geese and Tundra Bean Geese in October counts during 2016 – 2019. Using the method of moments, we specified a prior distribution for the mean proportion of Taiga Bean Geese in the October 1996 – 2015 Bean Goose counts in Sweden as:

$$p^{O,taiga} \sim \text{beta}(137, 17)$$

We then specified a prior for each year's proportion using the logit of the mean:

$$\mu = log\left(\frac{p^{O,taiga}}{(1 - p^{O,taiga})}\right)$$

and a mildly informative prior for the temporal variance σ:

$$\sigma \sim \text{Uniform}(0, 2)$$

with:

$$e_t \sim \text{Normal}(0, \sigma)$$

such that:

$$\text{logit}\left(p_t^{O,taiga}\right) = \mu + e_t$$

The likelihood of the October 1996 – 2015 counts is therefore:

$$C_{t=1996:2015}^{O} \sim \text{lognormal}\left(\log\left(N_{t=1996:2015}^{O} / p_t^{M,taiga}\right) - 0.5s^2, s^2\right)$$

where N_t^O is the system prediction of Taiga Bean Geese in October and s is a residual standard deviation.

Finally, in terms of counts, we have January counts of Bean Geese in Sweden and Denmark for all years of record (1996 – 2020), although subspecies identification has only been conducted in recent years. Notably, no January counts of Taiga Bean Geese are available from Germany. In our previous reports, we used only January counts from Sweden and these counts were positively correlated with January temperatures in southern Sweden. In the IPM, the difference between the January count and January population estimate (i.e, the degree of bias in the counts) was also greater in warmer winters. With the inclusion of January counts in Denmark, however, no such relationship between counts and winter temperature exists (Figure 1). Therefore, the IPM described herein does not use January temperature as a covariate to help predict the magnitude of bias in the January count. However, the absence of counts from Germany still renders the January count negatively biased on average, and it is possible that this bias varies temporally depending on how birds distribute themselves in winter.

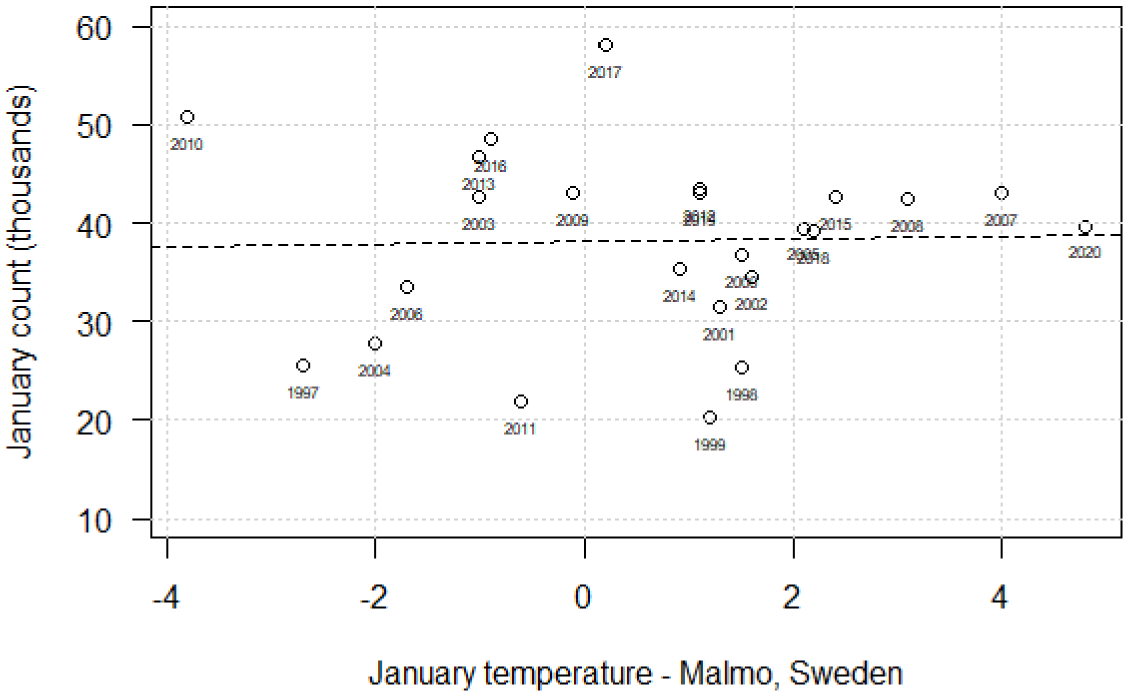

Figure 1. January counts of Bean Geese in Sweden and Denmark as a function of the average January temperature (Celsius) at the Malmo airport in southern Sweden. The dashed line represents the best-fitting linear model; the slope is not statistically significant ($P = 0.89$).

For January counts in Sweden, we pre-processed the counts for 2014 – 2020 as we did for the October counts by adding the Taiga counts and a portion of the unidentified Bean Goose counts based on the observed proportions of known Taiga and Tundra Bean Geese. For years prior to 2014, we used an approach analogous to that for the October counts by first calculating the mean ($\mu = 0.892$) and standard error ($SE = 0.033$) of the observed proportion of known Taiga Bean Geese among known Taiga Bean Geese and Tundra Bean Geese during January 2014 – 2020. Using the method of moments, we specified a prior distribution for the mean proportion of Taiga Bean Geese in the January 1996 – 2013 counts in Sweden as:

$$p^{S,J,taiga} \sim \text{beta}(78, 9)$$

Our initial intent was then to model the proportion of Taiga Bean Geese in the January count as a random-year effect, but did not do so for reasons described below.

For Denmark, we used total January Bean Goose counts for the period of record. While the country-wide counts are believed to contain some birds belonging to the WMU (e.g., in North Jutland), we only had access to regional counts during 2015 – 2020. Thus, it was only possible to identify potential WMU birds during that time period. In order to maintain comparability with earlier counts, we used total country-wide counts of Bean Geese throughout. Although subspecies identification did not take place prior to 2004, we assigned all unidentified geese to the Taiga subspecies during 1996 – 2003 because sightings of Tundra Bean Geese in these early years were rare (https://dofbasen.dk/; Pihl et al. 2015). During 2004 – 2009, only known Taiga Bean Geese and Tundra Bean Geese were reported and we therefore used the Taiga count. Beginning in 2010, unidentified Bean Geese also were reported. As with other counts, we pre-processed the data by adding to the Taiga count a portion of the unidentified Bean Geese each year, based on the proportion of known Taiga Bean Geese among known Taiga Bean Geese and Tundra Bean Geese.

The two different approaches for January counts in Sweden and Denmark described thus far present a problem, however. The structure of the IPM predicts a total January population size, and uses this to define the likelihood of January counts. Because the January counts from the two countries have a different structure, with Danish counts being pre-processed and Swedish counts being a combination of pre-processing (2014 – 2020) and IPM processing using a prior distribution for the proportion of Taiga Bean Geese (1996 – 2013), we cannot simply add the two counts. We would need to include separate likelihoods for the Swedish and Danish counts in January. Yet, we cannot do this without specifying in the IPM system model how birds distribute themselves in January among the two countries. That distribution, in turn, is unlikely to be constant and is probably influenced by the severity of the winter. And the absence of January counts from Germany makes such an exercise even more challenging. A simpler approach is to pre-process the January counts in Sweden during 1996 – 2013 using the mean proportion of 89% Taiga Bean Geese derived from the years 2014 – 2020. Then the count data from Sweden and Denmark could simply be summed and we could again use a single likelihood for the January count data. The key shortcoming of this approach, however, is that it does not account for uncertainty in the mean estimate of 89% (SE = 3%) used to separate Taiga Bean Geese from total Bean Geese during 1996 – 2013, nor does it allow temporal variation in that proportion. Nonetheless, we chose this simpler approach as a starting point.

We next turn to reported harvests from Finland, Sweden, and Denmark, which are considered the principal harvest areas for CMU Taiga Bean Geese (although the extent of harvest in Russia is unknown). In Finland, reported harvests do not differentiate among the two subspecies. However, during 2017 – 2019, hunter-collected heads (mean sample size: $\bar{n} = 28$) were identified to subspecies, with an average of only 20% ($SD = 10\%$) being Taiga Bean Geese. Also, during 2017 – 2019, Finnish hunters were required to report their total Bean Goose harvest. Thus, for 2017 – 2019, we can use actual estimates of country-wide Taiga Bean Goose harvest.

For years prior to 2017 in Finland, estimates of total Bean Goose harvest were based on questionnaires sent to a sample of hunters (http://statdb.luke.fi/). Using regional estimates of Bean Goose harvest based on those data, we first identified regions where the harvests are believed to be predominately Taiga Bean Geese, predominately Tundra Bean Geese, or a mix of the two subspecies (Mikko Alhainen, pers. commun.). For each year during 1996 – 2016, we added the harvest from areas that were believed to be predominately Taiga Bean Geese and a portion of the Bean Goose harvest from the "mix" areas, based on the proportion of Taiga Bean Geese among the regions that were considered to be predominately one subspecies or the other. Calculated in this way, the proportion of assumed Taiga Bean Goose harvest in the total Bean Goose harvest averaged 67% ($SD = 17\%$) for the period 1996 –

2013, but was highly variable and declined over time, likely due to restrictions in hunting regulations meant to protect Taiga Bean Geese. (Note that for the years 2014 – 2016, the estimated Bean Goose harvest in Finland was reported as zero due to a harvest moratorium.)
Swedish harvest records also do not differentiate between the Taiga and Tundra subspecies. In 2017, 233 hunter-collected heads were examined and 176 (75%) were classified as definitely or probably Taiga Bean Geese. Heads were also collected in 2018 and 2019, but those results are not yet available. Rather than rely on a single year of limited data, we pre-processed the harvest data using the differentiation of subspecies in the October count in Sweden during 2016 – 2019 to estimate the proportion of the Swedish harvest consisting of Taiga Bean Geese.

For years prior to 2016, we used the previously specified prior for the mean proportion of Taiga Bean Geese in the October count in Sweden during 2016 – 2019: $p^{O,taiga} \sim \text{beta}(137, 17)$. As with the October counts, we assumed a random-year effect for the proportion of Swedish harvest consisting of Taiga Bean Geese using:

$$\mu = log\left(\frac{p^{O,taiga}}{(1 - p^{O,taiga})}\right)$$

and a mildly informative prior for the temporal variance σ:

$$\sigma \sim \text{Uniform}(0, 1)$$

with:

$$e_t \sim \text{Normal}(0, \sigma)$$

such that:

$$\text{logit}\left(p_t^{O,taiga}\right) = \mu + e_t$$

The likelihood of the Swedish harvest during 1996 – 2015 is therefore:

$$H^S_{t=1996:2015} \sim \text{Poisson}\left(\lambda^S_{t=1996:2015} / p_t^{O,taiga}\right)$$

where λ_t^S are the system predictions of Taiga Bean Goose harvest in Sweden.

Like Finland and Sweden, Danish records of Bean Goose harvest do not differentiate among subspecies. As reported earlier, all Bean Geese in January in Denmark prior to 2004 were assumed to be Taiga Bean Geese and so we made no adjustments to the total Bean Goose harvest estimates during that period. For the period 2004 – 2019, we pre-processed the Bean Goose harvest estimates by assuming that the proportions of Taiga Bean Geese in the Danish Bean Goose harvest were the same as the proportions of Taiga Bean Geese in the Danish January count data. This approach likely over-estimates the harvest of Taiga Bean Geese in Denmark in the most recent years due to enactment of regional restrictions on Bean Goose hunting meant to protect the Taiga subspecies (I. H. Sørensen, pers. commun.).

4. Computation

To fit the IPM, we used JAGS 4.3.0 (Plummer 2003), run in the R computing environment (R Core Team 2018) using runjags (Denwood 2016). Including random-year effects for the proportions of Taiga Bean Geese in count and harvest data required long MCMC chains to achieve convergence. We used three chains of 1,050,000 iterations each and retained the last 50,000 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). Unless otherwise noted, we report the medians and 95% credible intervals of posterior estimates. Members of the EGMP - Taiga Bean Goose Task Force can access R code and data for running the model by first logging in to the Task Force workspace at: https://egmp.aewa.info/workspaces and then navigating to:
https://egmp.aewa.info/workspaces/Taiga-bean-goose-subgroup/groups/all-members-tbg-tf/modelling-work-tbg.

Results

Among the five key demographic parameters in the IPM $(\psi, \gamma, K, \theta, \alpha)$, the posterior distributions for mortality, ψ, and for reproductive rate, γ, were shifted somewhat to the right compared with their respective prior distributions (Figure 2). Posterior distributions for the density-dependence parameter, θ, and for carrying capacity, K, were shifted somewhat to the left compared to their respective prior distributions. The posterior distribution for the proportion of Swedish harvest occurring prior to the January count, α, was essentially identical to its prior. Prior and posterior medians and 95% credible intervals for the five parameters are provided in Table 1.

Posterior estimates of population size compared to the data-based counts are compared in Figure 3. As expected, March and October population estimates are generally lower than their respective counts because the latter contain varying numbers of Tundra Bean Geese. In March, the posterior estimate of the mean proportion of Taiga Bean Geese in the count is 0.93 (0.92 – 0.93), which is essentially identical to its prior. Similarly, for the October counts, the posterior estimate of the mean proportion of Taiga Bean Geese in the count is 0.90 (0.85 – 0.94), which is also essentially identical to its prior. For January, the posterior estimates of abundance are generally higher than the count data. This was expected because of the lack of January counts from Germany.

Posterior estimates of abundance exhibited less variability than the counts due to the random observation errors of the latter and the autoregressive nature of the population model. Posterior estimates of abundance were reasonably precise, but it is important to remember that these estimates are from a deterministic model that omits any environmental variation (which would lead to less precision and less smoothing of the population trajectory). Posterior estimates of population size increased over the last decade for all three months in which Bean Geese were counted, especially so after the Finnish harvest moratorium in 2014. Estimated population size was 72,800 (68,600 – 77,900) in October 2019, 68,400 (63,900 – 73,800) in January 2020, and 66,200 (61,300 –72,000) in March 2020. These estimates are lower than that reported in the 2020 harvest assessment because of the attempt to exclude Tundra Bean Geese in abundance and harvest data.

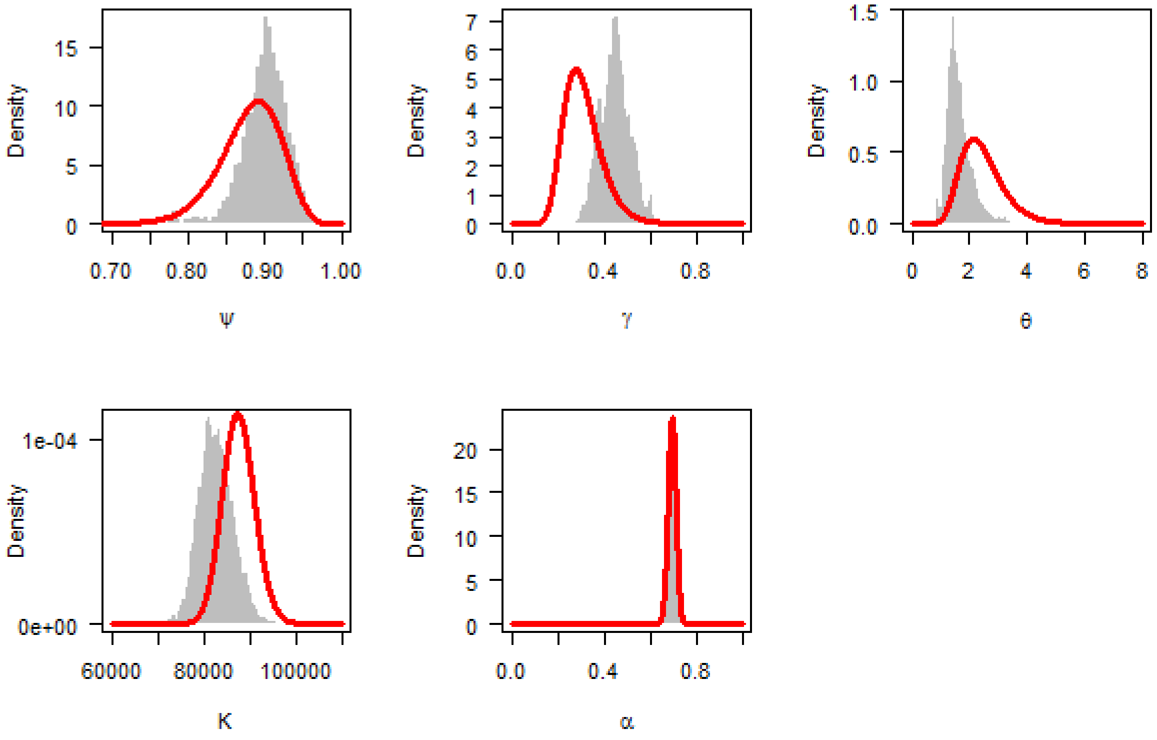

Figure 2. Prior (red) and posterior distributions (grey) of natural survival rate, ψ, reproductive rate, γ, carrying capacity, K, and form of density dependence, θ, in a theta-logistic population model of Taiga Bean Geese in the Central Management Unit as based on an IPM. The parameter α is the portion of Swedish harvest occurring prior to the January count.

Table 1. Prior and posterior estimates of demographic parameters in a theta-logistic population model for Taiga Bean Geese in the Central Management Unit as based on an IPM. Natural survival and reproductive rates are intrinsic values (i.e., biological maxima in the absence of anthropogenic mortality and density dependence).

Parameter	Prior median	Prior 95% CI	Posterior median	Posterior 95% CI
Natural survival (ψ)	0.884	0.793 – 0.947	0.896	0.832 – 0.952
Reproductive rate (γ)	0.298	0.179 – 0.496	0.447	0.329 – 0.589
Carrying capacity (K)	87553	80951 – 94693	82766	75964 – 90138
Form of density dependence (θ)	2.340	1.300–4.212	1.692	0.927 – 2.597
Proportion of Swedish harvest prior to 15 January (α)	0.696	0.662 – 0.729	0.697	0.664 – 0.730

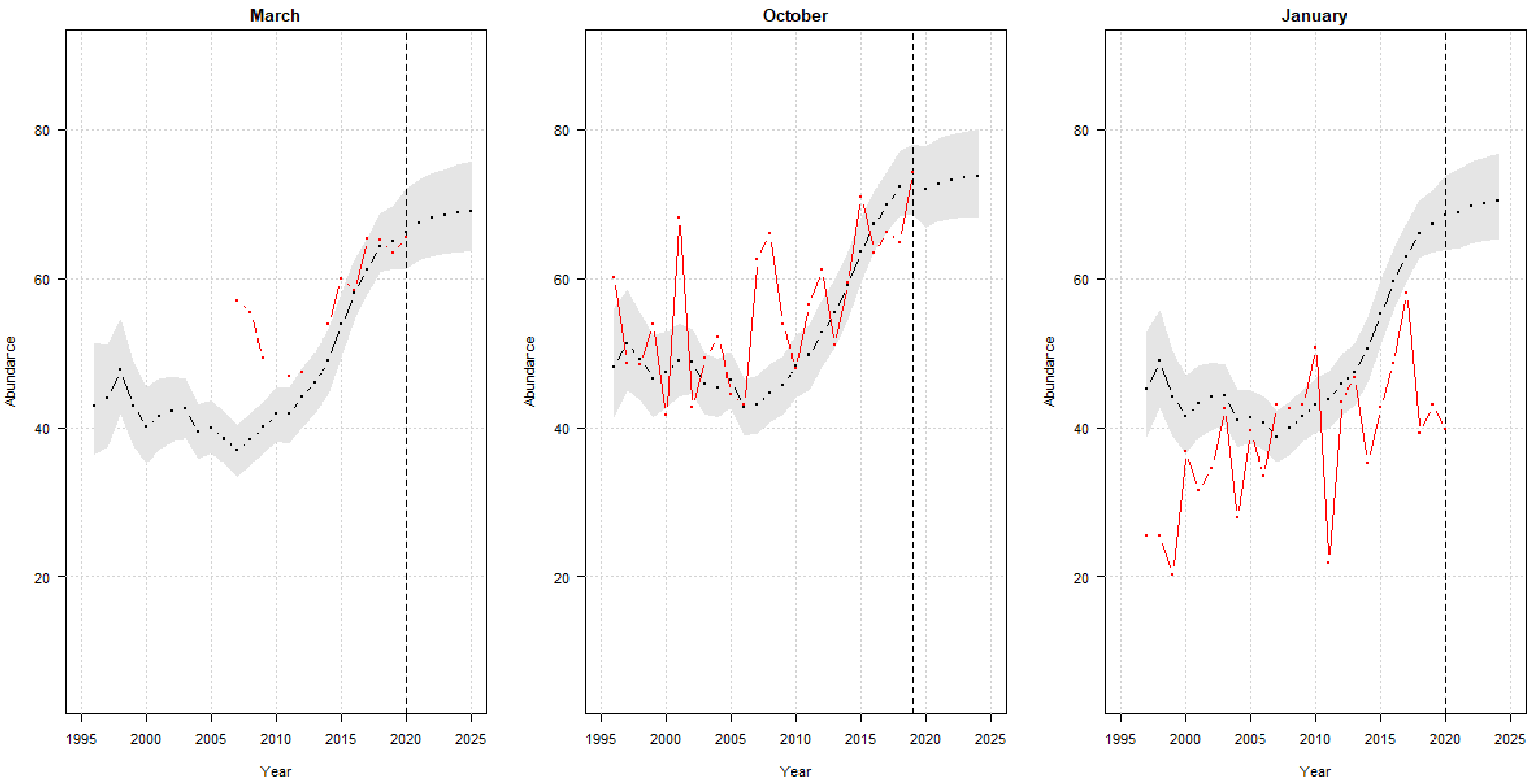

Figure 3. Posterior estimates of the abundance of Taiga Bean Geese in the Central Management Unit (in thousands, in black, with 95% credible intervals in grey) as based on an IPM. Data-based counts are in red. The vertical, dashed lines represent the last year of empirical data. Future abundances were projected based on a Taiga Bean Goose harvest (3,000) intended to produce a population size near the target level of 70,000 in spring after five years.

Posterior estimates of country-specific harvests of Taiga Bean Geese are provided in Figure 4. The forecasts of harvests for the years 2020 – 2024 are those intended to produce a population size close to the target level of 70,000 in spring after five years. Moreover, the country-specific harvests for these future years are in accordance with the agreed-upon allocation of total harvest among the three countries. The total harvest needed to attain a target population size of 70,000 in spring in five years is 3,000 (2,900 – 3,100). The country-specific allocations of this harvest are: Finland – 1,700 (1,600 – 1,800); Sweden – 900 (800 – 1,000); and Denmark – 400 (350 – 450). For comparison, the estimated total harvest averaged 3,300 (1,500 – 5,100) during 2014 – 2019. Notice that the projected harvests in Figure 4 are quite different in Finland and Sweden than they have been in the previous five years.

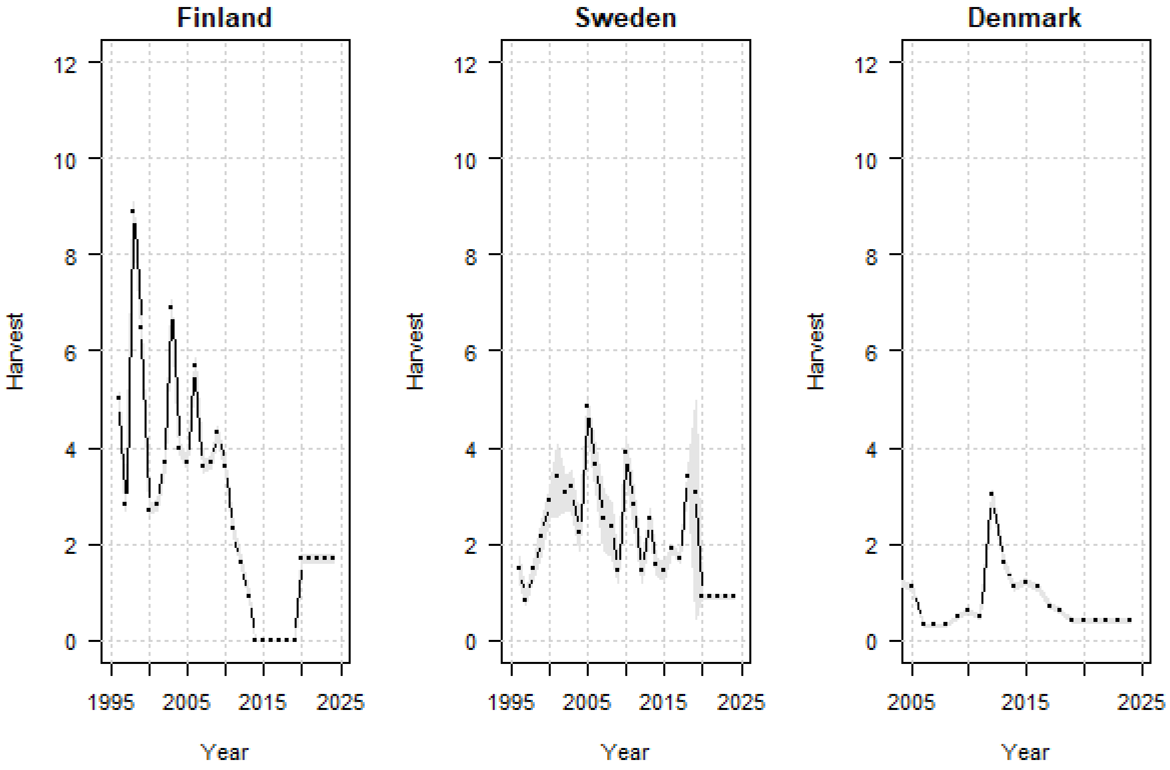

Figure 4. Estimated harvests (in thousands, with 95% credible intervals in grey) based on an IPM for Taiga Bean Geese in the Central Management Unit. Harvests during 2020 – 2024 are those intended to produce a population size near its target level of 70,000 after five years.

Based on a total allowable harvest of 3,000 (2,900 – 3,100) Taiga Bean Geese, we can estimate the total Bean Goose harvest (including the Tundra subspecies) for comparability to previous reports. Using the estimated proportions of Taiga Bean Geese in the total Bean Goose harvests as described in the Methods, the total allowable Bean Goose harvests are: Finland – 2,500 (1,800 – 5,500); Sweden – 1,000 (900 – 1,200); and Denmark – 400 (400 – 600). For Finland, the proportion of Taiga Bean Geese in the Bean Goose harvest was based on that observed during 1996 – 2013 prior to the harvest moratorium there. An allowable harvest of 3,900 total Bean Geese is substantially lower than that of 6,500 provided in the 2020 harvest assessment. We attribute this decrease in part to a decrease in the estimate of the parameter controlling the form of density dependence, θ, which would reduce harvestable surpluses. Other, more subtle, reasons are also possible due to the exclusion of the Tundra subspecies.

We also used the IPM to estimate as latent variables the annual harvest rates and apparent survival rates of the flyway population (Figure 5). Estimated harvest rates declined dramatically following the Finnish harvest moratorium in 2014, and this decrease in harvest rate coincides with strong growth in the population. Harvest rates during 2014–2019 (i.e., the period of the Finnish moratorium) averaged 0.047 (0.033 – 0.062), which is higher than the agreed upon harvest rate of 0.03 in the interim harvest strategy. Estimates of apparent survival increased markedly with implementation of the Finnish harvest moratorium, and have averaged 0.853 (0.840 – 0.866) in recent years. We refer to these estimates as "apparent" survival because actual survival rates may have been less if density dependence operated on survival in a significant way.

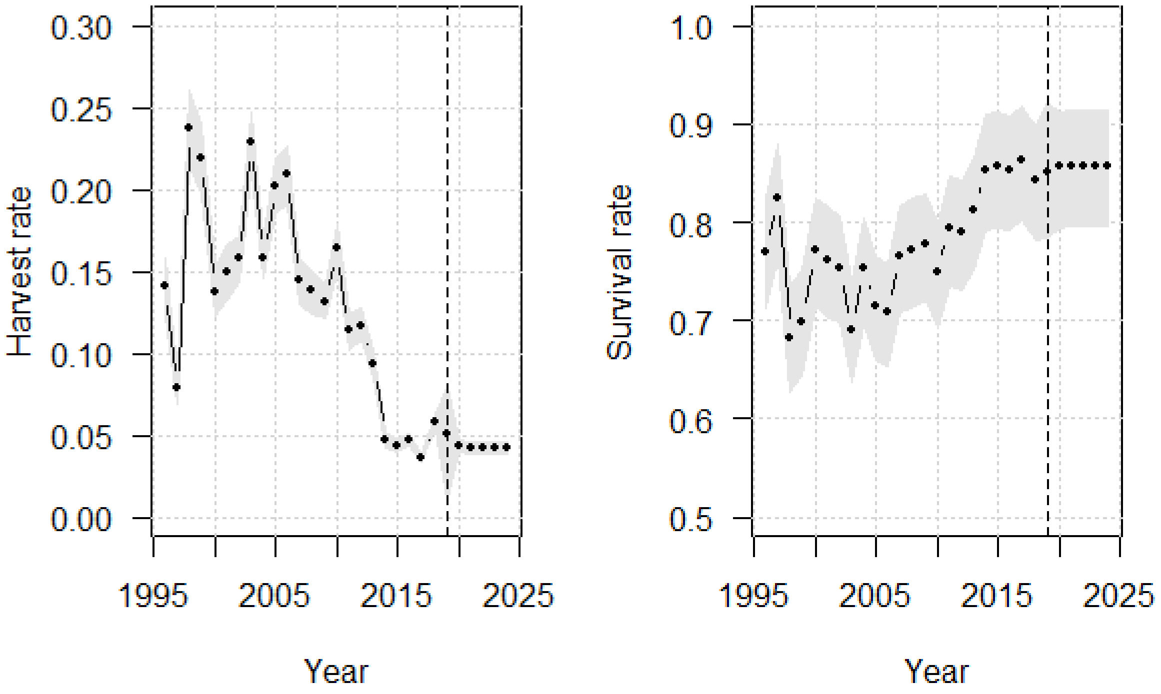

Figure 5. Posterior estimates of harvest and apparent survival rates based on an IPM for Taiga Bean Geese in the Central Management Unit, with 95% credible intervals in grey. The vertical, dashed lines represent the last year of empirical data. Future (mean) rates were projected based on a Taiga Bean Goose harvest (3,000) intended to produce a population size at the target level of 70,000 in spring after five years.

Finally, we used the MCMC samples of carrying capacity and survival and reproductive rates to estimate realized population growth rate for varying sizes of the March population using Equation 6. Similarly, we estimated net production of the population by multiplying Equation 6 by population size. A plot of net production as a function of population size represents harvestable surpluses and is often referred to as a "yield curve." Realized growth rate declines with increasing population size as a result of density dependence, with the decline being concave as indicated by an estimate of $\theta > 1$ (Figure 6). Thus, density dependence becomes increasingly stronger as the population approaches carrying capacity. Net production (i.e., the harvestable surplus) is maximized at a population size of 45,400, which is substantially lower than the target population size of 70,000. At a population size of 45,400, the harvestable surplus is 8,400 birds (7,900 – 9,000). In contrast, the harvestable surplus at a population size of 70,000 is 4,900 (3,000 – 6,700).

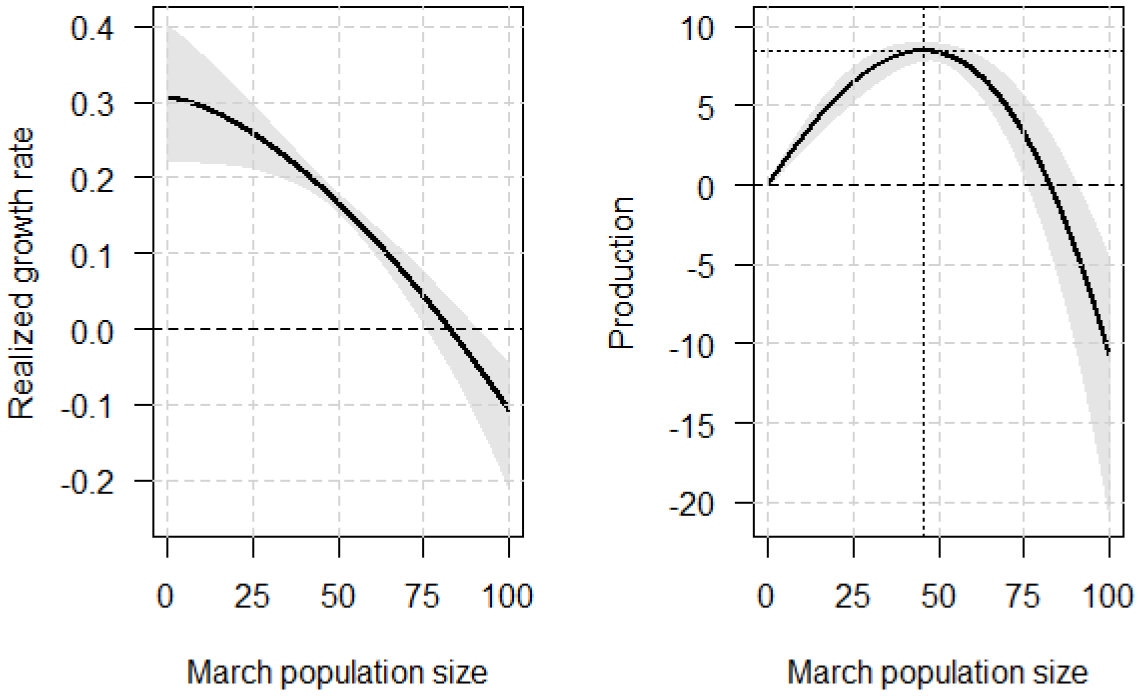

Figure 6. Estimates of realized growth rate and net production (in thousands) as a function of March population size (in thousands) as based on an IPM for Taiga Bean Geese in the Central Management Unit, with 95% credible intervals in grey. Maximum production and, thus, maximum sustainable yield, are attained with a median population size of 45,400. The median harvestable surplus at this population size is 8,400 birds.

Discussion

Not surprisingly, we found it challenging to estimate key demographic parameters using a time series of only counts and harvests, especially when those data include the Tundra subspecies to varying degrees. Posterior distributions of the parameters of the theta-logistic model were similar to their informative priors, with the exception of the intrinsic reproductive rate. Although the posterior median of 0.45, indicating the ratio of young to older birds at the end of the breeding season, may appear rather high, it is important to remember that this represents a biological maximum. If the effect of density dependence is considered, the proportion of young in the fall flight should typically be around 20%, which is similar to observations reported from Sweden for 2009 – 2013 (Marjakangas et al. 2015). We also note that the posterior median of θ, the form of density dependence, is lower (but more precise) than that reported in the 2020 harvest assessment, and this will make allowable harvests smaller than those reported previously. Finally, we note that the posterior distribution of the proportion of harvest occurring in Sweden prior to the January count, α, was identical to its prior. We have treated this parameter as fixed based on limited data from two years (2017 – 2018). If an estimate of January population size remains an objective of the IPM, then additional observational data is needed to apportion the Swedish harvest, preferably on an annual basis.

Results suggest strong population growth in all three months in which counts were conducted, coincident with a sharp decrease in harvest rate in 2014. Although harvests have generally been declining over the last decade for all three countries, the trend is most pronounced in Finland, where severe harvest restrictions were enacted. In contrast to the March 2020 population estimate of 75,200

(70,200 – 80,500) reported in the 2020 harvest assessment, our estimate is 66,200 (61,300 – 72,000). The lower value was expected due to the exclusion of the Tundra subspecies. While the median population estimate is just shy of the target of 70,000 for Taiga Bean Geese, we note that the ISSAP specifies a desired range of 60,000 – 80,000 birds in the CMU (Marjakangas et al. 2015).

Using the IPM, we project that March population size will approach 70,000 in five years (on the average) with a total annual harvest of 3,000. This is similar to the average realized harvest of 3,300 during 2014 – 2019. Nonetheless, somewhat higher harvests are still consistent with the desire for continued population growth. Based on the yield curve depicted in Figure 6, as long as March population size remains >25,000, a harvest ≤5,000 may be permissible. Obviously, harvests >3,000 will lengthen the amount of time required to reach the median target of 70,000 birds beyond five years (on the average). Finally, we note that while the average harvest has been that needed to help ensure population growth, the realized allocation of the harvest among countries has not been what has been agreed upon. Going forward, countries should consider bringing their harvests in line with the desired allocation of 58%, 30%, and 12% for Finland, Sweden, and Denmark, respectively.

In the six-month progress report, we modeled variation in the reproductive rate, γ, as both fixed-year and random-year effects, reasoning that in geese it is likely that temporal variation in reproduction exceeds that of natural mortality (Pfister 1998, Schmutz 2009). A fixed-year-effect model estimates reproductive rate independently for each year, while a random-year-effect model draws annual reproductive rates from a common distribution. In both case, the variation is of a density-independent nature; for example, as related to weather on the breeding grounds (Jensen et al. 2014). Allowing annual variation in reproduction generally improved the fit of abundance estimates to the count data. However, the estimated annual variation in reproduction was quite low. Notably, the inclusion of fixed-year or random-year effects typically increases the length of MCMC chains required to achieve convergence (Kéry and Schaub 2012). We chose not to investigate environmental variation in reproduction as part of this final report because: (1) previous efforts suggested only minor annual variation; and (2) the inclusion of random-year effects for the proportions of Taiga Bean Geese in the data made convergence difficult to achieve, with resulting long run-times of the IPM (>3 hours with Windows 10, 64-bit dual 2.6 GHz processors). Future work might pursue the consideration of environmental variation in reproductive and/or survival rates, possibly as a function of relevant covariates.

With respect to monitoring data, additional data on survival and/or reproduction from a capture-mark-recapture program and observations of the ratio of young to adults in the autumn would be helpful in deriving more robust estimates of key demographic parameters. In terms of population counts, we agree with the recommendation of the EGMP Taiga Bean Goose Task Force to maintain all three seasonal counts at least through 2021, when a more informed decision about monitoring efforts can be made. As expected, existing January counts appear to be negatively biased. Perhaps coincidentally, the average difference between January counts and median estimates from the IPM averaged about -10,000, which is similar to the 9,600 Taiga Bean Geese reported from Germany in January 2015 (Marjakangas et al. 2015). More frequent counts of Taiga Bean Geese in January in Germany might thus be helpful in eliminating the bias in January counts. Finally, we strongly recommend that recent efforts to better identify subspecies in both the counts and harvests be continued. As a longer time-series of these data accumulate, we should be able to more accurately focus the IPM on Taiga Bean Geese.

Ultimately, we seek development of an adaptive management framework to guide the annual setting of harvest quotas. Using the IPM and agreed upon management objectives, we can derive optimal, abundance-dependent harvest strategies using stochastic dynamic programming (SDP) (Marescot et al. 2013). A key advantage of SDP is its ability to produce a dynamic, feedback policy specifying optimal harvest decisions for all possible population sizes rather than relying on expected, future abundances. In practice, this makes SDP appropriate for systems that behave stochastically, absent any assumptions about the system remaining in a desired equilibrium or about the production of a constant stream of resource benefits. 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 or from external studies.

Acknowledgements

Financial support for this project was graciously provided by the Finnish Wildlife Agency and Natural Resources Institute (LUKE). We thank Mikko Alhainen, Anthony Fox, and Jesper Madsen for helpful reviews of an earlier draft.

Literature Cited

Bolker, B. M. 2008. Ecological models and data in R. Princeton University Press, Princeton, New Jersey.

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 71:1–25.

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 7:457–472.

Heldbjerg, H., A. D. Fox, T. K. Christensen, P. Clausen, H. Kampe-Persson, K. Koffijberg, V. Kostiushyn, N. Liljebäck, C. Mitchell, L. Nilsson, and others. 2020. Taiga Bean Goose Population Status Report 2019-2020. AEWA European Goose Management Platform, Bonn, Germany.

Heldbjerg, H., A. D. Fox, T. K. Christensen, P. Clausen, H. Kampe-Persson, K. Koffijberg, N. Liljebäck, C. Mitchell, L. Nilsson, U. Skyllberg, and others. 2019. Taiga Bean Goose population status report 2018--2019. AEWA European Goose Management Platform, Bonn, Germany.

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., M. Alhainen, A. D. Fox, J. Madsen, and M. Guillemain. 2018. Making do with less: must sparse data preclude informed harvest strategies for European waterbirds? Ecological Applications 28:427–441.

Johnson, F. A., M. A. H. Walters, and G. S. Boomer. 2012. Allowable levels of take for the trade in Nearctic songbirds. Ecological Applications 22:1114–1130.

Johnson, F., G. Jenseen, and H. Heldbjerg. 2020a. Harvest assessment for taiga bean geese in the Central Management Unit: 2020. AEWA European Goose Management Platform, Bonn, Germany.

Johnson, F., S. Mäntyniemi, and H. Heldbjerg. 2020b. An integrated population model for the Central Management Unit of taiga bean geese. AEWA European Goose Management Platform, Bonn, Germany.

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

Knape, J. 2008. Estimability of density dependence in models of time series data. Ecology 89:2994–3000.

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 4:872–884.

Marjakangas, A., M. Alhainen, A. D. Fox, T. Heinicke, J. Madsen, L. Nilsson, and S. Rozenfeld. 2015. International Single Species Action Plan for the Conservation of the Taiga Bean Goose (Anser fabalis fabalis). AEWA Technical Series No. 56.

Pfister, C. A. 1998. Patterns of variance in stage-structured populations: Evolutionary predictions and ecological implications. Proceedings of the National Academy of Sciences of the United States of America 95:213–218.

Pihl, S., T. E. Holm, P. Clausen, I. K. Petersen, R. D. Nielsen, K. Laursen, T. Bregnballe, and B. Søgaard. 2015. Fugle 2012-2013. Aarhus Universitet, Aarhus, Denmark.

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.

Schmutz, J. A. 2009. Stochastic variation in avian survival rates: life-history predictions, population consequences, and the potential responses to human perturbations and climate change. Pages 441–461 *in* D. L. Thomson, E. G. Cooch, and M. J. Conroy, editors. Modeling Demographic Processes In Marked Populations. Springer US, Boston, MA.

Skyllberg, U. 2015. Numbers of Taiga Bean Geese Anser f. fabalis utilizing the western and central flyways through Sweden during springtime 2007-2015. Ornis Svecica 25:153–165.

AEWA European Goose
Management Platform

UNEP AEWA

UNEP/AEWA Secretariat
UN Campus
Platz der Vereinten Nationen 1
53113 Bonn
Germany
Tel.: +49 (0) 228 815 2413
Fax: +49 (0) 228 815 2450
aewa.secretariat@unep-aewa.org
www.unep-aewa.org