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Authors: Johnson, Fred A., and Koffijberg, Kees

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Biased monitoring data and an info-gap model for regulating the offtake of greylag geese in Europe

Fred A. Johnson and Kees Koffijberg

F. A. Johnson (https://orcid.org/0000-0002-5854-3695) ✉ (fred.johnson@bios.au.dk), Aarhus Univ., Dept of Bioscience – Kalø, Rønde, Denmark. – K. Koffijberg (https://orcid.org/0000-0003-0146-2269), Savon, Dutch Centre for Field Ornithology, Nijmegen, the Netherlands.

The problem we address is motivated by the desire to regulate the size of the NW/SW European population of greylag geese *Anser anser* to meet a number of management objectives, including providing sustainable harvests and minimizing agricultural impacts and conflicts. Using simple models of population dynamics along with observed allometric relationships in birds, we have concluded that reported estimates of greylag goose population size and/or offtake at the flyway level are likely biased, perhaps severely so. Recognizing that resources are limited, we suggest that the most pressing need may be to investigate and strengthen monitoring protocols for offtake. We also describe a simple information-gap ('info-gap') decision model that could allow decision makers to make informed choices about changes in offtake until such time that more reliable monitoring information is available for greylag geese. With the info-gap decision model we were compelled to use a management criterion based on the growth rate of the flyway-wide population because true levels of abundance and offtake are unknown. Moreover, we emphasize that in the face of deep uncertainty about greylag goose abundance and offtake, decisions concerning management of the population carry a high risk of failing to meet conservation objectives, whatever they may be. While the info-gap analysis suggests an increase of offtake beyond the nominal level of 450 000 reported in the International Single Species Management Plan may be necessary to stabilize the population, we do not know the current level of offtake (i.e. whether it has recently changed from that last reported). Moreover, recent counts conducted by the range states and the International Waterbird Census suggest that the winter flyway population may no longer be increasing. For these reasons, management implications of the info-gap analysis must be viewed with caution.

Keywords: allometric methods, bias, greylag goose, info-gap decision model, monitoring, offtake, population growth, reproduction, survival

Like many arctic and subarctic breeding geese, the NW/SW European population of greylag geese *Anser anser* grew dramatically in the latter part of the 20th century, increasing almost eight-fold from about 125 000 individuals in the 1980s to 960 000 in the late 2000s (Madsen 1991, Fox and Leafloor 2018). The principal range of this population includes Norway, Sweden, Finland, Denmark, Germany, Netherlands, Belgium, France and Spain (hereafter collectively referred to as Range States) (Powolny et al. 2018). Geese from this population are also thought to occur regularly in Poland, the Czech Republic, Hungary and Portugal but, as numbers there constitute less than 1% of overall numbers, they are not included here. Although greylag geese provide important cultural and provisioning services, their numbers have increasingly brought them into conflict with other human activities (Buij et al. 2017). In 2018, the European Goose Management Platform (EGMP; <https://egmp.aewa.info/>) developed a flyway management plan, which was approved by the meeting of the parties of the African–Eurasian Waterbird Agreement (AEWA) in 2019. The plan's goal is to regulate the size of the flyway population to meet a number of management objectives, including providing sustainable harvests and minimizing agricultural damage and conflicts, while maintaining the population in a favorable conservation status (Powolny et al. 2018). Our research was thus motivated by the need to determine allowable levels of offtake of greylag geese, including both sport harvest and culling. Culling is often referred to as 'derogations' under Article 9 of the EU Birds Directive, which applies to countries that do not have an open hunting season or to countries where culling occurs outside the regular hunting season (<https://ec.europa.eu/environment/nature/legislation/birdsdirective/index_en.htm>).

Science-based population management requires at a minimum reliable estimates of population size and offtake. The International Single Species Management Plan (ISSMP) for

the NW/SW population of greylag geese provides estimates of abundance of 900 000–1 200 000 individuals in midwinter and an annual offtake of about 450 000 individuals during the mid-2010s (Powolny et al. 2018). One or both estimates appear to be biased, given that such a high rate of take is unlikely to be compatible with observed increases in abundance. The potential presence of bias in estimates of abundance and/or offtake make informed decisions concerning the attainment of management objectives in the ISSMP of this goose population challenging at best.

Recognizing that decision makers often cannot delay decisions until better data are available, we describe a simple information-gap decision model (Ben-Haim 2001) that could allow decision makers to make informed choices about changes in the level of offtake until such time that more reliable monitoring information is available for greylag geese. Information gap decision theory ('info-gap') is designed for cases of 'deep' uncertainty – those in which a stochastic (probabilistic) structure for uncertain consequences is either unreliable or unavailable (Ben-Haim 2001, Regan et al. 2005, van der Burg and Tyre 2011). It is similar to the concept of maxi–min (Polasky et al. 2011), in which a preferred management action is the one which maximizes the minimum level of management performance over all uncertain outcomes. Info-gap decision analyses poses a slightly different question: 'which action is most likely to satisfy a specified management criterion for the largest range of uncertainty?'

In the following sections, we first provide evidence for bias in reported estimates of abundance and/or offtake of greylag geese. We then describe a simple info-gap decision model that could allow decision makers to make informed choices about levels of offtake based on monitoring data currently available. We also provide a quantitative measure of the risk of not meeting a management criterion so that decision makers can account for their risk attitude. Finally, we discuss improvements to monitoring that are needed to manage greylag geese in accordance with the objectives expressed in the ISSMP.

Material and methods

A paucity of demographic data for greylag geese makes it difficult to test the veracity of reported estimates of abundance and offtake. Here we describe the use of established allometric relationships in birds, along with simple models of population dynamics, to help determine whether reported estimates of abundance and offtake in the ISSMP are reliable.

Intrinsic and realized growth rates of the greylag goose population

We used the allometric methods of Niel and Lebreton (2005) and Johnson et al. (2012) to estimate the intrinsic population growth rate (i.e. no density dependence and no anthropogenic mortality) of greylag geese. From Johnson et al. (2012), adult survival under ideal conditions for birds ranging in mass from 12 g to 8.66 kg is estimated as:

$$\theta = p^{\frac{1}{\left(\exp\left(3.22+0.24\log\left(M\right)+e\right)-\alpha\right)}} \quad (1)$$

where p is the observed proportion of the population alive at the observed maximum lifespan with $p \sim \text{beta}(3.34,101.24)$, M is body mass in kg, α is age at first breeding and e is the error in the model relating body mass to longevity with $e \sim \text{Normal}(0,\sigma^2 = 0.087)$. The distribution of p is constant, and is unrelated to body mass (Johnson et al. 2012).

Using both female and male mean body masses of 3.108 kg (SD = 0.274) and 3.509 (SD = 0.321), respectively (Dunning Jr. 2008), and an age at first breeding of $\alpha = 3$ (Nilsson et al. 1997, Kampp and Preuss 2005), the median (intrinsic) survival is $\theta = 0.889$ and the 95% confidence interval is 0.785–0.943. This represents a maximum longevity of about 30 years, which agrees well with that of birds in captivity (Nigrelli 1954). We note that the use of an age at first breeding of $2 < \alpha \leq 3$ (i.e. some portion of 2-year-olds breed; Nilsson and Kampe-Persson 2018) causes only minor differences in the value of θ.

Next, we used the values of $\theta = 0.889(0.785–0.943)$ and $\alpha = 3$ along with Eq. 15 from Niel and Lebreton (2005) to estimate the intrinsic population growth rate as:

$$\lambda \approx \frac{\left(\theta\alpha-\theta+\alpha+1\right)+\sqrt{\left(\theta-\theta\alpha-\alpha-1\right)^2-4\theta\alpha^2}}{2\alpha} \approx 1.159\left(1.120-1.206\right) \quad (2)$$

The median is similar to empirical values for snow geese *Chen caerulescens* and barnacle geese *Branta leucopsis* provided by Niel and Lebreton (2005).

We next estimated the realized mean growth rate, $\bar{\lambda}$, using a log-linear regression model of a temporal sequence of greylag goose counts in midwinter, N^w:

$$N_t^w = N_0^w \lambda^t \quad (3)$$

$$\log\left(N_t^w\right) = \log\left(N_0^w\right) + \log\left(\lambda\right) \times t$$

$$\log\left(N_t^w\right) = \beta_0 + \beta_1 t + e_t$$

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

The expectation of the intrinsic population growth rate arising from the log-normal distribution is thus: $\bar{\lambda} = \exp\left(\beta_1 + \frac{\sigma^2}{2}\right)$. For the period (2004–2012) in which national midwinter counts are available from all Range States (Heldbjerg et al. 2020), the estimated mean growth rate was $\bar{\lambda} = 1.063\left(1.048-1.079\right)$ (Fig. 1). Note that this analysis assumes that whatever the bias in national counts may be, it is relatively constant over the period 2004–2012.

We note, however, that the rate of population growth may have decreased since 2012. National counts are available from all Range States from 2004 to 2016 (i.e. four additional years) except Spain (outside Doñana) and Germany. If we use the observed growth rates in those two countries during 2004–2012 to extrapolate their respective counts through 2016, the growth rate of the flyway population was $\bar{\lambda} = 1.038\left(1.026-1.051\right)$ during 2004–2016. Counts of

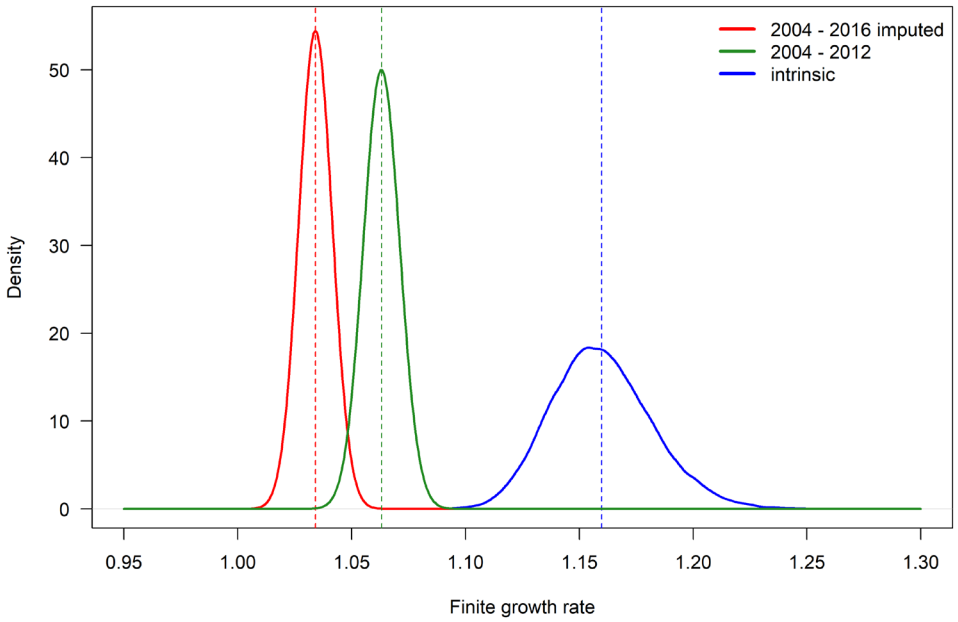

Figure 1. The intrinsic population growth rate of greylag geese as estimated using the methods of Niel and Lebreton (2005) and Johnson et al. (2012), and the realized growth rates based on national counts in the Range States of the NW/SW European population of greylag geese. Note that counts for Spain and Germany were imputed for 2013–2016. Dashed, vertical lines represent the means.

geese in the Netherlands and in Spain appear to be most responsible for the lower growth rate when compared to the 2004–2012 period. We use this estimate of population growth rate as it best conforms to the time period of reported abundance and offtake in the ISSMP.

Evidence of bias in abundance and/or offtake

We first assessed the potential for bias in reported estimates of abundance and/or offtake by examining expected kill and survival rates. Kill rate is defined here as the annual rate of mortality due to all anthropogenic sources, whether hunting/culling related or not. We assumed that: 1) the population is not subject to any significant density dependence; 2) all anthropogenic mortality is due to sport hunting or to take under derogations; 3) winter mortality is primarily due to hunting/culling; and 4) offtake is additive to other sources of mortality. While all of these assumptions are unlikely to be true, we believe they represent a reasonable starting point.

There are at least two ways to estimate the realized kill rate, $\bar{k}$, independently of estimates of abundance and offtake. In the first, we use estimates of the intrinsic and realized growth rates. Under the assumptions listed above, the realized kill rate is a function of the intrinsic and realized growth rates:

$$\bar{\lambda} = \lambda\left(1-\bar{k}\right) \tag{4}$$

such that:

$$\bar{k} = 1-\frac{\bar{\lambda}}{\lambda}$$

We can also use Eq. 4 to infer the maximum kill rate that would not cause the population to decline as:

$$k' = 1-\frac{1}{\lambda}$$

The second approach relies on Eq. 4, but uses intrinsic and realized survival rates, again under our four model assumptions:

$$\bar{\theta} = \theta\left(1-\bar{k}\right) \tag{5}$$

such that:

$$\bar{k} = 1-\frac{\bar{\theta}}{\theta}$$

We used Eq. 5, along with published values of realized survival, $\bar{\theta}$, from the literature (Frederiksen et al. 2004, Powolny et al. 2018) to estimate the realized kill rate of greylag geese. We then compared estimates from both methods to the kill rate implied by reported estimates of midwinter abundance and offtake in the ISSMP:

$$N^{w} = \frac{900\,000+1\,200\,000}{2} = 1\,050\,000$$

$$H = 450\,000$$

such that:

$$k = \frac{H}{N^{w}+H} = \frac{450\,000}{1\,500\,000} = 0.3$$

As described in Results, an examination of survival and kill rates suggested that estimates of abundance and/or offtake reported in the ISSMP are biased. Therefore, we used the estimated intrinsic and realized population growth rates to investigate the potential magnitude of that bias by using a modification of Eq. 4:

$$\bar{\lambda} \approx \lambda\left(1-\frac{\beta H}{\alpha N}\right) \quad (6)$$

where $\bar{\lambda}$ is the realized growth rate, λ is the intrinsic growth rate, H and N are the reported size of the offtake and the post-breeding population, respectively, and α and β are bias coefficients. If the (approximate) equality in Eq. 6 is satisfied for $\alpha=\beta=1$, then there is no apparent bias in estimates of abundance or offtake. We found combinations of α and β that satisfy the equality in Eq. 6 for reported values of H and N, using 5000 independent draws from the distributions for $\bar{\lambda}$ and λ (Fig. 1).

Info-gap decision analysis

The existence of bias of unknown magnitude in greylag goose monitoring renders traditional approaches to modeling population dynamics and decision analysis unsuitable. However, in an effort to guide decision making, we explored an info-gap approach, which poses the question: 'what level of offtake will most likely satisfy a management criterion for the largest range of uncertainty?' In our case, the deep uncertainty concerns the true values of α and β, expressing the degree of bias in estimates of abundance and offtake, respectively. Thus, we would like to choose a management action, in this case a level of proportional change in offtake, H, that would meet some management criteria for a larger range of uncertainty in α and β than any other potential change in level of offtake.

Ultimately, the management criterion will be represented by target population sizes for one or more management units defined for greylag geese, which are derived from the different migratory behavior of geese within the flyway (Bacon et al. 2019). However, population targets are not useful as criteria in this case because it is abundance itself that is uncertain. As an alternative, we can establish a management criterion based on the predicted growth rate of the NW/SW European flyway population using Eq. 4. In other words, we can determine the nominal level of offtake that would meet a growth-rate criterion for the largest possible range in values of α and β. This approach must assume that, whatever the bias in estimates of abundance and/or offtake, it is relatively constant over time.

Population growth based on national counts during 2004–2016 was $\bar{\lambda}=1.038\,(1.026-1.051)$ amid growing concern about the adverse impacts of population size. In the face of deep uncertainty about current levels of offtake and abundance, we suggest that decision makers might adopt a precautionary approach, for example, of seeking to reduce population size by 15% over the 10-year span of the ISSMP. Thus, the management goal would be an annual growth rate of $\lambda=\exp\left(\frac{\log(0.85)}{10}\right)=0.98$. The decision maker understands (s)he is unlikely to meet the criterion of a realized growth rate $\bar{\lambda}=0.98$ precisely, but would like to get as close as possible. The info-gap decision problem then is: 'what nominal level of offtake will meet a performance criterion of $|\bar{\lambda}-1|\le C$, where C is some critical threshold, for as large a range in α and β as possible?' For example, (s)he might consider $C=0.02$, such that $0.96 \le \lambda \le 1$ was acceptable (i.e. population size decreasing by 4% or less per year). Accordingly, an increasing population, or a population declining more than 4% per year, would be considered unacceptable. The lower limit of 0.96 could be anything, and here we simply note that an annual $\lambda=0.96$, if realized, would reduce population size by 34% in 10 years. In June 2020, the International Working Group of the EGMP decided that a reduction of at least 20% in abundance of greylag geese was in line with the management objectives of the ISSMP. We note that the critical limit is symmetric, as expressed by $|\bar{\lambda}-1|\le C$. However, it need not be symmetric; for example, in the case where negative growth rates are more or less desirable than positive ones.

We first established a range of uncertainty in α and β to examine. Based on the results of our bias investigation, it is likely that estimated offtake is biased high as long as true abundance exceeds nominal abundance by a factor < 3.5. Thus, we set $\alpha \sim$ uniform(0.5,3.5) and $\beta \sim$ uniform(0.2,1.0). We then examined a range of nominal values of offtake and, for each combination of α and β, predicted $|\bar{\lambda}-1|$ using Eq. 4.

While the info-gap analysis relies only on the estimated intrinsic growth rate (and not on an observed growth rate), it is nonetheless sensitive to nominal values of abundance and offtake. As with the investigation of bias, we used imputed, total winter counts, but used an average of the three most recent years available (2016–2018) from the International Waterbird Counts coordinated by Wetlands International (Heldbjerg et al. 2020). We used the most up-to-date information on abundance as we were interested in identifying a prospective level of take. Unfortunately, more contemporary estimates of offtake than those reported in the ISSMP are not available, so we continued to assume that the nominal level of offtake is 450 000. Thus, nominal offtake and post-breeding abundance was assumed to be:

$$H = 450\,000$$

$$N_{IWC}^{W} = \frac{709\,000+775\,000+751\,000}{3}$$

$$N = 745\,000+450\,000=1\,195\,000$$

Results

Evidence of bias

Using our estimates of the intrinsic growth rate, $\lambda \approx 1.159(1.120–1.206)$ and realized growth rate during 2004–2016, $\bar{\lambda}=1.038\,(1.026-1.051)$, the estimate of realized

kill rate was $\bar{k} \approx 0.10(0.07-0.14)$. The maximum kill rate that could be tolerated without inducing a decline in greylag goose abundance was $k \approx 0.14(0.11–0.17)$. Because the estimated growth rate of the flyway population was positive during 2004–2016, we would therefore expect the realized kill rate to be $\bar{k} < 0.14$.

Using survival rates of adults reported by Powolny et al. (2018) of $\bar{\theta} \in \{0.81, 0.92, 0.74, 0.95, 0.85\}$ and our median value of $\theta = 0.89$ in Eq. 5, estimates of realized kill rates are $\bar{k} \in \{0.09, -0.03, 0.17, -0.07, 0.04\}$ (where $\in$ means 'is an element of' the set denoted by {…}). Using estimates of greylag goose survival given in Frederiksen et al. (2004, Table 4) of $\bar{\theta} \in \{0.84, 0.80, 0.82, 0.85, 0.80, 0.68, 0.73\}$, estimates of realized kill rates are $\bar{k} \in \{0.06, 0.10, 0.08, 0.04, 0.10, 0.24, 0.18\}$. For values of $\bar{\theta} > \theta$ we get values of $\bar{k} < 0$, which are inadmissible, meaning that $\bar{\theta}$ is biased high or θ is biased low. We also note that if we assume $\theta = 0.89$ is approximately correct, values of $\bar{k} \geq 0.17$ would cause the population to decline (recall that for $k > 0.14$, $\lambda < 1$). If we ignore these irregularities and the fact that the annual survival rates from the literature are not independent, then the estimated mean kill rate is $\bar{k} = 0.08(-0.05-0.22)$, which is similar to that based on population growth rates.

Therefore, a kill rate of $\bar{k} = 0.3$ implied by estimates of abundance and offtake in the ISSMP seems doubtful at best. We can go one step further using a slight modification to Eq. 4, such that:

$$\bar{\lambda} = \lambda(1-k)$$

$$\bar{\lambda} = \theta(1+\gamma)(1-k)$$

where γ = post-breeding age ratio of young to older birds. If $\bar{k} = 0.3$ and we allow for no natural mortality such that $\theta = 1$, then $\gamma \geq 0.48$ (i.e. $\geq 32\%$ young in fall) is needed to prevent the population from declining. While this high level of productivity has been observed in the Netherlands (Hornman et al. 2020), it has not been observed in the past decade. Age-ratio data from mainly non-migratory populations in both the Netherlands and parts of western Germany show averages of 14% and 16% young in fall, respectively (Koffijberg and Kowallik 2018, Hornman et al. 2020). And we emphasize that $\gamma \geq 0.48$ is the minimum productivity assuming no natural mortality ($\theta = 1$), which is clearly unrealistic given the assessments mentioned before. For comparison, the allometric estimate of intrinsic productivity is $\gamma = 0.32(0.19–0.54)$, or about 24% young in the fall. Moreover, if we assume $\bar{k} = 0.3$ and the values of $\bar{\theta}$ reported in the literature, then survival under ideal conditions is $\theta > 1$ for every $\bar{\theta}$ except $\bar{\theta} = 0.68$, which is impossible (again, assuming additive anthropogenic mortality). Thus, it seems unlikely that $\bar{k} = 0.3$. We therefore conclude that reported abundance is biased low and/or reported offtake is biased high.

Using 5000 samples from the distributions for $\bar{\lambda}$ and λ, we solved Eq. 6 for β for a range of values of α. A plot of the resulting values of β against α can be divided into four quadrants, representing cases where: 1) H is biased low ($\beta > 1$) and N is biased high ($\alpha < 1$); 2) H is biased low ($\beta > 1$) and N is biased low ($\alpha > 1$); 3) H is biased high ($\beta < 1$) and N is biased low ($\alpha > 1$); and 4) H is biased high ($\beta < 1$) and N is biased high ($\alpha < 1$) (Fig. 2). If we were to assume that the nominal estimate of offtake is unbiased (horizontal dashed line in Fig. 2), abundance would be underestimated by a factor of about 2.5–3. On the other hand, if we assume that the nominal estimate of abundance is unbiased (vertical dashed line in Fig. 2), offtake would be overestimated by a factor of almost three. If one were to assume that actual goose abundance is unlikely to be more than about three times the nominal abundance, then inevitable conclusion is that the nominal estimate of offtake is biased high, perhaps severely so.

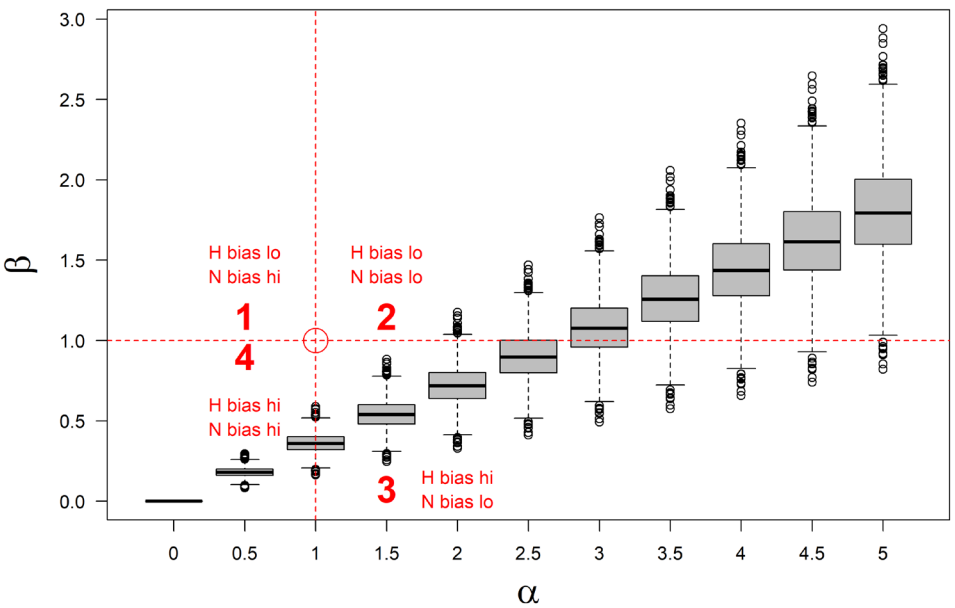

Figure 2. Combinations of α and β that satisfy the equality in Eq. (6) for nominal values of abundance and offtake of the NW/SW European population of greylag geese that were reported in the ISSMP. The horizontal dashed line represents an unbiased reported estimate of offtake, and the vertical dashed line represents an unbiased reported estimate of goose abundance.

The conclusion that reported offtake is biased high is further supported if we consider the possibility that the intrinsic growth rate is a maximum that may not be realized in a variable environment, or that density-dependent mechanisms are acting to reduce it. Consider the following modification to Eq. 6:

$$\bar{\lambda} \approx p\lambda\left(1-\frac{\beta H}{\alpha N}\right) \quad (7)$$

where $p < 1$ represents a potential reduction in the intrinsic growth rate. For any values $p < 1$, the combinations of α and β that satisfy the equality in Eq. (7) even more strongly suggest a positive bias in reported offtake.

Info-gap results

Based on 5000 samples from the distributions for $\bar{\lambda}$, the probabilities of meeting the management criterion of $0.96 \leq \lambda \leq 1.96$ for a range of potential levels of offtake are shown in Fig. 3. Notice that all probabilities are low (< 20%), reflecting the challenge of meeting the restrictive criterion of $0.96 \leq \bar{\lambda} \leq 1.00$ in the face of deep uncertainty concerning the true extent of bias, α and β. A nominal level of offtake of 40% higher than that reported in the ISSMP is expected to achieve the management criterion for a wider range in α and β than any other alternative. But we emphasize that this decision would be accompanied by an 86% chance that the criterion would not be met (assuming all examined values of α and β are considered equally plausible). In other words, there would be an 86% chance that abundance could either increase or decline by more the 4% annually. Finally, we note a very broad range of changes in offtake had nearly identical (mean) probabilities of meeting the management criterion, and indeed are not statistically distinguishable from each other.

Discussion

Evidence for bias in monitoring instruments has also been reported for greylag geese breeding in Iceland (Frederiksen et al. 2004) and has been identified at a regional level in Europe (Utrecht and Noord-Holland in the Netherlands; Stahl et al. 2013, Schekkerman et al. 2018). The source of the bias in greylag goose monitoring protocols is not easily identified, as other sources of corroborating information are lacking. However, IWC counts and estimates of the number of breeding pairs (which may have their own problems) in the ISSMP seem to suggest that national counts may be roughly of the correct magnitude or at least not severely underestimated. Corroborating estimates of sport and derogation harvest are lacking, but we note that Padding and Royle (2012) found that hunter-reported goose harvests in the U.S. were 49–64% higher than the actual harvests (e.g. hunters potentially exaggerated their harvest). This is a possible cause of a positive bias in offtake in the case of greylag geese, but bias could also arise from other factors. For example, there may be reporting errors or incentives to inflate the reported derogations, which may arise from local management practices designed to minimize agricultural damage.

It is also possible that reported population sizes and offtake for greylag geese are approximately correct, but this would demand higher survival and fecundity than is typical in arctic and subarctic breeding geese. Indeed, the proportion of young in the flyway population prior to hunting would have to be ≥ 32% (the minimum value of 32% would only be possible if there was no mortality other than harvest). Based

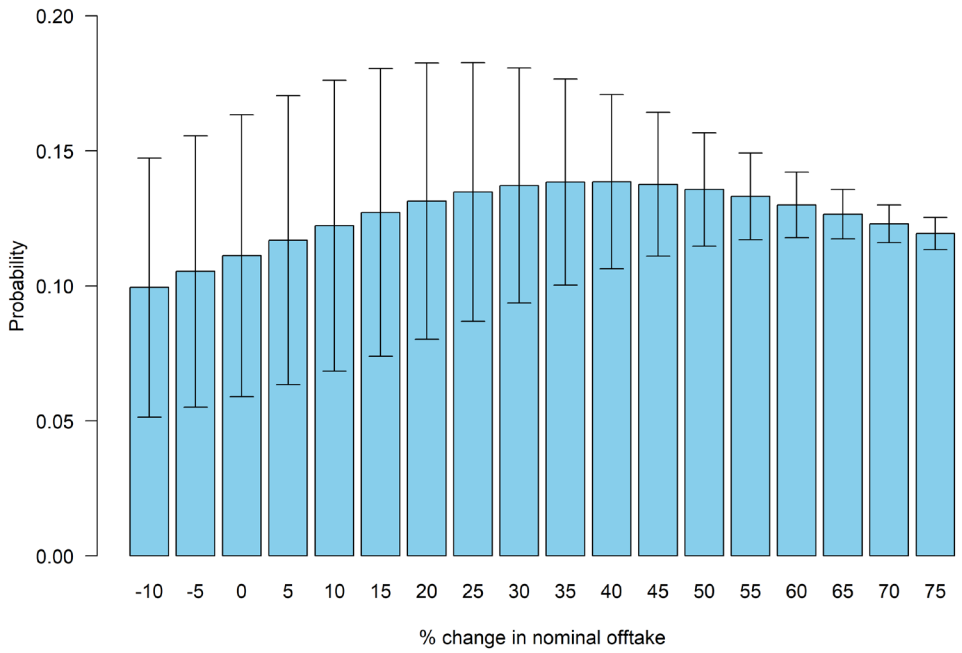

Figure 3. Probabilities of achieving a population growth rate of $0.96 \leq \lambda \leq 1.00$ for varying levels of change in reported offtake (relative to the value of 450 000 reported in the ISSMP) for NW/SW European population of greylag geese in the face of deep uncertainty about bias in estimates of abundance and offtake. Error bars represent 95% confidence limits, which account for uncertainty in the intrinsic growth rate of greylag geese.

on allometric relationships (Niel and Lebreton 2005, Johnson et al. 2012), we would expect about 23% young under ideal conditions. Recent assessments from the Netherlands and Germany suggest 14–16% young in mainly non-migratory populations in the southern portion of the population's range (Koffijberg and Kowallik 2018, Hornman et al. 2020). However, greylag geese breeding in temperate latitudes do so under exceedingly favourable environmental conditions and such high values of reproductive success cannot be completely dismissed as they were observed in the Netherlands in the late 1990s (Hornman et al. 2020).

Although an increase in nominal offtake may be needed to reduce population size, the info-gap analysis suggests that an increase in offtake may even be needed to stabilize population size. Yet recent IWC counts and the national counts suggest that the flyway population is no longer increasing (Heldbjerg et al. 2020). Assuming this recent population trend is real, there are at least three possible reasons for the contradictory conclusions arising from the info-gap analysis: 1) the current, reported winter abundance is lower than the value we used; 2) the current offtake is higher than the value we used (i.e. it has increased in recent years); or 3) there are factors beyond offtake (e.g. density dependence) acting to lower the growth rate. Indeed, all three reasons might be operative.

In the face of deep uncertainty about estimates of greylag goose abundance and offtake, decisions concerning management of this population carry a high risk of failing to meet conservation objectives, whatever they may be. If such decisions must be made, however, information-gap decision analysis offers perhaps the most robust choice of decision-analytic tools. Info-gap analysis seeks a decision among all possible choices that has the best chance of meeting a management criterion for the largest range of uncertainty. In the case of greylag geese, however, simplifying assumptions about population dynamics must be made, and only a management criterion based on the rate of flyway population growth is plausible, as almost any other objectives would likely be related in some way to population size or offtake, both of which are unknown. Even a management criterion based on a population growth rate is feasible only if we assume that the bias in abundance and offtake, whatever their magnitude, are relatively constant over time.

Using simple models of population dynamics along with observed allometric relationships in birds, we have inferred that reported estimates of greylag goose population size and/or offtake at the flyway level are likely biased, perhaps severely so. Our analysis also provides greater evidence that offtake is biased high than abundance is biased low, although bias in both cannot be discounted. Recognizing that resources are limited, we suggest that the most pressing need may be to investigate and strengthen monitoring protocols for greylag goose offtake. While population counts have been largely coordinated among countries using standardized methods (Heldbjerg et al. 2020), offtake reporting has been rather haphazard. For example, reporting is sometimes not required nor solicited, reported offtake is occasionally an unknown mix of sport harvest and derogations, data are sometimes not routinely compiled on a national basis, and monitoring protocols are sometimes changed without maintaining adequate documentation of the changes. A first step toward improvement in greylag goose monitoring would be to document the protocols used for generating estimates of offtake in each of the Range States, including identification of responsible parties and methods for data collection and reporting. The resulting compendium could provide useful insights into potential sources of bias. Also, if resources allow, a capture–mark–resight program could be useful for investigating potential bias in abundance (Clausen et al. 2019), and would have the additional benefit of providing independent estimates of survival (and potentially, harvest) rates. If greylag geese in Europe are to be managed as a shared resource, it seems clear that more international coordination will be essential for establishing rigorous and standardized protocols for data collection and archiving.

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References

Bacon, L. et al. 2019. Spatio–temporal distribution of greylag goose *Anser anser* resightings on the north–west/south–west European flyway: guidance for the delineation of transboundary management units. – Wildl. Biol. 2019: wlb.00533.

Ben-Haim, Y. 2001. Information gap decision theory: decisions under severe uncertainty. – Academic Press.

Buij, R. et al. 2017. Balancing ecosystem function, services and disservices resulting from expanding goose populations. – Ambio 46: 301–318.

Clausen, K. K. et al. 2019. Using re-sighting data to estimate population size of pink-footed geese *Anser brachyrhynchus*. – Ornis Fenn. 96: 112–123.

Dunning Jr., J. B. 2008. CRC handbook of avian body masses. – CRC Press.

Fox, A. D. and Leafloor, J. O. 2018. A global audit of the status and trends of Arctic and Northern Hemisphere goose populations. – Conservation of Arctic Flora and Fauna International Secretariat.

Frederiksen, M. et al. 2004. The dynamics of hunted Icelandic goose populations: a reassessment of the evidence. – J. Appl. Ecol. 41: 315–334.

Heldbjerg, H. et al. 2020. Greylag goose northwest/southwest European population status report 2016–2019. – <https://egmp.aewa.info/sites/default/files/meeting_files/documents/AEWA_EGM_IWG_5_13_GG_Status_Report_Rev.1.pdf>.

Hornman, M. et al. 2020. Watervogels in Nederland in 2014/2015. – Sovon Rapp 2020/01.

Johnson, F. A. et al. 2012. Allowable levels of take for the trade in Nearctic songbirds. – Ecol. Appl. 22: 1114–1130.

Kampp, K. and Preuss, N. O. 2005. The greylag geese of Utterslev Mose: a long-term population study of wild geese in an urban setting. – Dansk Ornitol. Foren. Tidsskr. 99: 1–78.

Koffijberg, K. and Kowallik, C. 2018. Sommerbestände von Gänsen in Nordrhein-Westfalen 2011–2017. – Charadrius 54: 151–166.

Madsen, J. 1991. Status and trends of goose populations in the western Palearctic in the 1980s. – Ardea 79: 113–122.

Niel, C. and Lebreton, J. 2005. Using demographic invariants to detect overharvested bird populations from incomplete data. – Conserv. Biol. 19: 826–835.

Nigrelli, R. F. 1954. Some longevity records of vertebrates. – Trans. N. Y. Acad. Sci. 16: 296–299.
Nilsson, L. and Kampe-Persson, H. 2018. Lifetime reproductive success of greylag geese *Anser anser* breeding in south Sweden. – Ornis Svecica 28: 39–47.
Nilsson, L. et al. 1997. Factors affecting survival of young greylag geese *Anser anser* and their recruitment into the breeding population. – Wildfowl 48: 72–87.
Padding, P. I. and Royle, J. A. 2012. Assessment of bias in US waterfowl harvest estimates. – Wildl. Res. 39: 336–342.
Polasky, S. et al. 2011. Decision-making under great uncertainty: environmental management in an era of global change. – Trends Ecol. Evol. 26: 398–404.
Powolny, T. et al. 2018. AEWA International Single Species Management Plan for the greylag goose *Anser anser* – northwest/southwest European population. – AEWA Tech. Ser. No. 71.
Regan, H. M. et al. 2005. Robust decision-making under severe uncertainty for conservation management. – Ecol. Appl. 15: 1471–1477.
Schekkerman, H. et al. 2018. Evaluatie van het Ganzenbeheerplan 2015–2020 Noord-Holland. – Sovon-rapport 2018/65.
Stahl, J. et al. 2013. Beheer van zomerganzen in de Provincie Utrecht. – Savon-rapport 2013/28.
van der Burg, M. P. and Tyre, A. J. 2011. Integrating info-gap decision theory with robust population management: a case study using the Mountain Plover. – Ecol. Appl. 21: 303–312.