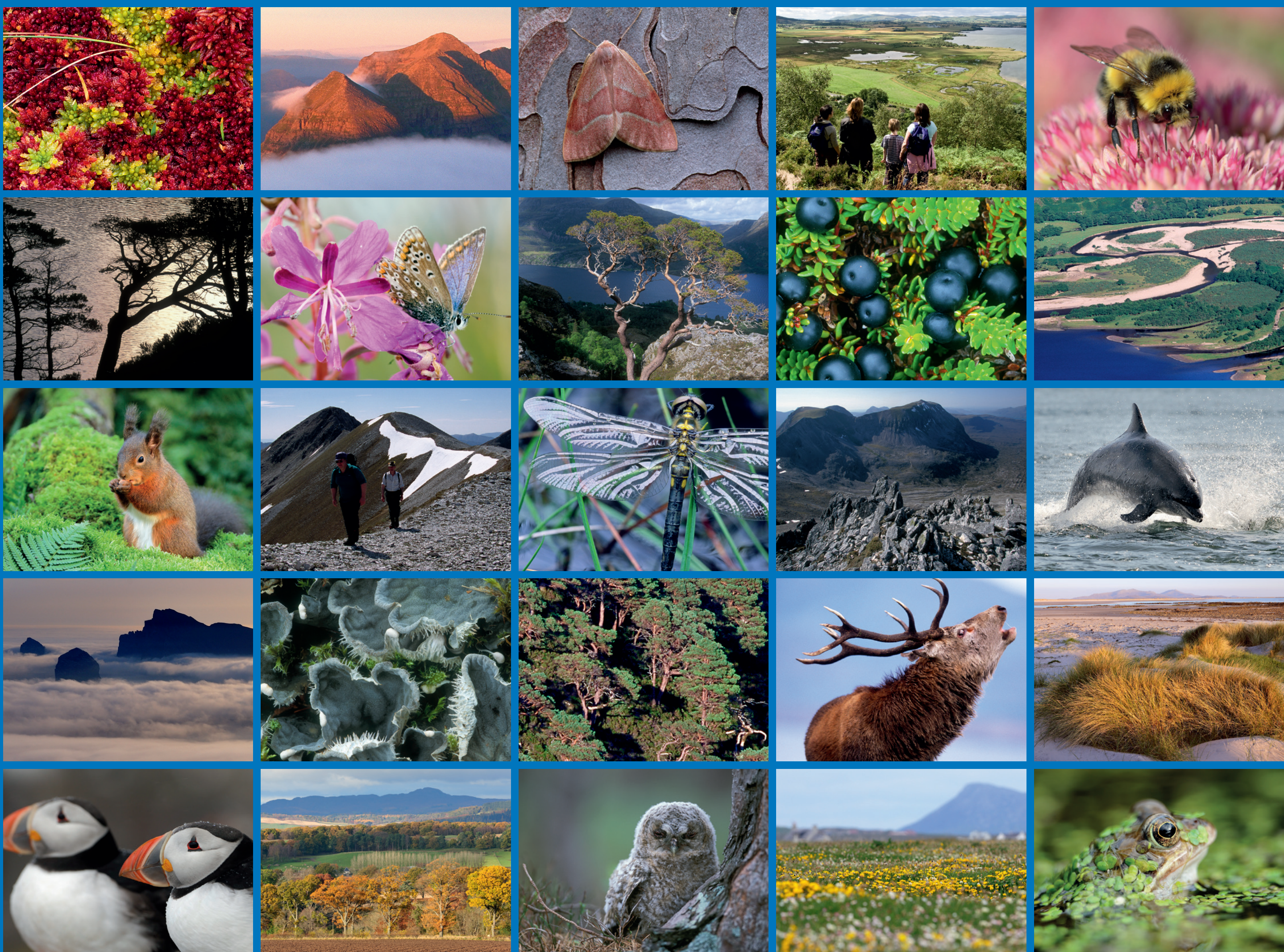
Scottish Natural Heritage
Research Report No. 1039

Development of a population model tool to predict shooting levels of Greenland barnacle geese on Islay



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RESEARCH REPORT

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Development of a population model tool to predict shooting levels of Greenland barnacle geese on Islay

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RESEARCH REPORT
Summary

Development of a population model tool to predict shooting levels of Greenland barnacle geese on Islay

Research Report No. 1039
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Keywords

Greenland barnacle geese; Islay; Scotland; population model; shooting bag; sustainable management; conservation conflicts

Background

As part of the 10-year Islay Sustainable Goose Management Strategy (ISGMS), population management has been carried out on Islay based on a previous Population Viability Analysis (PVA) (Trinder 2005, 2014). However, Scottish Natural Heritage (SNH) now wishes to update its existing population model because intended Greenland barnacle geese (GBG) reductions during the first years of the ISGMS have proved difficult to achieve. Here, we present a new modelling approach combining data on population size, land-use, climate, and shooting effort that will enable shooting bags to be derived under quantified levels of uncertainty.

Main findings

- The Greenland barnacle goose (GBG) population on Islay has shown a logistic growth rate. After an initial rapid increase in population size, the population growth rate has declined.
- The recent (e.g. 2003-2015) GBG Islay population fluctuates around 45,000 (± 4,082 standard deviation) individuals
- The population model (PM) developed here accurately predicts the average winter population of GBG on Islay measured between November and March (inclusive) in the absence of culling on Islay.
- Based on previous work, the PM assumes that both climate and the area of improved grassland (AIG) are strong predictors of the size of the GBG population on Islay. Similarly, the PM requires the inclusion of shooting bags implemented on Greenland and Iceland to estimate future population trends. Thus, all of the above (i.e. climate, AIG and shooting bags) need to be updated in the model to obtain future population predictions.
- Integration of the PM into the Generalised Management Strategy Evaluation (GMSE) framework provides a tool for forecasting the dynamics of geese based on management targets and maximum allowed shooting bags.
- The PM used here to inform shooting bags via the GMSE approach provides a good fit to available historic data and performs better than using the population count from the previous year alone, or using a simpler logistic growth model.

- For the PM-GMSE modelling approach to work, it is expected that the user updates the value for each predictor (climate, AIG and shooting bags) in the model so that it can be re-run each year. If such data are not available, a simpler (e.g. logistic growth approximation) population model should be used.
- The PM-GMSE approach produces an estimate of the future GBG mean winter count on Islay, as well as a range of shooting bags given a population target.
- For an initial run of 1,000 simulated managed populations with a management target of 29,000 and a maximum per year shooting bag of 2,500, most simulations came close to the management target within 10 years. But uncertainty and stochasticity could lead to the target being achieved in a shorter or longer time period, as well as higher or lower population sizes.
- Future access to individual-based datasets will allow the implementation of more sophisticated models (e.g. integral population model, IPM) able to account for demographic rates, including processes of immigration and emigration.

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1. INTRODUCTION

Islay – an 62,000 ha island in the Inner Hebrides of western Scotland – supports more than 50% of the global population of Greenland barnacle geese (*Branta leucopsis*) over winter (Trinder, 2014; Mason *et al.,* 2018). Every year, large flocks of geese arrive in October from breeding grounds in eastern Greenland, transiting via Iceland before arriving on Islay, with a large proportion wintering until mid-April (Mason *et al.,* 2018). Greenland barnacle geese (GBG, hereafter) are Amber listed in the UK Birds of Conservation Concern (Eaton *et al.*, 2009), and the species is protected under Annex 1 on the European Union (EU) Birds Directive. The flyway population size was estimated at 80,670 individuals in 2013 (Mitchell & Hall, 2013). Population numbers on Islay have increased in recent years from around 20,000 individuals in 1987 to more than 40,000 in 2016 (Trinder, 2014; Mason *et al.,* 2018). This increase has led to higher levels of damage to the agricultural economy on Islay, and has engendered conflicts between stakeholders with agricultural and conservation interests (Mason *et al.,* 2018; Cusack *et al.,* 2018). The cost of the damage caused by GBG has been estimated at £1.6 million per year. In response to this, a 10-year management plan was developed (the Islay Sustainable Goose Management Strategy, ISGMS) aimed at decreasing agricultural damage caused by geese by 25%-35% (McKenzie, 2014). A key component of this management plan is a significant reduction in barnacle goose numbers (by up to 25%-30%) through the implementation of controlled culling. It is hoped that these actions will help decrease the level of conflict between goose conservation and agricultural livelihoods on the island.

As part of the ISGMS, population management has been carried out on Islay based on a previous Population Viability Analysis (PVA) (Trinder, 2005; 2014). However, SNH now wishes to update its existing population model because intended GBG reductions during the first years of the ISGMS have proved difficult to achieve. In recent years, the trend in the GBG population on Islay has not matched the increase predicted by the PVA. At the same time, a recent analysis by Mason *et al.* (2018) shows that Islay GBG population growth is strongly related to both the area of improved grassland (AIG) on the island (positively), as well as climatic variables (temperature [positively] and rainfall [negatively]) on both Islay and Greenland. Such factors have not previously been used in Islay GBG predictions.

Thus, we present in this report a new modelling approach combining data on population size, land-use (AIG on Islay), climate (temperature and rainfall on Islay and Greenland) and shooting effort, that will enable shooting bags to be derived under quantified levels of uncertainty. As a first step, we construct and validate a Population Model (PM) for the GBG Islay population using historical datasets relating to counts, shooting bags, land-use and climate. We also derive from these historical datasets measures of uncertainty that are then added into the model. We then integrate the PM into a management strategy evaluation (MSE) framework, which enables management decisions on harvest rates and the resulting impacts on GBG population dynamics to be simulated. In particular, we integrate the PM into a generalised MSE (GMSE) to simulate adaptive decision-making (Duthie *et al.,* 2018). The use of both models (i.e. PM and GMSE) allows managers to take decisions under multiple sources of uncertainty by providing a distribution of shooting bag limits corresponding to desired population targets.

1.1 Objectives

The aims of this report are in line with the SNH adaptive ISGMS (McKenzie, 2014). The proposed modelling approach fulfils ISGMS's general objectives by providing a means to maintain a viable population of GBG that meets conservation obligations and reduces damage to grass crops, thereby sustainably reducing the impact of geese on the agricultural economy of Islay.

In particular, the specific objectives of this report are:

- To compile a complete dataset with all available data relating to population counts, shooting bags (i.e. for Islay, Greenland and Iceland), climate (i.e. temperature, rainfall) and land-use (i.e. area of improved grassland), relevant to building the PM and GMSE models.
- To parameterise a general PM for the GBG population on Islay, together with associated levels of uncertainty.
- To introduce observation error and test a range of manager decisions by incorporating the PM into a GMSE framework.
- To simulate the effect of different shooting bags applied to the Islay GBG population.

The modelling approach represents an adaptive, and therefore more realistic, method to estimate future population numbers than previous models. Indeed, not only does the modelling approach require an up-to-date dataset, but it also accounts for the effect of a range of environmental factors known to affect GBG population size (Mason *et al*., 2018) and some of the uncertainty associated with such factors. Moreover, the integration of PM-GMSE models will enable the simulation of SNH objectives and the testing of different shooting bags, thus ensuring the best outcome can be attained for GBG on Islay.

2. DATA COLLECTION

The data used in this study relate to the entire migratory population of Greenland barnacle geese (GBG). The compiled dataset provided here is made up of the following six components: a) population counts, b) shooting bags, c) land-use data, d) climate data, e) productivity data, and f) survival data. Please see Table 1 for details of each component and Annex 1 for the full dataset. Each row of the dataset corresponds to a single year between 1964 and 2017 (Annex 1). Although we include productivity and survival data (from Trinder, 2014) in the collated dataset (Table 1), it is important to clarify that this study does not include these in either the PM or GMSE models. The individual-based dataset from which survival would have been estimated was not available to us at the time of this study and so we were unable to build an integrated population model as initially intended (see section 4). Nevertheless, productivity and survival data are provided in this report as part of the compiled dataset for future use by SNH.

It is important to note that we used data collected between the years 1987 and 2015 to parameterise and validate our modelling approach. Although SNH provided data for the years 2016 and 2017, issues with the values given for the area of improved grass meant that we could not validate the model against observed mean winter counts for these years. We have, however, requested this information from the Agricultural, Fisheries and Rural department and will add it to future versions of this report.

Table 1. Summary of datasets compiled to parameterise PM and GMSE models. Dataset columns correspond to the 6 components mentioned in section 2. Each column relates to: a) Description of each dataset included, b) Components (i.e. columns within the full dataset) of that specific dataset, c) Notation as written in the full dataset, d) Definition of each variable in that particular dataset, e) Years of data included in the analysis, and f) Source for each dataset included. The full version of the compiled dataset is provided in Annex 1.

Dataset	Description	Components	Notation	Definition	Years	Source
Population counts	Monthly counts and mean winter count for the GBG population on Islay recorded between November and April each year.	Monthly counts	November, December, January, February, March & April	mean number of GBG counted within two days each month over winter (i.e. November to April) on Islay.	1987-2017	Islay international count dataset
		Mean counts	mean.counts	average number of GBG counted over each winter (i.e. November to March) in Islay		Barnacle goose Islay monthly counts 1987-2015 International counts comparisons 2005-2015
Shooting bags	Number of GBG individuals culled each year	Islay cull target	islay.cull.tar	number of GBG to be culled on Islay	1982-2016	Islay Goose Management Annual Reports; Mason et al. 2018
		Islay culled	islay.culled	number of GBG effectively culled on Islay		
		Proportion of target culled	prop.target.culled	percentage of GBG culled from the total number of individuals targeted		
		Iceland cull	iceland.cull	number of GBG culled in Iceland		Statistics Iceland; Mason et al. 2018 (https://www.statice.is/statistics/business-sectors/agriculture/hunting/)
		Greenland cull	greenland.cull	number of GBG culled in Greenland		Mason et al. 2018 SNH data pers. comm.
Land-use	Area (ha) of improved grassland on Islay	Grassland hectare	grass.ha	combined hectares of temporary (<5yrs) and permanent (5yrs+) grassland	1987-2015	Mason et al. 2017; For years post 2015, please contact Paul Gavin (from the Agricultural Census Analysis Team (Rural and Environmental Science and Analytical Services)

Climate	Characterization of Islay climate during the GBG non-breeding season (October-April)	Mean temperature	mean.temp	mean temperature on Islay over winter season (October-April)	1964-2017	Met Office UK (http://www.metoffice.gov.uk/climate/uk/summaries/datasets) Choose “Scotland W” as Region; “Mean temp”/”Min temp”/”Rainfall”/”Days of air frost” as Parameter
		Minimum temperature	min.temp	minimum temperature registered over winter season (October-April) in Islay		
		Rainfall	rainfall	amount of rain (mm) fall on Islay over winter season (October-April)		
		Frost days	frost.d	number of days of air frost over winter season (October-April)		
	Characterization of Greenland climate in Danmarkshavn, which corresponds to the GBG population distribution during breeding months (May-August)	Precipitation May	precip.may	amount of rain (mm) fall at Danmarkshavn in May	1964-2015	Danish Meteorological Institute (https://www.dmi.dk/vejrarkiv/) Choose (in order of drop down menus): “Grønland” (Greenland) “Danmarkshavn” “Måneder” (Monthly) “Temperatur” (Temperature) OR “Nedbor” (Rain) Can be downloaded as .csv by clicking icon on top right of the graph.
		Precipitation August	precip.aug	amount of rain (mm) fall at Danmarkshavn in August		
		Mean temperature may	mean.temp.may	mean temperature at Danmarkshavn in May		
		Mean temperature August	mean.temp.aug	mean temperature at Danmarkshavn in August		
Additional datasets						
Productivity	Age counts carried out on GBG between November and March each year	Juvenile percentage	juv.perc	percentage of GBG juveniles within the sampled group	1964-2016	Breeding success of Barnacle Geese wintering on Islay by Ogilvie, M. 2009-2017. [*Not used in model parameterisation*]
		Sample size	sample.size	number of individuals sampled and aged each year		

		Mean brood size	mean.brood	mean number of GBG juveniles per brood pair sampled		
		Number of brood pairs	no.broods.pairs	number of GBG brood pairs sampled		
		Number of juveniles	num.juv	number of GBG juveniles sampled		
		Number of adults	num.ad	number of GBG adults sampled		
Survival	Estimated survival rates for the GBG population on Islay	Juvenile survival	juv.surv	estimated GBG juvenile survival	1982-2010	SNH-Status and population viability of Greenland barnacle geese on Islay by Trinder, M. 2014. [*Not used in model parameterisation*]
			SE_js	standard error for estimated GBG juvenile survival		
		Adult survival	ad.surv	estimated GBG adult survival		
			SE_as	standard error for estimated GBG adult survival		

3. POPULATION MODEL (PM)

We initially proposed the development of an integrated population model (IPM) that would combine count, brood size and re-sighting data to estimate demographic rates (e.g. survival and productivity) and expected population sizes for GBG on Islay. We were, however, unable to access individual based re-sighting data collected on Islay, which were needed to reliably estimate survival over time. Although a Leslie matrix model was considered as an alternative, we decided not to use this approach owing to the constraints on modelling a limited environment within this framework, and the uncertainty associated with survival estimates derived by Trinder (2014). Instead, we implemented a population-level model (PM) based on the principle of logistic growth. This latter approach is in many ways more tractable and – as described in the following sections – was found to perform reasonably well.

3.1 Overall PM approach

The logistic growth model assumes an effect of population density on growth rate. It is typically represented by a sigmoidal population growth curve. After an initial rapid increase in population size, growth rate declines at higher population sizes due to space or resource limitations, which results in an asymptote, also known as the population carrying capacity. This is a widely used basic model in population ecology, and preliminary data analysis showed that a model of this form provided a good fit to the count data of wintering GBG on Islay. In addition, as outlined above, we also know that the Islay GBG population size is affected by a number of environmental factors, including climate, land-use and management (Mason *et al.,* 2018). Thus, our PM represents a variant of the logistic growth model that accounts for a number of additional effects:

- The effect of area of improved grassland (AIG) on the GBG carrying capacity on Islay;
- The effects of average temperature and rainfall measured in Greenland, average temperature the previous winter on Islay, and the AIG two winters ago on Islay on the intrinsic growth rate of the GBG population;
- The effect of hunting bags recorded in Greenland and on Iceland.

3.2 PM structure

The population model is defined as follows (for *t* defined from 1st October – 30th September):

$$N_{t+1} = \left[r_{max} \times N_t \times (a \times AR_t + b \times AT_t + c \times IT_t + d \times AIG_{t-1}) \times \left(1 - \frac{N_t}{k_0 + k \times AIG_t}\right)\right] + N_t - e \times N_t$$

where,

- N_t represents mean winter count of GBG on Islay in year <u>*t*</u>;
- r_{max} represents the maximum (or intrinsic) growth rate, note that this is an intrinsic maximum rate and is unaffected by extraneous factors such as shooting;
- k_0 represents a baseline carrying capacity for GBG on Islay in the absence of AIG, this is a constant with its value derived from a separate analysis, see below and Figure 2;
- *k* represents the effect of AIG at time *t* on population carrying capacity;
- *AIG* represents the area of improved grassland on Islay;
- *AR* represents the mean August rainfall on Greenland;
- *AT* represents the mean August temperature on Greenland;
- *IT* represents the mean winter temperature on Islay;
- *a, b, c* and *d* represent coefficients of climate and AIG effects
- *e* represents the combined hunting rate for Greenland and Iceland, as a proportion of the mean winter count of GBG on Islay.

We chose to fit the model using the mean (monthly) winter count so as to dampen the inter-month variability in counts within a given winter. As seen in Figure 1, counts in April tended to be much lower than those in previous months, so we removed April counts before calculating the mean winter count for each year. The lower counts observed in April likely reflect the onset of the migration back to the breeding grounds in Greenland. In addition, it is important to note that the mean winter count is affected by culling occurring on Islay during the winter. To account for this, for a given year, we added back to each monthly count the average number of birds shot per month of that year, prior to averaging counts across months. Thus, our PM predicts the average winter population of GBG on Islay measured between the months of November and March (inclusive) in the absence of culling.

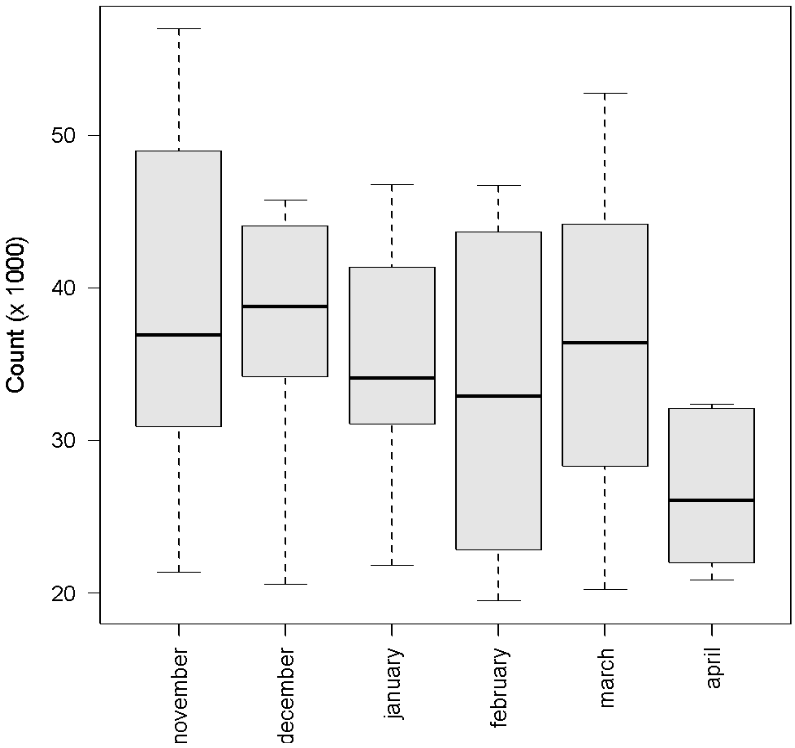

Figure 1. Variation in monthly counts of Greenland barnacle goose on Islay (years 1987 to 2015). Thick back lines represent the median count and the lower and upper ends of the grey boxes are the first and third quartiles of the counts, respectively.

Our model assumes that there is a fixed, minimum carrying capacity for GBG on Islay (k_0) that is independent from the area of improved grassland. To estimate k_0, we modelled the GBG count on Islay as a function of AIG and AIG^2 using a Poisson generalised linear model (Figure 2). k_0 was taken as the model intercept, which in this case has a value of 673 individuals, and was maintained as a constant parameter (with error, see below) in subsequent analyses.

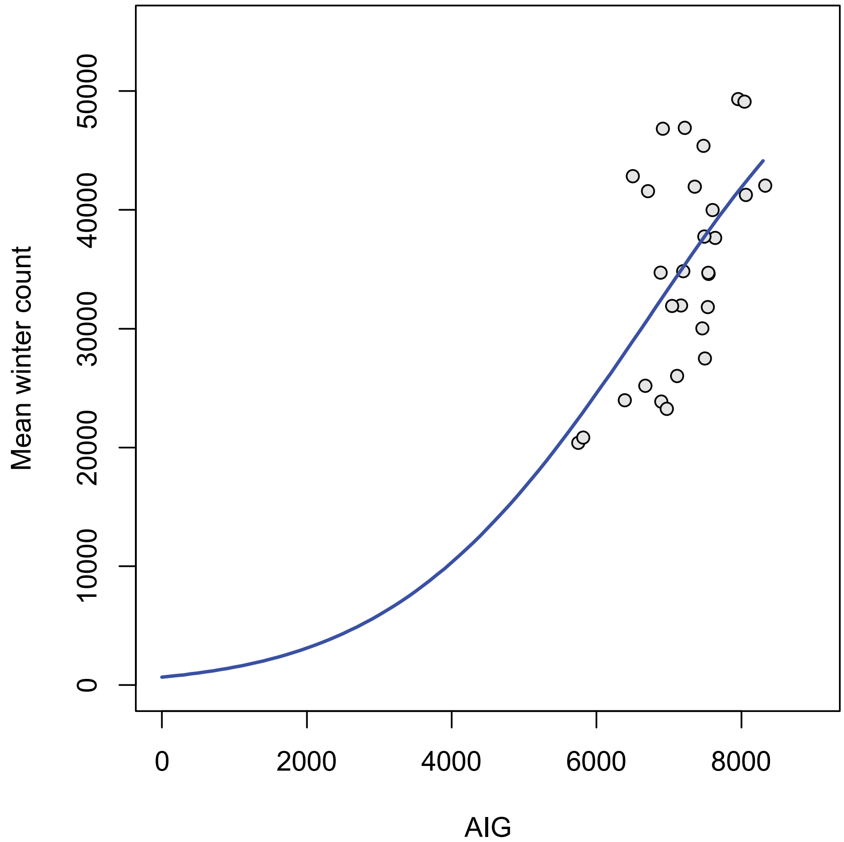

Figure 2. Mean winter count of Greenland barnacle geese on Islay as a function of the area of improved grassland (AIG). The blue curve represents the fit of a Poisson generalised linear model with AIG and AIG^2 as predictor variables ($b_1 = 6.512 \pm 0.10$, $b_2(AIG) = 8.48*10^{-4} \pm 2.09*10^{-9}$, $b_2(AIG^2) = -4.15*10^{-8} \pm 2.99*10^{-5}$). The model intercept is 673 individuals.

Our model also assumes that the area of improved grassland is a strong predictor of the size of the GBG population on Islay, through its positive effect on both the carrying capacity (AIG_t in the model) and the intrinsic growth rate (r_{max}) (Mason *et al.* 2018). However, we stress that our model does not explicitly assign the effect of AIG to survival and/or recruitment owing to lack of suitable data.

Similarly, climate on both Islay and Greenland were shown to influence the population size on Islay during the winter. Mason *et al.* (2018) found that goose abundance was higher following warmer non-breeding seasons on Islay, hence the inclusion of an effect of average temperature on Islay the previous winter in the model (the term c x IT_t). Rainfall and temperature on the breeding grounds in Greenland (AR_t and AT_t in the model, respectively) also affect the size of the population counted on Islay the following winter, respectively. Similarly to AIG, these effects act on the intrinsic growth rate of the population and not specific demographic parameters. It is interesting to note however that these factors likely affect brood rearing, as well as the ability of birds to prepare for the upcoming migration.

We chose to implement the effect of shooting bags on Iceland and Greenland as the removal of a constant proportion (e) of the mean winter count of GBG on Islay (N_t). We note that this removal occurs after the full effect of density dependence has taken place. Between 1995-2015 e was 4.4% on average, and this has remained relatively stable over this period with a symmetrical distribution (Figure 3). Because we have no other information available to predict (changes in) shooting levels in Greenland and Iceland, a constant proportional removal is the best and simplest way to implement this in the population model. Note that although this does assume that all the individuals shot in Iceland and Greenland are individuals that would have wintered on Islay, taking this as the mean proportion shot implies that it could have been higher or lower (Figure 3).

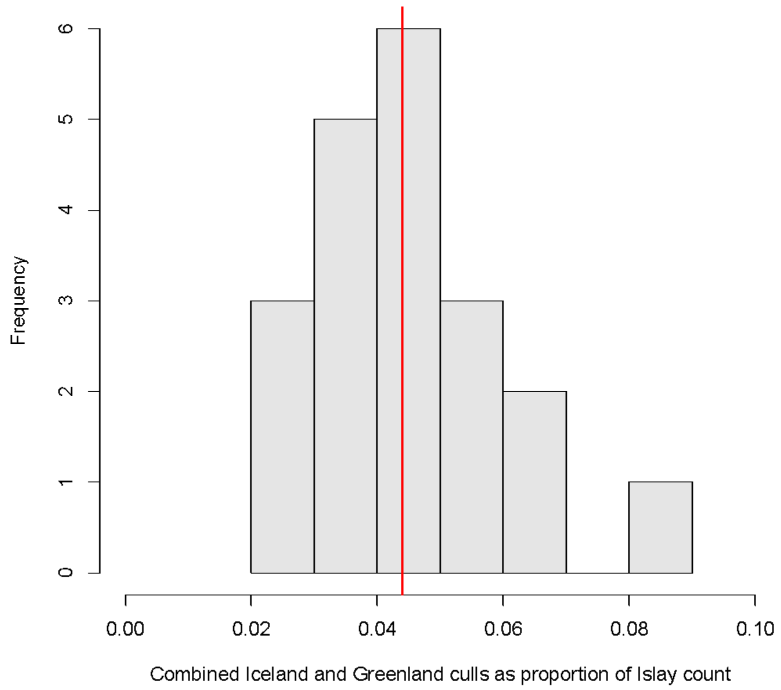

Figure 3. Frequency distribution of the combined Iceland and Greenland hunting bags as a proportion of the Islay Greenland Barnacle goose count, 1995-2015. The mean proportion over this period is 4.4% (red vertical line).

3.3 PM optimisation

We parameterised the PM using relevant historical datasets (see Section 2), including the required Islay GBG count, climate, land-use and shooting bag variables. Parameters were estimated by maximum likelihood estimation, assuming a Poisson distribution for the model residuals. We ensured that our PM provided predictions that were closer to observed counts than simpler approaches whereby a) the mean winter count was modelled as a linear function of the previous year's mean, or b) the logistic model was implemented without environmental and management effects (Table 2; Cusack *et al*., 2018). Model comparison was based on Akaike's Information Criterion (AIC). Figure 4 shows the performance of tested models against observed mean winter counts.

Table 2. Comparison of tested models based on Akaike's Information Criterion (AIC) values. The "Previous year" model represents a linear relationship between the previous year's count and the prediction for the following year (i.e. with slope and intercept parameters). The logistic model with no effects is a basic logistic growth model with no effects of environmental conditions. The logistic model with effects is the main model presented here (see Section 3.2) with a baseline carrying capacity k0 (when AIG = 0) and an effect of AIG on carrying capacity (k), as well as further effects of climatic conditions on population numbers. AIC values are derived from the log likelihood and the number of parameters, with lower values taken to represent a relatively better fit of the model to the data.

Model	# parameters	Log-likelihood	AIC
Previous year (linear model)	2	-4281.7	8567.4
Logistic model (no effects)	2	-3223.9	6451.8
Logistic model (with effects)	6	-3169.0	6350.0

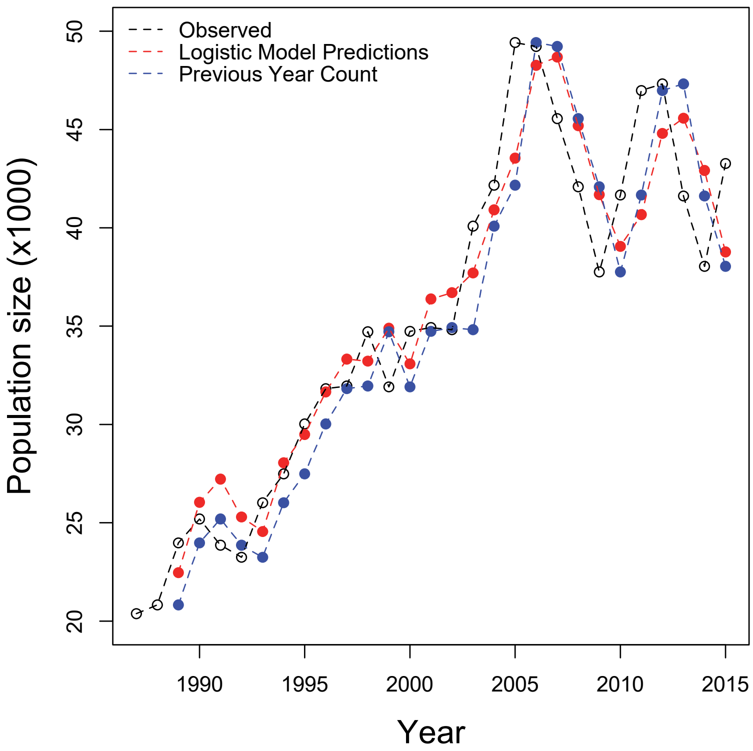

Figure 4. Comparison of model predictions against observed historical mean winter counts of GBG on Islay. Red dots denote predictions from the logistic population growth model accounting for climate, land-use and management effects. Blue dots represent predictions from a model assuming mean winter count at winter t is the same as the mean winter count at winter t-1.

The optimisation procedure resulted in the model parameter estimates shown in Table 3. When interpreting estimates, the following points need to be considered.

- The term (k_0 + kAIG$_t$) represents the population carrying capacity; with constant k_0 = 673 geese representing "baseline" carrying capacity, i.e. the carrying capacity on Islay in the absence of any improved grassland (for explanation of the derivation of this value see Section 3.2), and k representing the effect of changes in area of improved grassland on the total carrying capacity, which is estimated in the parameter optimisation (i.e. estimated as an increase of 6.7 birds per ha on average, see Table 3).

- Both mean August temperature in Greenland and mean temperature on Islay the previous winter have a strong positive effect on the intrinsic growth rate of the GBG population on Islay. In contrast, mean August rainfall in Greenland and AIG on Islay two years ago have weaker negative and positive effects, respectively.
- Standard errors for estimated parameters are small, indicating that most of the uncertainty relating to model predictions is due to error surrounding monthly winter counts and proportional hunting bag in Iceland and Greenland.

Table 3. Model parameter estimates derived from the optimisation procedure.

Parameter	Notation	Estimate (±SE)
Maximum growth rate	r_{max}	0.129 (0.002)
Effect of AIG on population carrying capacity	k	6.655 (0.003)
Effect of mean August rainfall in Greenland	a	-0.007 (0.002)
Effect of mean August temperature in Greenland	b	0.375 (0.003)
Effect of mean temperature on Islay the previous winter	c	0.268 (0.003)
Effect of area of improved grassland on Islay 2 years ago	d	0.0002 (<0.001)

3.4 Count and parameter uncertainty

In this section, we consider and combine uncertainties relating to mean winter counts (N_t in our model), the baseline population carrying capacity (k_0), model parameter estimation (r_{max}, k, a, b, c and d), and the combined Iceland and Greenland cull (e).

There are two sources of error associated with N_t. The first relates to variation across winter months, and the second to observation error due to birds that are missed or counted twice during a given count. It is possible to get an idea of the latter by considering the difference between the count observed on the first day of an “international census” on Islay and the mean of the first and second day counts, which occur on subsequent days. To derive a measure of uncertainty that combined both intra- and inter-month variation, we implemented a two-way ANOVA with count as a response variable and both month and year as interacting factors. From this model, we extracted the distribution of residuals and used this to describe the spread of error surrounding mean winter counts. The resulting normal distribution was characterised by a mean of 0 and a standard deviation of 2846.3 individuals. To account for the variance across five monthly counts within a given winter, we further divided the standard deviation by the square root of five. The subset of international censuses that were used in this analysis is shown in Table 4. This subset was used because both the first and the second day counts were considered to be reliable.

Parameter uncertainty was estimated from the standard errors shown in Table 3. For each parameter, we defined a normal distribution with mean equal to the estimate and standard deviation equal to the associated standard error. Lastly, we assumed the distribution of the combined Iceland and Greenland hunting bags as a proportion of the Islay Greenland Barnacle goose count to be normal (Figure 3), with a mean of 0.044 and a standard deviation of 0.015. For k_0, we assumed a Poisson distributed error with a mean value of 673.

We derived uncertainty surrounding our model predictions by re-running our model 10,000 times, each time inputting values sampled randomly from the error distributions described for N_t, r_{max}, k_0, k, a, b, c, d and e. From these iterations, we estimated the 95% confidence interval surrounding each yearly mean winter count prediction of GBG on Islay. From Figure 5, we can see that the observed mean winter count falls within the 95% confidence interval of the model prediction for all years considered.

Table 4. Subset of Islay international counts used to estimate observation error.

Date 1	Date 2	Month	Count 1	Count 2
15/11/05	16/11/05	November	54035	47565
14/11/06	15/11/06	November	48974	53636
07/12/06	08/12/06	December	45429	46013
20/03/07	21/03/07	March	54884	50533
12/11/07	13/11/07	November	48449	45769
11/12/07	12/12/07	December	45391	43082
12/02/08	13/02/08	February	45526	44906
18/03/08	19/03/08	March	45673	44249
18/11/08	19/11/08	November	41890	39112
16/12/08	17/12/08	December	37803	39664
10/02/09	11/02/09	February	47774	39564
17/03/09	18/03/09	March	44733	45059
16/11/09	17/11/09	November	37036	39458
15/12/09	16/12/09	December	40164	42031
19/01/10	20/01/10	January	31588	33578
16/03/10	17/03/10	March	39222	38020
14/12/10	15/12/10	December	42345	47342
18/01/11	19/01/11	January	37025	34771
10/03/11	11/03/11	March	34912	36410
14/12/11	15/12/11	December	40941	44249
17/01/12	18/01/12	January	40748	41922
20/03/12	21/03/12	March	43090	49733
13/11/12	14/11/12	November	50359	55569
15/01/13	16/01/13	January	44111	44014
19/03/13	20/03/13	March	45871	43837
17/12/13	18/12/13	December	36291	36197
13/01/14	14/01/14	January	46453	37450
18/03/14	19/03/14	March	40590	39228
18/11/14	19/11/14	November	37607	34898
16/12/14	17/12/14	December	40010	38360
17/03/15	18/03/15	March	37284	36694
17/11/15	18/11/15	November	51830	45305
15/12/15	16/12/15	December	45643	42122
19/01/16	20/01/16	January	41125	42346
15/03/16	16/03/16	March	35637	38694

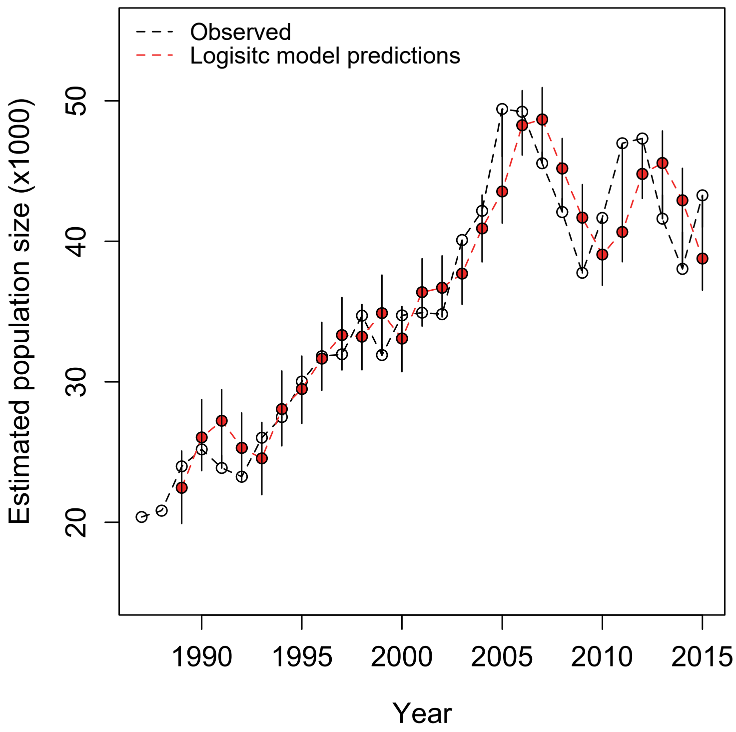

Figure 5. Comparison of model predictions under count and parameter uncertainty against observed historical mean winter counts of GBG on Islay. Red dots denote predictions from the logistic population growth model accounting for climate, land-use and management effects. Vertical bars represent 95% confidence intervals surrounding model predictions, which were derived by resampling parameter error distributions.

4. GENERALISED MANAGEMENT STRATEGY EVALUATION (GMSE)

4.1 Overall GMSE approach

Adaptive approaches allow managers to update datasets and effectively respond to the ever-dynamic environmental challenges (Keith *et al.,* 2011). This is particularly important in socio-ecological systems where multiple variables have to be taken into account, including resource dynamics and stakeholder decision-making (Bunnefeld *et al.,* 2011). Management strategy evaluation (MSE) has been used as a framework to model the interaction of all aspects of resource management. Until now, however, MSE frameworks have been limited in their use due to the inability to model decision-making under changing resource availability (Melbourne-Thomas *et al.,* 2017; Duthie *et al.,* 2018). Here, we use a new modelling tool – the generalised MSE (GMSE) – in order to simulate resource dynamics together with dynamically modelled manager decision-making based on specific management targets (Duthie *et al.,* 2018).

4.2 GMSE components

GMSE runs in the free R environment (https://cran.r-project.org) and is publicly available and full details on both its background and use are documented extensively elsewhere (Duthie *et al.,* 2018). In the following, we briefly summarise the method used by GMSE in general and how this relates to the models we present here.

GMSE employs a game-theoretic approach to model stakeholder decision-making in an adaptive framework using four pre-defined sub-models (Figure 6; adapted from Bunnefeld *et* *al.,* 2011; 2017). A population of conservation interest (here: GBG, Natural resources model Figure 6) is simulated using empirically derived initial conditions and given variation in environmental variables (here: land use and climate). In the present case, these are the population predictions from our PM (Section 3.2). This population is counted (with some error) in the observation model (Figure 6). The manager model then implements a management strategy (here: a shooting bag for Islay) given this observation and a particular target (desired population size). The user model in Figure 6 allows the user to turn policy into action (the actual shooting bag with a potential upper limit). The resulting population size becomes the starting point for the next year. Here, we use GMSE v0.4.0.7 software to integrate the population model with the remaining three aforementioned sub-models to simulate population dynamics and manager decision-making.

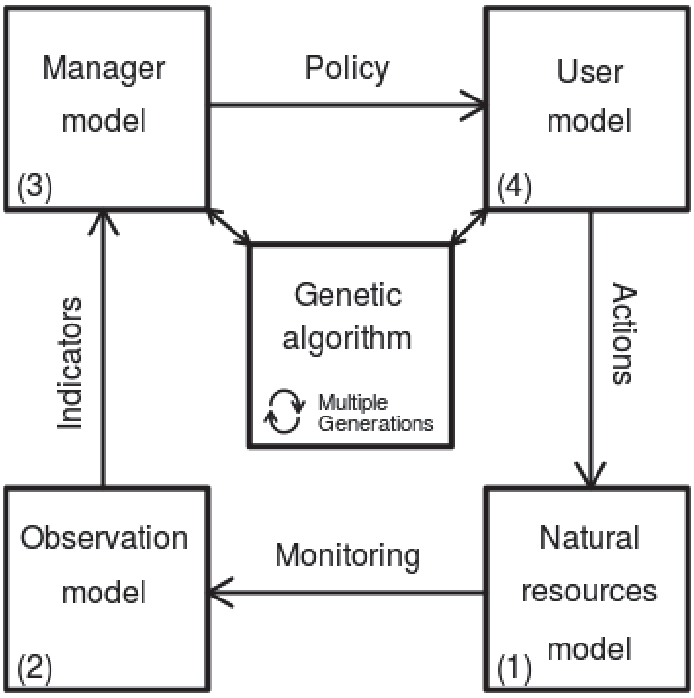

Figure 6. Description of a single time step of the generalised management strategy evaluation framework, which is comprised of four separate sub-models (Duthie et al., 2018) and forms the "internals" of Goose-GMSE. The "natural resources model" (1) in our case uses the PM described in Section 3. Note that the "user model" (4) here refers to the user sub-model of GMSE itself, simulating the responses of resource users; it is distinct from the user interface for Goose-GMSE. Note that the genetic algorithm shown above is not used in Goose-GMSE simulations.

5. INTEGRATION OF PM AND GMSE

5.1 Methods

GMSE incorporates data from the PM and winter counts of GBG into a broader modelling framework using the *gmse_apply* function. This function acts as a wrapper linking each of the four sub-models shown in Figure 6, and does not by itself introduce any new assumptions into simulations apart from the order of operations over the course of one year. Each time step of GMSE (Figure 6) simulates one year of goose population dynamics, observation, management decision, and culling as follows:

- The population model described in section 3 is used as the **natural resource model** to simulate goose population change in the simulated year. All assumptions of the population model are retained in its integration with GMSE; assumptions of the population model are discussed in more detail in Section 6.3. Projected population dynamics are stochastic due to sampling of parameter values with error around long-term trends (see below).

- The **observation model** simulates goose population counts with error that is determined from the count uncertainty data, specifically the standard deviation around count estimates caused by missed or double-counted birds (section 3.4). We assume that the expected observed goose count equals the actual count produced by the population model, with an error sampled from a normal distribution with a standard deviation equal to that obtained from the count uncertainty data.

- The **manager model** uses the counts obtained from the observation model to decide how many geese should ideally be culled to achieve management target objectives as closely as possible. If there are fewer counted geese than the management target, then no geese should be culled; if there are more counted geese than the management target, then the number of excess geese to potentially be culled is returned. Hence, we assume that managers would ideally prefer the cull count to be equal to the number of geese that they observe in excess of the target (but see the user model below).

- The **user model** applies a maximum shooting bag that sets an upper limit on the number of geese that can be culled. If the number of excess geese is greater than this upper limit, then the maximum shooting bag is applied; if the number of excess geese is not greater than this upper limit, then only excess geese are culled (shooting bags from Greenland and Iceland are assumed to continue at their historic levels as estimated from the PM, and are factored into the GMSE natural resource model before simulated culling occurs). Hence, we assume that there is an upper bound on the number of geese that can be culled (referred to as “maximum shooting bag” below).

Additional code was generated in R to simulate the integration of PM and GMSE, and to project goose population dynamics under adaptive management 10 years into the future as based on data from the PM and count uncertainty. In making these projections, linear models are fit for relevant environmental parameter values (AIG and climate data [temperature and rainfall]), as well as for the total number of geese shot in Iceland and Greenland in the preceding summer, over years. Values of these parameters are then modelled by randomly sampling the residuals around this trend from previous years of data and adding them to the expectation for subsequent years. This random sampling of residuals thereby generates stochasticity reflective of the environmental uncertainty that might be expected in future years, while also preserving any long-term trends in parameter values, when predicting future population change. Count estimates in simulations are also stochastic because the count error generated by the GMSE observation model is randomly sampled in each simulated year from a normal distribution with a standard deviation equal to that of the difference between counts (see above). The uncertainty caused by these sources of stochasticity required us to simulate population management several times under the same starting conditions to understand the range of likely outcomes over a 10-year period of management. As an example of the application of the PM-GMSE approach, the results below show 1,000 simulations projecting over 10 years for a management target of 29,000 geese with a maximum shooting bag of 2,500. Additional simulations can be run for different management targets, maximum shooting bags, and degrees of uncertainty in observation and environment.

5.2 Results: ten-year simulation PM-GMSE geese management

Results of projected goose population growth over a 10-year period of management shows that population dynamics might be stabilised at 29,000 geese, but with considerable uncertainty. Figure 7 shows the observed population size up to the most recent prediction for 2016 (white background), while projected population dynamics from 2017 onward (grey background) diverge due to stochasticity of environment and observation uncertainty. Each line represents one of 1,000 unique simulations; some of these simulations reach population sizes close to the 29,000 individuals target, but some also result in population sizes considerably higher or lower than this target due stochastic effects. Figure 8 more clearly shows the same distribution of simulated population sizes over the 10-year projected management period. Points on the line of the projected years show the median population size in a given year, while dashed lines show the maximum 2.5% and 95% percentiles of the estimated counts. These extremes show that even if factors affecting goose population growth and management do not change (e.g., environmental conditions, count estimation, Iceland and Greenland shooting bags, etc.), a range of population change is possible. If factors affecting goose population do change substantially (e.g., temperature or AIG on Islay change more or less than current trends predict), or if additional factors are discovered that are especially relevant for goose population dynamics, then such factors would need to be incorporated into the PM-GMSE approach to make meaningful inferences.

A projection for a single year ahead (in the example presented here, 2016) is included in the simulation runs presented in Figures 7 and 8 as the first projected year. In addition, we also produced a series of projections for just a single year ahead, varying the maximum cull level set (from 0 to 20000). Figure 9 shows the anticipated decline in estimated population size for the following year as resulting from increasing the maximum cull level, with associated (parameter estimation) uncertainty. Both the “starting” population size (blue dashed line) and an arbitrary population target (red dotted line) are also shown in the figure. Using the extent of overlap of the population target with the estimated population size can be used to assess the risk of the population declining to below the target, at a given maximum cull level. Note, however, that (1) Figure 9 shows population projections based on currently available data, and as more data are added its pattern is likely to change; and (2) this figure should not be taken as a direct recommendation for a cull level, only as decision support.

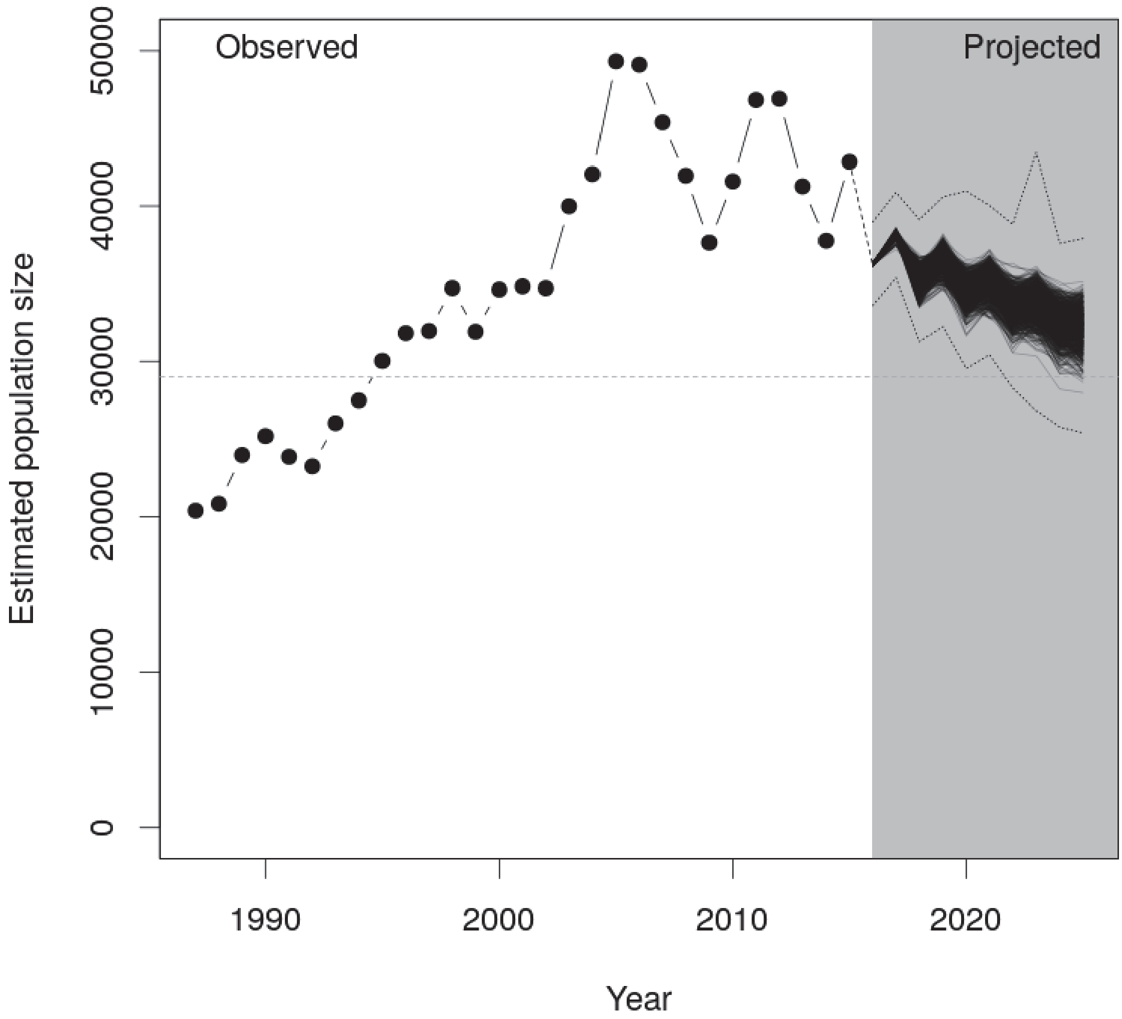

Figure 7. Projected goose population dynamics from the integration of the population model with Generalised Management Strategy Evaluation (GMSE). Years (x-axis) showing goose population size (y-axis) from the observed data are shown in the white background, while years projected using GMSE are shown in the grey background. In the projections, each individual solid black line represents the mean population size for a single simulation (1,000 total simulations) for an example target population size of 29,000 and maximum shooting bag of 2,500. The dotted lines are the minimum and maximum 2.5th and 97.5th percentile of the distribution of all simulations for a given year, representing uncertainty in population trajectories. The horizontal dotted line shows the management target for population size.

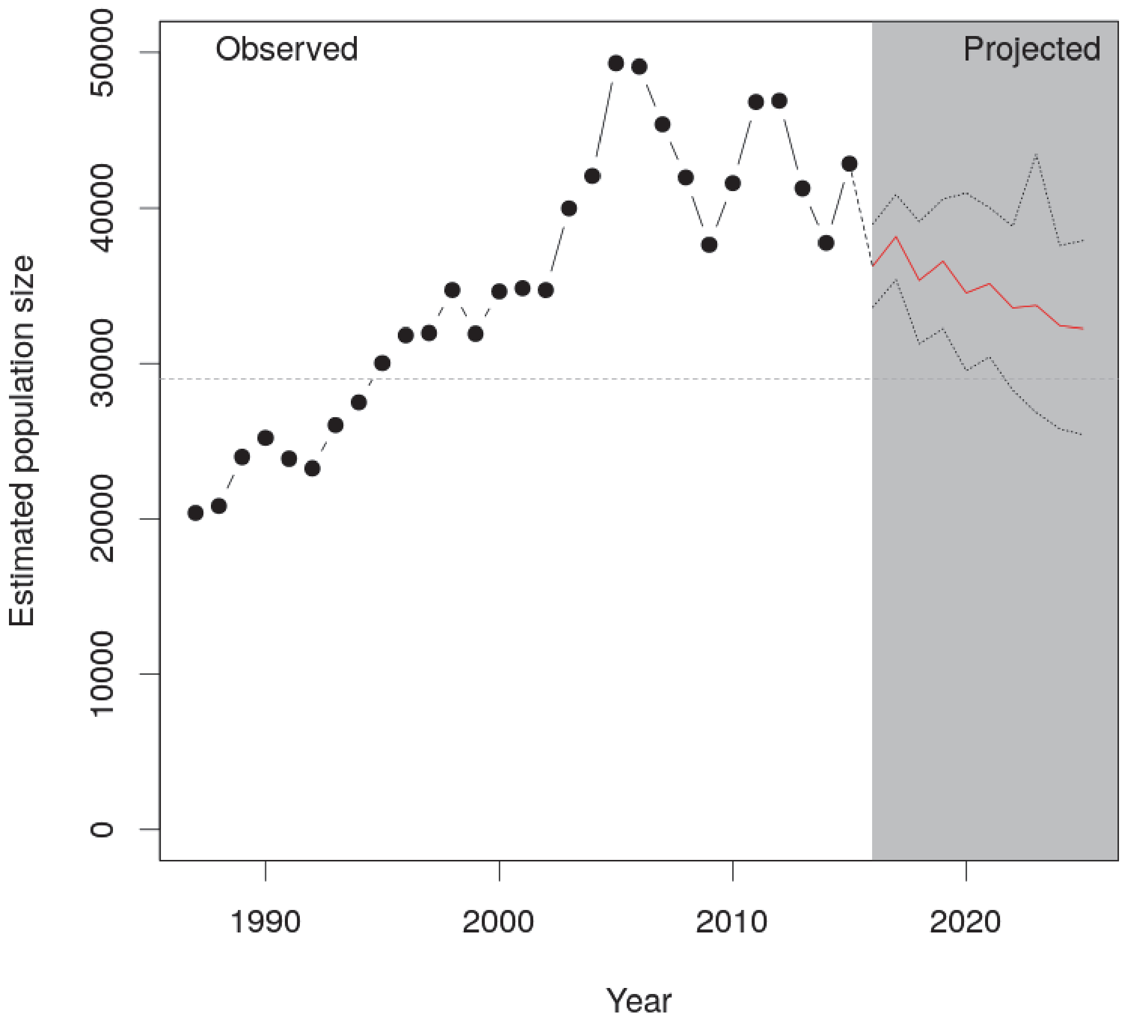

Figure 8. Projected goose population dynamics from the integration of the population model with Generalised Management Strategy Evaluation (GMSE). Years (x-axis) showing goose population size (y-axis) from the observed data are shown in the white background, while years projected using GMSE are shown in the grey background, for an example target population size of 29,000 and maximum shooting bag of 2,500. In the projections, the solid red line represents the mean population size across all simulations (1,000 total simulations). The dotted lines are the minimum and maximum 2.5th and 97.5th percentile of the distribution of all simulations for a given year, representing uncertainty in population trajectories. The horizontal dotted line shows the management target for population size.

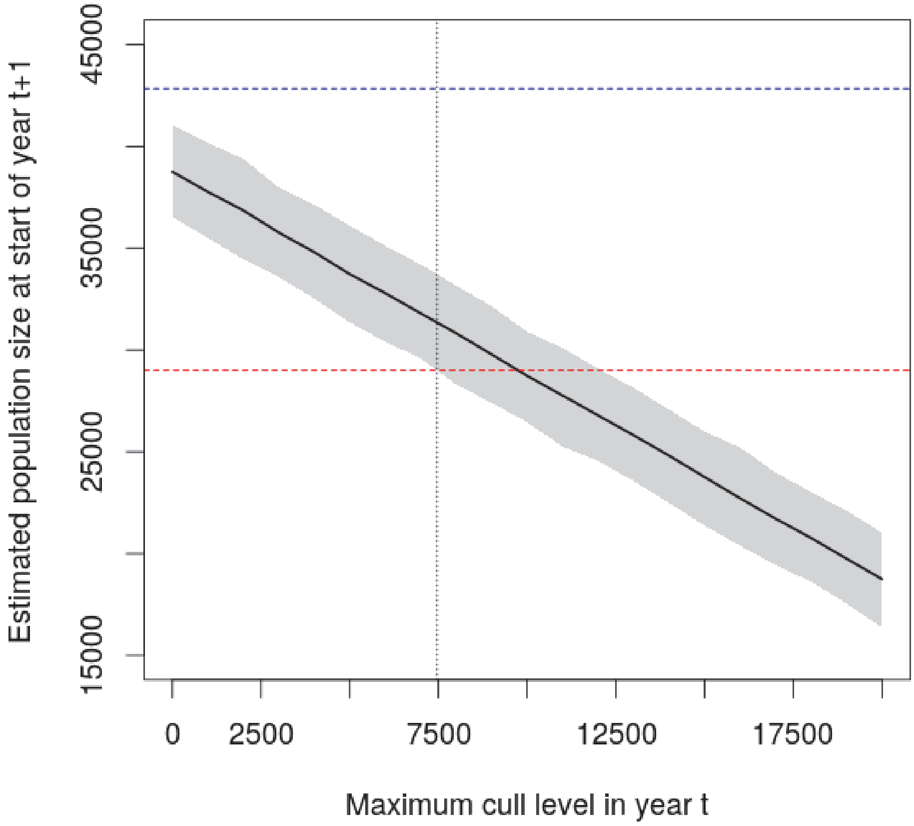

Figure 9. The effect of varying maximum cull level in year t on the estimated population size (minus the culling having taken place) in year t+1. The black line is the mean projected population size with the grey polygon representing the upper and lower 95% percentiles of error distributions. The blue (dashed) line is the estimated population size in year t, and the dotted red line represents an (arbitrary) population target, here N = 29000. The vertical dashed line represents the point at which the 2.5th percentile of the estimated population size (analogous to the lower 95% CI) equals the population target. To the right of this line, the estimated population size in t+1 overlaps the population target, to the left of the line the estimated population size does not overlap the population target. Note, that this figure shows single population projections based on currently available data alone, and as more data are added its pattern is likely to change. Thus, this figure should not be taken as a direct recommendation for a cull level, only as decision support.

6. DISCUSSION AND FUTURE WORK

6.1 Model outcomes

In line with SNH objectives, the PM-GMSE approach developed here provides a realistic and straightforward modelling tool to inform the management of the wintering population of GBG on Islay. The simulated management strategy described in section 5.2 used a target of 29,000 geese and a maximum shooting bag of 2,500 individuals/year as representative of current management on Islay. The model runs show that given these parameters, the population target may be achieved over a ten-year period of management. However, the model includes considerable uncertainty caused by observation error and environmental stochasticity – e.g., in some simulated runs the population size drops well below the target. It is also important to note that our model does not incorporate demographic uncertainty directly, but only via environmental effects, which is likely to increase uncertainty.

These findings highlight the importance of considering different sources of uncertainty when setting management strategies and, therefore, the need for continuously reassessing the data collected and included in the approach taken. In particular, as already mentioned above, the current simulations assume (1) linear trends in environmental variables (Greenland temperature and rainfall, Islay temperature and AIG on Islay), (2) the residual distribution of these trends do not change into the future. While this has incorporated the effects of environmental change on population dynamics to some degree, it should be stressed that these are relative simple environmental models and are based on input data only. Thus, **it is important to note that any future changes in these assumed relationships (i.e. environmental change that substantially deviates from linear increases/decreases, or changes in their expected effect on goose population dynamics) will affect the population projections from the model presented here.** However, provided all up-to-date data are supplied, this is particularly relevant for projections more than one year in the future (projections for a single year ahead use observed data only, and thus no projection of environmental conditions is necessary).Thus, for now, it is important to consider that although the PM-GMSE approach is a reliable modelling tool to predict and assess the effect of shooting bags on the Islay GBG population, the outcomes of future model runs will depend on the quality of the data included in the model. Moreover, in future model runs it will be important to continuously consider the validity of the linear trends proposed in environmental variables.

6.2 Model prerequisites

The PM used here to inform shooting bags via the GMSE approach provides a reasonable fit to available historic data. As shown, this combined model approach performs better than both using the population count from the previous year alone, or using a simple logistic growth model (Table 2). It is important to note, however, that this means that using the approach outlined here relies on inputting the best available and current data on a number of key predictors: (1) the area of improved grassland on Islay in both: the previous year (i.e. *t-1*) and two years previously (i.e. *t-2*); (2) measures of temperature and rainfall on Greenland during the preceding August; (3) a measure of mean winter temperature on Islay in the previous year; and (4) a shooting bag for both Iceland and Greenland since the last breeding season (i.e. on return migration).

As more data become available, it is expected that the value for each of the predictors above is updated as the model is re-run (i.e. in each year, see below). If such data are not available, a much simpler (e.g. logistic growth approximation) population model should be used, bearing in mind that it is then not possible to take account of the known effects of e.g. climate and habitat availability on goose populations.

6.3 Model assumptions and limitations

As discussed throughout, our model makes a number of important assumptions, some explicit (see model structure) and others implicit. Although not exhaustive, the following is a summary of the most important ones.

1. The total population carrying capacity (represented by term k_0 + kAIGt is time-varying through the effect of AIG on Islay in the current year (reflecting a smaller/larger overall carrying capacity on Islay in any given winter), and a constant "baseline" carrying capacity in the absence of any AIG. Population growth rate is also affected by AIG on Islay but in the previous year, representing increased population productivity in the following summer.

2. Hunting rate (shooting effort) on Iceland and Greenland is assumed to remain constant in the future (implemented as a proportional take from the population).

3. Shooting on Islay is assumed to be distributed equally across winter months (in the absence of additional information on the timing of culls).

4. As discussed in Section 6.2, environmental conditions, (AIG, temperature, and rainfall) are assumed to change according to linear trends, with stochasticity introduced through random draws from error in those relationships.

5. All individuals shot in Iceland and Greenland are individuals that would have wintered in Islay, i.e. shooting mortality on Islay is additive to shooting mortality on migration.

6. There is no additional effect (e.g. decreased fitness and thus negative effect on population size) through "wounding" (individuals shot but not killed) or disturbance.

It should be stressed that the accuracy of population projections could be adversely affected by any of these assumptions not applying. With regards to assumptions 1-4, either lack of data to support alternative assumptions (e.g. hunting rates in Iceland/Greenland, or specific data on within-winter variation in shooting effort on Islay), lack of evidence for alternative relationships, or limitation of scope for the report, prevented us from considering alternative parameters. Broadly speaking, these first four assumptions represent the best data currently available, but changes in environmental conditions or management are likely to change this. For example, climate as well as the mean numbers shot in Iceland and Greenland may change unpredictably in the future (e.g. changes in climate trends or sudden consistent changes in shooting effort in Iceland or Greenland). For these reasons, to maintain model validity and reliability in the future, it is vital that (1) the most up to date data for all input variables are used, and (2) model assumptions 1-4 are checked periodically, e.g. by re-assessing relevant statistical relationships or temporal patterns.

Assumptions 5-6 listed above were primarily the result of a lack of data to parameterise model structures that would address this. Although the majority of the population of GBG is known to winter on Islay, smaller numbers overwinter in e.g. Northern Island and the Outer Hebrides (Mitchell & Hall, 2013). Specific data to quantify which proportion of the "Islay wintering" population is exposed to shooting in Iceland and Greenland is not available, so for simplicity we here assume that shooting in the latter countries is simply proportional to the size of the wintering population in Islay.

Contrary to Assumption 6, both disturbance (through increased flight times due to shooting, Fox & Madsen 1997, Madsen *et al.*, 1998; Béchet *et al.*, 2004; Juillet *et al.*, 2012) and wounding (individuals being shot but not killed, Noer *et al.*, 2007) may have consequences for population size, through decreased individual fitness. However, a detailed review of these effects is beyond the scope of this report. Moreover, properly accounting for such effects would require a more sophisticated, individual-based approach to a PM, as well as the required data to parameterise it (e.g. systematic colour ring re-sightings throughout the winter in different sites in Islay; detailed behavioural observations of individuals shot). While we are aware of (past) ringing- and re-sighting efforts on Islay (Percival, 1991; Trinder, 2014) we do not have access to the raw form of either past- or present data.

As mentioned in previous sections, we decided not to go ahead with building an integrated population model (IPM) for GBG on Islay owing to a lack of individual-based data (e.g. in the form of ringing and re-sighting records from multiple over-wintering sites). IPMs make use of such data to estimate both survival probabilities and immigration/emigration rates over time. Whilst we have shown that our approach based on a logistic population growth model performs well, it is important to emphasise that it does not account for changes to the Islay GBG population that result from emigration and/or immigration from other wintering sites. This could occur, for example, if a significantly larger or smaller proportion of migrating birds chose to over-winter on Islay, leading to sudden and unexpected changes in population size. This process is likely to have contributed to the sudden changes in mean winter count observed between 2004 and 2005, and between 2010 and 2011, which our model was unable to accurately predict. Indeed, in these latter cases, the observed mean winter counts fell towards the extreme ends of the model prediction confidence intervals. In the absence of further data, it is difficult to speculate what caused these fluctuations. Having said this, fluctuations in population size (e.g. at or near carrying capacity) may in part be due to immigration/emigration, it is just that in our population-level approach we cannot specifically separate such effects from “true” births or deaths.

In summary, both the implementation of more sophisticated population models and the estimation of immigration and emigration rates for GBG on Islay in the future will be dependent on the availability of individual-based data, which we can only recommend be incorporated into future ecological monitoring strategies on Islay. If this were the goal, we would suggest a continuous marking- and re-sighting scheme (e.g. through colour ringing) both within Islay in different sites (during and outwith shooting periods) and in other key wintering sites; both individual identity, sex and where possible age and body condition should be recorded. Combined with detailed data on reproductive success on Greenland, this would allow the estimation of vital rates and their variability, and thus the parameterisation of a mechanistic integrated population model.

6.4 Model interface: Goose-GMSE

A graphical user interface to the model was developed and allows the user to re-run the model presented here given new and/or different input parameters (Table 5). Both the model and interface are coded in R (v. 3.3.4). The model functions themselves use packages *GMSE* (0.4.0.6, Duthie *et al.*, 2018) and *readxl (1.1.0,* Wickham & Bryan, 2018*)*; the interface additionally uses packages *shiny* (1.1.0., Chang *et al.*, 2018)*, DT* (0.4, Xie, 2018a)*, markdown* (0.8, Allaire *et al.*, 2017)*, rmarkdown* (1.9, Allaire *et al.*, 2018)*, knitr* (1.2, Xie, 2018b) and *kableExtra* (0.9, Zhu, 2018).

The interface has been made available on a secured website and the code has been provided to SNH. Alternatively, given the installation of the software above, a local instance of the interface can be run offline, although this would not allow taking account of future updates to the code.

This interface allows the user to set the desired number of years to project, the number of simulations to be run, the population target, and the maximum cull per year. Before doing so, the user is asked to upload a data file (.csv, .xls, or .xlsx) with up to date data on population counts, numbers culled, and environmental data (full parameters as in Table 5). This has to be organised in a specific format outlined in both the 'Help' file in the interface. Simulations can then be run to produce a population projection for the desired number of years, as well as a summary of the mean, variation and range of geese culled per year.

We strongly suggest taking note of the following points for the practical use of Goose-GMSE.

- New projections should be produced at least once a year when all new data are available (e.g. in autumn before culling targets are due to be set and when numbers shot in Iceland and Greenland have been collated).

- Both the population target, as well as the maximum number to cull per year should be reconsidered each year. Only the number of individuals culled in the first future year should be used for policy setting (i.e. for the coming winter). Not doing so would not allow for a reactive/adaptive approach and invalidate the value of the model.

- While population projections further into the future can be used for assessing the likely population trajectory towards a longer-term target (and the likelihood of "undershooting" the target), it should be clear that when observations for the following year become available, both the predicted population for subsequent years as well as the suggested mean numbers culled are likely to change.

- At least 1000 simulations are used to produce projections; this will improve the ability to assess the likely level of uncertainty.

Although the model will produce predictions without a complete dataset we strongly recommend against producing projections without a fully populated input data set. Table 5 has a list of columns, their names, and how missing data are treated.

Table 5. A list of data columns and their header ('Parameter') in input files required by Goose-GMSE, their interpretation and how missing data is treated.

Parameter	Interpretation and units	
Year	Year in four-digit format	Required
November	Average monthly count of GBG on Islay	No
December		
January		
February		
March		
Count	Average over-winter count of GBG on Islay	Required. Needs to be the average of the monthly counts (rounded).
IcelandCull	No. of GBG shot in Iceland	Sampled randomly from previous years' data if not input (as part of total in Iceland + Greenland)
IslayCull	No. of GBG shot on Islay	Required
GreenlandCull	No. of GBG shot in Greenland Sampled randomly from previous years' data if not input	Sampled randomly from previous years' data if not input (as part of total in Iceland + Greenland)
AIG	The area of improved grassland (ha) available on Islay	Sampled randomly from previous years' data if not input
IslayTemp	The average temperature on Islay (°C)	
AugRain	The average rainfall (mm) in Greenland in August	
AugTemp	The average temperature (°C) in Greenland in August	

In addition to the above, it is important that the caveats discussed in this report are taken account of when interpreting the model projections, particularly with regards to (1) the absence of any consideration of behavioural or non-lethal effects of shooting, (2) the lack of any environmental trends (e.g. climate change), and (3) that failing to use up-to-date input data will severely affect the value of projections.

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ANNEX 1: COMPILED GBG DATASET

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