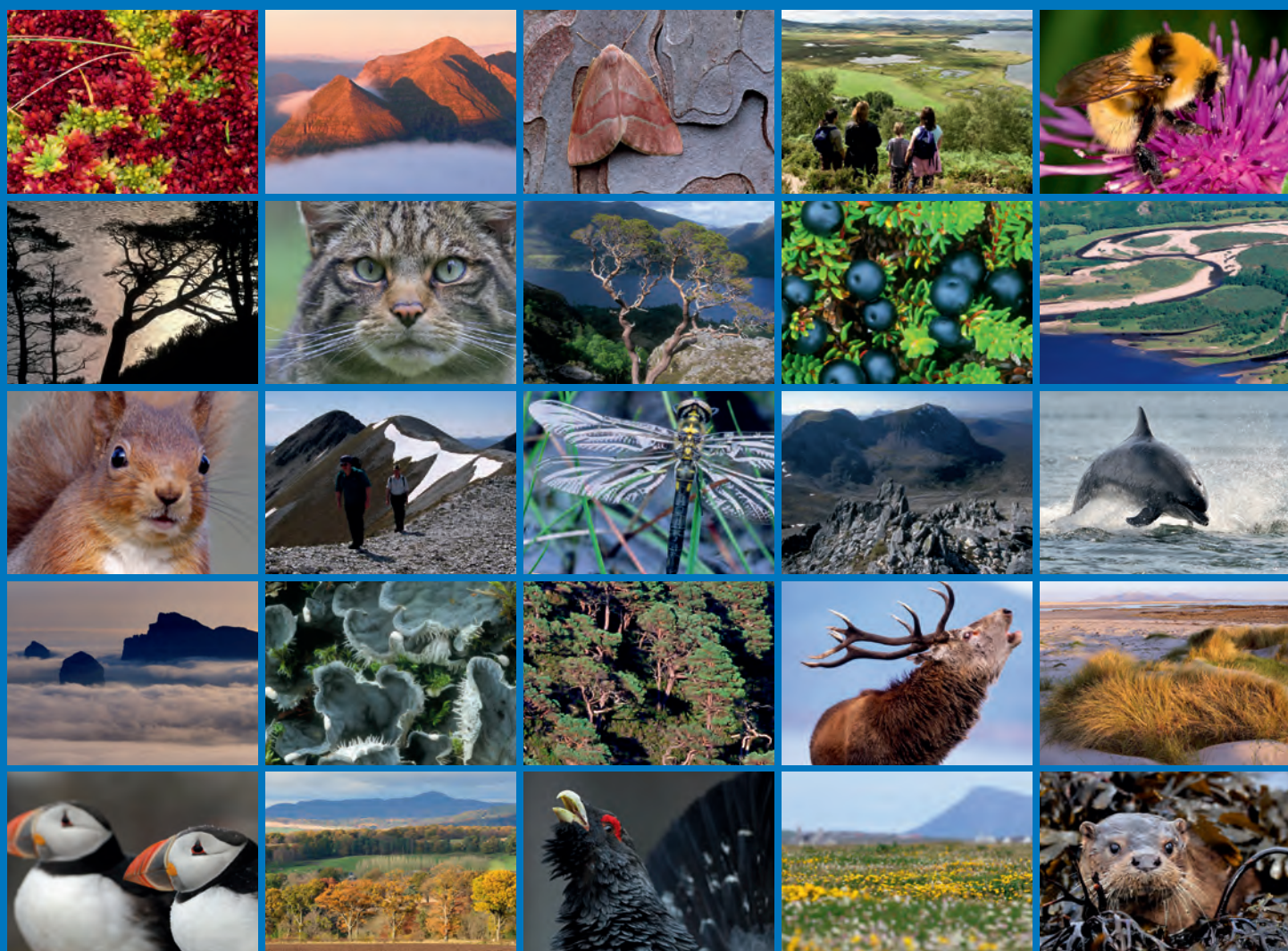


# Status and population viability of Greenland barnacle geese on Islay





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# COMMISSIONED REPORT

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**Commissioned Report No. 568**

## **Status and population viability of Greenland barnacle geese on Islay**

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## COMMISSIONED REPORT

# Summary

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## Status and population viability of Greenland barnacle geese on Islay

**Commissioned Report No. 568**

**Project no: 14092**

**Contractor: MacArthur Green**

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### **Keywords**

Islay; *Branta leucopsis*; harvest; MARK; survival analysis; population viability analysis; management.

### **Background**

This report provides analysis and predictive modelling of the Greenland barnacle goose population which winters on Islay.

### **Main findings**

- The Greenland barnacle goose population which winters on Islay was around 44,000 birds in winter 2011-12. This represents approximately 70% of the flyway population.
- Analysis of population data found no evidence for trends in survival or reproduction. Average rates were estimated and were used to develop a population model.
- The model accounts for shooting on Iceland and Islay (under licence to SNH) and makes predictions for how changes in shooting pressure on Islay may influence future population growth.
- Between 2000 and 2011 an average of 1.5% of the adult Islay-wintering population (593 individuals) were shot on Iceland. Over the same period an average of 1.4% of the Islay population (all age classes) were shot on Islay (585 individuals).
- The Islay population was predicted to continue to increase at between 2.6% and 3.0% per year, dependent on whether shooting on Iceland was modelled as a harvest rate which tracked the simulated population (averaging 1.5% of the adult Islay population) or remained at the level observed between 2000 and 2011 (averaging 593 adults per year).
- The risk of population decline within 10 years was estimated to be 7.2% to 7.3% (with the Icelandic harvest averaging 593 or 1.5% respectively), with the equivalent predictions of decline within 25 years at 1.0% to 1.2%.
- When Icelandic shooting was modelled as a rate (1.5% of Islay adults shot per year), the model predicted that on average (in 50% of the simulations) the population continued to

grow until shooting on Islay removed more than 3.8% of the population annually, while in 95% of simulations the population continued to grow until this percentage was no greater than 1.8%. This is slightly higher than the average percentage shot on Islay over the last 11 years (1.4%). Similar results were obtained when Icelandic shooting was modelled as an average bag of 593 adults.

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## 1. INTRODUCTION

Two populations of barnacle goose (*Branta leucopsis*) are recognised in the UK. One breeds on the Svalbard archipelago and winters exclusively around the Solway Firth. The other breeds on the east coast of Greenland and winters across a much wider area, extending from north Scotland to west Ireland, with discrete wintering populations on many islands. Of these, by far the largest population is found on the island of Islay. While populations in several other locations have been monitored each winter since the mid-1990s, the longest time-series of counts and other demographic data have been collected on Islay. In addition, the birds wintering on Islay represent over 75% of the Scottish wintering population. Consequently, the Islay population is the subject of this report, which updates the previous Population Viability Analysis (PVA) reported in 2005 (Trinder *et al.*, 2005). Two models were developed at that time to generate predictions for how the population would change; one included density-dependent population regulation and the other did not. Comparison of each model's predictions with the observed population indicates that the density-independent one produced a closer match to how the population has grown since. Here we present a revised PVA based on updated analysis of demographic data from Islay and shooting data from Iceland and Islay. Using the outputs from this PVA, predictions of future population trends are presented and discussed, together with the potential impacts of future management changes.

## 2. DATA AND METHODS

### 2.1 Population counts and demographic trends

The Greenland-breeding population of barnacle geese winters predominantly on offshore islands along the northern and western coasts of Scotland and Ireland. Due to the remote location of many of these sites, estimating the total population size is only practicable from a combination of air and ground surveys. Between 1959 and 2007, 12 full surveys were conducted at approximately five-year intervals. The total population has grown from 11,800 in 1957 to over 70,000 in 2007 (the most recent full census for which data are available).

Since the early 1970s, the single largest population has been found on Islay, which currently holds an estimated 78% of the Scottish population and 63% of the global population (Mitchell *et al.*, 2008). Since the mid-1950s, between two and six counts have been conducted each winter on Islay on behalf of WWT and SNH (Mitchell *et al.*, 2008). In addition, annual estimates of the proportion of juveniles present and the mean brood size have been made since the 1960s. Since the mid-1990s, annual counts have also been conducted at six other locations along the west and north coasts of Scotland: Uists, South Walls, Tiree, Coll, Colonsay/Oronsay and Danna. In 2011/12, none of these sites individually held more than 8% of the Scottish population, and in total they held 21%. Very few estimates of the proportion of juvenile geese and mean brood size have been recorded at these sites. Since the majority of the geese and the majority of the data come from Islay, the analysis and modelling are focused on this site. Count and demographic data for Islay and other wintering sites within Scotland are presented in Annex 1 (Tables A1.1 and A1.2).

The Islay population grew steadily from around 7,000 birds in the early 1960s to a peak of 50,000 in 2006. The population then declined to fewer than 38,000 in 2009, before recovering to 44,000 in 2011 (Figure 1, Table A1.1). The total population summed across the six smaller sites increased from 5,000 in 1996 to 12,000 in 2011 (Figure 1, Table A1.2).

A sample of the flocks on Islay have been studied each autumn/winter to determine the proportion of juveniles (PJ) and the mean brood size (BS); <http://monitoring.wwt.org.uk/our-work/goose-swan-monitoring-programme/species-accounts/greenland-barnacle-geese/>. From these data together with the population estimate (N), it is possible to calculate annual values for the rate of survival (CS) and the minimum proportion of adults (aged three or older) which bred in the preceding summer (PB).

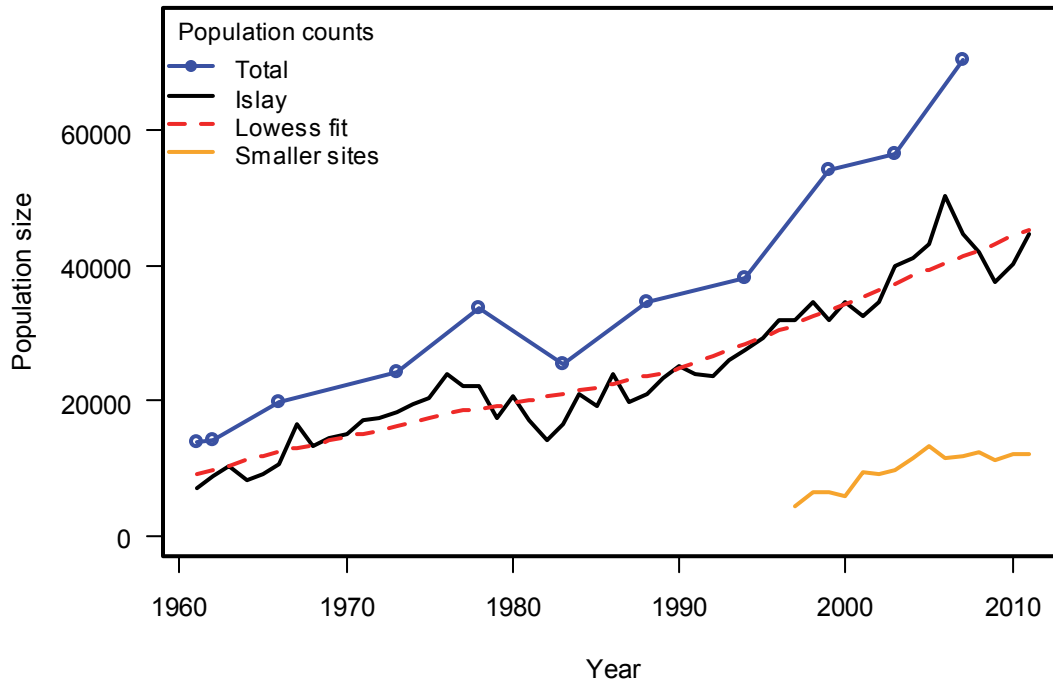


Figure 1. Winter population estimates for Greenland breeding barnacle geese. Total population as counted by aerial census (blue), Islay population (black line) and summed populations on small Scottish sites where regular counts are conducted (Uists, South Walls, Tiree, Coll, Colonsay / Oronsay and Danna). Red dashed line is a locally smoothed regression (Lowess) fitted to the Islay counts.

## 2.2 Estimation of demographic rates

Demographic rates for use in the population model were estimated using the following field data, collected each winter on Islay:

- Population count (N);
- Age ratio (proportion of juveniles in the population; PJ); and,
- Mean brood size (BS).

In addition, the Iceland and Islay shooting bag data were used to 'correct' for shooting mortality in the estimates of survival rates. Since the Iceland shooting data were available from 1995, data from the period 1995–2011 were used.

In the following equations, subscript 't' is used to denote the current year and 't-1' the previous year.

1. The mean brood size was calculated as the average across all years;
2. Using the age ratio, the number of adults and juveniles was calculated in each year;

$$J_t = PJ_t * N_t$$

3. Survival was estimated as the number of adults in year t divided by the total population in year t-1 (thus this value represents winter-to-winter survival of adults, sub-adults and juveniles combined);

$$CS_t = \frac{N_t - J_t}{N_{t-1}}$$

4. The number of second year birds in year t+1 was calculated as the product of the number of juveniles in year t and the survival rate from year t to t+1;

$$N2_t = J_{t-1} * CS_t$$

5. From this, the number of adults in their third year or older was found by subtraction from the counts;

$$N3_t = N_t - (J_t + N2_t)$$

6. The minimum proportion of breeding adults (age 2+) was calculated as the number of juveniles divided by the mean brood size to get the number of family units, which was divided by the number of third-age class or older birds.

$$PB_t = \frac{J_t / BS_t}{0.5 * N3_t}$$

Estimates of reproduction based on observations made on Islay in the winter show quite wide inter-annual variation (Figure 2). This reflects variations in Arctic conditions between years, with factors such as the timing of the spring thaw having a marked impact on goose breeding success (e.g. Trinder *et al.*, 2009). Generalised Linear Models (GLMs) of reproduction (the proportion of juveniles, mean brood size and proportion of breeding adults) and survival modelled as a function of year and population size were used to look for the presence of trends (both temporal and density-dependent) in these demographic rates. This analysis was conducted twice; first using all years (1961-2011), and then using just the last 20 years. The latter was included to test for the presence of recent trends in the data. Full model results are presented in Annex 1 (Table A1.3).

The proportion of juveniles in the Islay population has declined significantly since 1961 (Figure 2, top-left, blue line,  $p < 0.001$ ). However, when just the last 20 years were considered, a non-significant positive trend was obtained (red line). A similar result was obtained using population size as the explanatory variable (Figure A1; note that since population size is also used in the calculation of the demographic rates, the models presented in this figure are potentially unreliable and are provided for indicative purposes only). Mean brood size (Figure 2, top-right) has not shown any trend in relation to year or population size either across all years or just the last 20 years. The proportion of breeding birds shows the same relationship as the proportion of juveniles, with significant negative trends against year (Figure 2, bottom-left, blue line,  $p < 0.001$ ) and population size (Figure A1) across all years, but no significant trends were detected from just the last 20 years of data. Survival (Figure 2, bottom-right) has not shown any trends in relation to year or population size, either across all years or for just the last 20 years. The absence of trends in the demographic rates over the last 20 years could be considered at odds with the continued population increase. However, the combinations of survival and reproduction during this period have been sufficient for gains to the population to exceed losses.

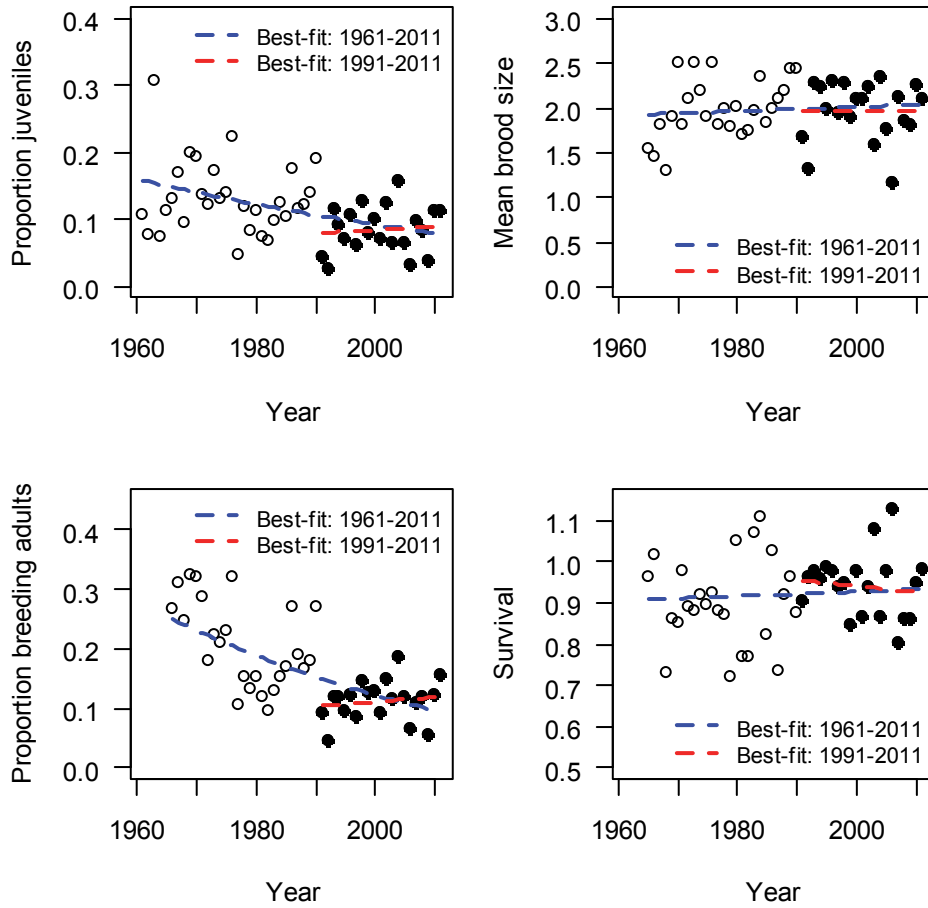


Figure 2. Trends in demographic rates of the Islay barnacle goose population since 1961. Open symbols used for 1961 to 1990, filled symbols for 1991 to 2011. Dashed lines are from Generalised Linear Model fits obtained for rate vs. year (blue: 1961-2011; red: 1991-2011); see Table A1.3 for model details.

Greenland barnacle geese are legal quarry in Iceland on autumn migration (bag data are available from 1995), and they have also been subject to shooting on Islay between October and April since 2000 (Figure 3). Shooting on Islay is undertaken under licence to Scottish Government (since 2011 to SNH), and Icelandic hunters are required to provide an anonymous record of all birds shot in order to renew their shooting licences. Assessments of these data have found them to be reliable and accurate (Frederiksen *et al.*, 2004). Illegal shooting may occur in other locations along the population's flyway, but there are no records of how many birds are shot (although the number is probably much smaller than the known shooting).

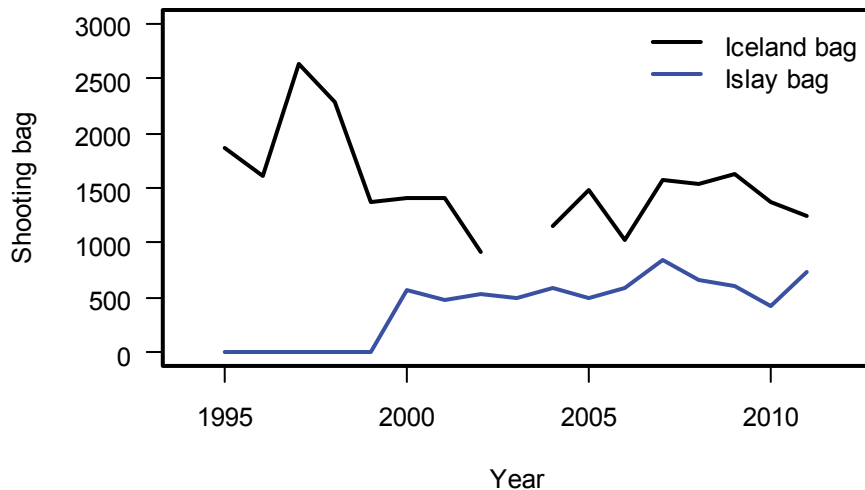


Figure 3. Barnacle goose shooting bag data for Iceland and Islay. Data for Iceland were downloaded from Statistics Iceland (<http://www.statice.is/>); the full website address and tabulated values are provided in Table A1.4.

To account for shooting mortality, survival rates (and the rates dependent on these rates) were re-calculated as follows:

1. The estimated number of Islay adults in the Iceland shooting bag was calculated by multiplying the total Iceland bag by 0.66 (the proportion of the global population estimated to winter on Islay over the period of bag data) and 0.67 (the estimated proportion of Icelandic goose shooting bags made up of adults (Frederiksen *et al.*, 2004));
2. The sum of Islay adults in the Iceland bag in year  $t$ , the number of adults on Islay in year  $t$  and the Islay shooting bag in year  $t-1$  was divided by the total Islay population in year  $t-1$ .

In this manner the shot birds were added back into the population at each time step and the rate of survival before shooting could therefore be estimated.

Adding the number of birds shot back into the population makes the assumption that shot individuals would not have otherwise died (i.e. it assumes their survival from the point of being shot to the next census would have been 100%). For the relatively short period between shooting on Iceland and population counts on Islay this assumption was considered to be reasonable. However, the validity of this assumption for the period between shooting on Islay in winter  $t$  and the subsequent count in winter  $t+1$  was tested by reducing the number of Islay shot birds added back by the estimated rate of post-shooting mortality of 6.3% for the equivalent period (Table 1). This had a small effect, reducing the estimated pre-shooting survival rate by 0.05% to 0.965. This value was used as the pre-shooting survival rate in the population model.

Table 1 - Demographic rates used in the Greenland barnacle goose population model. Simulations used the average survival rate estimated before shooting (0.965) and the standard deviation estimated from the running mean counts (0.045).

Demographic rate (1995-2011)	Average	Standard deviation
Survival (including shooting mortality)	0.937	0.086
Survival (without shooting mortality)	0.965	0.086
Survival (estimated using 5 year running mean of counts)	0.940	0.045
Mean brood size	1.992	0.302
Proportion breeding adults	0.105	0.030

Estimating survival from population counts tends to inflate inter-annual variation due to errors in the counts themselves. While these errors tend to cancel each other out across a time series (i.e. high and low years balance one another), minimising bias in the average survival rate, the variance is exaggerated. To reduce the estimated variance, survival for the period 1989 to 2011 was re-calculated after substituting running mean population counts (of 3, 5 and 7 years) for the annual counts. This smoothing reduced the magnitude of variation in the counts, and thereby reduced the variance in survival. The mean and standard deviation of survival, calculated using population counts averaged over 1, 3, 5 and 7 years, are shown in Figure 4.

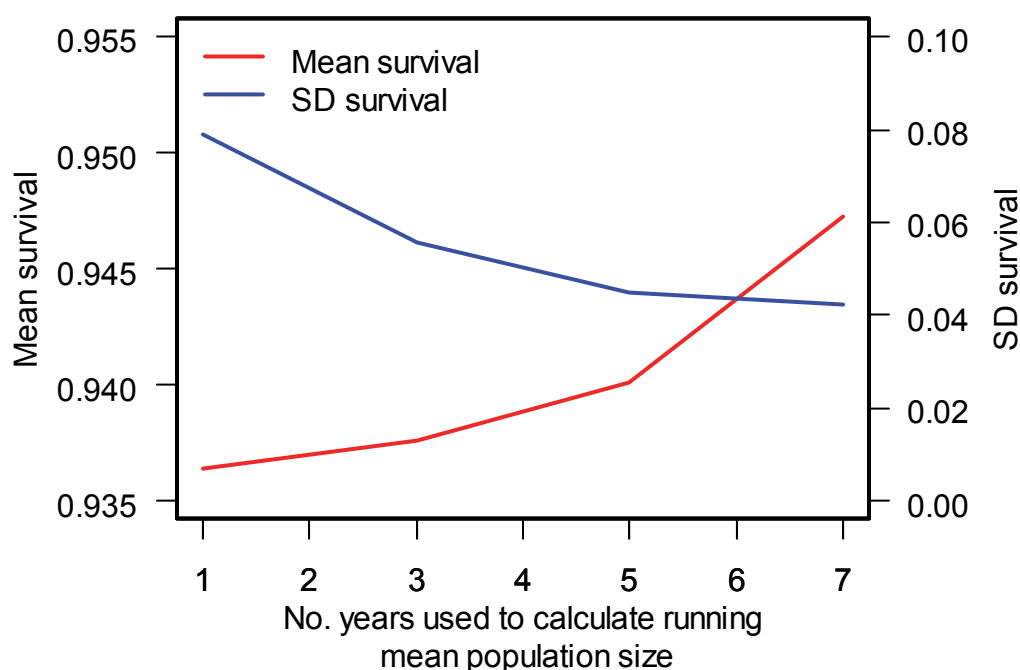


Figure 4. Average and standard deviation (SD) of survival of Islay barnacle geese plotted against the number of years of population counts used to calculate the running mean.

With each incremental increase in the number of years used to calculate the running mean population size, the gain in precision became smaller (i.e. the slope of the SD line in Figure 4 became flatter), while at the same time, the estimated survival rate increased (i.e. the slope

of the mean line increased). Thus, the duration of running mean considered to balance improved precision, with minimum impact on the estimated mean survival rate, was identified as 5 years. Compared with the annual counts the standard deviation was nearly halved (from 0.086 to 0.045) while mean survival differed by only 0.0037 (using seven years the additional improvement in precision was small, but the mean rate increased by a further 0.007).

The standard deviation in survival rate estimated above was much closer to that estimated from the analysis of ringed individuals (0.035, see below). For the purposes of population simulations therefore, the lower estimate of standard deviation obtained using the 5-year running mean counts was combined with the average survival rates estimated from the analysis including shooting bags. The demographic rates used in the model are provided in Table 1. These were estimated for the period 1995-2011, as this matched the span of shooting data available.

### 2.3 Survival analysis

As well as estimating survival from the count and productivity data (above), survival was estimated using re-sighting observations of marked birds; survival estimated from such observations is less prone to errors than that estimated using count data. However, re-sighting survival estimates may be subject to bias because of the confounding of permanent emigration and death, unless re-sighting effort includes all possible wintering sites. For this reason the population model used the count-based estimates. Nonetheless, survival estimates derived from ringing studies can still provide useful information, for example with regard to trends and annual variation; hence the following analysis was conducted.

A dataset comprising over 3,600 individual birds, caught and fitted with unique leg-rings since 1982, was used for this analysis (earlier data were excluded due to low numbers of individuals). The breakdown of birds by sex and age at first capture is provided in Table 2.

*Table 2 – Age and sex of Islay barnacle geese at first capture used to estimate survival.*

	Juvenile	Yearling	Adult
Female	287	37	1,333
Male	299	29	1,618

Survival analysis of winter-to-winter re-sighting data was conducted using Program MARK (White & Burnham, 1999), accessed using the RMark library within the statistical programming environment R (<http://www.R-project.org>).

Goose catches and re-sightings were made across a wide spread of months. The standard survival analysis model (Cormack-Jolly-Seber, CJS) is based on a presumption of short capture / re-sighting windows, separated by longer periods, with survival and re-sighting rate estimated across the latter. A variation of the standard model (the Barker model) has been developed which can accommodate additional re-sightings made during the inter-capture periods. This is therefore much more suitable for species such as geese, and makes use of more of the available data. In order to do this, the Barker model includes additional parameters such as rates for recovery and site fidelity, in addition to the basic survival model's rates of survival and re-sighting. For most datasets at least some of these additional parameters are likely to be poorly estimated, and they are often referred to as 'nuisance' parameters. It is generally recommended therefore that simple structures (e.g. constant rates) are fitted to these parameters and that estimated values for these parameters are treated with caution (Richard Barker, pers. comm.).

Goodness-of-fit testing of the data to a general model was conducted using the bootstrap procedure implemented in MARK. This test revealed some lack of fit, with an estimated adjustment value (c-hat) of 1.61. However, this was well within the maximum recommended allowable value for c-hat of 3, so analysis proceeded using the value for c-hat to accommodate over-dispersion in the data.

Preliminary assessment established there were no differences in survival for males and females, and sex was therefore not included as a factor in the analysis. Determination of the best-fit model to the data was conducted through initial simplification of the nuisance parameters. Following this, the best-fit structures for survival and re-sighting rates were derived. Model fit was assessed on the basis of Akaike's Information Criterion (AIC; although in the table this is denoted as QuasiAICc due to adjustments for sample size and over-dispersion).

A total of seven demographic parameters are estimated by the Barker model:

- survival (S),
- re-sighting rate within designated windows (p),
- recovery rate (r),
- re-sighting rate between windows (R),
- re-sighting rate of subsequently shot and unreported individuals (R'),
- site fidelity rate (F) and
- return rate for temporary migrants (F').

Each parameter was modelled using a combination of some or all time and age classes (juveniles and adults: 'a2'). For each parameter a selection of realistic possible models was defined *a priori*. The starting point for the analysis was a general model:

$$S(\sim\text{time} * a2)p(\sim\text{time})r(\sim 1)R(\sim\text{time})R'(\sim 1)F(\sim\text{time})F'(\sim a2).$$

Identification of a best-fit model proceeded through simplification of a single parameter at a time, in reverse order of interest: R', R, p, F', F, r, S. Juvenile birds are defined in this analysis as aged less than one year, thus juvenile demographic rates could only be estimated in years immediately following captures of juveniles.

Model refinement failed to identify any constrained models which gave a better fit than the most general model (Table 3). This model had time-dependent survival fitted independently to the two age classes (defined as first year birds and older), time-dependent re-sighting with no age differences (both within and between re-sighting windows), a constant recovery rate for all birds, constant probabilities of being seen alive prior to being shot, time-dependent site fidelity and age-dependent return rates of temporary migrants. Rate estimates for this model are provided in Annex 2.

Table 3 – Barker models fitted to Greenland barnacle goose data ranked by AIC. Modelled elements: survival (S), re-sighting rate within designated windows (p), recovery rate (r), re-sighting rate between windows (R), re-sighting rate of subsequently shot and unreported individuals (R'), site fidelity rate (F) and return rate for temporary migrants (F'). Each was modelled using combinations of time and age (a2) or as constants (1).

Model	No. par.	QAICc	Delta QAICc	Model weight	QDeviance
S(~time * a2)p(~time)r(~1)R(~time)R'(~1)F(~time)F'(~a2)	152	33465.05	0	1	19519.10
S(~a2)p(~time)r(~a2)R(~time)R'(~1)F(~time)F'(~a2)	95	33625.68	160.63	0	19794.55
S(~time)p(~time)r(~1)R(~1)R'(~1)F(~a2)F'(~a2)	66	33753.78	288.73	0	19980.92
S(~time * a2)p(~a2)r(~1)R(~1)R'(~1)F(~time)F'(~a2)	96	33768.15	303.10	0	19935.00
S(~time * a2)p(~time)r(~1)R(~1)R'(~1)F(~time)F'(~a2)	123	33775.32	310.27	0	19887.83
S(~time)p(~a2)r(~1)R(~1)R'(~1)F(~a2)F'(~a2)	39	34038.34	573.29	0	20319.64
S(~time * a2)p(~a2)r(~1)R(~1)R'(~1)F(~a2)F'(~a2)	69	34116.22	651.17	0	20337.33
S(~a2)p(~1)r(~1)R(~1)R'(~1)F(~a2)F'(~1)	9	34141.04	675.99	0	20482.42
S(~a2)p(~a2)r(~1)R(~1)R'(~1)F(~a2)F'(~1)	10	34142.95	677.90	0	20482.34
S(~a2)p(~a2)r(~1)R(~1)R'(~1)F(~a2)F'(~a2)	11	34144.95	679.90	0	20482.34
S(~1)p(~1)r(~1)R(~1)R'(~1)F(~1)F'(~1)	7	34169.25	704.20	0	20514.64
S(~a2)p(~1)r(~1)R(~1)R'(~1)F(~1)F'(~1)	8	34171.16	706.11	0	20514.55

### Survival

Survival rates for adults and juveniles are plotted in Figure 5. Adult survival rate, averaged between 1983 and 2006, was 0.84 (sd = 0.035; years outside this range were poorly estimated due to low numbers at the beginning and declines in re-sightings after 2006, so were excluded). The average juvenile survival rate between 1984 and 2005 was 0.82 (sd = 0.16). No trends in survival were apparent across this period.

### Re-sighting

The re-sighting rates (p, R) were generally high, as expected given the combination of a relatively small study area, the highly visible nature of the geese and the effort put into ring reading. The rate (p) is derived from re-sightings made during the period when ringing usually occurred (October to December) which corresponds with the period of greatest re-sighting effort. Therefore the average value for p (0.914, sd = 0.06) is not surprisingly higher than that for R (0.752, sd = 0.1).

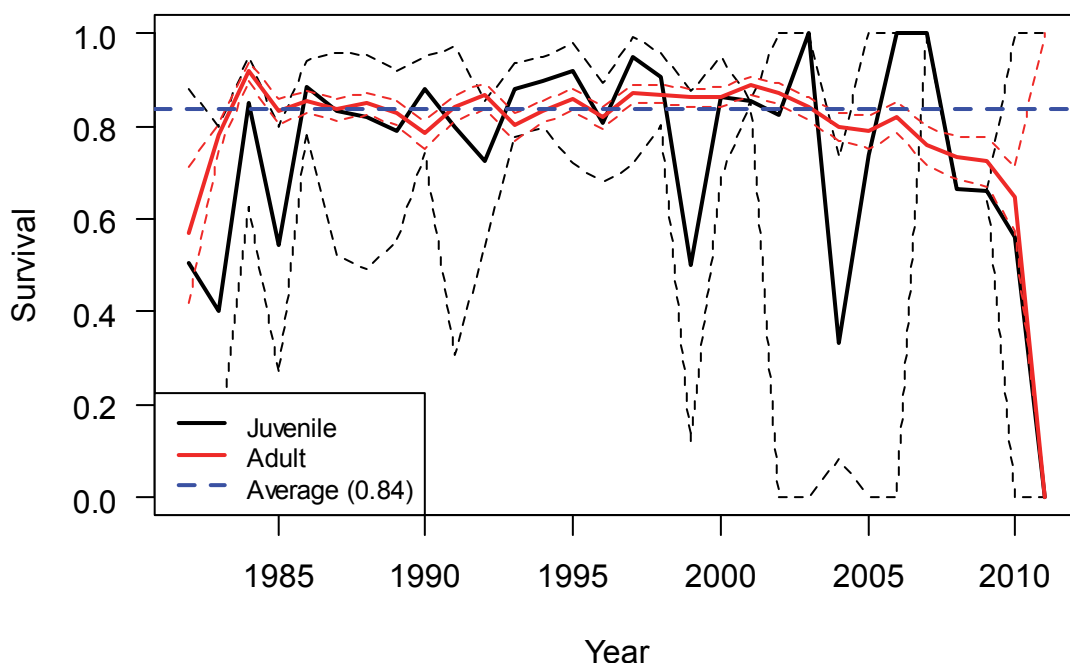


Figure 5. Greenland barnacle goose survival rates estimated using marked individuals. Rates from best-fit model (Table 3), including confidence intervals (dashed lines). The average adult rate (0.84) calculated between 1983 and 2006 is included for comparison.

### Recovery

The recovery rate was low at 0.017, but of a similar magnitude to the proportion of the population shot across the estimation period (see below for analysis of shooting bags). Thus it appears that ringed birds are represented in the shooting bags (and reported) at rates which match the overall shooting levels.

### Site fidelity and return rate of temporary migrants

While the site-fidelity ( $F$ ) and temporary immigrant return rate ( $F'$ ) parameters offer potentially interesting information about both permanent and temporary movement in and out of the Islay population (average  $F = 0.94$ ,  $F' = 0$ ), the parameter estimates should be treated with caution as their estimation is based on inference. Nonetheless, it appears that while the Islay population is highly site faithful ( $F = 0.94$ ), individuals which do move to alternative wintering sites do so permanently ( $F' = 0$ ).

### Differences in survival rates between count based and ring based methods

The average count-based survival rate was 0.94, while the average ring-based estimate (for adults) was 0.84. This is a large difference for a long-lived species and seems to represent the difference between survival estimated for a population which includes movement in and out (count-based) compared with one which assumes a closed population (ring-based). The most plausible explanation for this difference is that a proportion of ringed individuals move permanently out of the study area, with the result that an equivalent proportion of the apparent mortality is in fact permanent emigration. Since the average number of birds ringed each year was around 125, the 10% difference in survival would occur with permanent emigration of roughly 12 ringed individuals each year. While established adult birds (i.e. older than 2 years) may be expected to remain faithful to known wintering locations, younger adults are more likely to move between wintering locations. Adult survival was estimated using all birds older than 1, thus movement out of the Islay population by

these second year individuals would result in reduced adult survival estimates. The population modelling assumes that this emigration is balanced by an equivalent immigration from other wintering populations.

## 2.4 Population model

A stochastic, density-independent population model was developed, based on the demographic rates in Table 1. Survival was modelled using the rate estimated before shooting (0.965) with the standard deviation estimated using the 5-year running mean (0.045). This survival rate was used for all age classes. This was justified on the basis of the similarity of the rates estimated from the re-sighting data (adults 0.84; juveniles 0.82). Reproduction was modelled using the mean and standard deviations for the proportion of adults (age 2+) estimated to breed each year (0.105, sd = 0.03), and the mean and standard deviation of the mean brood size (1.992, sd = 0.302).

While survival estimated from marked individuals is less prone to errors than that estimated using count data, such estimates are subject to bias due to the inability to distinguish permanent emigration and death in studies where re-sighting effort does not include all possible sites. This is likely to account for the difference between the count-based survival estimates and the lower ringing-based one. Since the population model was developed to provide insight into the Islay population, the count-based estimates are considered more suitable. The ringing-based estimates could only be used if re-sighting effort was extended spatially, or if robust estimates of movement rates between wintering sites were available (which would also require a greater spatial spread of effort).

The model has three age classes and simulates an annual time step. Individuals move from the 0-1 year (juvenile) group to the 1-2 year (immature) group and finally to the 2+ (adult) age group, with a probability defined by the survival rate. Only the adult age group breeds, with the number of juveniles a product of survival (only surviving birds breed), the proportion of breeding birds and the mean brood size. Both sexes are modelled together, thus in the above calculation the mean brood size is halved prior to calculation. Survival rates and the proportion of breeders were modelled using beta distributions (survival for each age class was modelled independently, although the mean and variance were the same), while the mean brood size was modelled using a stretched beta distribution (a rescaled beta distribution with a user defined maximum and minimum; Morris & Doak, 2002). The same survival rate was used for all age classes as it is not possible to estimate age-specific rates from the count data. This may introduce some over-estimation of survival for birds in their first year. However, it should be noted that the mean brood size value is derived from observations made on the wintering grounds, which is the brood size after the loss of eggs, goslings and mortality of fledglings and young birds on their first migration up until their first winter (i.e. a period of approximately 4 months). Thus the period when survival would be expected to be most different from older birds is represented by the brood size estimates and incorporated into the reproductive rate. Furthermore, the results of the survival analysis using marked birds did not find strong evidence for differences in survival between juveniles and adults.

The analysis of demographic rates found no evidence for trends in survival, the proportion of breeding birds or the mean brood size over the last 20 years (Figure 2). Thus, while there appear to have been declines in reproduction during the earlier years of data (1960-1990), the demographic rates have since levelled off. Therefore, for the purposes of predictive modelling, a density-independent model was developed.

Shooting mortality can be simulated either as a harvest rate (i.e. a percentage of the population is removed each year) or as a static number (e.g. up to a fixed bag limit). For

shooting on Islay which is conducted under licence and closely regulated, shooting was modelled as a harvest rate. This matches the basis under which shooting is conducted since it is used to reduce agricultural damage, and hence shooting intensity will reflect the population size. The relatively constant Iceland bag size since 1995, despite growth in the population, suggests that Icelandic shooting should be simulated as a fixed bag. However, as this situation may not remain the case in the future, Icelandic shooting was modelled as both a harvest rate and as a fixed bag. The important distinction between the two approaches is that the former tracks the population as it changes in size (i.e. a constant magnitude of limitation), while the latter will represent an increasingly small take if the population grows and a larger one if it falls. Values used for simulating shooting were estimated from the data (Table 4). The Icelandic values include two adjustments. The first is to match the estimated proportion of the Icelandic take which comprises the Islay wintering population (0.66). The second is to account for the inclusion of juveniles (birds fledged in the immediately preceding breeding season) in the following autumn's Icelandic bag (0.33, derived from previous analysis of wings; Frederiksen *et al.*, 2004). This juvenile mortality is implicitly included in the estimated productivity values, since these birds are never counted on the wintering grounds, and productivity is estimated after the birds arrive on Islay. The variability in the Icelandic shooting bag observed between 2000 and 2011 was incorporated by making the harvest level applied in each year of a simulation a value drawn at random from a normal distribution with mean and standard deviation as per Table 4 (either as a rate or a fixed bag).

*Table 4 – Estimated harvest rates and bag sizes for Islay barnacle geese shot on Iceland and Islay, 2000-2011.*

Shooting rates used in the simulations		Average	Standard deviation
Icelandic shooting:	harvest rate (adults only)	0.015	0.003
	fixed bag (adults only)	593	101
Islay shooting:	harvest rate (all ages)	0.014	0.003
	fixed bag (all ages)	585	121

While shooting on Islay could also be modelled stochastically, in order to simplify interpretation of the results a constant rate was used. Furthermore it is likely this is more representative of how shooting would continue to be conducted.

The number removed from the population at each time step was estimated as a combination of the numbers shot on Islay and Iceland. The Islay component was calculated as the product of the proportion (as defined for that simulation) and the population size in the previous year. A one year delay was used between setting the shooting bag size and the count data as this is equivalent to the situation on Islay, with the limit set on the basis of the previous year's census. For each time step of each simulation, the Icelandic component was generated as a random variable, either proportional or absolute. This was then added to the Islay component to provide the total shooting bag for that year.

The starting year for simulations was 2011, the year of the most recent available Islay count data. Three alternative initial population sizes were considered for the modelling; the most recent count (44,503), the 10-year average count (41,839) and the fitted value for 2011 obtained from a linear model of the most recent 10 counts against year (43,560). Preliminary model runs were used to estimate how sensitive the model predictions were to the choice of initial population. A comparison of the outputs obtained using the largest and

smallest count values found that the probability of population decline varied by an average of 0.2% (this was averaged across different measures of decline). The maximum variation found between the predicted decline probabilities using the two starting values was 1.5%. The modelling reported below used the intermediate starting value (43,560), thus a margin of +/-1% should be included when assessing the predicted probabilities of population decline to account for uncertainty in the initial population estimate.

## 2.5 Model validation

The baseline model used the survival rate estimated to apply before shooting (0.965). To test the reliability of this model against the observed population counts, the model was run using the count from 2000 (34,620) as the starting point and then projecting forward for 25 years beyond the most recent count (i.e. a simulation period of 36 years). The model was run twice; first with the Icelandic bag modelled as a rate (randomly-drawn from a normal distribution with average = 0.015, sd = 0.003) and then as a bag (randomly-drawn from a normal distribution with average = 593, sd = 101). In both cases Islay shooting was included as the average annual proportion (0.014). A close correspondence between the median model prediction and the observed trend in the population between 2000 and 2011 was obtained with both methods for simulating shooting on Iceland (Figures 6 and 7). The observed annual growth rate for this period was 2.3%, while the model predictions were 2.6% and 2.7% for the proportional and absolute simulations respectively. However, wider confidence intervals were obtained when Icelandic shooting was modelled as a bag rather than a rate. This reflects the fact that when shooting is simulated as an absolute bag, the relative magnitude of population regulation resulting from the additional harvest decreases as the population grows and increases as it falls. In contrast, shooting modelled as a rate maintains a constant level of regulation irrespective of population size.

Whilst this test is not completely robust, since the demographic rates used in the model were based on the count data, the shooting and productivity data are independent. Thus the ability of the model to predict the overall observed trend is a reasonable indication of the model's predictive reliability.

In its baseline form, with shooting simulated at the level estimated for the period 2000 to 2011, but projecting the population forward from the 2011 count (43,560), the proportional model predicted the same population growth rate (median 2.6%; 95% CI 0.41 - 4.44) as found from the validation test. This is to be expected since in this format shooting removes the same proportion of the population at each time step irrespective of the starting population size. However, when Icelandic shooting was modelled as the average number removed between 2000 and 2011 this then represented both a smaller proportion of the starting population and an increasingly small proportion of a growing population. Hence the predicted baseline growth rate from the 2011 count using the absolute shooting model was higher at 3.0% (95% CI 0.57 – 5.12).

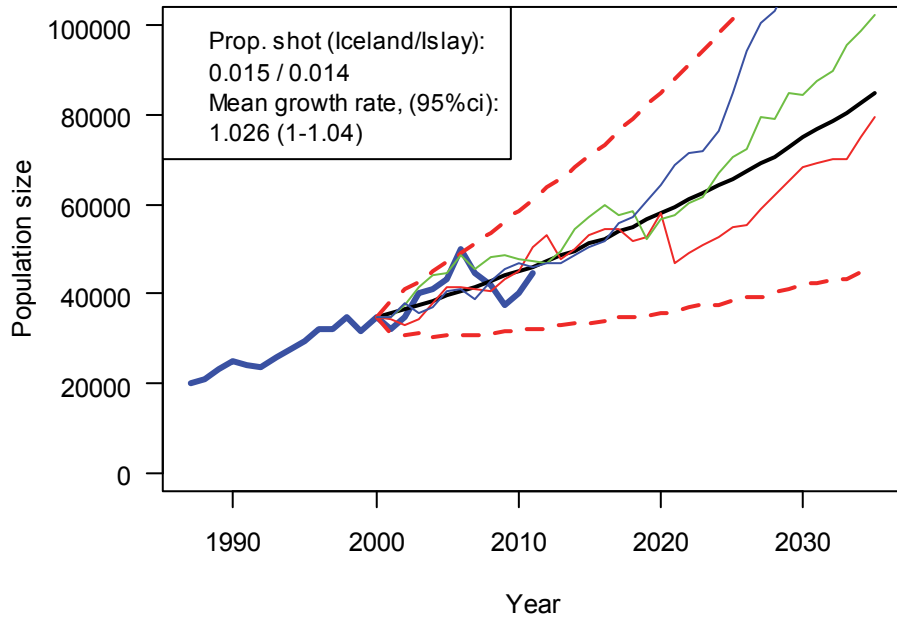


Figure 6. Comparison between the median model prediction of Islay barnacle goose population size (black line) and 95% confidence range (red dashed lines), and the observed population trend (heavy blue line) with Iceland shooting modelled as a rate (mean = 0.015, sd = 0.003). Three randomly selected individual trajectories (thin red, green and blue lines) are included for illustration.

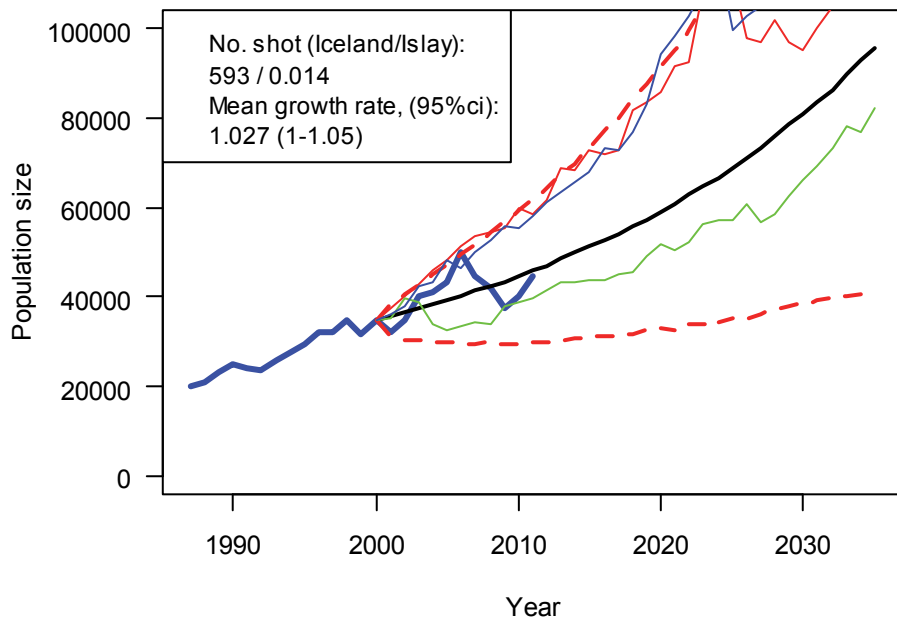


Figure 7. Comparison between the median model prediction of Islay barnacle goose population size (black line) and 95% confidence range (red dashed lines), and the observed population trend (heavy blue line) with Iceland shooting modelled as a bag (mean = 593, sd = 101). Three randomly selected individual trajectories (thin red, green and blue lines) are included for illustration.

### 3. SIMULATION RESULTS

#### 3.1 Icelandic shooting modelled as a harvest rate

The model was used to project the population from the estimated 2011 population size (43,560; derived as described in the methods) with no shooting on Islay, using the baseline survival rate estimated in the absence of all shooting, and then applying a randomised annual harvest rate on Iceland on autumn passage (with an average of 0.015 and sd of 0.003). Based on this, the model predicted an annual population growth rate of 4.0% (Figure 8, top-left). When shooting on Islay was included, within a range from 1% to 5% of the population shot each year, the average population growth rate decreased by approximately the same amount (Figure 8).

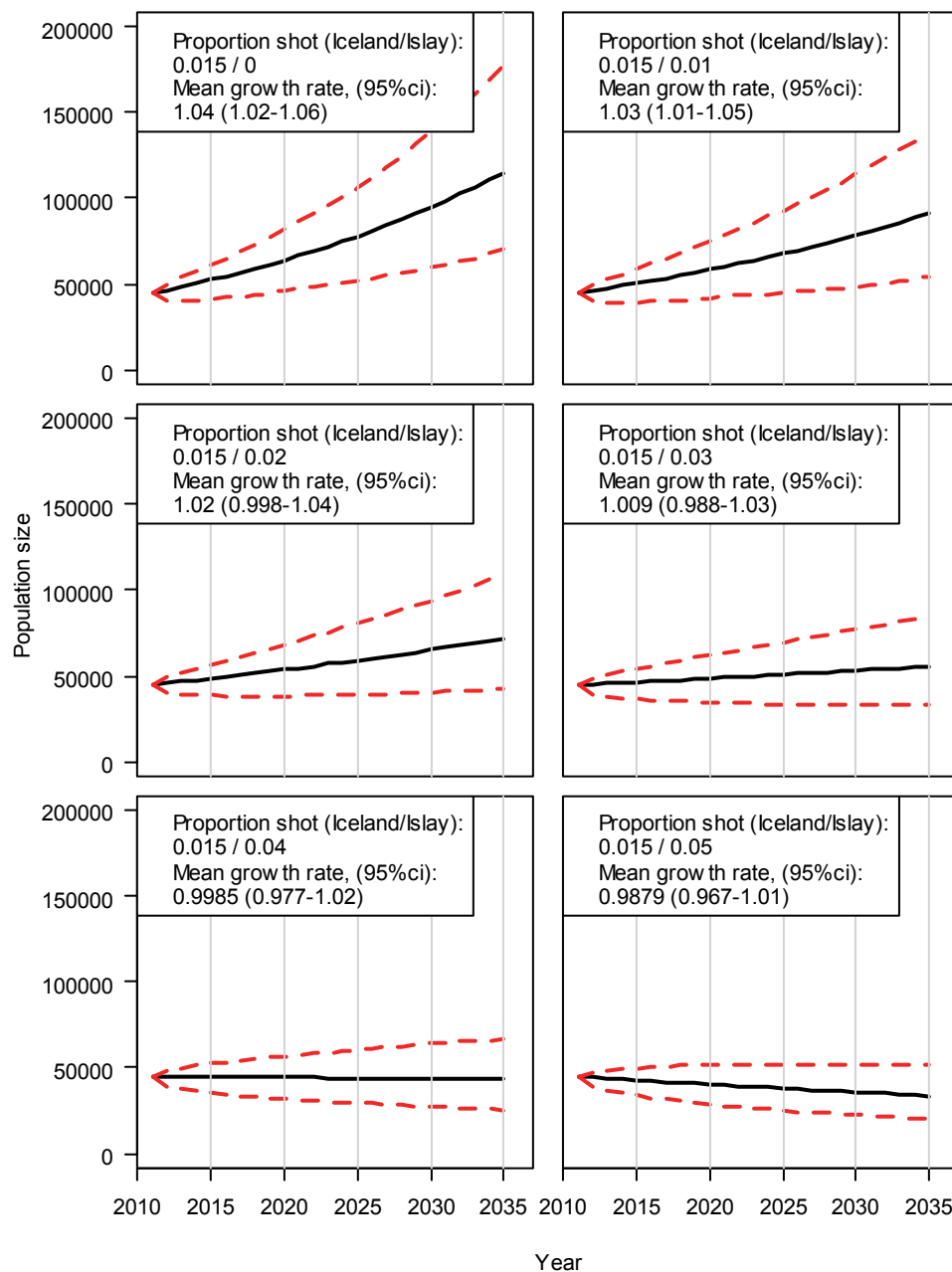


Figure 8. Simulation of the Islay barnacle goose population over 25 years with increasing rates of shooting on Islay (proportion shot ranges from 0 – 0.05). In all cases the harvest rate on Iceland was modelled as a random variable with an average of 0.015 (sd = 0.003). The total proportion shot is the sum of the values for Iceland and Islay.

The change in population growth against the total proportion shot throughout the flyway can be seen in Figure 9. At all shooting rates the randomised annual harvest rate on Iceland averaged 0.015 (sd = 0.003). Population growth remained positive on average until the proportion shot on Islay was 0.038, while the lower 95% confidence interval remained greater than 1 (i.e. positive growth) until the proportion shot on Islay was 0.018. This level is slightly higher than the average proportion shot over the last 11 years (0.014).

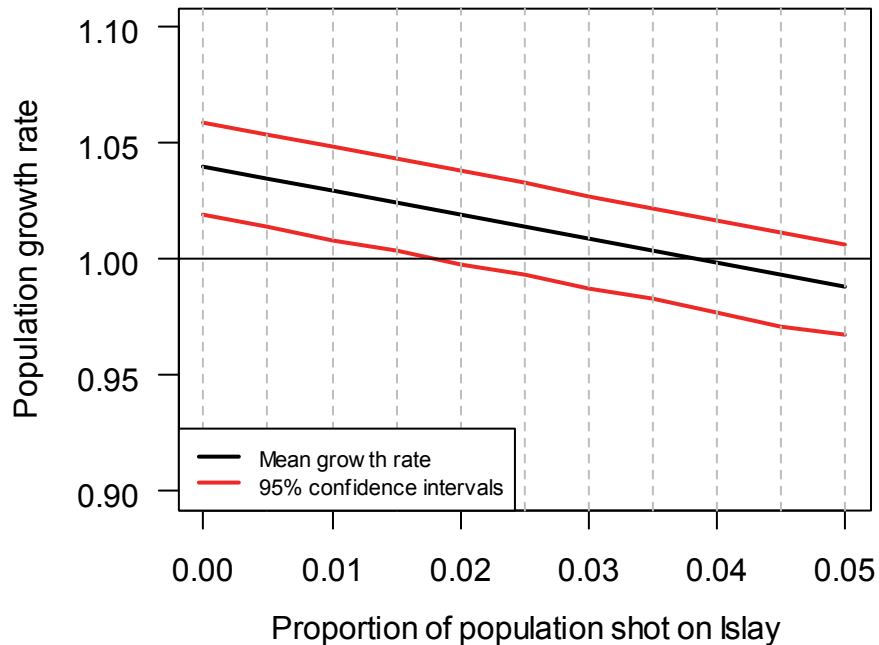


Figure 9. Population growth rate of Islay barnacle geese predicted with increasing total proportion shot on Islay (0 to 0.05). In all cases the harvest rate on Iceland was modelled as a random variable with an average of 0.015 (sd = 0.003).

The probability of any population decline after 10 years in response to shooting on Islay increased from 1.7% with no shooting on Islay (zero on x-axis) to 77% with 0.05 of the population shot on Islay (Figure 10, red line). The probability of decline below percentage thresholds of the initial population size (to 95%, 90%, 85% and 80% of the initial size) is incrementally lower, since each represents a larger reduction in population. For example, the probability of a population reduction to 80% of the initial size increased from <1% with no shooting on Islay to 21% with 0.05 of the population shot on Islay (Figure 10, purple line). In all cases the annual harvest rate on Iceland was included as a random draw with an average of 0.015 (sd = 0.003).

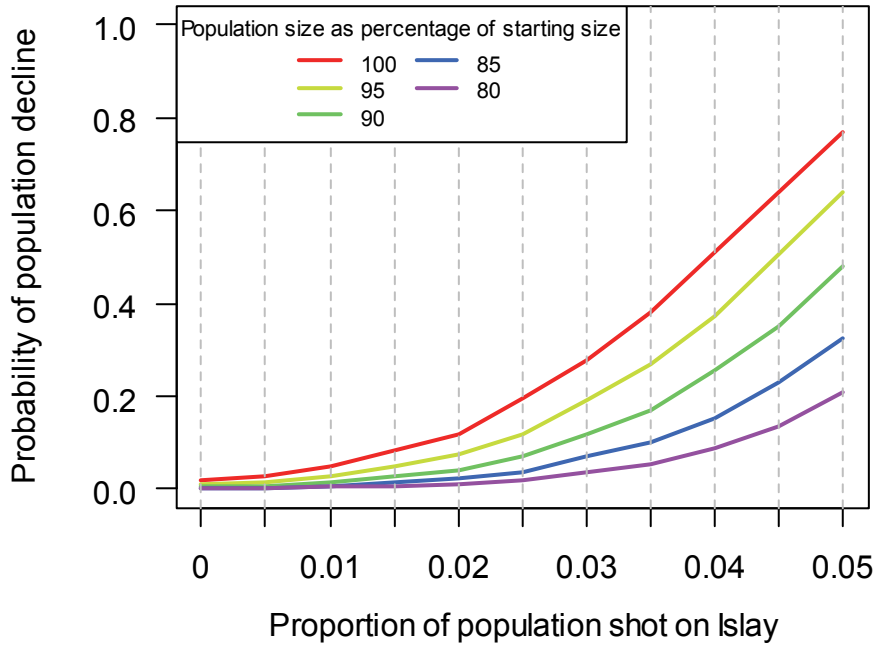


Figure 10. Probability of the Islay barnacle goose population declining below percentage thresholds of the initial size after 10 years, with increasing total proportion shot on Islay (0 to 0.05). In all cases the harvest rate on Iceland was modelled as a random variable with an average of 0.015 (sd = 0.003).

The probability of any population decline after 25 years in response to shooting on Islay was lower with no shooting on Islay than that predicted after 10 years (<1%), but rose to 90% with 0.05 of the population shot on Islay (Figure 11, red line). In all cases the harvest rate on Iceland was modelled as a random variable with an average of 0.015 (sd = 0.003). Similarly, the equivalent risk of a population reduction below 80% of the initial size increased from <1% to 59% (Figure 11, purple line) when considered over 25 years. Thus, while the risk of population decline after 25 years was lower at lower rates of shooting than when considered over 10 years, at higher shooting rates the reverse was true, with greater probabilities of decline predicted for the same level of shooting.

At current shooting levels on Islay (0.014) the predicted probability of population decline after 10 years was 7.3% and after 25 years was 1.2%.

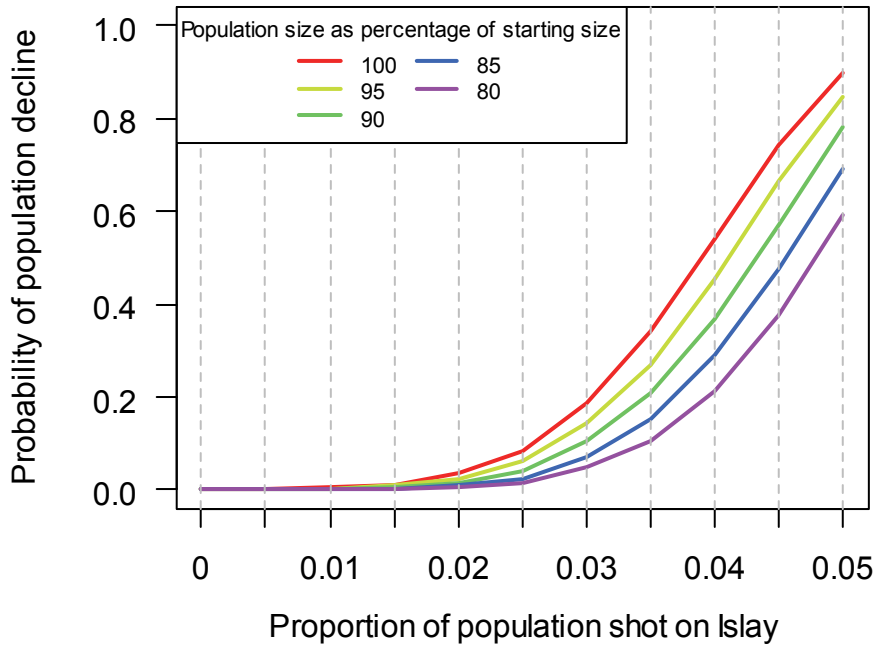


Figure 11. Probability of the Islay barnacle goose population declining below percentage thresholds of the initial size after 25 years, with increasing total proportion shot on Islay (0 to 0.05). In all cases the harvest rate on Iceland was modelled as a random variable with an average of 0.015 (sd = 0.003).

### 3.2 Icelandic shooting modelled as an absolute harvest

The model was also used to project the population from the 2011 size (43,560; derived as described in the methods) with no shooting on Islay, using the baseline survival rate estimated in the absence of all shooting, and then removing a random shooting bag value (with an average of 593 and sd = 101) to represent the annual number shot on Iceland on autumn passage. Based on this, the model predicted an annual population growth rate of 4.7% (Figure 12, top-left). When shooting on Islay was included within a range from 1% to 5% of the population shot each year, the average population growth rate decreased by approximately 1.2% for every additional 1% shot (Figure 12). Thus the rate of decrease in the population growth rate with increasing shooting on Islay was slightly greater than that seen when Icelandic shooting was modelled as a harvest rate, and the confidence intervals were approximately 50% wider.

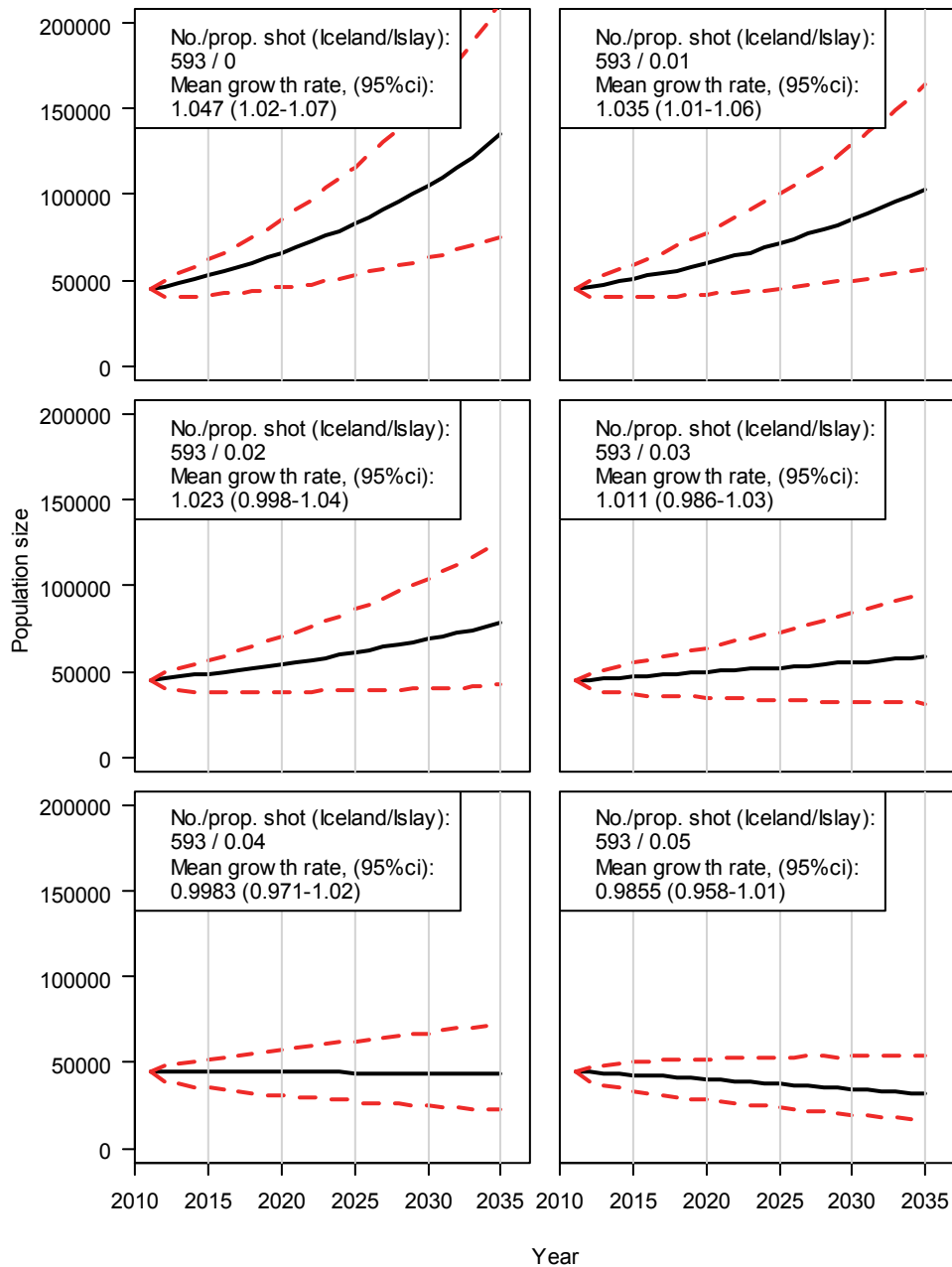


Figure 12. Simulation of the Islay barnacle goose population over 25 years with increasing rates of shooting on Islay (proportion shot ranges from 0 – 0.05). In all cases the number shot on Iceland was modelled as a randomised shooting bag with an average of 593 (sd = 101).

The change in population growth against the proportion shot on Islay can be seen in Figure 13. At all levels of Islay shooting, Icelandic shooting was simulated as a randomised shooting bag value drawn from a normal distribution with an average of 593 (sd = 101). Population growth remained positive on average until the proportion of the population shot on Islay exceeded 0.038, while the lower 95% confidence interval dropped below 1 (i.e. moving from positive to negative growth) when the proportion shot on Islay exceeded approximately 0.018. This proportional shooting rate is slightly higher than the average proportion shot over the last 11 years (0.014).

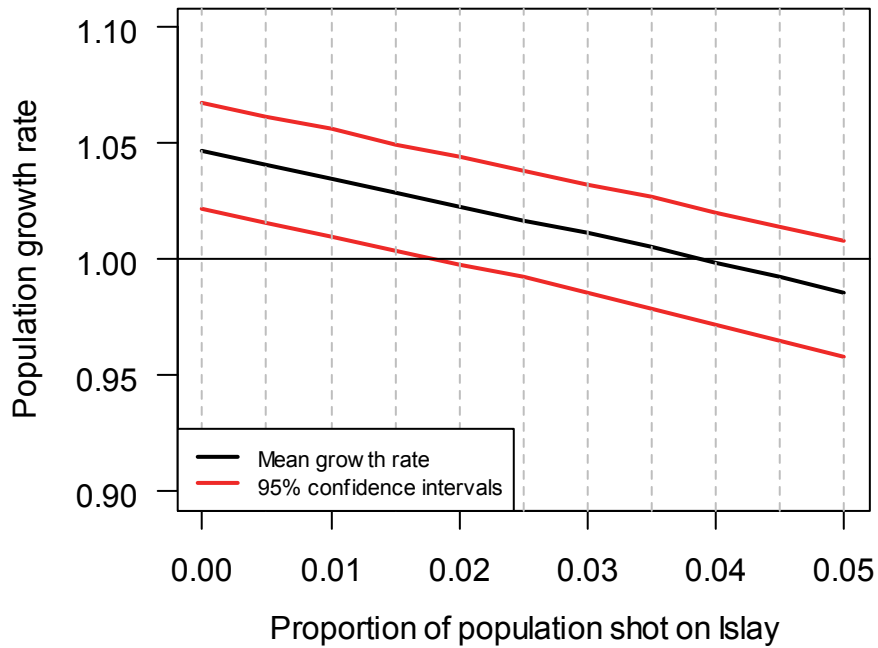


Figure 13. Population growth rate of Islay barnacle geese predicted with increasing proportion shot on Islay. In all cases the number shot on Iceland was modelled as a randomised shooting bag with an average of 593 (sd = 101).

The probability of any population decline after 10 years in response to shooting on Islay increased from 1.8% with no shooting on Islay (zero on x-axis) to 76% with 0.05 of the population shot on Islay (Figure 14, red line). In all cases Icelandic shooting was simulated as a randomised shooting bag value drawn from a normal distribution with an average of 593 (sd = 101). The probability of decline below percentage thresholds of the initial population size (to 95%, 90%, 85% and 80% of the initial size) was incrementally lower, since each represents a larger reduction in population. For example, the probability of a population reduction to 80% of the initial size increased from <1% with no shooting on Islay to 23% with 0.05 of the population shot on Islay (Figure 14, purple line).

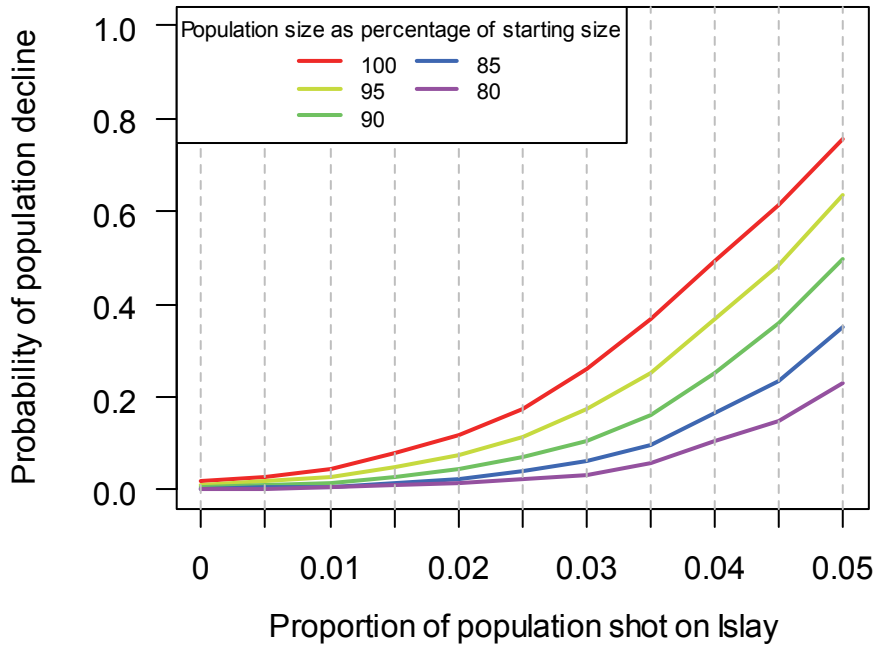


Figure 14. Probability of population decline of Islay barnacle geese below percentage thresholds of the initial size after 10 years, against increases in the proportion of the population shot on Islay. In all cases the number shot on Iceland was modelled as a randomised shooting bag with an average of 593 (sd = 101).

The probability of any population decline after 25 years in response to shooting on Islay was lower (<0.1%) with no shooting on Islay than that predicted after 10 years (1.8%), but rose to 88% with 0.05 of the population shot on Islay (Figure 15, red line). In all cases Icelandic shooting was simulated as a randomised shooting bag value drawn from a normal distribution with an average of 593 (sd = 101). Similarly, the equivalent risk of a population reduction below 80% of the initial size increased from <0.1% to 64% (Figure 15, purple line) when considered over 25 years. Thus, while the risk of population decline after 25 years was lower at lower rates of shooting than when considered over 10 years, at higher shooting rates the reverse was true, with greater probabilities of decline predicted for the same level of shooting.

At current shooting levels on Islay (0.014) the predicted probability of population decline after 10 years was 7.2% and after 25 years was 1.0%.

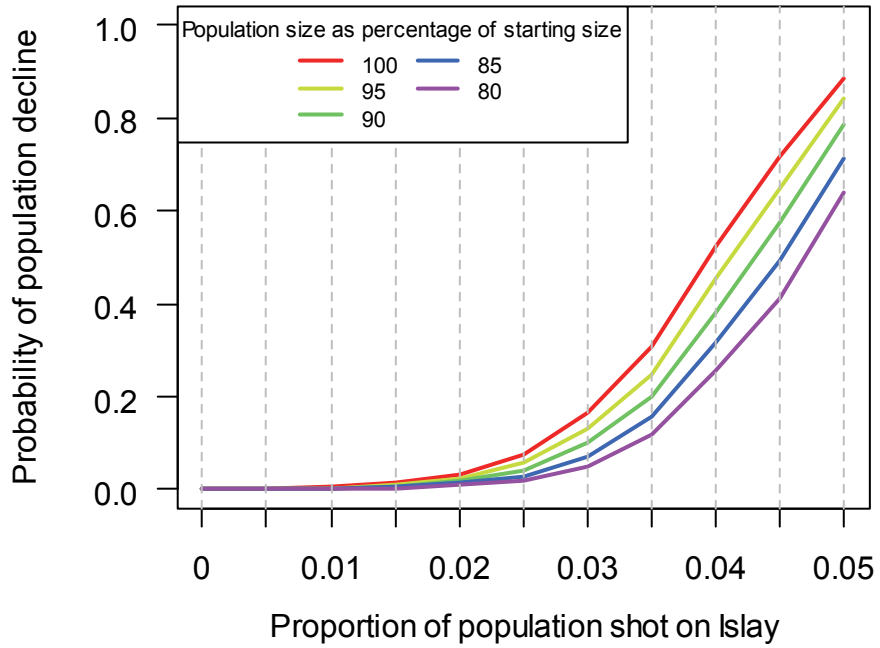


Figure 15. Probability of population decline of Islay barnacle geese below percentage thresholds of the initial size after 25 years, against increases in the proportion of the population shot on Islay. In all cases the number shot on Iceland was modelled as a randomised shooting bag with an average of 593 (sd = 101).

#### 4. DISCUSSION

The Greenland barnacle goose population has continued to grow since the previous PVA for this population was conducted (Trinder *et al.*, 2005). While the population on Islay has fluctuated in recent years, the overall trend over 50 years remains positive. Analysis of the count and reproductive data found no evidence for density-dependent population regulation during the last 20 years. This is matched by similar studies of other Arctic-breeding geese (e.g. Morrissette *et al.*, 2010), although detecting density-dependent regulation is challenging in slow-breeding species such as geese so this result should not be unexpected. Nevertheless, there is currently little to suggest that the goose population has been regulated by competition for resources.

Given the above results the population was modelled as density-independent which, over the prediction period presented here, generated projected populations in line with the recent observed trend. If the population on Islay continues to increase, it is reasonable to suppose there must be some point at which resources will become limiting and density-dependent regulation will take place, particularly as 10 years of growth at the recent observed rate of 2.3% annually will lead to a 25% increase in population size, and a 76% increase after 25 years. While density-dependence would presumably result in birds being in poorer condition by the end of the winter, it is not clear whether it would act primarily through reductions in reproduction or survival. Furthermore, how such inherent regulation would interact with shooting on Islay is difficult to predict. However, harvesting a population which is regulated around an equilibrium size would probably just improve conditions for the remaining population, without actually influencing the equilibrium population size itself.

As well as modelling the population as density-independent, another assumption made relates to survival. We have limited information on age-related survival, thus the adult rate has been used for all age classes. While this is a simplification, it is unlikely to have an important effect on the model results. This is because the model structure is such that juveniles are actually several months old and have survived their first autumn migration before they are included. Their survival rate is probably quite similar to older age classes from this point.

On the assumption that shooting on Iceland removes individuals from the different wintering areas in proportion to their relative population sizes (i.e. there is no geographical bias in the Iceland shooting effort), the Iceland bag has equated to an average of 1.5% of the adult Islay population since 2000 (i.e. birds older than 6 months). Over the same period, shooting on Islay has equated to an average additional removal of 1.4% of the population (all age classes). Including annual shooting bags into estimation of survival suggests that combined annual shooting mortality has averaged approximately 3%, of which about half is due to Icelandic shooting and half due to shooting on Islay (although note that this 50:50 split between Islay and Iceland does not include the removal of newly fledged birds shot in Iceland prior to their first migration, since these have already been incorporated into the model through the proportion of juveniles in the population). Removing shooting mortality from the overall mortality estimate permits prediction of the population growth rate in the absence of all shooting; this was 5.6% per year. This compares with an average growth since 1995 (to match the period of Iceland shooting data) of 2.7% and since 2000 (to match the period of Islay shooting data) of 2.3%. Thus the model suggests that shooting has reduced population growth over this period. It is important to stress that shooting mortality is treated as additive to natural mortality (i.e. the shot birds would otherwise have survived) rather than compensatory. This is unlikely to be completely accurate, however there are no data with which to estimate the extent to which variation in shooting mortality is compensated for by variation in natural mortality. The estimated growth rate in the absence of all shooting should therefore be treated as a theoretical maximum rate.

The average combined rate of shooting has removed 2.9% of the Islay population per year (not including the removal of newly fledged birds). At this level of simulated shooting the model predicted an average population growth rate of 2.6% per year, close to the observed trend since 2000 (2.3%). The Iceland harvest rate version of the model predicted that on average, the Islay population would be held at its initial (2011) size with a combined shooting level of 5.3% (3.8% on Islay, 1.5% on Iceland) of the population per year. At this level of shooting, 50% of simulations show a decline and 50% show an increase. To keep the risk of population decline to a minimum (i.e. for the 95% confidence range on the population growth rate to remain greater than 1) a combined harvest rate of no more than 3.3% was required (1.8% on Islay and 1.5% on Iceland). This is close to the level of shooting experienced between 2000 and 2011 of 2.9% (1.4% on Islay, 1.5% on Iceland). At this level, the risk of population decline after 10 years was predicted to be 3.4% and the risk of a 20% decline after 10 years was 0.4%.

For the simulations, the rate of shooting was only varied on Islay. This is a reasonable assumption to make since shooting on Islay is conducted under licence, and the level can be modified rapidly in response to population changes. In contrast, shooting on Iceland is unregulated, insofar as there are no limits set. Icelandic shooting was modelled as either a rate or a bag size; in both cases as a random draw from appropriate probability distributions. The former method maintains a harvest in proportion with fluctuations in population size, while the latter imposes a smaller reduction if the population grows and a larger one if it falls. Both approaches are potentially unrealistic, although there is some suggestion that the latter is closer to the pattern observed between 1995 and 2011. This implies that hunters have shot similar numbers irrespective of population change. This is a potentially surprising result since a quarry species which is either easier or harder to find (due to population change) would be expected to be shot in higher or lower numbers respectively. Therefore, it is considered plausible that the level of shooting on Iceland has combined aspects of both approaches. Thus, the two alternative methods used here to simulate shooting can be expected to represent the ends of the spectrum, with the reality somewhere in the middle. It is also worth noting that if Icelandic shooting is closer to the bag size model, then as the population grows the reduction in population growth due to shooting will get smaller (and the converse will also apply should the population begin to decline). This effect explains the difference seen in the baseline growth rate predictions (harvest rate = 2.6%, bag size = 3.0%).

Shooting as a harvest rate represents a simple means to minimise the risks of either under- or over-exploiting a population. It thus has an obvious appeal for population management. As can be seen from the results presented here, the model with a harvest rate yielded narrower confidence intervals and lower risks of triggering population declines. However, from a precautionary perspective, and in light of the fact that shooting on Iceland may not operate as a rate, the results of the bag size model should perhaps be considered as a safer guide for goose management since this will result in a lower risk of triggering an unwanted population decline.

It is also worth noting that the Islay population is closely monitored each winter and there is therefore little risk of triggering a significant population decline (e.g. due to local over-harvesting) without this becoming rapidly apparent and remedial management actions being undertaken. Thus, the risks of the larger declines predicted by the modelling in this report should be avoidable.

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## ANNEX 1: GREENLAND BARNACLE GOOSE POPULATION DATA AND ANALYSIS

Table A1.1 Greenland barnacle goose counts and demographic data from Islay and the co-ordinated aerial censuses. Details of methods for counts, age ratios and mean brood sizes from [http://monitoring.wwt.org.uk/species/greenland\\_barnacle\\_status.php](http://monitoring.wwt.org.uk/species/greenland_barnacle_status.php).

Year	Total count	Islay count	Count method and data source	Proportion juveniles on Islay	Mean brood size on Islay	Proportion breeding adults	Survival
1961	13904	6900		0.107	NA	NA	NA
1962	13990	8700		0.076	NA	NA	NA
1963		10400		0.306	NA	NA	NA
1964		8300		0.075	NA	NA	NA
1965		9000		0.112	1.55	NA	0.963
1966	19797	10500		0.13	1.45	0.266	1.015
1967		16500		0.171	1.80	0.310	1.303
1968		13300		0.095	1.30	0.246	0.729
1969		14300		0.2	1.90	0.325	0.860
1970		15100		0.194	2.50	0.321	0.851
1971		17100	Winter peak;	0.136	1.80	0.286	0.978
1972		17300	Ogilvie 1983	0.121	2.10	0.180	0.889
1973	24082	18400		0.174	2.50	0.222	0.878
1974		19400		0.13	2.20	0.208	0.917
1975		20200		0.139	1.90	0.230	0.896
1976		24000		0.224	2.50	0.320	0.922
1977		22200		0.049	1.80	0.104	0.880
1978	33815	22000		0.12	1.98	0.153	0.872
1979		17300		0.083	1.79	0.133	0.721
1980		20500		0.114	2.02	0.153	1.050
1981		17000		0.073	1.70	0.120	0.769
1982		14000		0.067	1.75	0.096	0.768
1983	25252	16600		0.099	1.97	0.129	1.068
1984		21000	Winter peak,	0.124	2.34	0.151	1.108
1985		19230	WeBS	0.105	1.83	0.170	0.820
1986		23900		0.176	2.00	0.270	1.024
1987		19873		0.115	2.11	0.190	0.736
1988	34542	20828		0.122	2.19	0.165	0.920
1989		23316		0.141	2.44	0.178	0.962
1990		25194		0.19	2.43	0.269	0.875
1991		23862		0.046	1.68	0.093	0.904
1992		23565		0.026	1.31	0.045	0.962
1993		26023		0.115	2.29	0.120	0.977
1994	38012	27490		0.093	2.24	0.119	0.958
1995		29233		0.072	2.00	0.095	0.987
1996		31920		0.107	2.30	0.122	0.975
1997		31956	Mean of	0.061	1.95	0.085	0.940
1998		34711	international	0.128	2.28	0.147	0.947
1999	54123	31908	counts, SNH	0.081	1.90	0.125	0.845
2000		34620		0.101	2.10	0.128	0.975
2001		32353		0.071	2.10	0.091	0.868
2002		34708		0.125	2.23	0.149	0.939
2003	56386	39985		0.064	1.59	0.115	1.078
2004		41181		0.1593	2.35	0.185	0.866
2005		43185		0.0662	1.76	0.118	0.979
2006		50232		0.0318	1.16	0.065	1.126
2007	70501	44756		0.098	2.12	0.109	0.804
2008		41950		0.082	1.86	0.119	0.860

2009	37637	0.04	1.8	0.055	0.861
2010	40252	0.112	2.26	0.121	0.950
2011	44503	0.112	2.1	0.155	0.982

*Table A1.2. Counts of Greenland barnacle geese from Scottish wintering sites other than Islay.*

Year	Uists	South Walls	Tiree	Coll	Colonsay/Oronsay	Danna
1996	1720	1170	1456	612	-	-
1997	1414	1180	1158	715	-	-
1998	1654	1140	1572	929	463	720
1999	1491	1500	1607	788	576	610
2000	1957	1500	1162	718	244	280
2001	3327	2600	2132	933	-	420
2002	2732	1800	2786	855	510	400
2003	2782	1800	2796	844	793	640
2004	2839	2390	3273	1297	1000	708
2005	4659	2000	3474	2010	716	468
2006	2124	1710	3454	2264	1332	627
2007	3632	1874	3439	800	1200	711
2008	3365	1800	3362	1271	1874	550
2009	2392	1600	3729	880	2100	588
2010	2546	1861	4190	775	2056	715
2011	3719	1932	4295	809	740	532

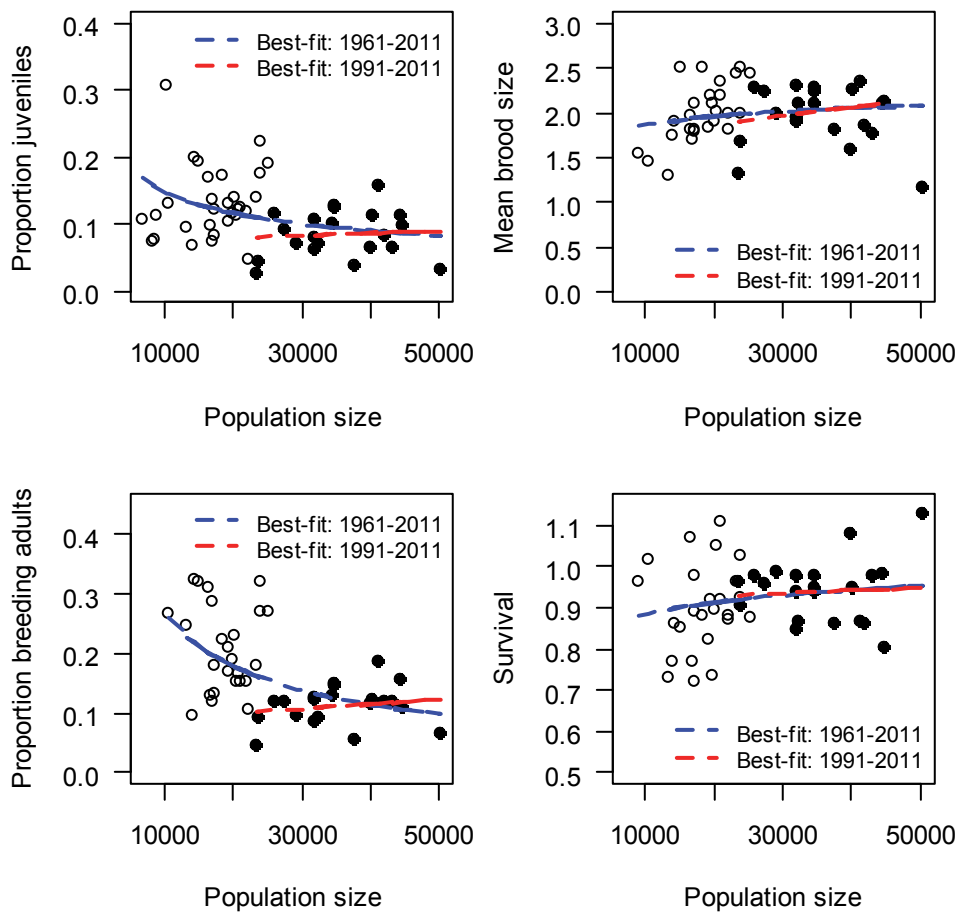


Figure A1. Trends in Islay barnacle goose population demographic rates since 1961 in relation to population size. Open symbols used for 1961 to 1990, filled symbols for 1991 to 2011. Dashed lines are from Generalised Linear Model fits obtained for rate vs. year (blue: 1961-2011; red: 1991-2011). See Table A1.3 for model details.

*Table A1.3. Outputs of a Generalised Linear Model of Islay barnacle goose reproduction and survival; significant trends (at  $p < 0.05$ ) are highlighted.*

Explanatory variable	Dependent variable	Years	Deviance	df	t	p	Slope	se
Year	Prop. Young	1961-2011	23748	1 49	-3.535	<0.001	-0.015	0.004
	Mean brood size	1961-2011	253	1 45	0.678	0.501	0.001	0.002
	Prop. Breeding	1961-2011	18393	1 44	-5.7	<0.001	-0.025	0.004
	Survival	1961-2011	0.622	1 45	0.467	0.643	0.0006	0.001
Islay population	Prop. Young	1961-2011	25895	1 49	-2.69	0.01	-0.41	0.15
	Mean brood size	1961-2011	248	1 45	1.18	0.24	0.07	0.06
	Prop. Breeding	1961-2011	22255	1 44	-4.35	<0.001	-0.75	0.17
	Survival	1961-2011	0.61	1 45	1.1	0.28	0.05	0.04
Year	Prop. Young	1991-2011	11449	1 19	0.39	0.701	0.007	0.017
	Mean brood size	1991-2011	118	1 19	0.016	0.987	0.0001	0.006
	Prop. Breeding	1991-2011	7065	1 19	0.577	0.571	0.007	0.013
	Survival	1991-2011	0.127	1 19	-0.54	0.597	-0.002	0.003
Islay population	Prop. Young	1991-2011	11478	1 19	0.3	0.8	0.2	0.5
	Mean brood size	1991-2011*	73.3	1 18	0.9	0.4	0.2	0.2
	Prop. Breeding	1991-2011	7006	1 19	0.7	0.5	0.3	0.4
	Survival	1991-2011	0.128	1 19	0.29	0.77	0.03	0.09

\* The mean brood size value for 2006 was identified as an outlier and removed from this analysis in order to obtain an acceptable fit of the model to the data. This year had the lowest recorded mean brood size and the second lowest recorded percentage of young birds.

Generalised linear models were used with the following error structures:

- Prop. Young – quasibinomial (response variable was number of juveniles : number of adults and sub-adults)
- Mean brood size – quasipoisson (response variable was mean brood size multiplied by 100 to transform to an integer)
- Prop. Breeding – quasibinomial (response variable was number of breeding adults : number of non-breeding adults)
- Survival – gaussian (response was log transformed)

In all cases model residuals were tested for normality using the Shapiro-Wilks test. All tests returned non-significant results indicating that selected models were appropriate.

Table A1.4. Greenland barnacle goose shooting data. Icelandic shooting data from Statistics Iceland (see below, and note that there are no data for 2003 from Iceland due to a protest by hunters), and Islay data from SNH.

Year	Iceland bag*	Islay bag
1995	1,876	0
1996	1,619	0
1997	2,629	0
1998	2,283	0
1999	1,376	0
2000	1,412	564
2001	1,409	473
2002	925	534
2003	-	491
2004	1,153	589
2005	1,478	490
2006	1,025	584
2007	1,577	851
2008	1,534	658
2009	1,624	616
2010	1,370	423
2011	1,246	744

\*[http://www.statice.is/?PageID=2093&src=/temp\\_en/Dialog/varval.asp?ma=SJA10303%26ti=Hunting+1995-2011+%26path=../Database/sjavarutvegur/landveidi/%26lang=1%26units=Number](http://www.statice.is/?PageID=2093&src=/temp_en/Dialog/varval.asp?ma=SJA10303%26ti=Hunting+1995-2011+%26path=../Database/sjavarutvegur/landveidi/%26lang=1%26units=Number)

## ANNEX 2: INDIVIDUAL BASED PARAMETER ESTIMATES

Demographic rates for the Greenland barnacle goose marked population derived from the best-fit Barker model  $[S(\sim\text{time} * a2)p(\sim\text{time})r(\sim 1)R(\sim\text{time})R'(\sim 1)F(\sim\text{time})F'(\sim a2)]$ . For details see Section 1.3.

Parameter	Age class	Period		Estimate (S.E.)	Confidence interval (95%)
		from	to		Lower - Upper
S	adult	1982	1983	0.572 (0.076)	0.42 - 0.712
S	adult	1983	1984	0.779 (0.016)	0.747 - 0.808
S	adult	1984	1985	0.92 (0.01)	0.898 - 0.938
S	adult	1985	1986	0.831 (0.014)	0.801 - 0.857
S	adult	1986	1987	0.853 (0.012)	0.829 - 0.875
S	adult	1987	1988	0.837 (0.012)	0.812 - 0.859
S	adult	1988	1989	0.851 (0.012)	0.825 - 0.873
S	adult	1989	1990	0.83 (0.014)	0.801 - 0.855
S	adult	1990	1991	0.784 (0.015)	0.752 - 0.812
S	adult	1991	1992	0.841 (0.015)	0.809 - 0.867
S	adult	1992	1993	0.867 (0.013)	0.839 - 0.891
S	adult	1993	1994	0.793 (0.015)	0.762 - 0.82
S	adult	1994	1995	0.831 (0.013)	0.804 - 0.854
S	adult	1995	1996	0.857 (0.012)	0.832 - 0.878
S	adult	1996	1997	0.819 (0.012)	0.796 - 0.841
S	adult	1997	1998	0.87 (0.01)	0.848 - 0.889
S	adult	1998	1999	0.869 (0.01)	0.848 - 0.887
S	adult	1999	2000	0.862 (0.011)	0.839 - 0.881
S	adult	2000	2001	0.863 (0.011)	0.841 - 0.883
S	adult	2001	2002	0.889 (0.01)	0.867 - 0.907
S	adult	2002	2003	0.871 (0.012)	0.846 - 0.892
S	adult	2003	2004	0.84 (0.014)	0.812 - 0.865
S	adult	2004	2005	0.799 (0.016)	0.766 - 0.829
S	adult	2005	2006	0.789 (0.018)	0.751 - 0.822
S	adult	2006	2007	0.821 (0.018)	0.783 - 0.854
S	adult	2007	2008	0.759 (0.021)	0.715 - 0.798
S	adult	2008	2009	0.734 (0.024)	0.684 - 0.778
S	adult	2009	2010	0.727 (0.028)	0.668 - 0.778
S	adult	2010	2011	0.647 (0.035)	0.576 - 0.713
S	adult	2011	2012	0 (0)	0 - 1
S	juv	1982	1983	0.501 (0.25)	0.124 - 0.877
S	juv	1983	1984	0.4 (0.219)	0.1 - 0.8
S	juv	1984	1985	0.85 (0.08)	0.624 - 0.951
S	juv	1985	1986	0.545 (0.15)	0.268 - 0.797
S	juv	1986	1987	0.886 (0.038)	0.788 - 0.942
S	juv	1987	1988	0.833 (0.108)	0.523 - 0.958
S	juv	1988	1989	0.818 (0.116)	0.493 - 0.954
S	juv	1989	1990	0.79 (0.094)	0.555 - 0.919

Parameter	Age class	Period		Estimate (S.E.)	Confidence interval (95%)
		from	to		Lower - Upper
S	juv	1990	1991	0.881 (0.05)	0.744 - 0.95
S	juv	1991	1992	0.8 (0.179)	0.309 - 0.973
S	juv	1992	1993	1 (0)	1 - 1
S	juv	1993	1994	0.879 (0.04)	0.776 - 0.938
S	juv	1994	1995	0.897 (0.037)	0.799 - 0.95
S	juv	1995	1996	0.917 (0.056)	0.721 - 0.979
S	juv	1996	1997	0.808 (0.055)	0.678 - 0.893
S	juv	1997	1998	0.95 (0.049)	0.718 - 0.993
S	juv	1998	1999	0.905 (0.037)	0.804 - 0.957
S	juv	1999	2000	0.5 (0.25)	0.123 - 0.877
S	juv	2000	2001	0.862 (0.064)	0.685 - 0.947
S	juv	2001	2002	0.905 (8.521)	0 - 1
S	juv	2002	2003	0.702 (24.609)	0 - 1
S	juv	2003	2004	1 (0)	1 - 1
S	juv	2004	2005	0.333 (0.192)	0.084 - 0.732
S	juv	2005	2006	0.92 (11.96)	0 - 1
S	juv	2006	2007	1 (0)	1 - 1
S	juv	2007	2008	1 (0)	1 - 1
S	juv	2008	2009	0.629 (18.632)	0 - 1
S	juv	2009	2010	0.608 (19.154)	0 - 1
S	juv	2010	2011	0.673 (20.197)	0 - 1
S	juv	2011	1982	0 (0)	0 - 0
p	adult	-	1983	0.946 (0.325)	0 - 1
p	adult	-	1984	0.92 (0.031)	0.836 - 0.963
p	adult	-	1985	0.956 (0.014)	0.918 - 0.977
p	adult	-	1986	0.977 (0.012)	0.939 - 0.991
p	adult	-	1987	0.963 (0.011)	0.933 - 0.98
p	adult	-	1988	0.911 (0.019)	0.866 - 0.942
p	adult	-	1989	0.851 (0.023)	0.799 - 0.891
p	adult	-	1990	0.855 (0.027)	0.794 - 0.9
p	adult	-	1991	0.814 (0.025)	0.76 - 0.858
p	adult	-	1992	0.871 (0.025)	0.813 - 0.912
p	adult	-	1993	0.911 (0.019)	0.865 - 0.942
p	adult	-	1994	0.948 (0.013)	0.915 - 0.968
p	adult	-	1995	0.97 (0.009)	0.945 - 0.984
p	adult	-	1996	0.899 (0.014)	0.867 - 0.924
p	adult	-	1997	0.959 (0.012)	0.93 - 0.977
p	adult	-	1998	0.98 (0.009)	0.951 - 0.992
p	adult	-	1999	0.926 (0.011)	0.901 - 0.946
p	adult	-	2000	0.967 (0.011)	0.939 - 0.983
p	adult	-	2001	0.956 (0.012)	0.927 - 0.974
p	adult	-	2002	0.961 (0.012)	0.931 - 0.979
p	adult	-	2003	0.93 (0.013)	0.9 - 0.952
p	adult	-	2004	0.939 (0.017)	0.897 - 0.965

Parameter	Age class	Period		Estimate (S.E.)	Confidence interval (95%)
		from	to		Lower - Upper
p	adult	-	2005	0.903 (0.023)	0.849 - 0.939
p	adult	-	2006	0.743 (0.031)	0.677 - 0.799
p	adult	-	2007	0.815 (0.033)	0.74 - 0.872
p	adult	-	2008	0.852 (0.041)	0.753 - 0.916
p	adult	-	2009	0.764 (0.033)	0.694 - 0.822
p	adult	-	2010	0.821 (0.033)	0.747 - 0.876
p	adult	-	2011	1 (0)	0 - 1
r	adult	constant		0.017 (0.002)	0.013 - 0.022
R	adult	-	1983	0.955 (0.009)	0.934 - 0.969
R	adult	-	1984	0.697 (0.018)	0.661 - 0.731
R	adult	-	1985	0.737 (0.018)	0.7 - 0.772
R	adult	-	1986	0.88 (0.011)	0.856 - 0.9
R	adult	-	1987	0.79 (0.014)	0.76 - 0.817
R	adult	-	1988	0.697 (0.017)	0.662 - 0.729
R	adult	-	1989	0.636 (0.019)	0.598 - 0.672
R	adult	-	1990	0.629 (0.02)	0.589 - 0.666
R	adult	-	1991	0.589 (0.022)	0.546 - 0.631
R	adult	-	1992	0.743 (0.018)	0.707 - 0.777
R	adult	-	1993	0.8 (0.016)	0.768 - 0.829
R	adult	-	1994	0.853 (0.013)	0.827 - 0.876
R	adult	-	1995	0.872 (0.012)	0.847 - 0.894
R	adult	-	1996	0.861 (0.011)	0.838 - 0.882
R	adult	-	1997	0.84 (0.012)	0.815 - 0.862
R	adult	-	1998	0.854 (0.011)	0.832 - 0.875
R	adult	-	1999	0.775 (0.014)	0.747 - 0.801
R	adult	-	2000	0.841 (0.012)	0.816 - 0.863
R	adult	-	2001	0.807 (0.014)	0.779 - 0.833
R	adult	-	2002	0.802 (0.015)	0.771 - 0.829
R	adult	-	2003	0.799 (0.016)	0.766 - 0.829
R	adult	-	2004	0.779 (0.018)	0.741 - 0.813
R	adult	-	2005	0.705 (0.023)	0.658 - 0.748
R	adult	-	2006	0.627 (0.025)	0.577 - 0.675
R	adult	-	2007	0.688 (0.026)	0.636 - 0.736
R	adult	-	2008	0.627 (0.03)	0.565 - 0.684
R	adult	-	2009	0.544 (0.037)	0.472 - 0.615
R	adult	-	2010	0.616 (0.044)	0.526 - 0.698
R	adult	-	2011	0 (0)	0 - 0
R'	adult	constant		0.994 (0.001)	0.99 - 0.996
F	adult	1982	1983	0.041 (0.042)	0.005 - 0.261
F	adult	1983	1984	0.713 (0.029)	0.653 - 0.766
F	adult	1984	1985	0.95 (0.014)	0.916 - 0.971
F	adult	1985	1986	0.933 (0.015)	0.895 - 0.957
F	adult	1986	1987	0.892 (0.014)	0.861 - 0.916
F	adult	1987	1988	0.907 (0.019)	0.863 - 0.938

Parameter	Age class	Period		Estimate (S.E.)	Confidence interval (95%)
		from	to		Lower - Upper
F	adult	1988	1989	0.919 (0.023)	0.862 - 0.953
F	adult	1989	1990	0.895 (0.028)	0.827 - 0.938
F	adult	1990	1991	0.948 (0.02)	0.891 - 0.976
F	adult	1991	1992	0.948 (0.022)	0.882 - 0.978
F	adult	1992	1993	0.917 (0.019)	0.87 - 0.948
F	adult	1993	1994	0.942 (0.013)	0.91 - 0.964
F	adult	1994	1995	0.969 (0.009)	0.945 - 0.983
F	adult	1995	1996	0.98 (0.011)	0.943 - 0.993
F	adult	1996	1997	0.911 (0.013)	0.882 - 0.934
F	adult	1997	1998	0.924 (0.012)	0.897 - 0.944
F	adult	1998	1999	0.942 (0.01)	0.918 - 0.96
F	adult	1999	2000	0.958 (0.011)	0.929 - 0.975
F	adult	2000	2001	0.946 (0.012)	0.918 - 0.965
F	adult	2001	2002	0.948 (0.012)	0.919 - 0.967
F	adult	2002	2003	0.984 (0.01)	0.948 - 0.995
F	adult	2003	2004	0.938 (0.017)	0.895 - 0.964
F	adult	2004	2005	0.937 (0.022)	0.879 - 0.969
F	adult	2005	2006	0.997 (0.026)	0 - 1
F	adult	2006	2007	0.965 (0.031)	0.817 - 0.994
F	adult	2007	2008	0.851 (0.04)	0.756 - 0.914
F	adult	2008	2009	1 (0)	0 - 1
F	adult	2009	2010	1 (0)	1 - 1
F	adult	2010	2011	1 (0)	1 - 1
F'	adult	constant		0.389 (0.012)	0.366 - 0.412
F'	juv	constant		0 (0)	0 - 0

### ANNEX 3: TABULATED MODEL PREDICTIONS

#### Outputs from model with Iceland shooting simulated as a proportional harvest

Table A3.1. Population growth rates, with an average Icelandic shooting rate of 0.015 (sd = 0.003) included.

Proportion shot on Islay	Mean population growth rate	95% confidence intervals	
		Lower	Upper
0	1.0400	1.0190	1.0592
0.005	1.0349	1.0137	1.0539
0.01	1.0297	1.0084	1.0487
0.015	1.0244	1.0038	1.0435
0.02	1.0195	0.9981	1.0383
0.025	1.0143	0.9934	1.0330
0.03	1.0088	0.9878	1.0270
0.035	1.0036	0.9832	1.0220
0.04	0.9985	0.9772	1.0167
0.045	0.9933	0.9715	1.0113
0.05	0.9879	0.9674	1.0060

Table A3.2. Probability of decline below population thresholds within 10 years, with an average Icelandic shooting rate of 0.015 (sd = 0.003) included.

Proportion shot on Islay	Population reduction thresholds				
	0	0.05	0.1	0.15	0.2
0	0.0172	0.0096	0.0046	0.0020	0.0010
0.005	0.0268	0.0144	0.0074	0.0038	0.0020
0.01	0.0486	0.0278	0.0150	0.0078	0.0042
0.015	0.0838	0.0486	0.0266	0.0142	0.0046
0.02	0.1174	0.0748	0.0402	0.0216	0.0104
0.025	0.1946	0.1166	0.0710	0.0368	0.0196
0.03	0.2794	0.1904	0.1196	0.0710	0.0354
0.035	0.3830	0.2678	0.1716	0.1004	0.0556
0.04	0.5088	0.3736	0.2550	0.1530	0.0900
0.045	0.6410	0.5050	0.3528	0.2304	0.1370
0.05	0.7698	0.6378	0.4804	0.3244	0.2074

Table A3.3. Probability of decline below population thresholds within 25 years, with an average Icelandic shooting rate of 0.015 (sd = 0.003) included.

Proportion shot on Islay	Population reduction thresholds				
	0	0.05	0.1	0.15	0.2
0	0.0004	0.0004	0.0002	0.0002	0.0000
0.005	0.0020	0.0016	0.0006	0.0004	0.0000
0.01	0.0044	0.0032	0.0016	0.0010	0.0006
0.015	0.0114	0.0084	0.0056	0.0030	0.0012
0.02	0.0352	0.0238	0.0156	0.0098	0.0068
0.025	0.0822	0.0612	0.0398	0.0246	0.0128
0.03	0.1884	0.1442	0.1036	0.0722	0.0474
0.035	0.3408	0.2682	0.2096	0.1506	0.1060
0.04	0.5408	0.4530	0.3676	0.2920	0.2148
0.045	0.7424	0.6648	0.5688	0.4752	0.3768
0.05	0.8990	0.8458	0.7832	0.6928	0.5924

### Outputs from model with Iceland shooting simulated as an absolute harvest

Table A3.4. Population growth rates, with an average Icelandic shooting bag of 593 (sd = 101) included.

Proportion shot on Islay	Mean population growth rate	95% confidence intervals	
		Lower	Upper
0	1.0466	1.0223	1.0671
0.005	1.0409	1.0163	1.0615
0.01	1.0350	1.0097	1.0560
0.015	1.0288	1.0038	1.0498
0.02	1.0231	0.9977	1.0446
0.025	1.0171	0.9924	1.0384
0.03	1.0112	0.9857	1.0320
0.035	1.0052	0.9788	1.0270
0.04	0.9983	0.9715	1.0200
0.045	0.9925	0.9649	1.0144
0.05	0.9855	0.9578	1.0080

Table A3.5. Probability of decline below population thresholds within 10 years, with an average Icelandic shooting bag of 593 (sd = 101) included.

Proportion shot on Islay	Population reduction thresholds				
	0	0.05	0.1	0.15	0.2
0	0.0184	0.0108	0.0048	0.0026	0.0010
0.005	0.0290	0.0194	0.0112	0.0064	0.0034
0.01	0.0436	0.0292	0.0160	0.0082	0.0042
0.015	0.0802	0.0482	0.0274	0.0158	0.0084
0.02	0.1186	0.0752	0.0446	0.0238	0.0136
0.025	0.1758	0.1124	0.0712	0.0398	0.0226
0.03	0.2622	0.1742	0.1064	0.0632	0.0318
0.035	0.3662	0.2510	0.1632	0.0966	0.0598
0.04	0.4952	0.3670	0.2538	0.1670	0.1036
0.045	0.6150	0.4862	0.3580	0.2354	0.1472
0.05	0.7560	0.6354	0.4956	0.3524	0.2296

Table A3.5. Probability of decline below population thresholds within 25 years, with an average Icelandic shooting bag of 593 (sd = 101) included.

Proportion shot on Islay	Population reduction thresholds				
	0	0.05	0.1	0.15	0.2
0	0.0004	0.0002	0.0002	0.0002	0.0000
0.005	0.0016	0.0012	0.0006	0.0006	0.0006
0.01	0.0046	0.0020	0.0014	0.0010	0.0002
0.015	0.0142	0.0088	0.0058	0.0044	0.0032
0.02	0.0328	0.0254	0.0188	0.0132	0.0098
0.025	0.0768	0.0558	0.0402	0.0280	0.0196
0.03	0.1676	0.1310	0.0988	0.0724	0.0500
0.035	0.3074	0.2474	0.1990	0.1572	0.1172
0.04	0.5254	0.4534	0.3818	0.3176	0.2556
0.045	0.7154	0.6480	0.5752	0.4934	0.4126
0.05	0.8844	0.8420	0.7872	0.7136	0.6412

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