# SEAGREEN PVA REPORT

Prepared for T. Folland, I. Ellis & M. Hazleton, NIRAS

DMP Statistical Solutions UK Ltd

15 August 2018

DMP STATS The Coach House, Mount Melville House, St. Andrews, Scotland KY 168 NT, UK +44(0) 1334 477 544 mail@dmpstats.com

| DOCUMENT INFORMATION | |
|---|---|
| VERSION | 1.4 |
| ISSUED DATE | 15 August 2018 |
| AUTHOR | B. Caneco & C. Donovan |
| STATUS | Final |

**REVISION HISTORY**

| VERSION | ISSUED DATE | REASON FOR ISSUE |
|---|---|---|
| 1.0 | 15 May 2018 | Issued for Information & review |
| 1.1 | 29 May 2018 | Updated following model re-runs for revised figures of initial population sizes |
| 1.2 | 25 June 2018 | Updated results for 25-years simulation models |
| 1.3 | 23 July 2018 | Correction of initial population sizes |
| 1.4 | 15 August 2018 | Update following rectification of initial population size for Kittiwake in the Fowlsheugh SPA |

DMP STATS The Coach House, Mount Melville House, St. Andrews, Scotland KY 168 NT, UK +44(0) 1334 477 544 mail@dmpstats.com

## CONTENTS

**1 OVERVIEW** **4**

**2 METHODS** **5**

2.1 Matrix Models and parameterisation 5

2.2 Implementation 10

2.3 Key outputs 10

**3 REFERENCES** **11**

**4 APPENDIX** **12**

4.1 Gannet – Forth Islands 13

4.2 Puffin – Forth Islands 18

4.3 Razorbill – Forth Islands 23

4.4 Razorbill – Fowlsheugh 28

4.5 Guillemot – Forth Islands 33

4.6 Guillemot – Fowlsheugh 38

4.7 Kittiwake – Forth Islands 43

4.8 Kittiwake – Fowlsheugh 48

DMP STATS The Coach House, Mount Melville House, St. Andrews, Scotland KY 168 NT, UK +44(0) 1334 477 544 mail@dmpstats.com

# 1 OVERVIEW

This document presents the underpinnings of the Population Viability Analyses (PVAs) conducted for NIRAS and the Seagreen wind farm EIA. The analysis was performed for breeding colonies of five species of seabirds in two different Special Protected Areas (SPAs). Stochastic, density independent, age-structured matrix models were used to simulate population trends over time for a range of impacts scenarios. Full details of the analysis, including model specifications and demographic rates used, are provided below.

# 2 METHODS

The potential impacts of Seagreen wind farm development on the population growth and size of five seabird species inhabiting two local SPAs were predicted via population viability analysis (PVA). Table 1 describes the populations and the SPAs analysed.

## 2.1 Matrix Models and parameterisation

**Table 1:** Populations and SPAs considered for analysis, and corresponding initial population sizes used in the modelling

| Species | SPA | Initial population size (breeding individuals) | Year | Source |
|---|---|---|---|---|
| **Gannet** | Forth Islands | 150518 | 2014 | SNH Advice to Seagreen November 2017 |
| **Puffin** | Forth Islands | 90010 | 2009-2014 | SNH Advice to Seagreen November 2017 |
| **Razorbill** | Forth Islands | 7792 | 2017 | SNH Advice to Seagreen May 2018 |
| | Fowlsheugh | 9950 | 2015 | |
| **Guillemot** | Forth Islands | 38573 | 2017 | SNH Advice to Seagreen May 2018 |
| | Fowlsheugh | 74379 | 2015 | |
| **Kittiwake** | Forth Islands | 9326 | 2017 | SNH Advice to Seagreen November 2017 |
| | Fowlsheugh | 19310 | 2015 | |

For each species, an age-structured matrix model (Caswell, 2001) was built to simulate the population's progress through time in terms of abundance and age distribution, based on species-specific demographic rates and count estimates. The model assumes individuals to be grouped into discrete year age-classes, and all members of an age-class are considered equal with respect to their demographic vital rates (i.e. survival, growth and reproduction). The model dynamics involves predicting the population numbers at age in the next year given its previous year's numbers and vital rates.

The generic population model can be written in compact form as

$$\mathbf{n}_{y+1} = \mathbf{L}\mathbf{n}_y$$

where $\mathbf{n}_y$ is the population vector with elements $n_{a,y}$ denoting the number of individuals at each age-class $a = 1, \dots, A$ at year $y$, $\mathbf{n}_{y+1}$ is the numbers at age-class in the following year, and $\mathbf{L}$ represents the $A \times A$ projection matrix (also known as the Leslie matrix). The projection matrix $\mathbf{L}$ defines the expected contribution of individuals in each age-class in a given year to each age-class in the subsequent year.

Models used in this analysis were built under the following assumptions, for all considered species:

- models represent an annual post-breeding census over a period of $y = 1, \dots, Y$ year steps. Therefore, the model annual cycle comprises a census immediately after fledging on the first day of the biological year, with the first age-class ($a = 1$) containing newly hatched birds, followed by a 12 months period of survival. Then, on the first day of the subsequent year, surviving animals increment in age, adult age-classes reproduce and resultant newborns fledge, and the next census is carried out.
- reproduction is considered to be confined to adult birds, with age of first breeding being species-specific.
- population size is density independent, and therefore projections will either increase to infinity or decrease to extinction.
- population is considered a closed system, i.e. age distributions are not affected by migration exchanges between neighbouring colonies
- the final age-class $A$ is an aggregated age group, representing $A$ years-old birds and older. This implies the absence of senescence, i.e. the survival and reproductive performances of the oldest animals remain constant over time. The value of $A$, and hence the size of the projection matrix, of each species is determined by either the age of first breeding or the oldest adult age-class for which survival data was available (the largest of the two values).

Based on the above assumptions, the expanded version of the generic population model used in this analysis can be expressed as

$$\begin{bmatrix} n_{1,t+1} \\ n_{2,t+1} \\ n_{3,t+1} \\ \vdots \\ n_{A,t+1} \end{bmatrix} = \begin{bmatrix} 0 & \cdots & 0 & P_{A-1}(0.5)S_{A-1\to A} & P_A(0.5)S_A \\ S_{1\to 2} & 0 & 0 & \cdots & 0 \\ 0 & S_{2\to 3} & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & S_{A-1\to A} & S_A \end{bmatrix} \times \begin{bmatrix} n_{1,t} \\ n_{2,t} \\ n_{3,t} \\ \vdots \\ n_{A,t} \end{bmatrix}$$

where $P_A$ denotes the annual productivity rate of age-class $A$, expressed as the annual average number of fledged young per breeding pair; and $S_{a\to a+1}$ represents the annual survival transition rate of animals of age-class $a$, i.e. the average proportion of birds in age-class $a$ that will survive the whole year and transition to age-class $a + 1$. Elements in the top row of the projection matrix $\mathbf{L}$ (i.e. half of the productivity rate multiplied by the survival rate) reflect the annual fecundity rate per capita of each adult age-class.

Environmental stochasticity, which accounts for the variation arising from environmental changes affecting individuals in the same group (e.g. between-year differences in weather conditions), was incorporated in the models at the level of productivity and survival rates. For each simulated year, a value for each demographic rate was randomly generated from a probability distribution defined by the mean and standard deviation estimates of that rate for the population under consideration.

Random survival rates, which are theoretically bounded at 0 and 1, were drawn from beta distributions. Stretched beta distributions were used to generate productivity rates as it allows an upper limit greater than one, which was set based on the maximum number of eggs laid per pair per year for each species. These two distributions are considered to provide biologically reasonable random values of each vital rate (Morris and Doak, 2002).

Demographic stochasticity, which accounts for individual-level variation affecting transition probabilities between age-classes, was not included in the models. For large populations, like the ones considered in this analysis (Table 1), the effects of environmental stochasticity are deemed more important than those associated with demographic stochasticity (Morris and Doak, 2002).

Table 2 provides the demographic parameters used to specify the models for each species. With exception of maximum number of eggs per pair (taken from Snow and Perrins, 1998), all remaining parameter were obtained from Horswill and Robinson (2015).

**Table 2:** Species features and demographic rates used in the population models (Snow & Perrins, 1998; Horswill & Robinson, 2015).

| | Reproduction | | | | Survivals | | | | | | Productivities | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | Age first breeding | Final age (A) | Eggs/pair | | $S_{1\to2}$ | $S_{2\to3}$ | $S_{3\to4}$ | $S_{4\to5}$ | $S_{5\to6}$ | $S_A$ | $P_{A-1}$ | $P_A$ |
| **Gannet** | 5 | 5 | 2 | **Mean** | 0.424 | 0.829 | 0.891 | 0.895 | | 0.919 | 0 | 0.698 |
| | | | | **SD** | 0.007 | 0.004 | 0.003 | 0.003 | | 0.042 | 0 | 0.071 |
| **Puffin** | 5 | 6 | 3 | **Mean** | 0.892 | 0.892 | 0.892 | 0.76 | 0.805 | 0.906 | 0.642 | 0. 642 |
| | | | | **SD** | 0.009 | 0.009 | 0.009 | 0.019 | 0.017 | 0.083 | 0.135 | 0. 135 |
| **Razorbill** | 5 | 5 | 1 | **Mean** | 0.794 | 0.794 | 0.895 | 0.895 | | 0.895 | 0 | 0.459 |
| | | | | **SD** | 0.134 | 0.134 | 0.067 | 0.067 | | 0.067 | 0 | 0.236 |
| **Guillemot** | 6 | 6 | 1 | **Mean** | 0.56 | 0.792 | 0.917 | 0.939 | 0.939 | 0.939 | 0 | 0.659 |
| | | | | **SD** | 0.013 | 0.034 | 0.022 | 0.015 | 0.015 | 0.015 | 0 | 0.133 |
| **Kittiwake** | 4 | 4 | 2 | **Mean** | 0.79 | 0.854 | 0.854 | | | 0.854 | 0 | 0.819 |
| | | | | **SD** | 0.092 | 0.051 | 0.051 | | | 0.051 | 0 | 0.332 |

Annual productivity rates were selected from regional-specific estimates available in Horswill and Robinson (2015). Thus, for the Seagreen site, U.K. eastern productivity estimates were used whenever possible (Table 3). Single survival estimates attributed to multiple age-classes (e.g. Puffin) were split evenly into annual survival rates, with associated standard deviations computed via simulation (Table 3).

**Table 3:** Comments on values selected for demographic rates

| Species | Demographic Rate | Comments |
|---|---|---|
| **Gannet** | Productivity | Eastern UK figures. Suggested experience-specific productivity not applied |
| **Puffin** | Productivity | Isle of May estimates |
| | Survivals $S_{1\to2}$, $S_{2\to3}$ & $S_{3\to4}$ | Literature provides a single mean (0.709) and SD (0.022) for the first 3 age-classes.<br>Corresponding annual mean rate computed as exp(log(0.709)/3) = 0.892.<br>Approximate annual SD (0.009) derived from 1000 draws from a beta distribution with mean=0.709 and SD=0.022. |
| **Razorbill** | Productivity | Northern UK figures |
| | Survivals $S_{1\to2}$ & $S_{2\to3}$ | Literature provides a single mean (0.630) and SD (0.209) for the first 2 age-classes.<br>Corresponding annual mean rate computed as exp(log(0.63)/2) = 0.794.<br>Approximate annual SD (0.134) derived from 1000 draws from a beta distribution with mean=0.63 and SD=0.209. |
| **Guillemot** | Productivity | Eastern UK figures |
| **Kittiwake** | Productivity | Eastern UK figures |

For each model, assuming the population was at equilibrium before the windfarm development, the initial population size in terms of breeding individuals (Table 1) was converted to total size (i.e. number of birds in the whole population) using the proportion of breeders under the population's stable age distribution (i.e. the proportion of individuals per age-class). The stable age distribution was provided by the right eigenvector associated with the dominant eigenvalue of the population projection matrix using the mean of the demographic rates (Table 2). The (average) stable age distribution for each species is provided in Table 4. The initial population vector ( $\mathbf{n_1}$) was then obtained by multiplying the initial total size by the stable age distribution vector.

Starting with the initial population vector for the first simulated year, new population vectors were calculated by multiplying the previous year's population vector by a new projection matrix generated from sampling each demographic rate (i.e. different projection matrices prevailing in each simulated year).

Models were run for 25 years, representing the likely lifespan of the wind farm developments. Each 25-years simulation was run 1000 times to obtain indicative population trends and estimates of uncertainty surrounding those trends. Models were run for each SPA separately taking the associated population size estimate as the initial population size (Table 1).

**Table 4:** Stable age structure for each species under analysis

| Age-class | Gannet | Puffin | Razorbill | Guillemot | Kittiwake |
|---|---|---|---|---|---|
| **1** | 0.192 | 0.146 | 0.127 | 0.167 | 0.187 |
| **2** | 0.081 | 0.126 | 0.101 | 0.090 | 0.143 |
| **3** | 0.067 | 0.109 | 0.080 | 0.069 | 0.118 |
| **4** | 0.059 | 0.095 | 0.072 | 0.061 | 0.553 |
| **5** | 0.602 | 0.070 | 0.619 | 0.056 | |
| **6** | | 0.454 | | 0.557 | |

Wind farm impacts from collision and displacement effects were incorporated in the models in terms of additional mortalities. Displacement effects were assumed to have no impact on productivity rates. Additional mortalities were assumed to be applied to all age classes in proportion to their presence (i.e. the likelihood of a bird being killed due to wind farm effects assumed to be independent of its age).

A range of absolute additional adult mortalities per annum, from 0 to a species-specific maximum value by incremental steps of 50, were used as impact scenarios. The related absolute number of additional deaths over all ages was derived via the stable age distribution. While impact scenarios are expressed in terms of absolute annual deaths, this is not expected to remain constant as population sizes change over time. As such, the absolute number of additional deaths only strictly applies in the first year of simulation. It is converted to per-capita mortality rate for projection forwards i.e. the number of additional deaths in a year will increase proportionately with an increase in the simulated population size and vice-versa.

## 2.2 Implementation

All modelling was done in the R statistical programming environment v3.3.x (R Core Team, 2017). All code was bespoke.

## 2.3 Key outputs

Outputs here focus on reference points indicated in the relevant consultation (Scottish Natural Heritage, 2017; Scottish Natural Heritage, 2018). The principal metrics indicated in the scoping document follow recommendations by Jitlal *et al.* (2017) and are the:

1. median of the ratio of impacted to unimpacted annual growth rate.
2. median of the ratio of impacted to unimpacted population size.
3. centile for unimpacted population that matches the 50th centile for impacted population.

Where annual population growth rate was required, this was calculated as the average over years 5 to 25 of the simulations, as per scoping recommendations – the first 5 years being discarded to mitigate against effects of starting conditions.

Furthermore, each unimpacted to impacted metric was derived following a matched runs approach (Green, 2014), whereby stochasticity is applied to the population before wind farm impacts are applied (i.e. survival and productivity rates simulated at each time step are the same for the unimpacted and impacted populations, with additional impact mortalities rates being subsequently deducted from simulated survivals).

## 3 REFERENCES

Caswell, H. 2001. Matrix Population models, Second Edition. Sinauer Associates, Inc. Sunderland, MA.

Green, R.E. 2014. Misleading use of science in the assessment of probable effects of offshore wind projects on populations of seabirds in Scotland. Unpublished RSPB paper.

Horswill, C. & Robinson R. A. 2015. Review of seabird demographic rates and density dependence. JNCC Report No. 552. Joint Nature Conservation Committee, Peterborough.

Jitlal, M., Burthe, S., Freeman, S. and Daunt F. 2017 Testing and validating metrics of change produced by Population Viability Analysis (PVA) – Marine Scotland Science commissioned report (currently unpublished)

Morris, W.F. and Doak, D.F. 2002. Quantitative conservation biology: theory and practice of population viability analysis. Sinauer, MA.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Scottish Natural Heritage 2017. Ornithology update to non-breeding season illustrative example and colony counts. [email] Message from G Holland (Personal communication sent Thursday 30 November 2017 15:43).

Scottish Natural Heritage 2018. Seabird Population Counts – guillemot and razorbill for us in population modelling. [email] Message from G Holland (Personal communication sent Monday 21 May 2018 16:07).

Snow, D.W. & Perrins, C.M. 1998. The birds of the western Palearctic, Concise edition. Oxford University Press.

# 4 APPENDIX

The following are selected outputs for the simulations run for:

- Gannet: Forth Islands
- Puffin: Forth Islands
- Razorbill: Forth Islands /Fowlsheugh
- Guillemot: Forth Islands /Fowlsheugh
- Kittiwake: Forth Islands /Fowlsheugh

Outputs from PVAs can be voluminous and may be summarised in many ways. Outputs here focus on reference points indicated in the relevant scoping document[1], as well as over-arching views of the simulations. The principal metrics indicated in the scoping document follow recommendations by Jitlal *et al.* (2017) and are the:

1. median of the ratio of impacted to unimpacted annual growth rate
2. median of the ratio of impacted to unimpacted population size
3. centile for unimpacted population that matches the 50th centile for impacted population

Here for each species/population we present:

1. Plots of the distributions of simulated final population sizes after 25 years. Unimpacted distributions are presented in each, along with a range of impact scenarios, in terms of varying additional adult mortalities.
2. Plots of the population size projections through time, 0 - 25 years post-construction. A range of impact scenarios are presented in terms of varying additional adult mortalities, ranging from 0 (unimpacted) to a species/population-specific upper limit.
3. Plots comparing the 50$^{th}$ percentile points of the simulated impacted and unimpacted populations sizes through time (two representations are given).
4. Plots comparing the growth rates of simulated impacted and unimpacted populations, for a range of impact sizes.
5. A table of growth rates under varying impact scenarios, with several reference points expressed: the 2.5%, 50% & 97.5% points of the distribution of simulated rates.

[1] Marine Scotland - Licensing Operations Team (10 August 2017) Scoping Opinion Addendum: Ornithology. SCOPING OPINION FOR THE PROPOSED SECTION 36 CONSENT AND ASSOCIATED MARINE LICENCE APPLICATION FOR THE REVISED INCH CAPE OFFSHORE WINDFARM AND REVISED INCH CAPE OFFSHORE TRANSMISSION WORKS – ORNITHOLOGY ASPECTS ONLY

## 4.1 Gannet – Forth Islands

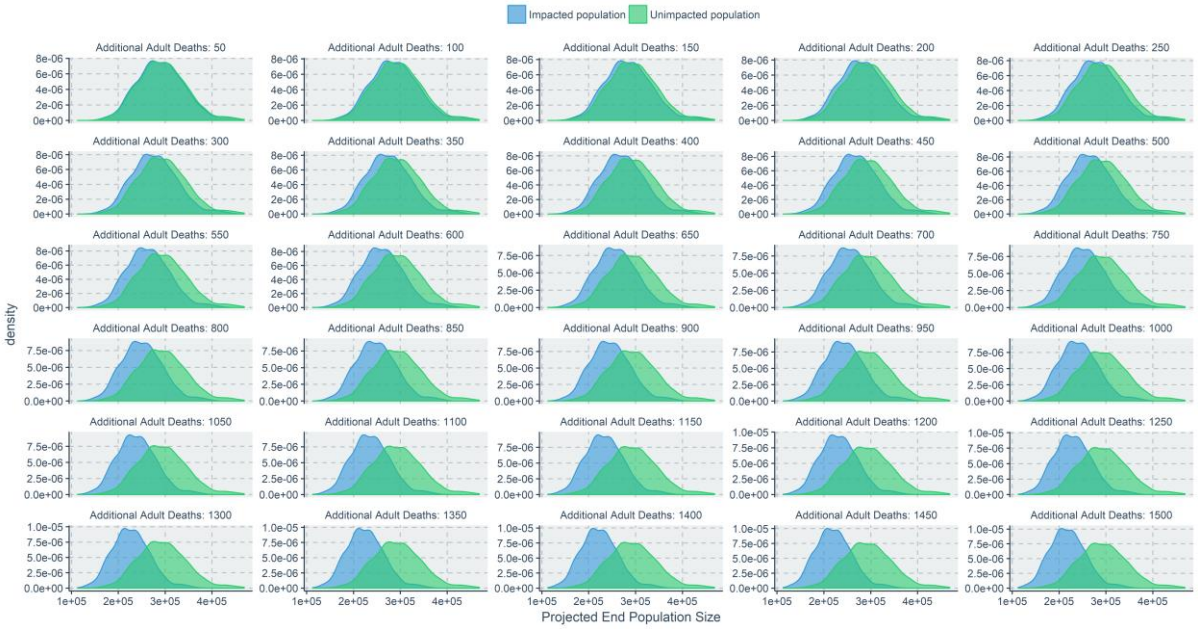


**Figure 1:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

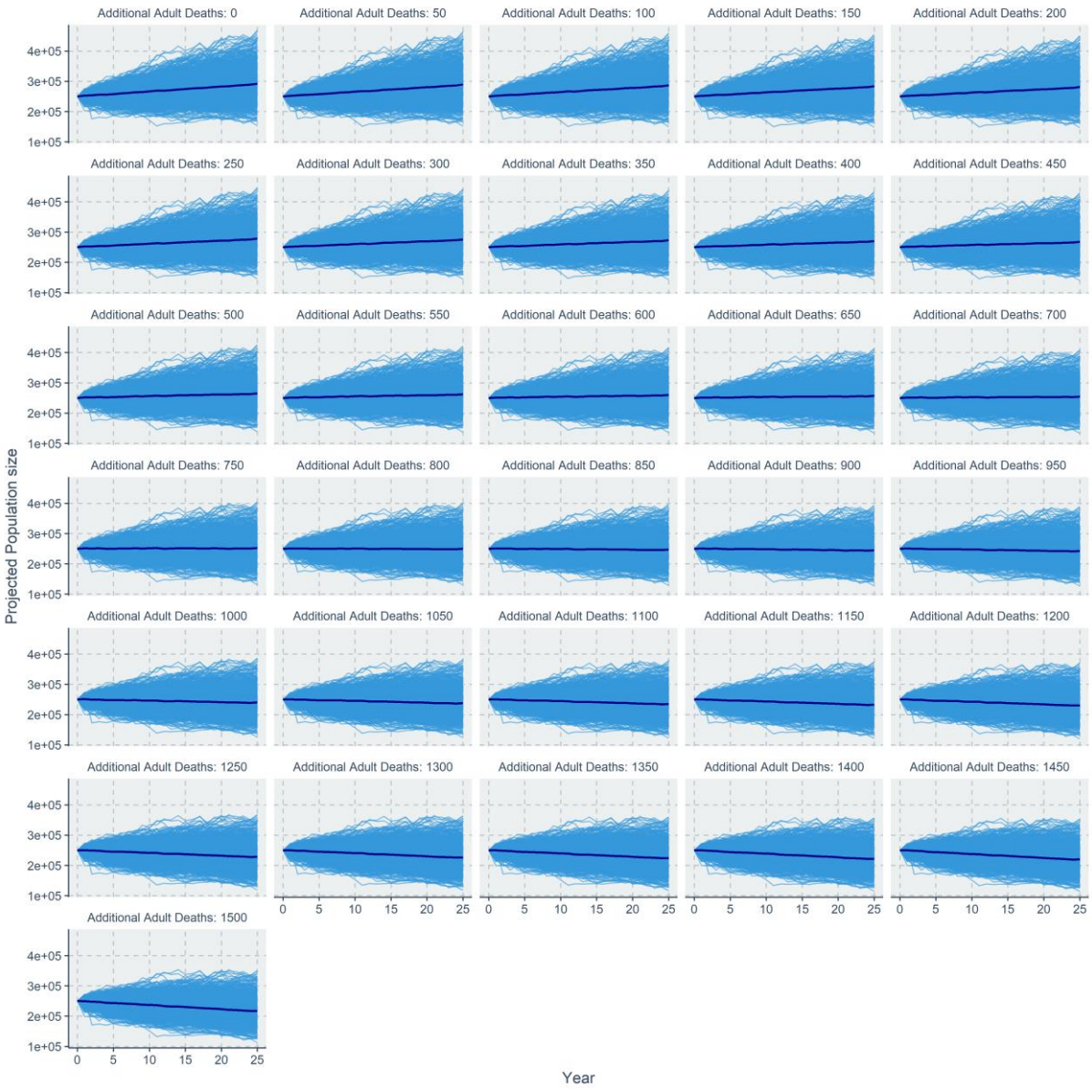


**Figure 2:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

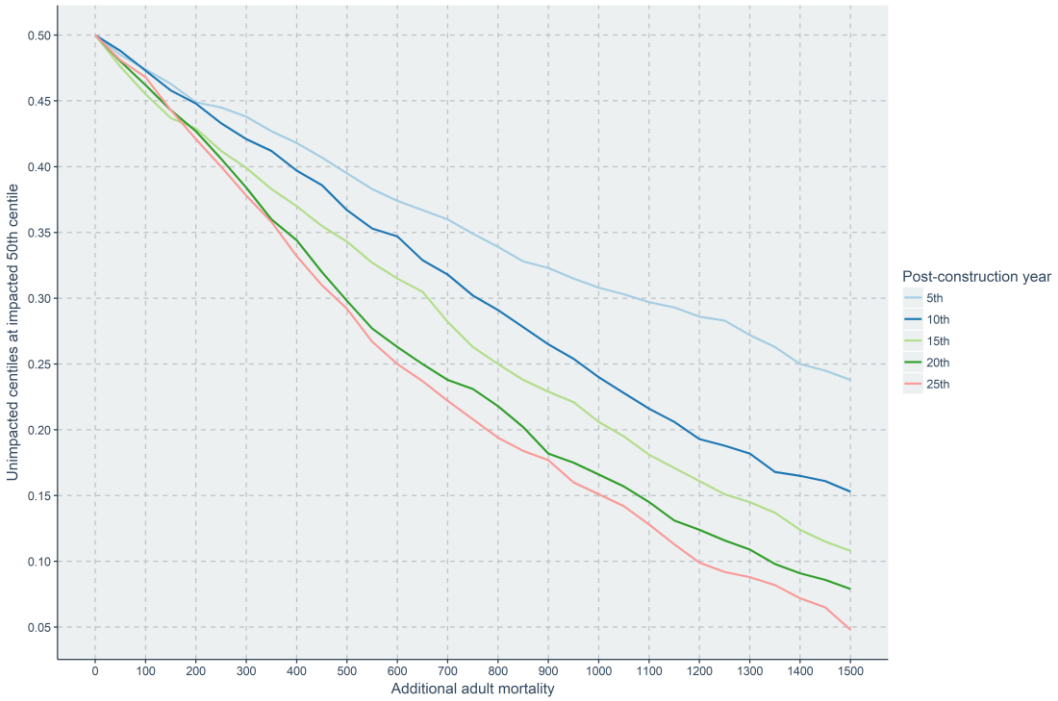


**Figure 3:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (5-25 years).

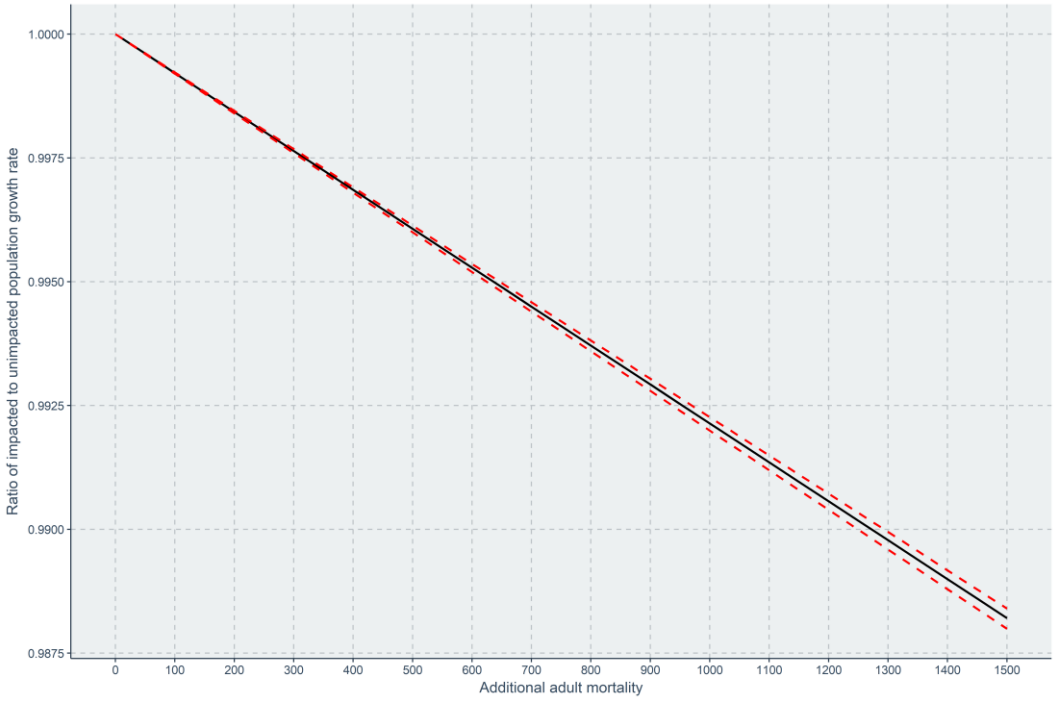


**Figure 4:** Ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

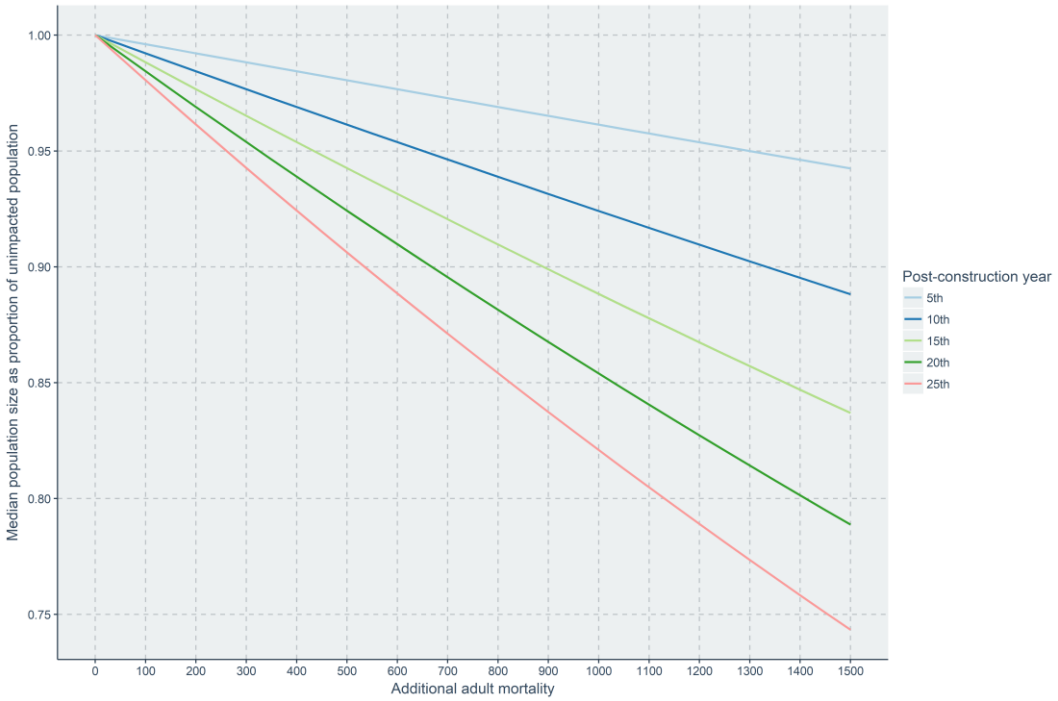


**Figure 5:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 5:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 1.006 | 0.991 | 1.021 |
| **50** | 1.006 | 0.990 | 1.021 |
| **100** | 1.006 | 0.990 | 1.021 |
| **150** | 1.005 | 0.990 | 1.020 |
| **200** | 1.005 | 0.989 | 1.020 |
| **250** | 1.004 | 0.989 | 1.019 |
| **300** | 1.004 | 0.988 | 1.019 |
| **350** | 1.004 | 0.988 | 1.019 |
| **400** | 1.003 | 0.988 | 1.018 |
| **450** | 1.003 | 0.987 | 1.018 |
| **500** | 1.002 | 0.987 | 1.017 |
| **550** | 1.002 | 0.986 | 1.017 |
| **600** | 1.002 | 0.986 | 1.017 |
| **650** | 1.001 | 0.986 | 1.016 |
| **700** | 1.001 | 0.985 | 1.016 |
| **750** | 1.000 | 0.985 | 1.015 |
| **800** | 1.000 | 0.984 | 1.015 |
| **850** | 1.000 | 0.984 | 1.015 |
| **900** | 0.999 | 0.984 | 1.014 |
| **950** | 0.999 | 0.983 | 1.014 |
| **1000** | 0.998 | 0.983 | 1.014 |
| **1050** | 0.998 | 0.983 | 1.013 |
| **1100** | 0.998 | 0.982 | 1.013 |
| **1150** | 0.997 | 0.982 | 1.012 |
| **1200** | 0.997 | 0.981 | 1.012 |
| **1250** | 0.997 | 0.981 | 1.012 |
| **1300** | 0.996 | 0.981 | 1.011 |
| **1350** | 0.996 | 0.980 | 1.011 |
| **1400** | 0.995 | 0.980 | 1.010 |
| **1450** | 0.995 | 0.979 | 1.010 |
| **1500** | 0.995 | 0.979 | 1.010 |

## 4.2 Puffin – Forth Islands

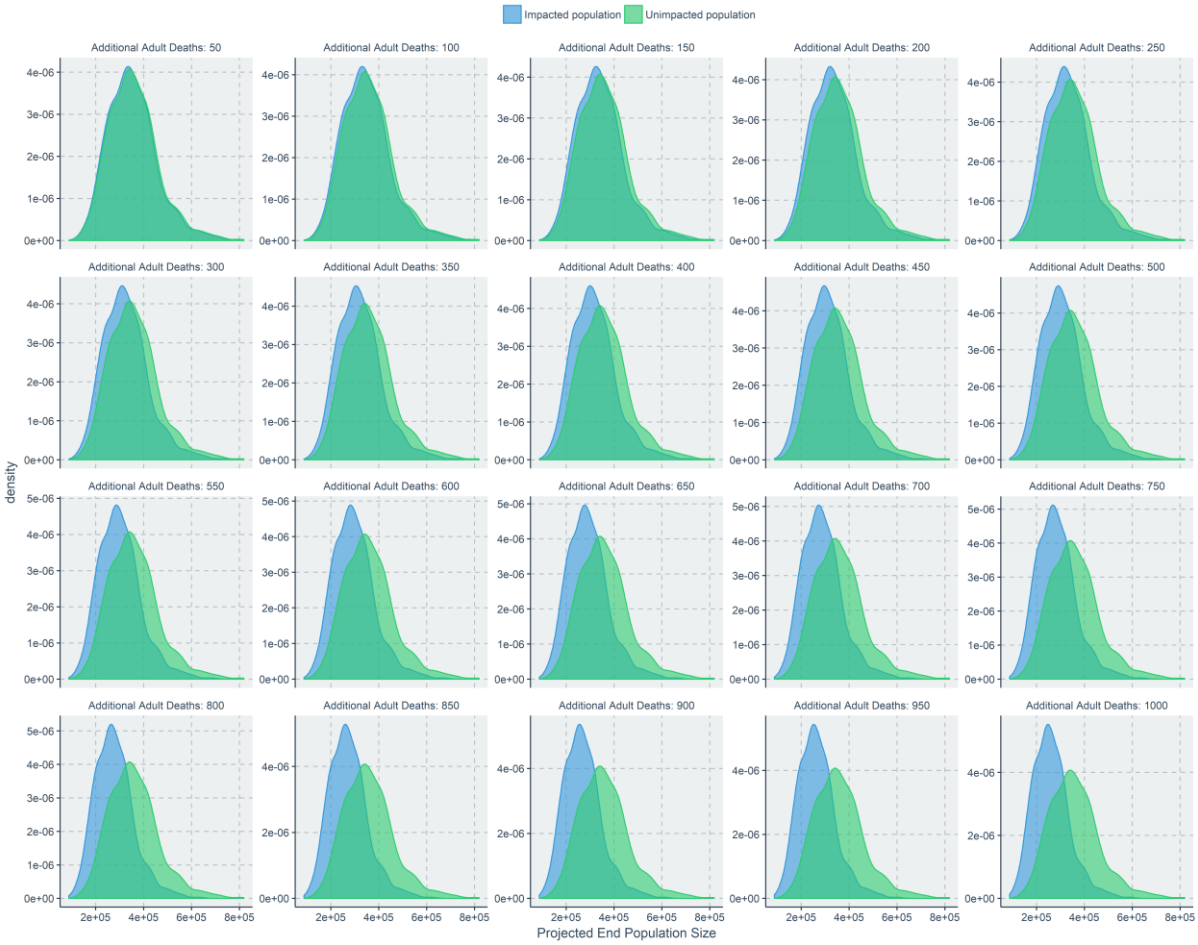


**Figure 6:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

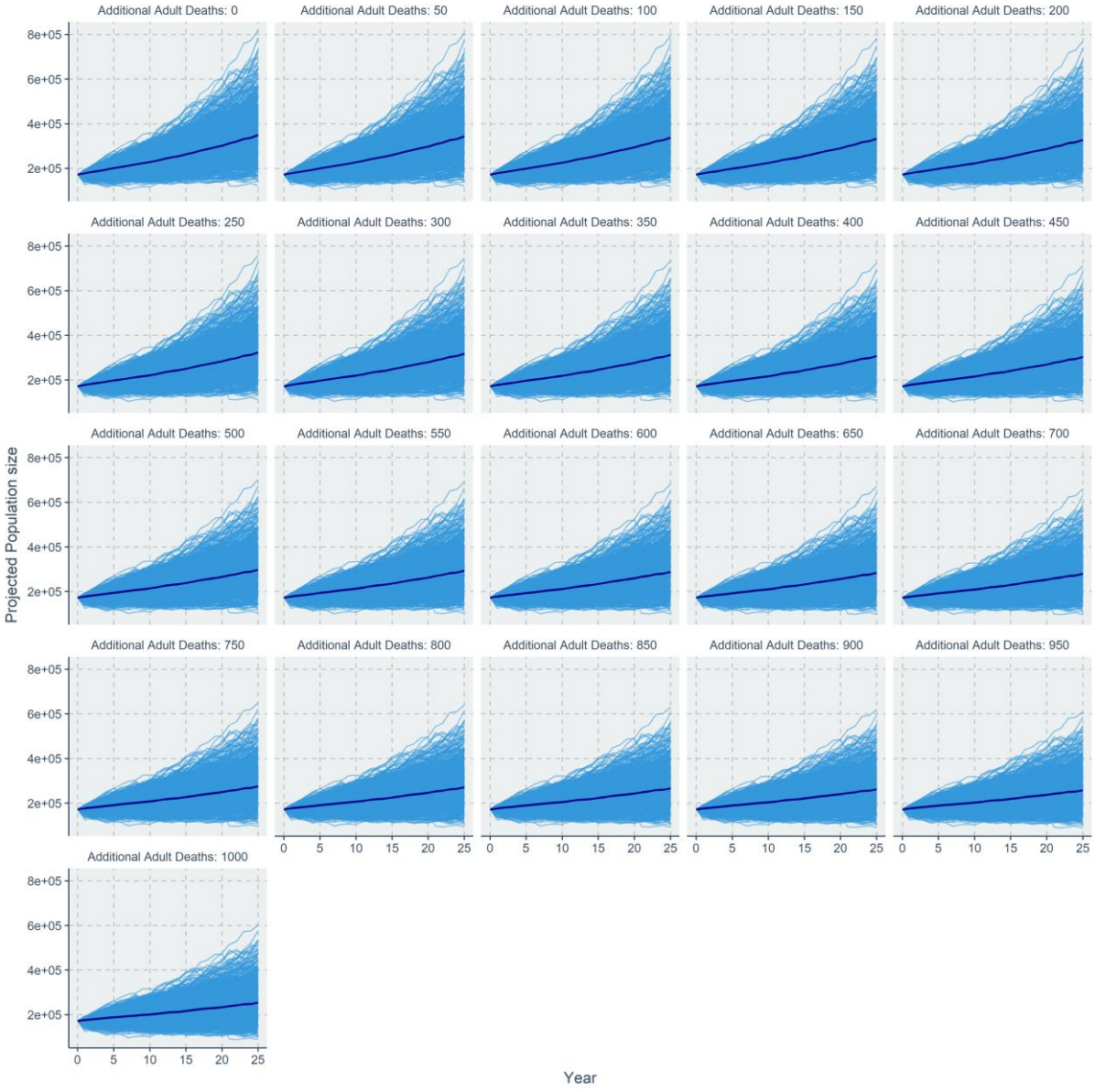


**Figure 7:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

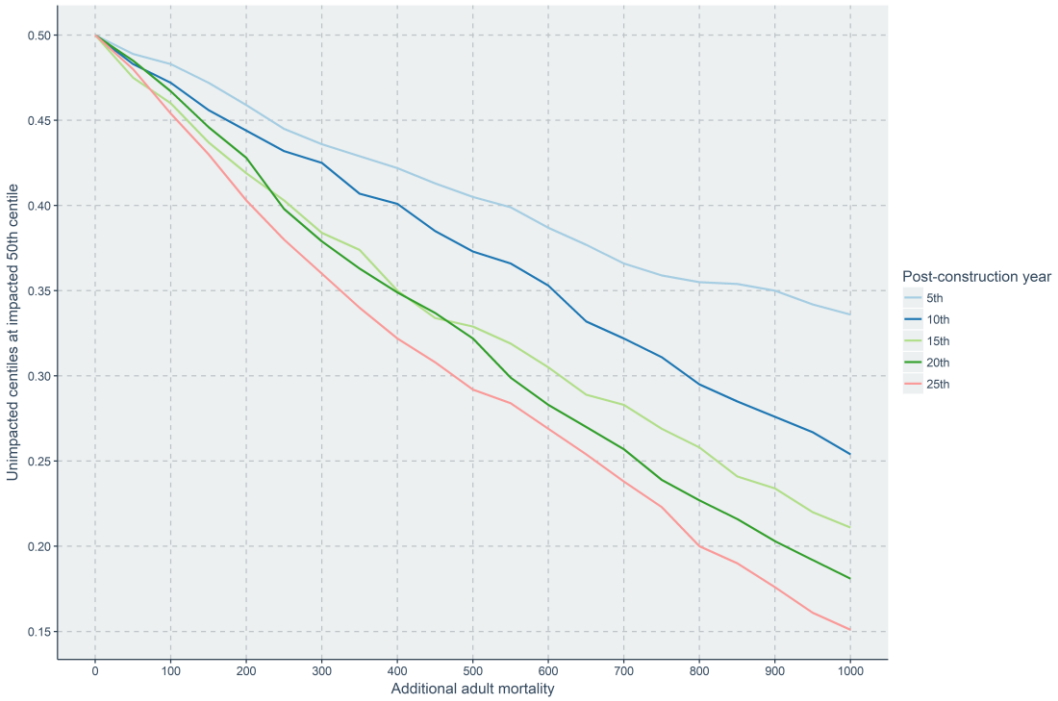


**Figure 8:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

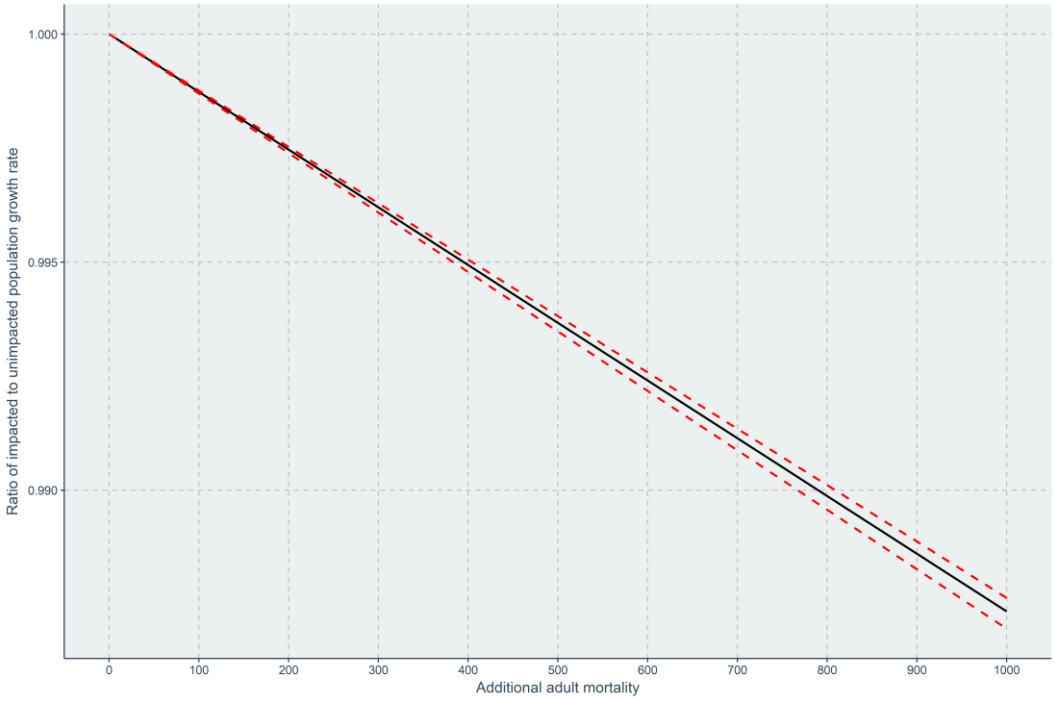


**Figure 9:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

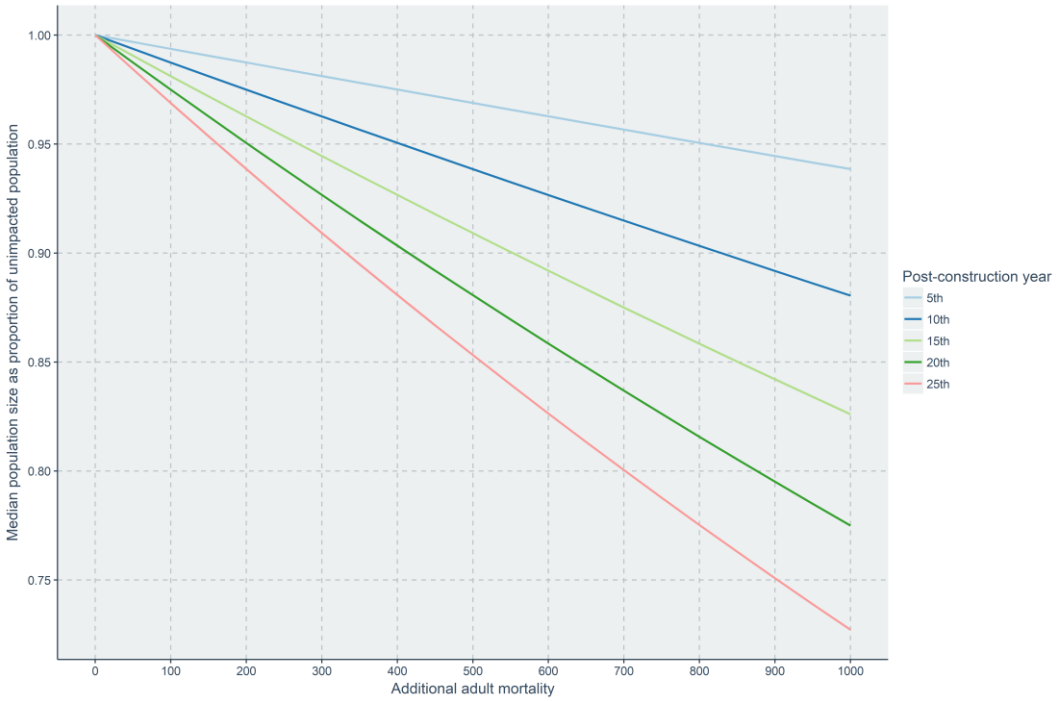


**Figure 10:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 6:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 1.029 | 1.001 | 1.053 |
| **50** | 1.029 | 1.000 | 1.052 |
| **100** | 1.028 | 0.999 | 1.051 |
| **150** | 1.027 | 0.999 | 1.051 |
| **200** | 1.027 | 0.998 | 1.050 |
| **250** | 1.026 | 0.997 | 1.049 |
| **300** | 1.025 | 0.997 | 1.049 |
| **350** | 1.025 | 0.996 | 1.048 |
| **400** | 1.024 | 0.996 | 1.047 |
| **450** | 1.023 | 0.995 | 1.047 |
| **500** | 1.023 | 0.994 | 1.046 |
| **550** | 1.022 | 0.994 | 1.045 |
| **600** | 1.021 | 0.993 | 1.045 |
| **650** | 1.021 | 0.992 | 1.044 |
| **700** | 1.020 | 0.992 | 1.043 |
| **750** | 1.019 | 0.991 | 1.043 |
| **800** | 1.019 | 0.990 | 1.042 |
| **850** | 1.018 | 0.990 | 1.041 |
| **900** | 1.017 | 0.989 | 1.041 |
| **950** | 1.017 | 0.988 | 1.040 |
| **1000** | 1.016 | 0.988 | 1.040 |

## 4.3 Razorbill – Forth Islands

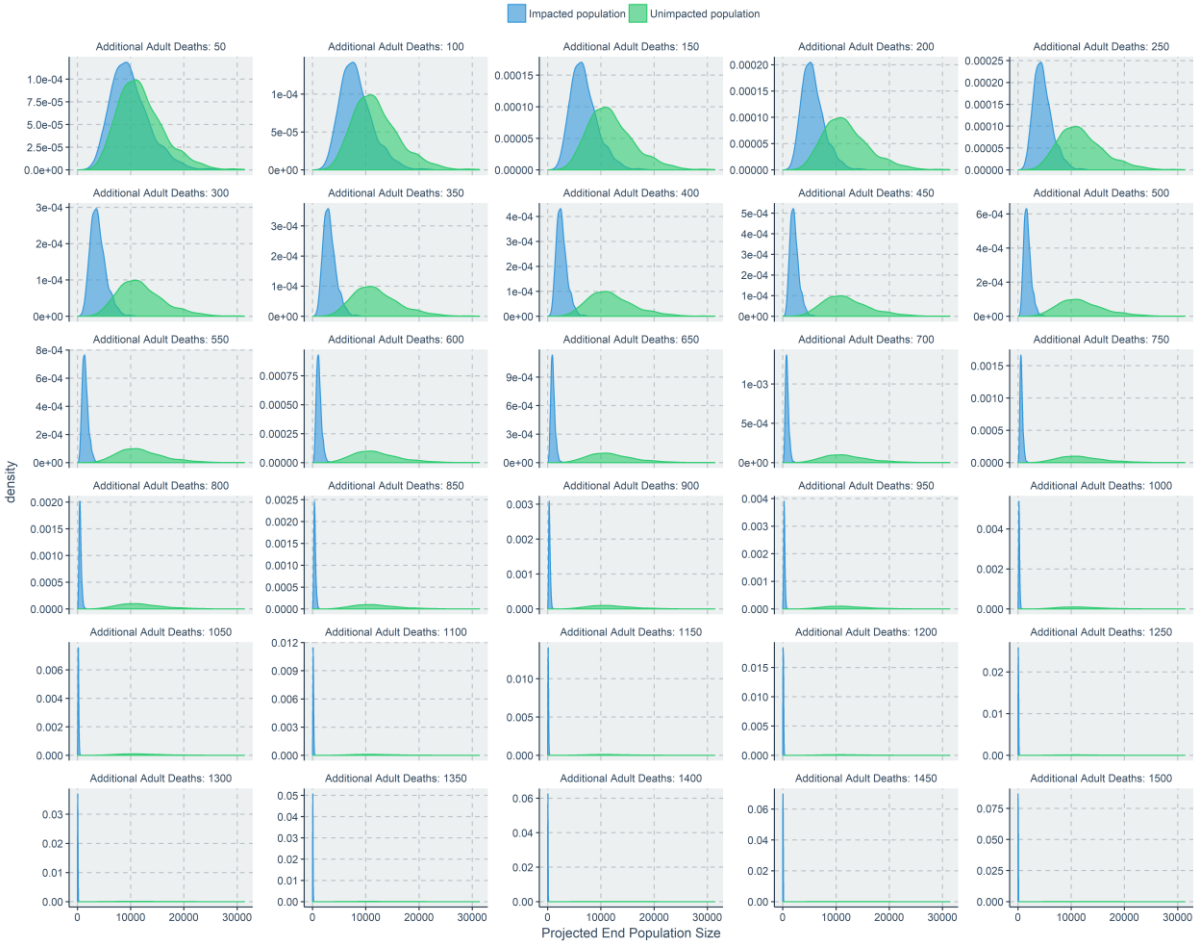


**Figure 11:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

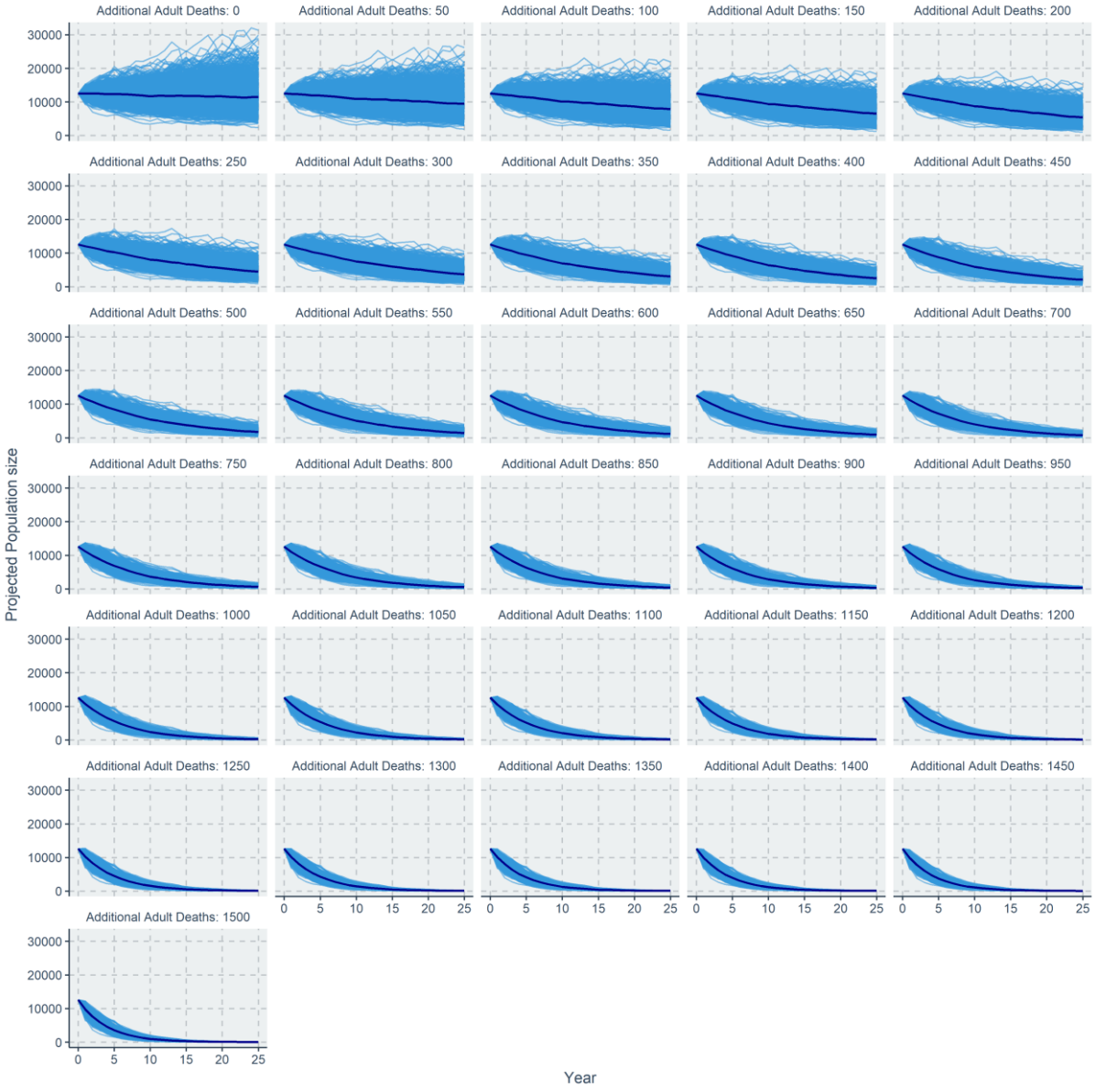


**Figure 12:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

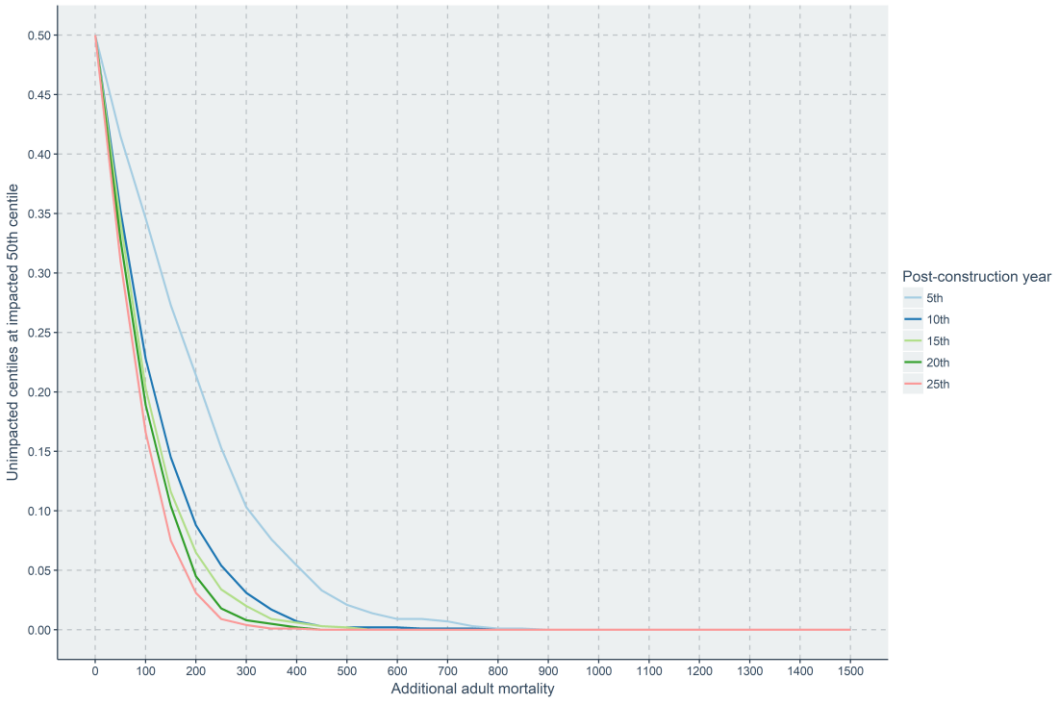


**Figure 13:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

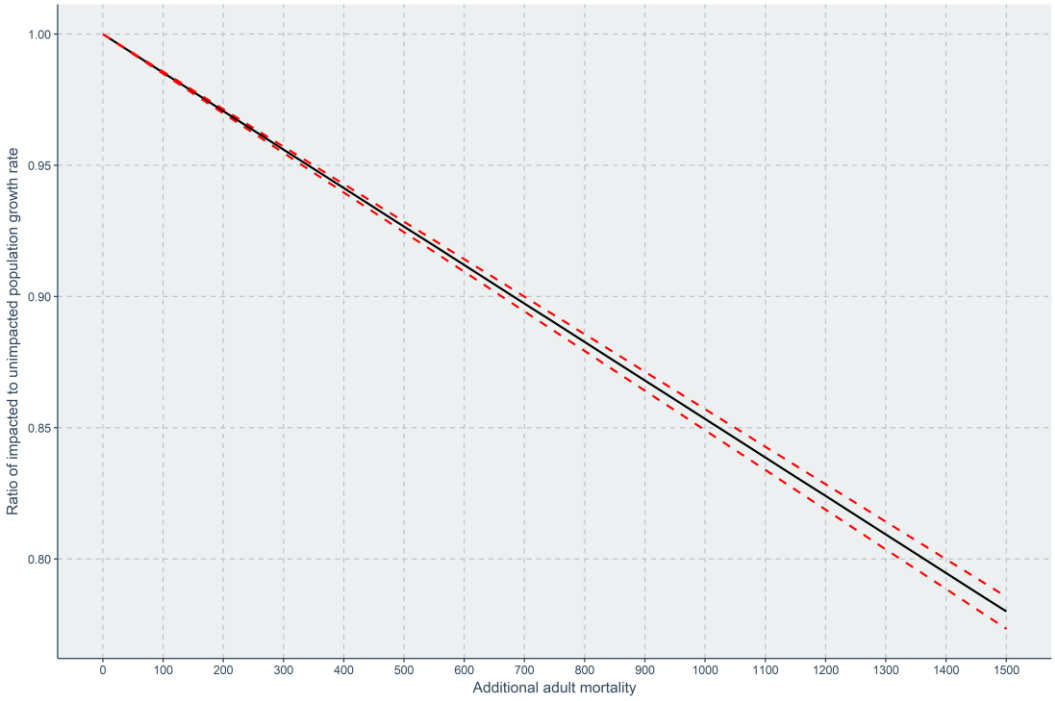


**Figure 14:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

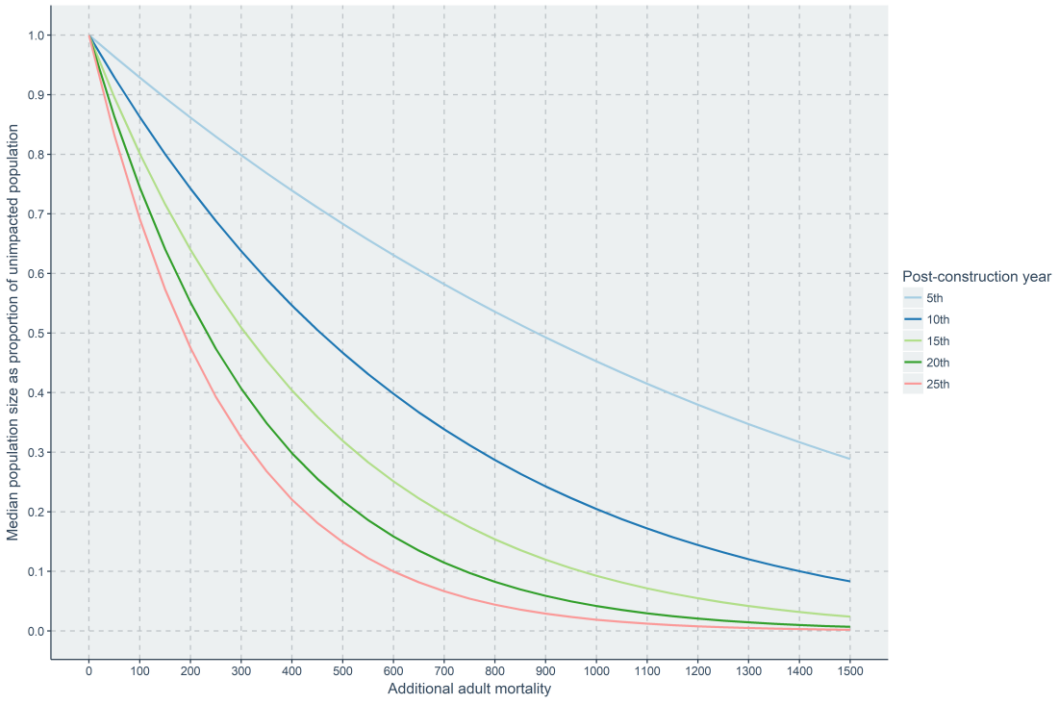


**Figure 15:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 7:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 0.997 | 0.963 | 1.027 |
| **50** | 0.990 | 0.956 | 1.020 |
| **100** | 0.982 | 0.948 | 1.013 |
| **150** | 0.975 | 0.941 | 1.005 |
| **200** | 0.968 | 0.934 | 0.998 |
| **250** | 0.960 | 0.927 | 0.990 |
| **300** | 0.953 | 0.920 | 0.983 |
| **350** | 0.946 | 0.913 | 0.975 |
| **400** | 0.939 | 0.906 | 0.968 |
| **450** | 0.931 | 0.898 | 0.961 |
| **500** | 0.924 | 0.891 | 0.953 |
| **550** | 0.917 | 0.884 | 0.946 |
| **600** | 0.909 | 0.877 | 0.938 |
| **650** | 0.902 | 0.869 | 0.931 |
| **700** | 0.895 | 0.862 | 0.923 |
| **750** | 0.887 | 0.855 | 0.916 |
| **800** | 0.880 | 0.848 | 0.909 |
| **850** | 0.873 | 0.840 | 0.901 |
| **900** | 0.865 | 0.833 | 0.894 |
| **950** | 0.858 | 0.826 | 0.886 |
| **1000** | 0.851 | 0.818 | 0.879 |
| **1050** | 0.843 | 0.811 | 0.872 |
| **1100** | 0.836 | 0.804 | 0.864 |
| **1150** | 0.829 | 0.796 | 0.857 |
| **1200** | 0.821 | 0.789 | 0.849 |
| **1250** | 0.814 | 0.782 | 0.842 |
| **1300** | 0.807 | 0.775 | 0.835 |
| **1350** | 0.799 | 0.767 | 0.827 |
| **1400** | 0.792 | 0.760 | 0.820 |
| **1450** | 0.785 | 0.753 | 0.813 |
| **1500** | 0.778 | 0.746 | 0.805 |

## 4.4 Razorbill – Fowlsheugh

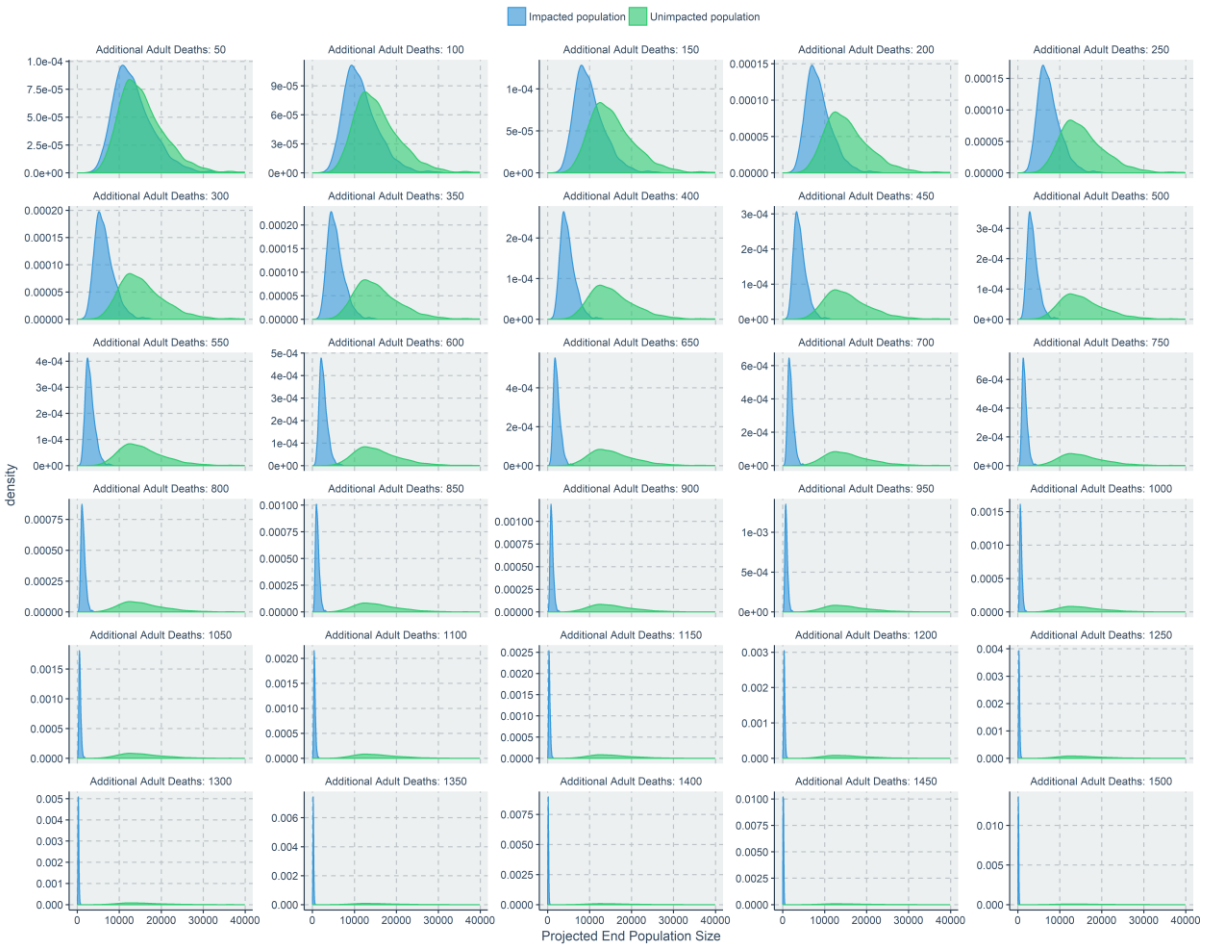


**Figure 16:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

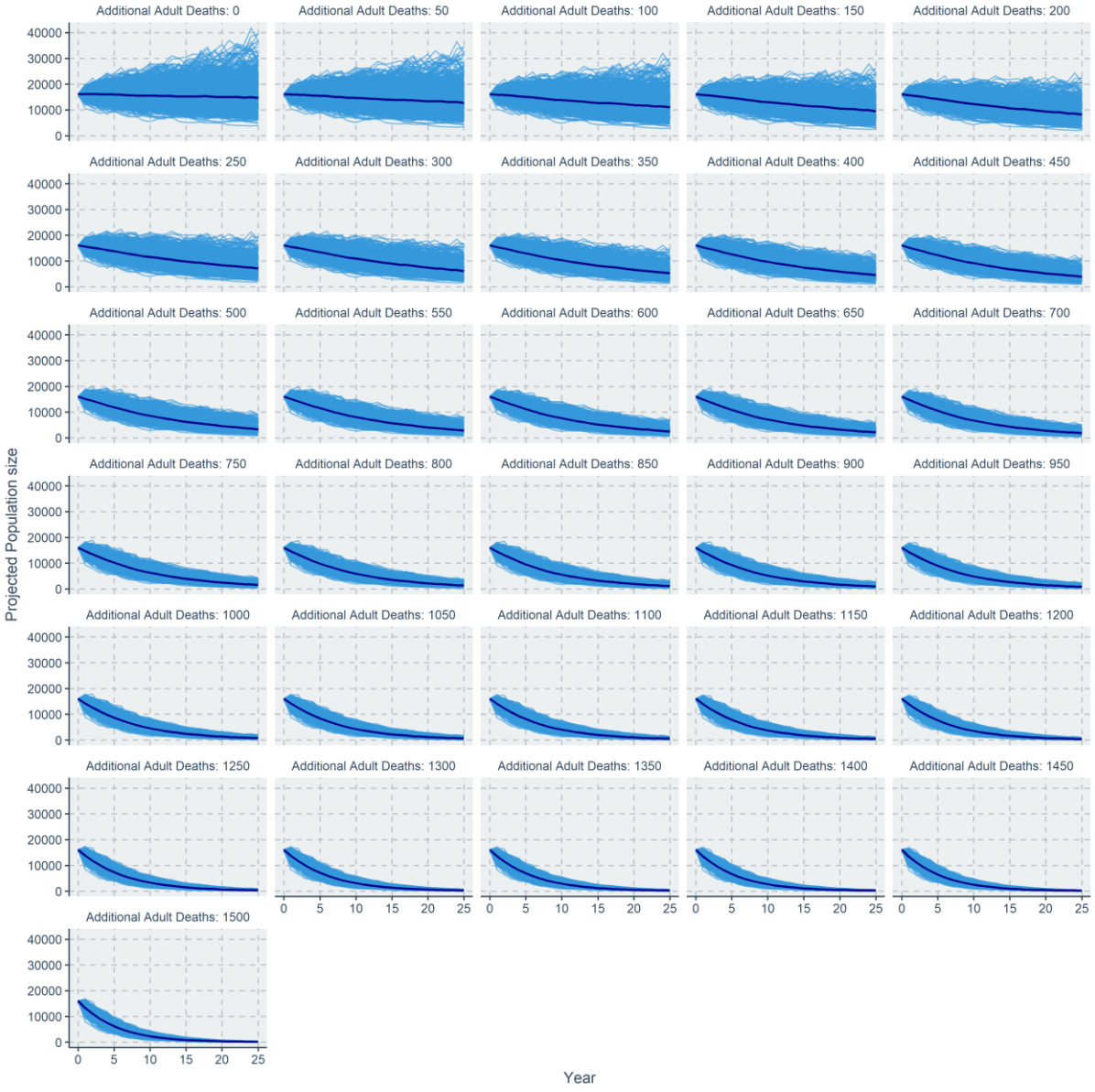


**Figure 17:** projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

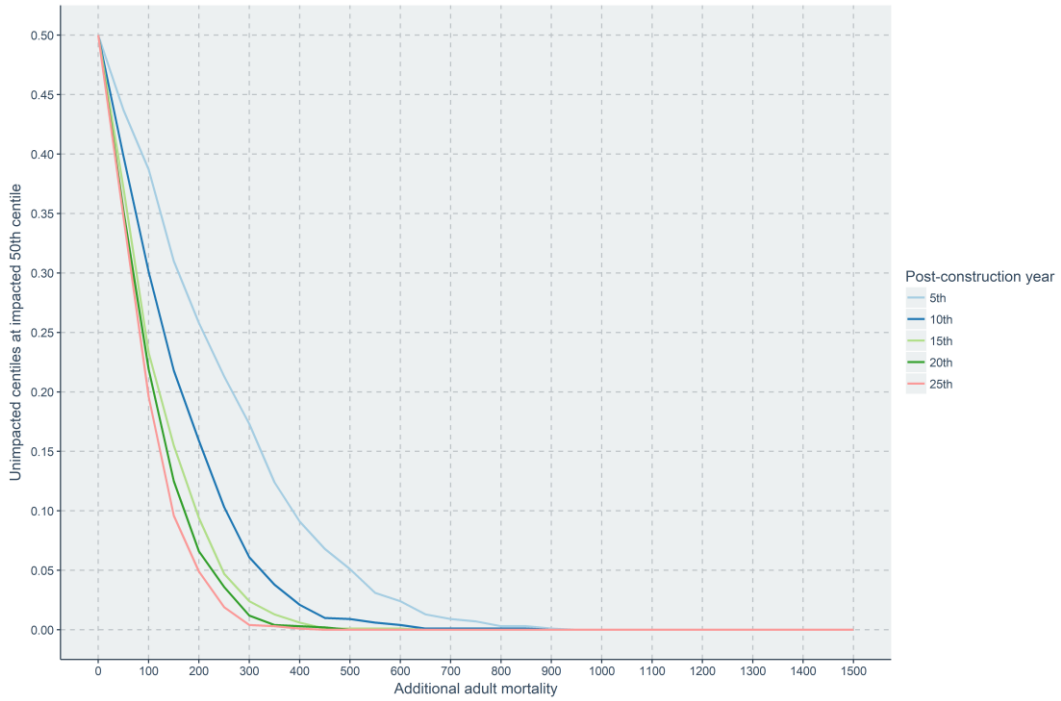


**Figure 18:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

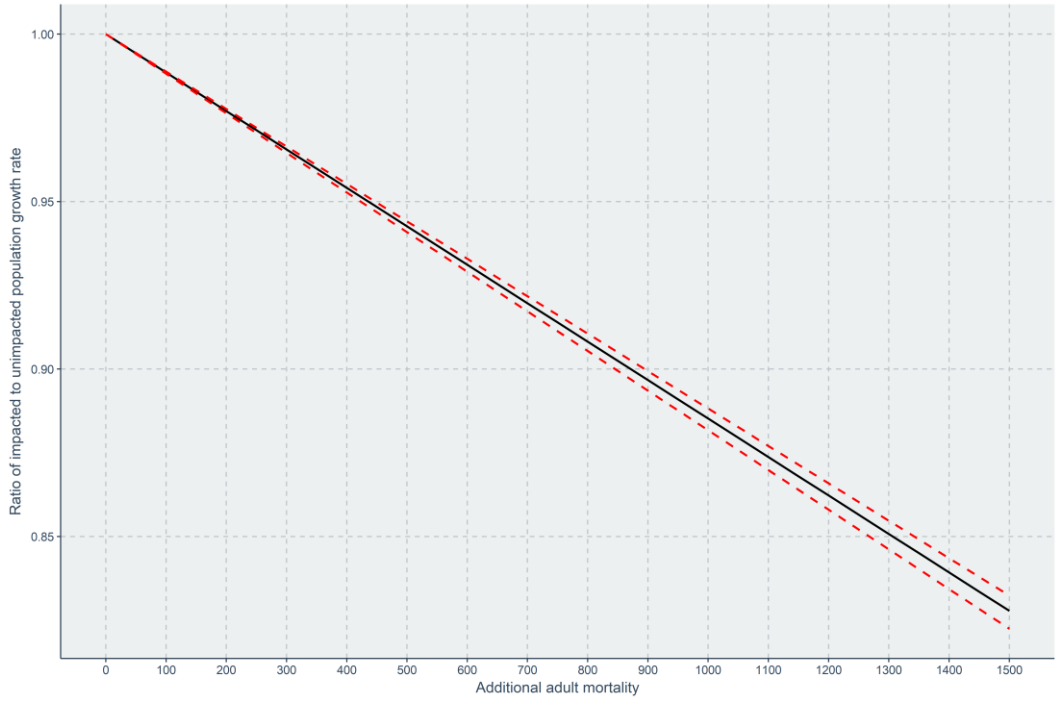


**Figure 19:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

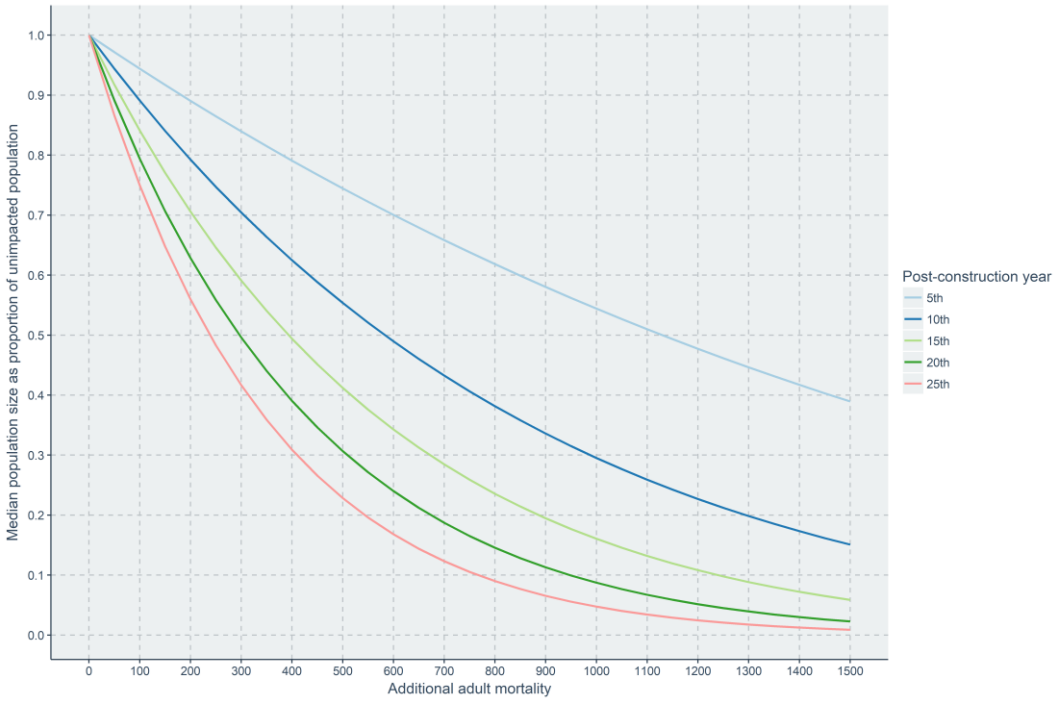


**Figure 20:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 8:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 0.997 | 0.965 | 1.025 |
| **50** | 0.991 | 0.960 | 1.019 |
| **100** | 0.986 | 0.954 | 1.013 |
| **150** | 0.980 | 0.948 | 1.007 |
| **200** | 0.974 | 0.943 | 1.002 |
| **250** | 0.969 | 0.937 | 0.996 |
| **300** | 0.963 | 0.931 | 0.990 |
| **350** | 0.957 | 0.926 | 0.984 |
| **400** | 0.951 | 0.920 | 0.978 |
| **450** | 0.946 | 0.914 | 0.973 |
| **500** | 0.940 | 0.908 | 0.967 |
| **550** | 0.934 | 0.903 | 0.961 |
| **600** | 0.928 | 0.897 | 0.956 |
| **650** | 0.923 | 0.891 | 0.950 |
| **700** | 0.917 | 0.885 | 0.944 |
| **750** | 0.911 | 0.880 | 0.938 |
| **800** | 0.906 | 0.874 | 0.933 |
| **850** | 0.900 | 0.868 | 0.927 |
| **900** | 0.894 | 0.863 | 0.921 |
| **950** | 0.889 | 0.857 | 0.916 |
| **1000** | 0.883 | 0.852 | 0.910 |
| **1050** | 0.877 | 0.846 | 0.904 |
| **1100** | 0.871 | 0.840 | 0.898 |
| **1150** | 0.866 | 0.835 | 0.892 |
| **1200** | 0.860 | 0.829 | 0.886 |
| **1250** | 0.854 | 0.823 | 0.881 |
| **1300** | 0.848 | 0.818 | 0.875 |
| **1350** | 0.843 | 0.812 | 0.869 |
| **1400** | 0.837 | 0.806 | 0.863 |
| **1450** | 0.831 | 0.801 | 0.858 |
| **1500** | 0.825 | 0.795 | 0.852 |

## 4.5 Guillemot – Forth Islands

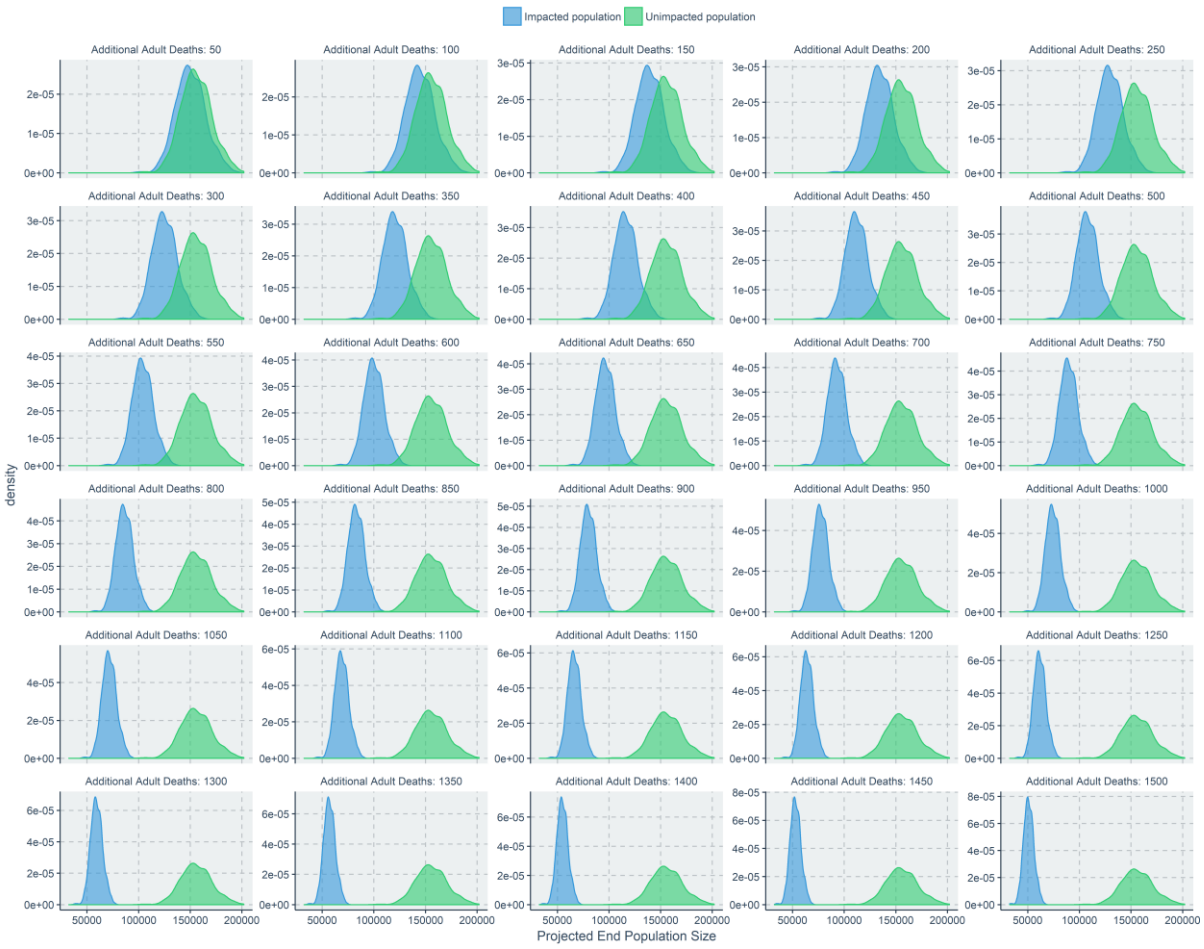


**Figure 21:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

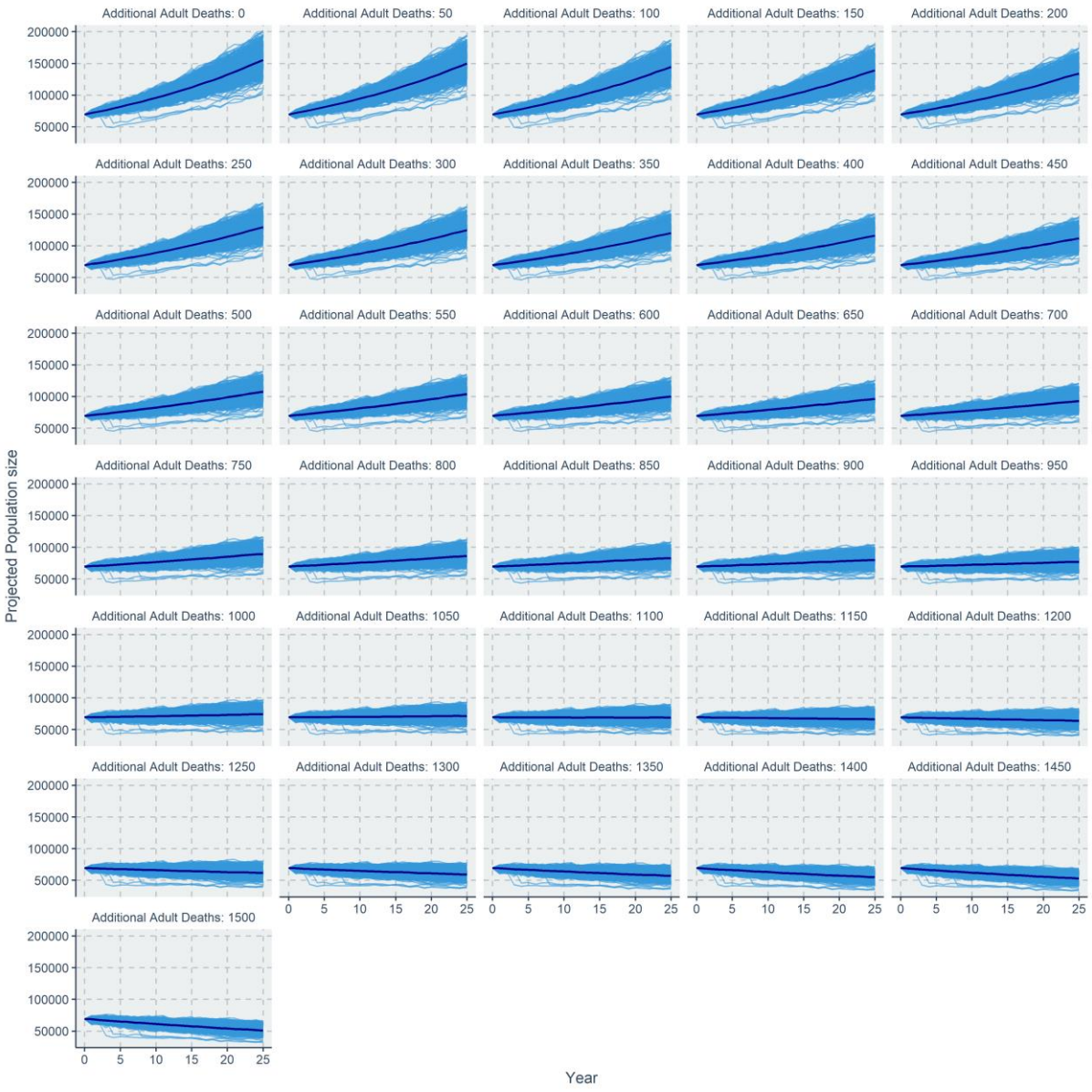


**Figure 22:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

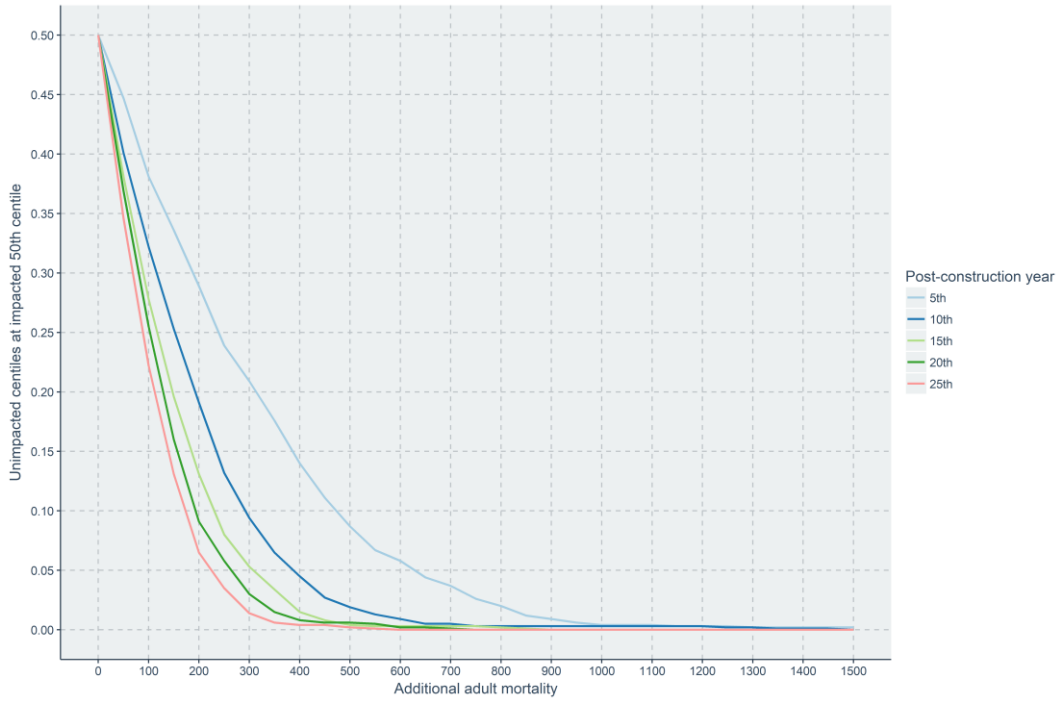


**Figure 23:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

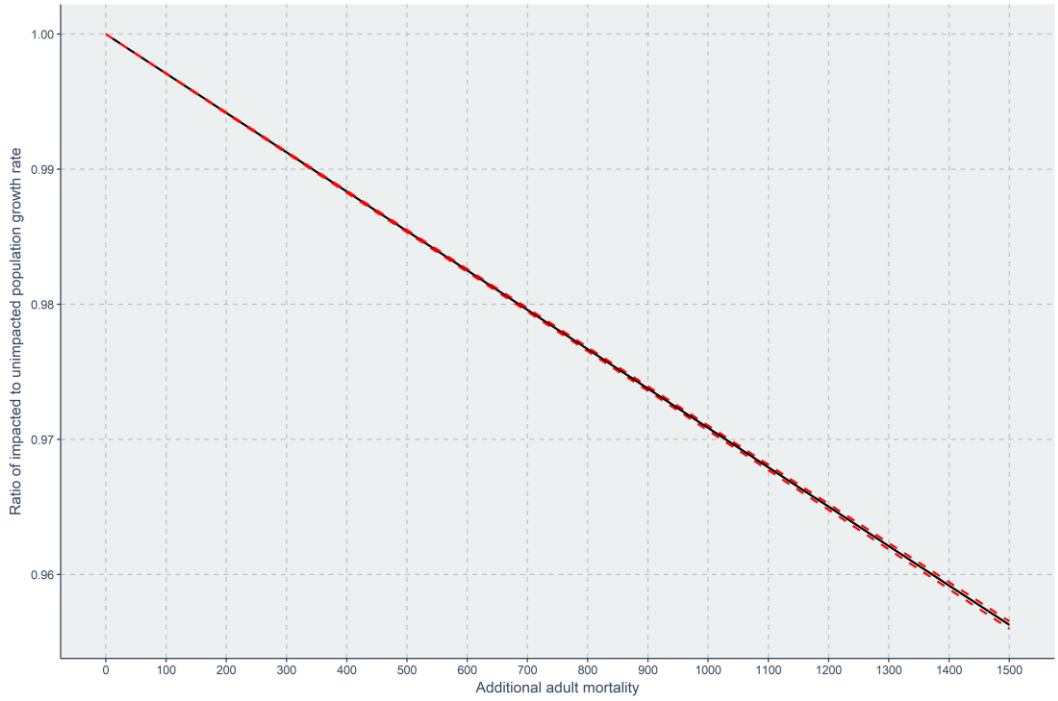


**Figure 24:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

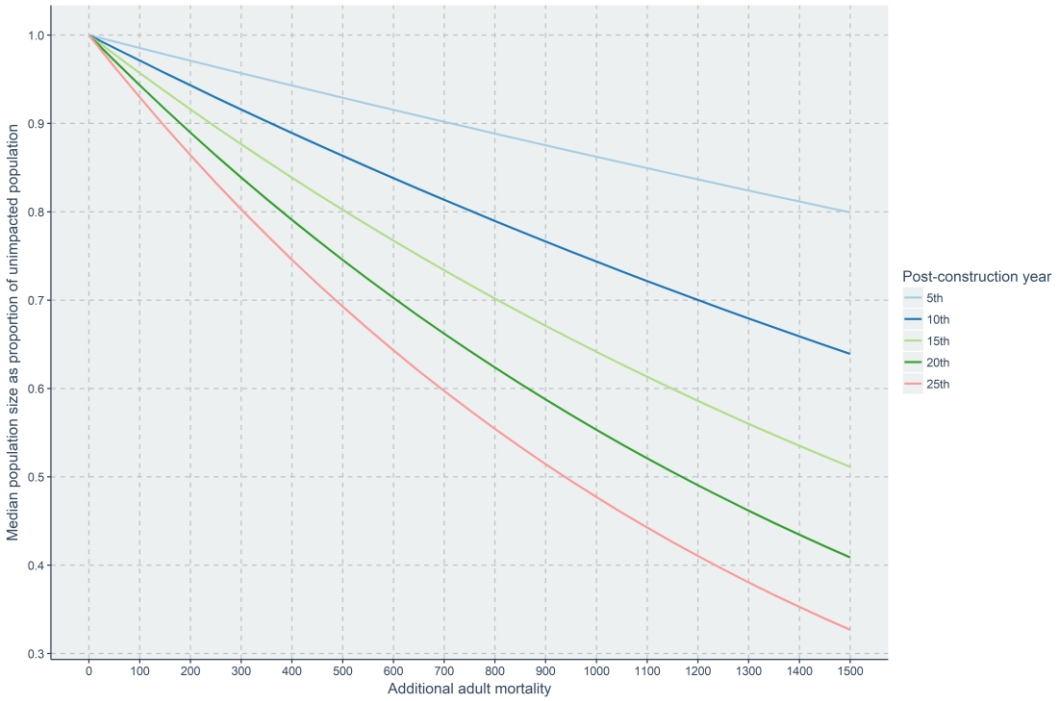


**Figure 25:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 9:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 1.033 | 1.024 | 1.042 |
| **50** | 1.032 | 1.022 | 1.040 |
| **100** | 1.030 | 1.021 | 1.039 |
| **150** | 1.028 | 1.019 | 1.037 |
| **200** | 1.027 | 1.018 | 1.036 |
| **250** | 1.025 | 1.016 | 1.034 |
| **300** | 1.024 | 1.015 | 1.033 |
| **350** | 1.022 | 1.013 | 1.031 |
| **400** | 1.021 | 1.012 | 1.030 |
| **450** | 1.019 | 1.010 | 1.028 |
| **500** | 1.018 | 1.009 | 1.027 |
| **550** | 1.016 | 1.007 | 1.025 |
| **600** | 1.015 | 1.006 | 1.024 |
| **650** | 1.013 | 1.004 | 1.022 |
| **700** | 1.012 | 1.003 | 1.020 |
| **750** | 1.010 | 1.001 | 1.019 |
| **800** | 1.009 | 1.000 | 1.017 |
| **850** | 1.007 | 0.998 | 1.016 |
| **900** | 1.006 | 0.997 | 1.014 |
| **950** | 1.004 | 0.995 | 1.013 |
| **1000** | 1.003 | 0.994 | 1.011 |
| **1050** | 1.001 | 0.992 | 1.010 |
| **1100** | 1.000 | 0.991 | 1.008 |
| **1150** | 0.998 | 0.989 | 1.007 |
| **1200** | 0.997 | 0.988 | 1.005 |
| **1250** | 0.995 | 0.986 | 1.004 |
| **1300** | 0.994 | 0.985 | 1.002 |
| **1350** | 0.992 | 0.983 | 1.001 |
| **1400** | 0.991 | 0.982 | 0.999 |
| **1450** | 0.989 | 0.980 | 0.998 |
| **1500** | 0.988 | 0.979 | 0.996 |

## 4.6 Guillemot – Fowlsheugh

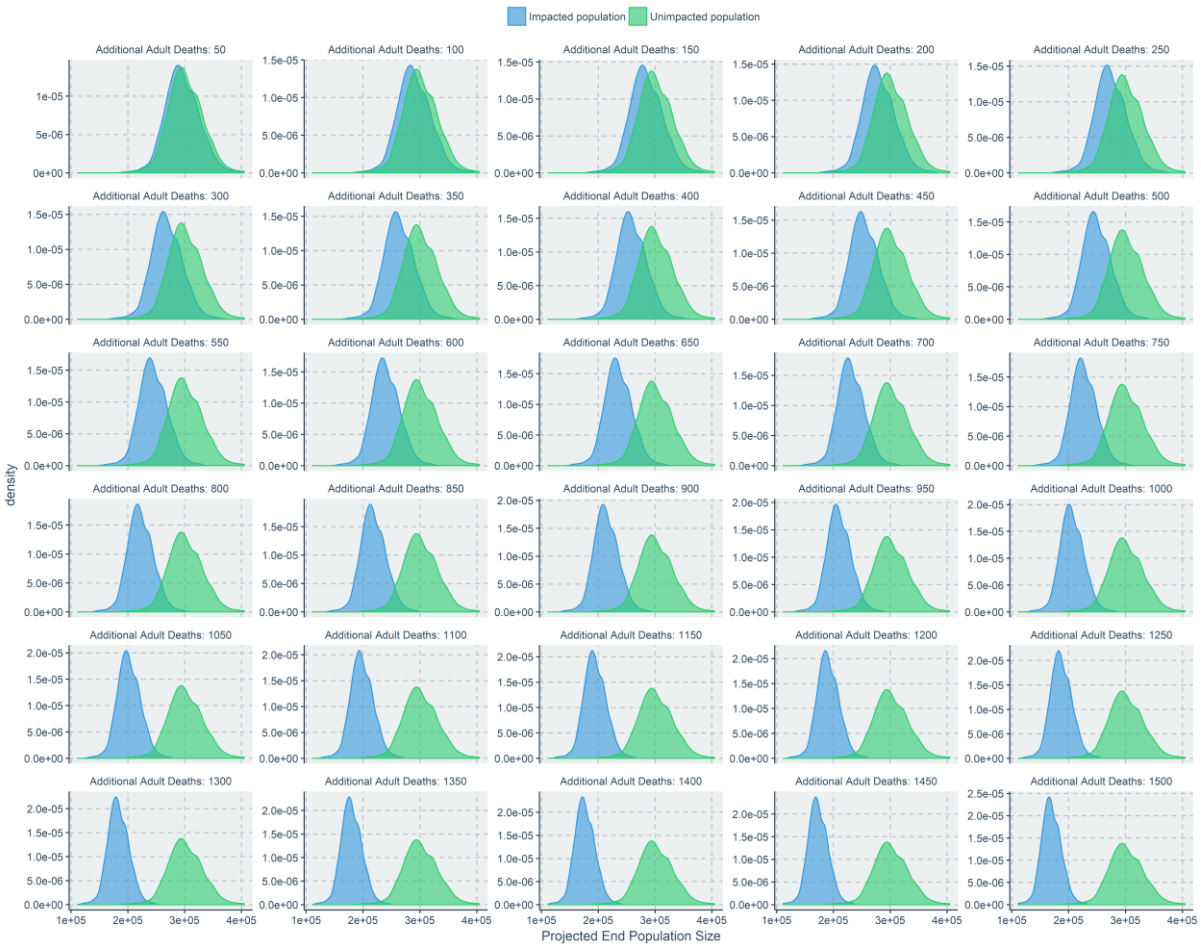


**Figure 26:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

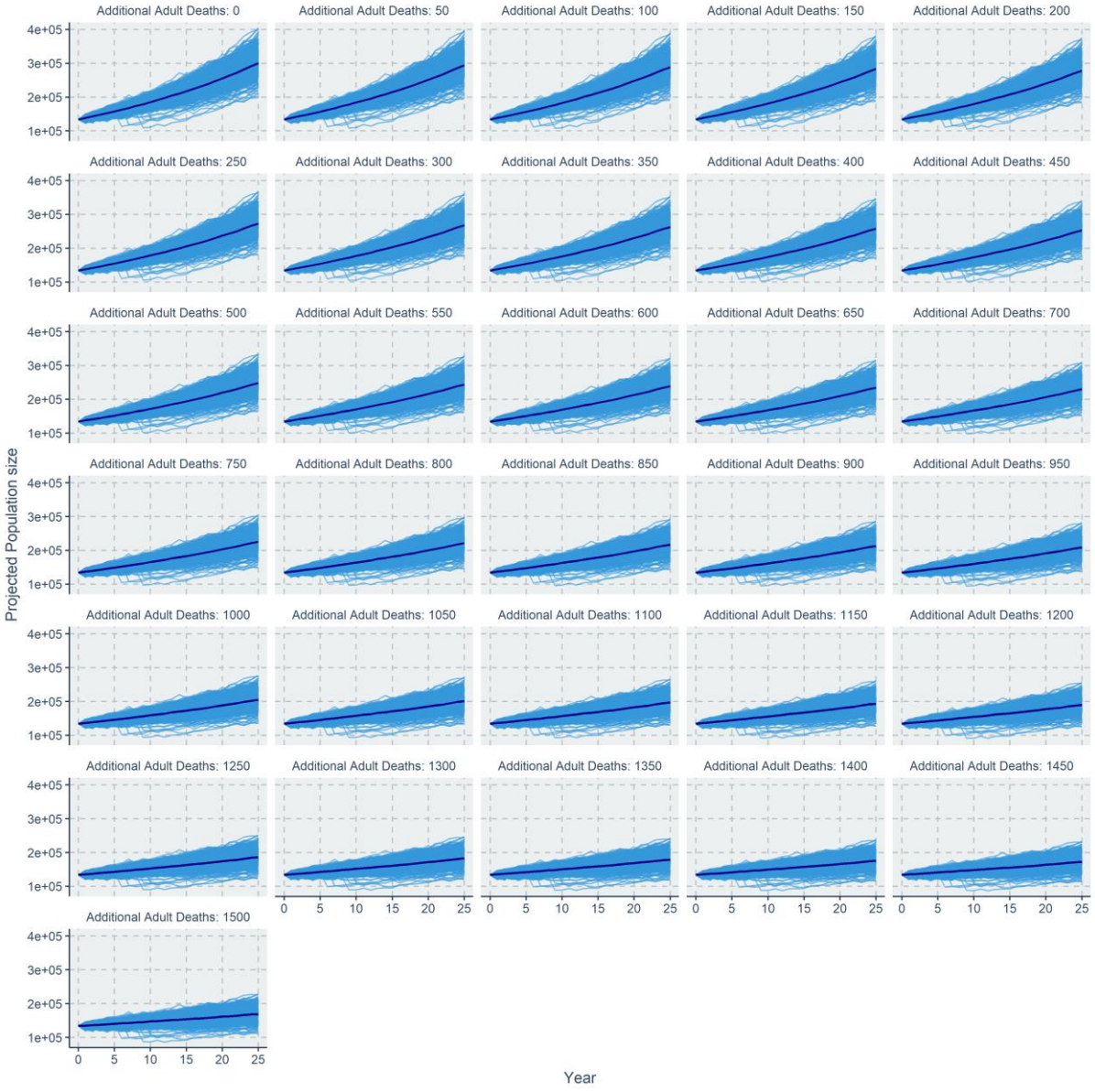


**Figure 27:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

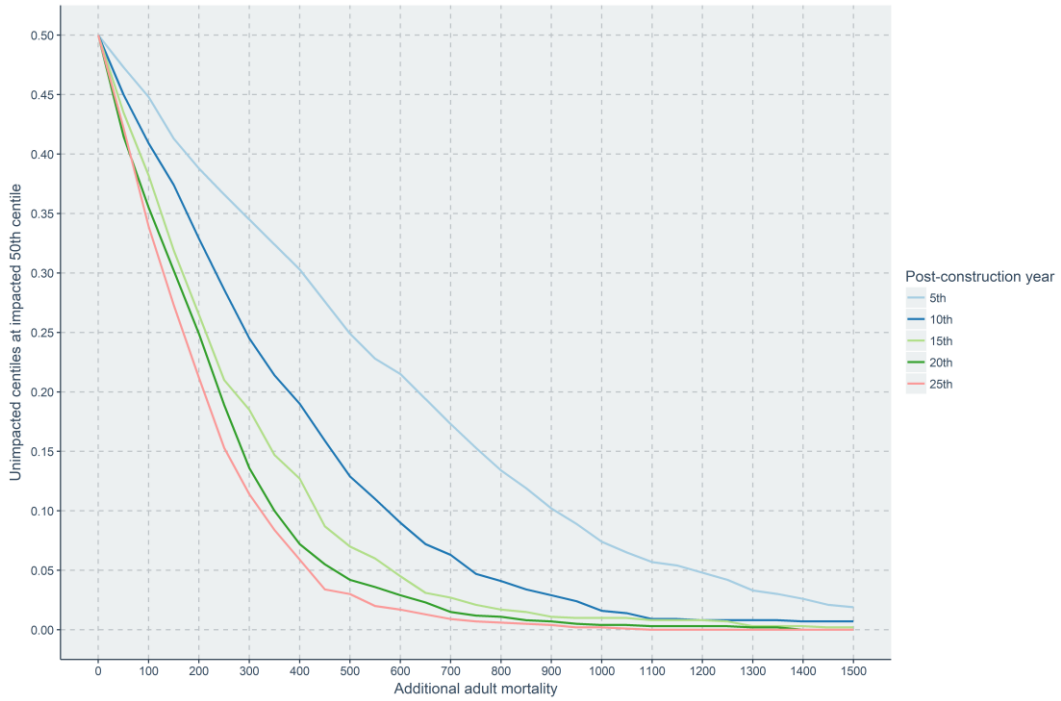


**Figure 28:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

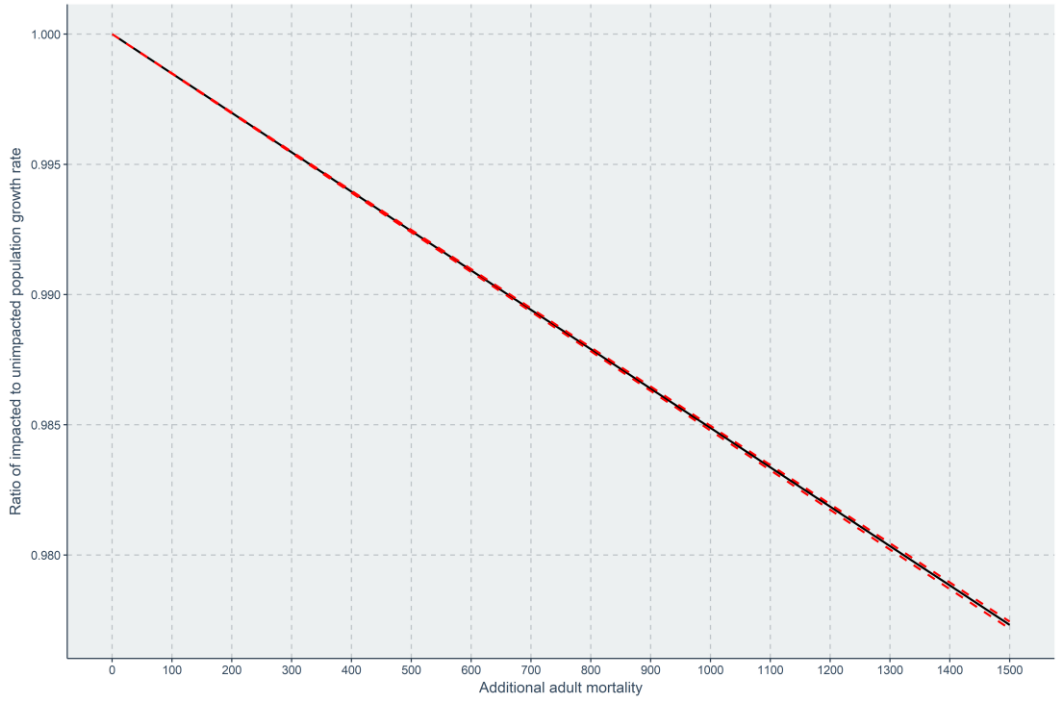


**Figure 29:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

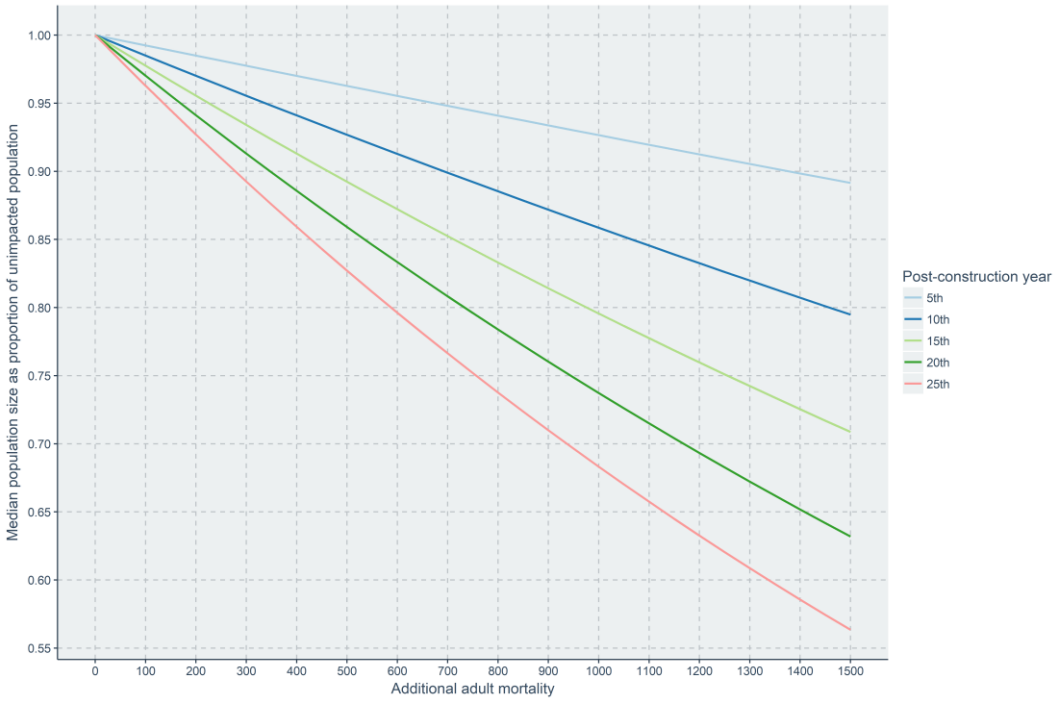


**Figure 30:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 10:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 1.033 | 1.023 | 1.043 |
| **50** | 1.032 | 1.023 | 1.042 |
| **100** | 1.032 | 1.022 | 1.041 |
| **150** | 1.031 | 1.021 | 1.040 |
| **200** | 1.030 | 1.020 | 1.039 |
| **250** | 1.029 | 1.020 | 1.039 |
| **300** | 1.028 | 1.019 | 1.038 |
| **350** | 1.028 | 1.018 | 1.037 |
| **400** | 1.027 | 1.017 | 1.036 |
| **450** | 1.026 | 1.016 | 1.035 |
| **500** | 1.025 | 1.016 | 1.035 |
| **550** | 1.025 | 1.015 | 1.034 |
| **600** | 1.024 | 1.014 | 1.033 |
| **650** | 1.023 | 1.013 | 1.032 |
| **700** | 1.022 | 1.013 | 1.031 |
| **750** | 1.021 | 1.012 | 1.031 |
| **800** | 1.021 | 1.011 | 1.030 |
| **850** | 1.020 | 1.010 | 1.029 |
| **900** | 1.019 | 1.009 | 1.028 |
| **950** | 1.018 | 1.009 | 1.028 |
| **1000** | 1.017 | 1.008 | 1.027 |
| **1050** | 1.017 | 1.007 | 1.026 |
| **1100** | 1.016 | 1.006 | 1.025 |
| **1150** | 1.015 | 1.006 | 1.024 |
| **1200** | 1.014 | 1.005 | 1.024 |
| **1250** | 1.014 | 1.004 | 1.023 |
| **1300** | 1.013 | 1.003 | 1.022 |
| **1350** | 1.012 | 1.002 | 1.021 |
| **1400** | 1.011 | 1.002 | 1.020 |
| **1450** | 1.010 | 1.001 | 1.020 |
| **1500** | 1.010 | 1.000 | 1.019 |

## 4.7 Kittiwake – Forth Islands

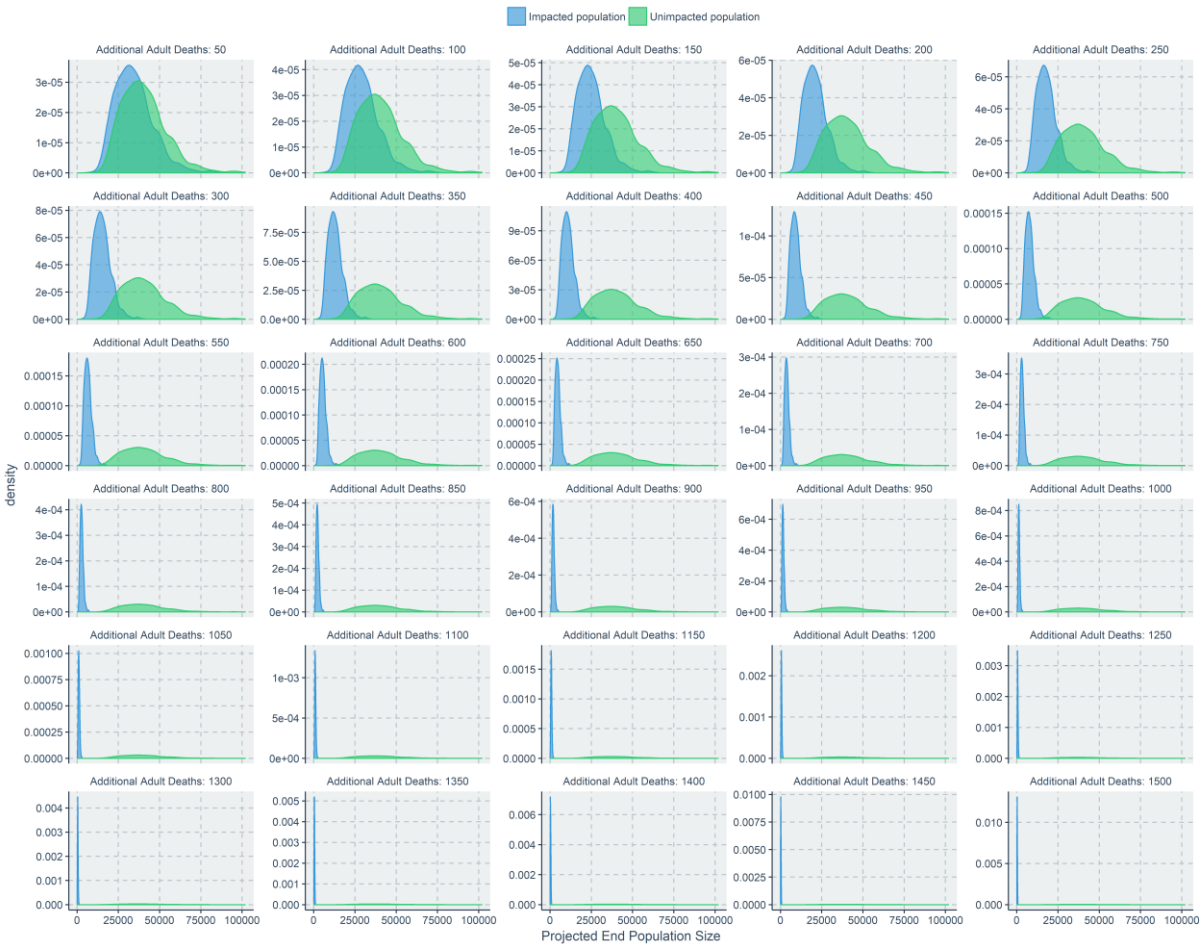


**Figure 31:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

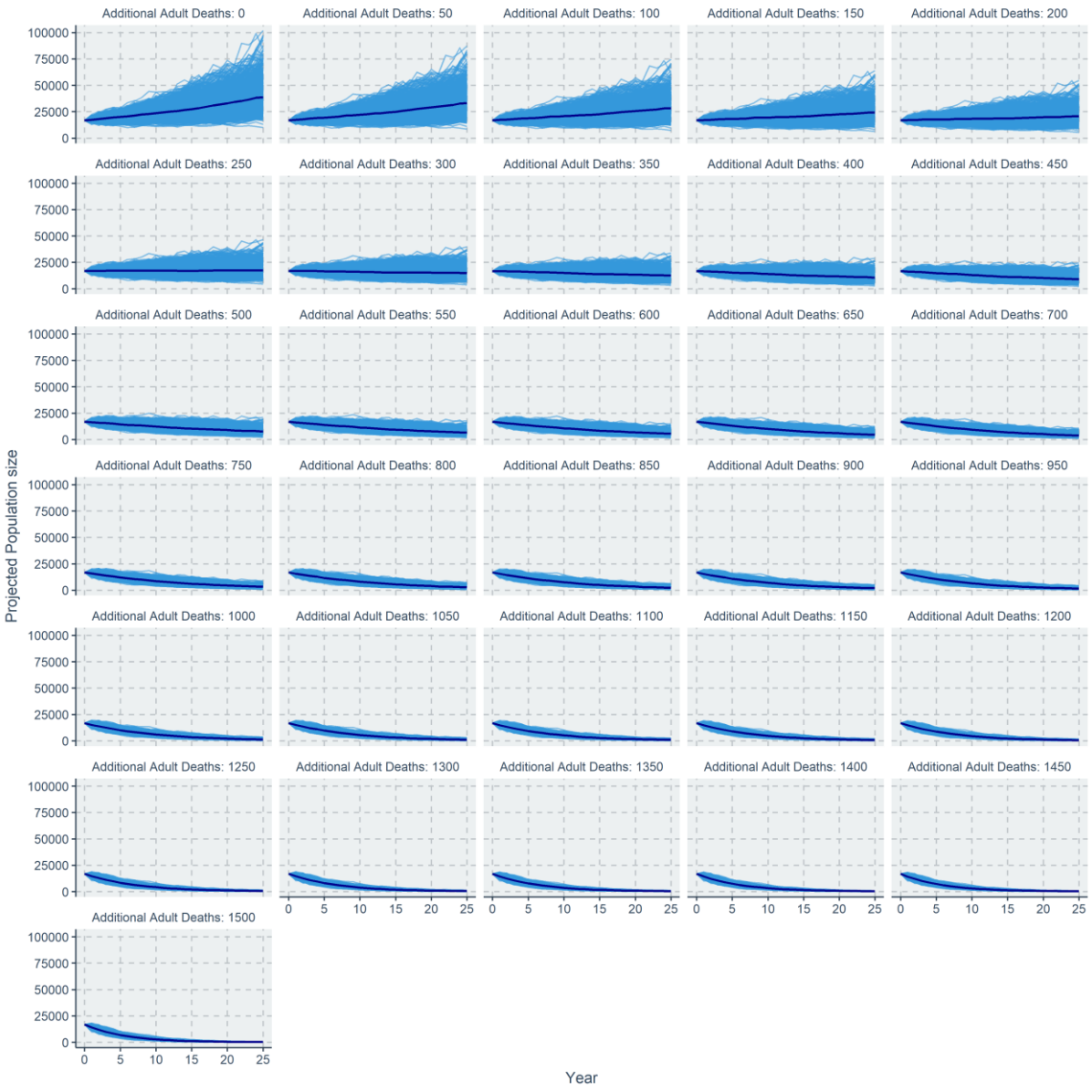


**Figure 32:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

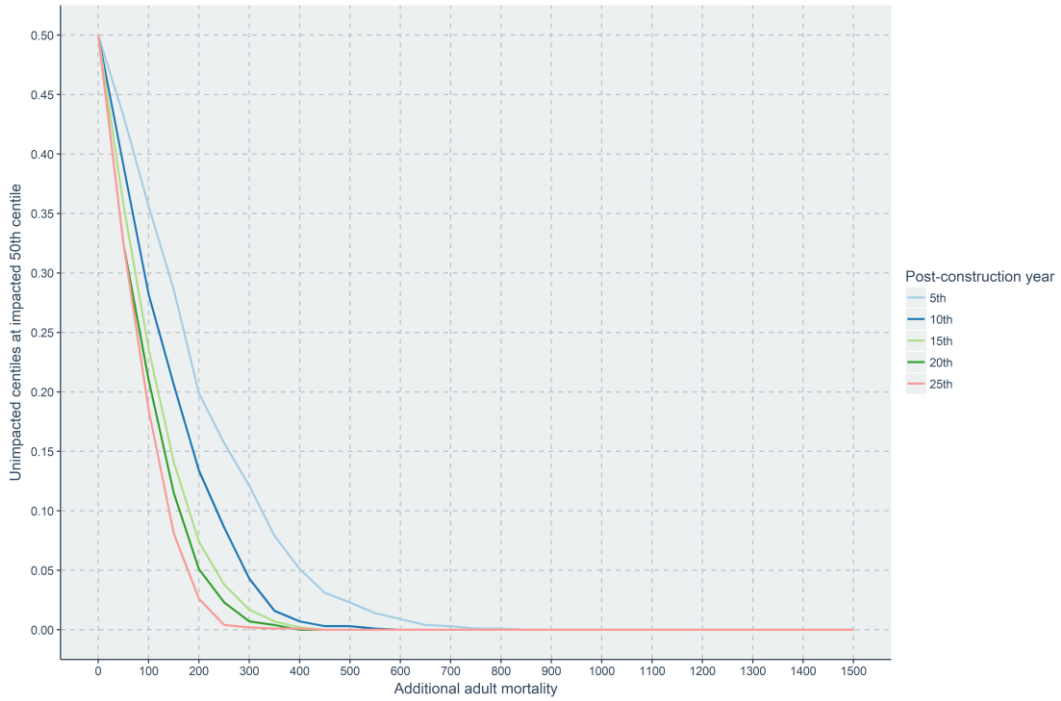


**Figure 33:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

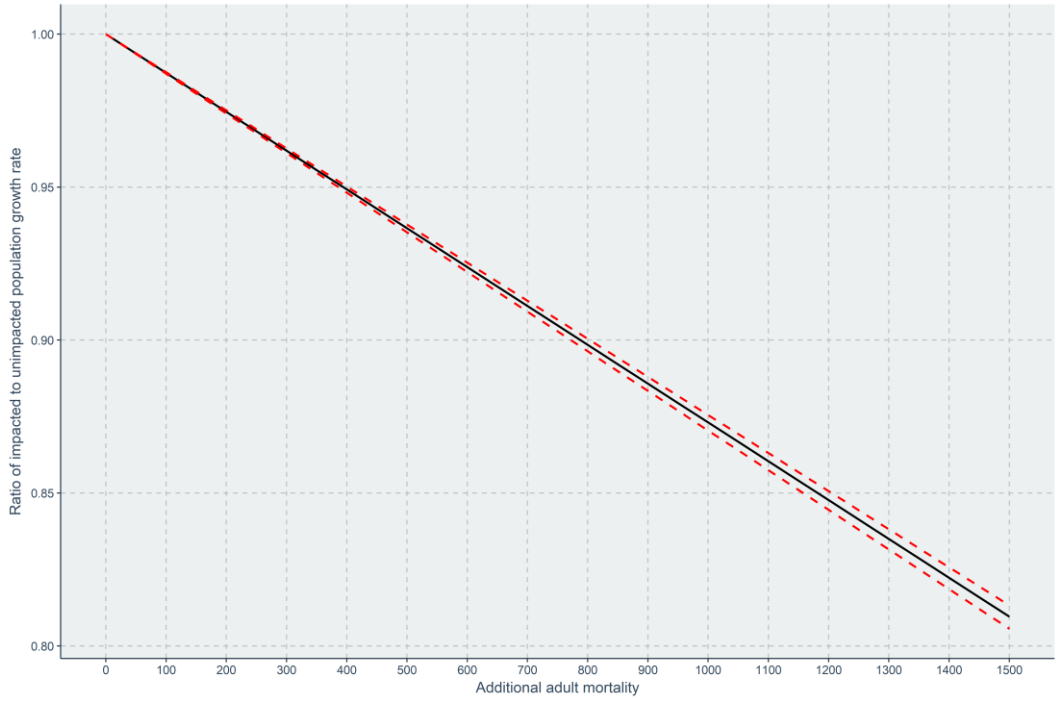


**Figure 34:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

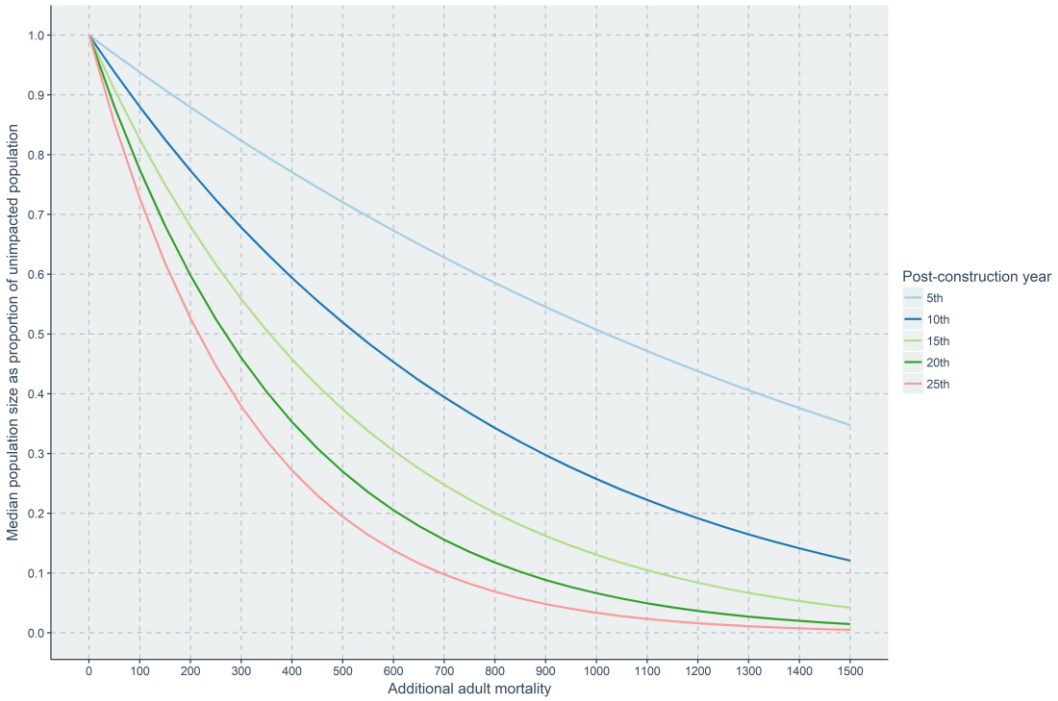


**Figure 35:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 11:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 1.034 | 1.004 | 1.064 |
| **50** | 1.028 | 0.998 | 1.057 |
| **100** | 1.021 | 0.991 | 1.050 |
| **150** | 1.015 | 0.985 | 1.044 |
| **200** | 1.008 | 0.978 | 1.037 |
| **250** | 1.001 | 0.972 | 1.030 |
| **300** | 0.995 | 0.965 | 1.024 |
| **350** | 0.988 | 0.959 | 1.017 |
| **400** | 0.982 | 0.953 | 1.010 |
| **450** | 0.975 | 0.946 | 1.004 |
| **500** | 0.969 | 0.940 | 0.997 |
| **550** | 0.962 | 0.933 | 0.991 |
| **600** | 0.956 | 0.927 | 0.984 |
| **650** | 0.949 | 0.920 | 0.977 |
| **700** | 0.943 | 0.914 | 0.971 |
| **750** | 0.936 | 0.907 | 0.964 |
| **800** | 0.929 | 0.901 | 0.957 |
| **850** | 0.923 | 0.894 | 0.951 |
| **900** | 0.916 | 0.888 | 0.944 |
| **950** | 0.910 | 0.881 | 0.937 |
| **1000** | 0.903 | 0.875 | 0.930 |
| **1050** | 0.897 | 0.868 | 0.924 |
| **1100** | 0.890 | 0.862 | 0.917 |
| **1150** | 0.884 | 0.855 | 0.911 |
| **1200** | 0.877 | 0.849 | 0.904 |
| **1250** | 0.870 | 0.842 | 0.897 |
| **1300** | 0.864 | 0.836 | 0.891 |
| **1350** | 0.857 | 0.829 | 0.884 |
| **1400** | 0.851 | 0.823 | 0.877 |
| **1450** | 0.844 | 0.816 | 0.871 |
| **1500** | 0.838 | 0.810 | 0.864 |

## 4.8 Kittiwake – Fowlsheugh

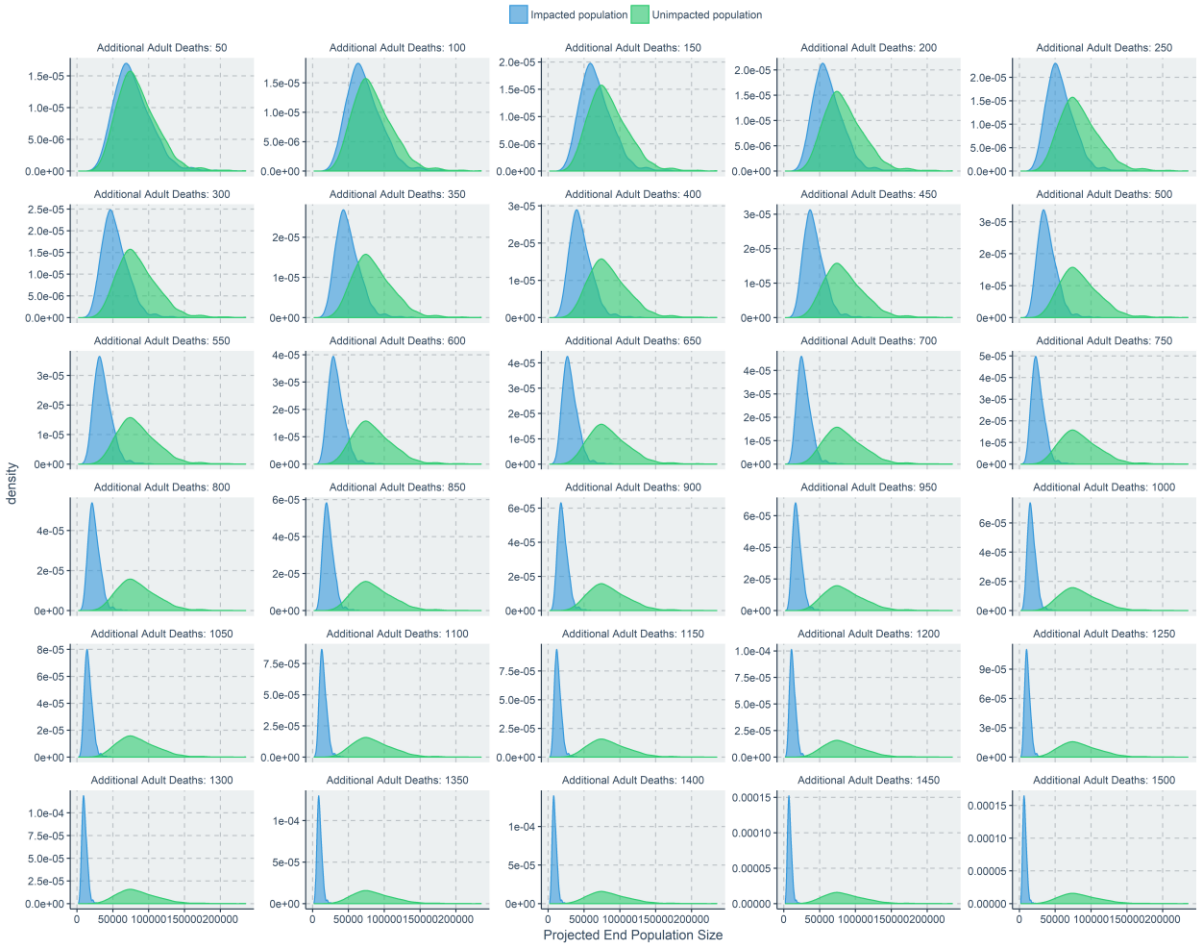


**Figure 36:** Distributions of end population sizes under simulation. Each plot represents a different impact scenario in terms of additional adult mortalities. The distribution of end population sizes for the unimpacted simulations are given in each.

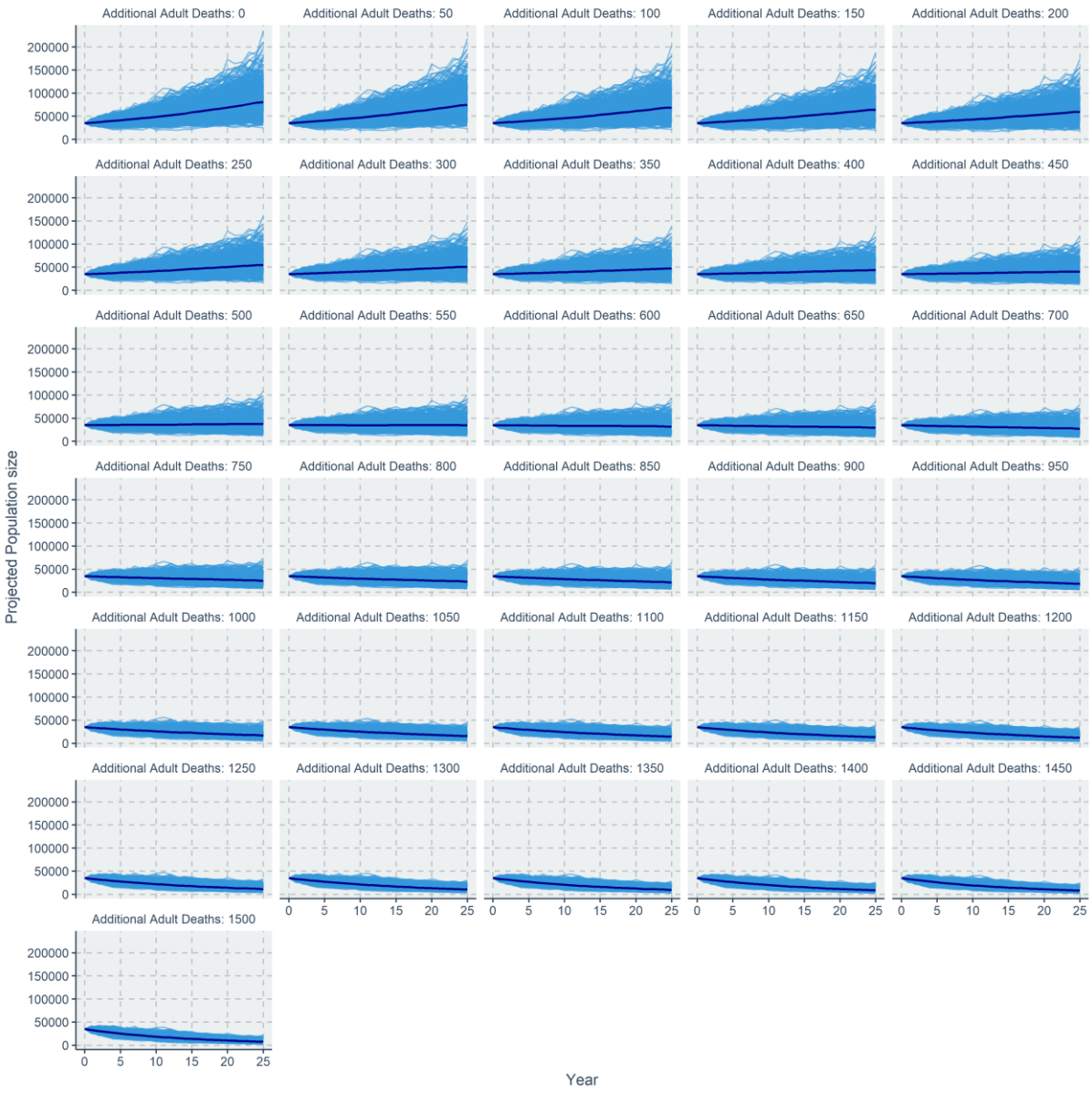


**Figure 37:** Projections of population sizes over a 25-year time-frame. Each plot represents a different impact scenario in terms of additional adult mortalities (starting at 0 i.e. unimpacted). Individual blue lines are different realisations of the population trajectory, when population parameters are sampled from their distributions. The dark blue line is the median at each time point.

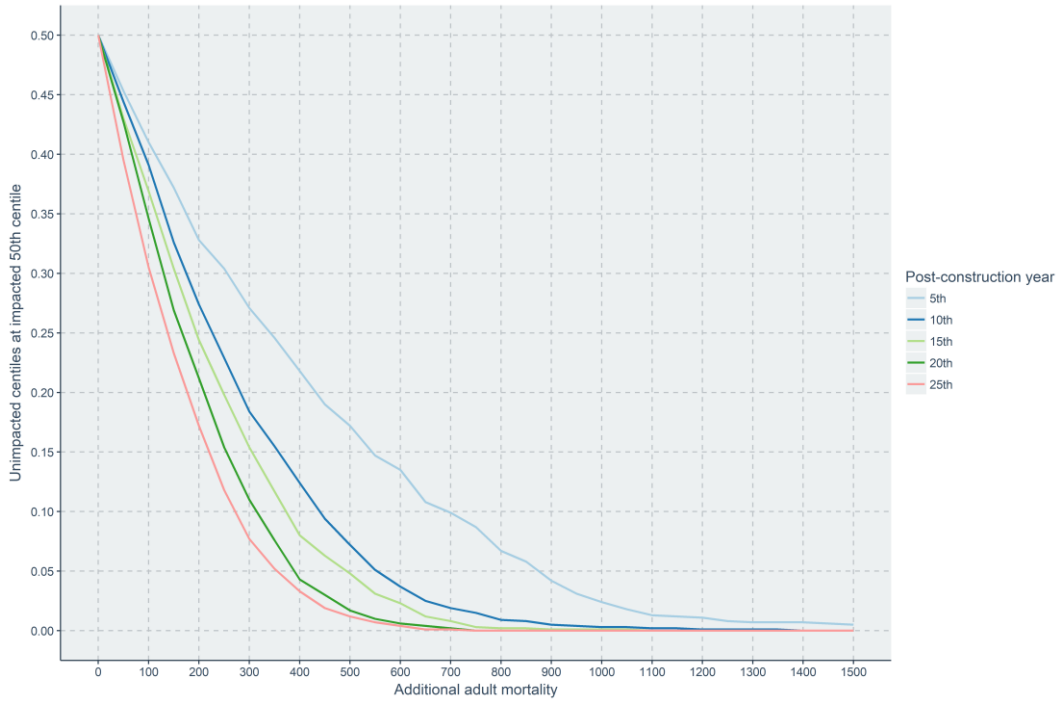


**Figure 38:** The median of the impacted population as a centile of the unimpacted population, under a range of impact scenarios (additional adult mortalities – x-axis). For example, 0.3 means the median (50th percentile) of the impacted projections sits at the 30th percentile of the unimpacted projections. Individual lines represent years post-construction (0-25 years).

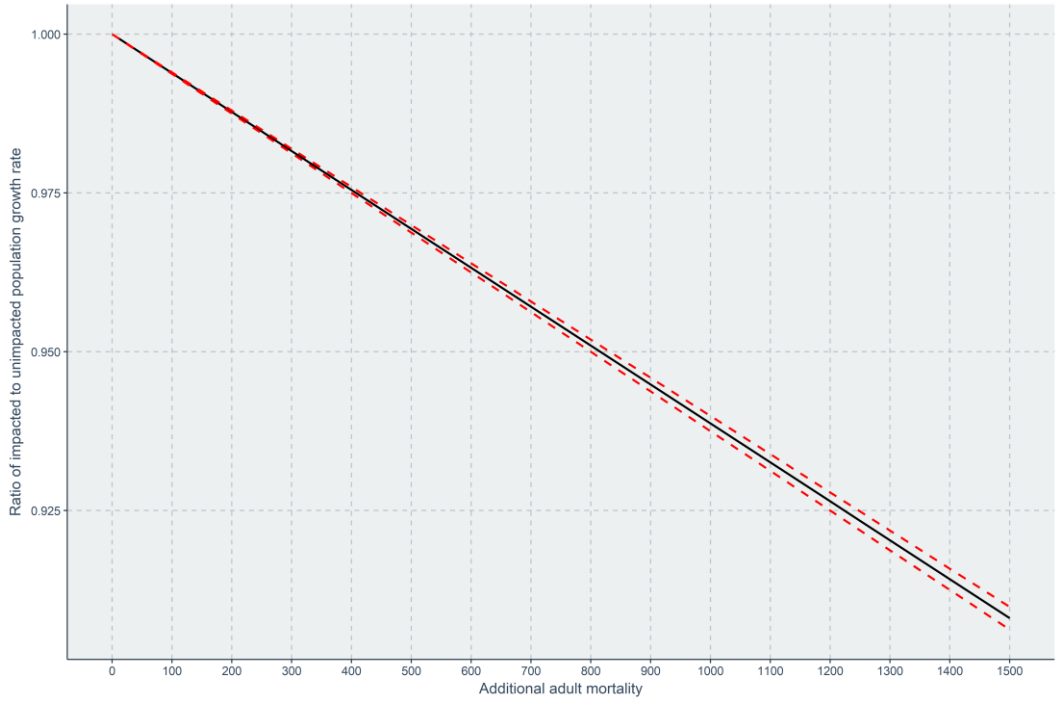


**Figure 39:** The ratio of impacted and unimpacted growth rates under a range of impact scenarios (additional adult mortalities – x-axis) i.e. 0.9 means a 10% decrease in the growth rate under the impact scenario. Figures are based on paired simulations for the impacted and unimpacted populations i.e. based on the same sampled population parameters. The black line represents the 50th percentile (median), red lines give the central 95% of simulated values (2.5% and 97.5% reference points).

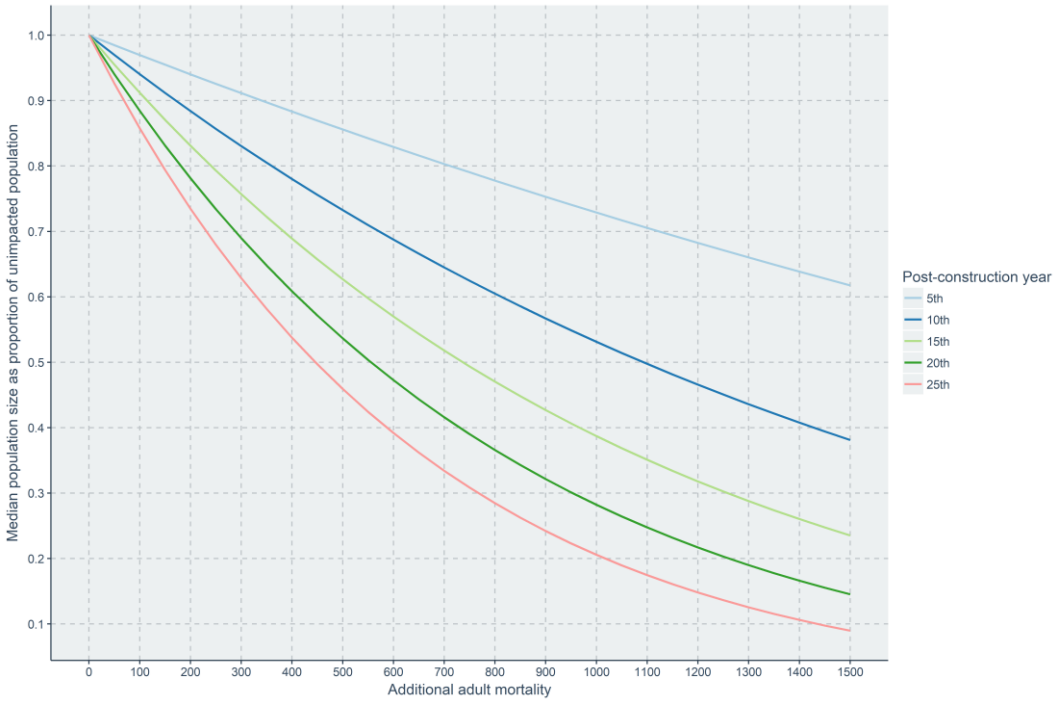


**Figure 40:** The ratio of the median impacted and median unimpacted population sizes from the simulations i.e. 0.5 means the median impacted population size is one-half the median unimpacted population size. Impact scenarios, in terms of additional adult mortalities, are given on the x-axis. Individual lines represent post-construction time points (projected 5 – 25 years).

**Table 12:** Growth rates of simulated populations under different impact scenarios. Reference points are 2.5%, 50% (median) and 97.5% of the distribution of simulated growth rates.

| Additional adult mortalities | Median growth rates | 2.5 percentile of simulated growth rates | 97.5 percentile of simulated growth rates |
|---|---|---|---|
| **0** | 1.034 | 1.005 | 1.064 |
| **50** | 1.030 | 1.002 | 1.061 |
| **100** | 1.027 | 0.999 | 1.058 |
| **150** | 1.024 | 0.996 | 1.054 |
| **200** | 1.021 | 0.993 | 1.051 |
| **250** | 1.018 | 0.990 | 1.048 |
| **300** | 1.015 | 0.987 | 1.045 |
| **350** | 1.012 | 0.983 | 1.041 |
| **400** | 1.008 | 0.980 | 1.038 |
| **450** | 1.005 | 0.977 | 1.035 |
| **500** | 1.002 | 0.974 | 1.032 |
| **550** | 0.999 | 0.971 | 1.029 |
| **600** | 0.996 | 0.968 | 1.025 |
| **650** | 0.993 | 0.965 | 1.022 |
| **700** | 0.989 | 0.961 | 1.019 |
| **750** | 0.986 | 0.958 | 1.016 |
| **800** | 0.983 | 0.955 | 1.012 |
| **850** | 0.980 | 0.952 | 1.009 |
| **900** | 0.977 | 0.949 | 1.006 |
| **950** | 0.974 | 0.946 | 1.003 |
| **1000** | 0.971 | 0.943 | 1.000 |
| **1050** | 0.967 | 0.940 | 0.996 |
| **1100** | 0.964 | 0.936 | 0.993 |
| **1150** | 0.961 | 0.933 | 0.990 |
| **1200** | 0.958 | 0.930 | 0.987 |
| **1250** | 0.955 | 0.927 | 0.983 |
| **1300** | 0.952 | 0.924 | 0.980 |
| **1350** | 0.948 | 0.921 | 0.977 |
| **1400** | 0.945 | 0.918 | 0.974 |
| **1450** | 0.942 | 0.915 | 0.970 |
| **1500** | 0.939 | 0.912 | 0.967 |