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Testing sensitivity of metrics of seabird population response to offshore wind farm effects

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The opinions expressed and statements made within this report are those of the BTO and do not necessarily represent those of the SNCBs and regulators. Please consult with the relevant SNCB and regulator as to the use of metrics in any impact assessment work.

Summary

Population models are often used to help understand the population level consequences of the impacts of offshore wind farms on seabirds. Metrics can be derived from these models in order to quantify the population level consequences of the impacts associated with the wind farm.

Based on a previous review of assessments of offshore wind farms, we identified 11 metrics which have been used to assess the population level consequences of impacts from offshore wind farms on seabirds. However, seabird demography is often not quantified accurately and may be subject to significant levels of uncertainty. This leads to concerns that these metrics may be sensitive to assumptions about population trend, demographic parameters and density dependence. As a consequence, it is important to understand the extent to which conclusions based on these metrics may be influenced by the assumptions underpinning them. With this in mind, we tested the sensitivity of each metric to assumptions about population trend, life history strategy, mis-specification of demographic parameters, the incorporation of density dependence and whether the metric was derived from a stochastic or deterministic population model.

Our analysis revealed that all metrics were sensitive to at least some of the assumptions underpinning them, but that some were more sensitive than others. We describe these sensitivities, indicating how to use each metric most effectively.

Contents

1 **Introduction** **1**

2 Approach **2**

2.1 Metrics used to quantify population level consequences of effects from offshore wind farms on seabirds 2

2.2 Sensitivity Analysis 7

2.2.1 Baseline Scenario 7

2.2.2 Deterministic or stochastic models 9

2.2.3 Sensitivity to impact 10

2.2.4 Sensitivity to population trend 11

2.2.5 Sensitivity to life history strategy 11

2.2.6 Sensitivity to mis-specification of demographic parameters 11

2.2.7 Sensitivity to density dependence 12

2.3 Population Models 16

2.3.1 Deterministic population model for r-selected species 16

2.3.2 Stochastic population model for r-selected species 17

2.3.3 Stochastic population model for increasing or decreasing r-selected species 18

2.3.4 Stochastic population model for an r-selected species incorporating density dependent impacts on survival or productivity 18

2.3.5 Stochastic Population Model for K-selected species 18

2.3.6 Additional Analyses 19

2.4 Assessing the value of metrics 20

2.5 R Code 22

3 Results **23**

3.1 Population Models 23

3.1.1 Deterministic population model for a seabird with the characteristics of an r-selected species with a stable population 23

3.1.2 Stochastic population model for a seabird with the characteristics of an r-selected species with a stable population 25

3.1.3 Stochastic population model for a seabird with the characteristics of an r-selected species with an increasing population 26

3.1.4 Stochastic population model for a seabird with the characteristics of an r-selected species with a declining population 27

3.1.5 Stochastic population model for a seabird with the characteristics of a K-selected species with a stable population 28

3.1.6 Stochastic population model with a density dependent response to productivity for a seabird with the characteristics of an r-selected species 29

3.1.7 Stochastic population model with a density dependent response to survival for a seabird with the characteristics of an r-selected species 30

3.2 Metrics for Population Level Impacts 31

3.2.1 Assessing the metrics 31

3.2.2 Recommendations 35
3.2.3 Population Growth Rate (GR) 43
3.2.4 Ratio of the Median Impacted to Unimpacted Population Growth Rate (RI:U) 48
3.2.5 Ratio of Impacted to Unimpacted Population Size (RI:U25) 57
3.2.6 Probability of population growth rate being <1, 0.95 or 0.8 (P(GR<1)) 65
3.2.7 Change in the probability of the population growth rate being <1, 0.95 or 0.8 (dP(GR<1)) 70
3.2.8 Probability of the population declining below its initial size at any point in time (P(p<p_0)) 75
3.2.9 Probability of a 10, 25 or 50% population decline (P(ld>0.25)) 79
3.2.10 Change in probability of a 10, 25 or 50% decline (dP(ld.0.1), dP(ld>0.25), dP(ld>0.5)) 83
3.2.11 Probability of an impacted population being a given magnitude below the median size predicted in the absence of an impact (P(I<25)) 88
3.2.12 Probability that impacted population growth rate is 2.5, 5 or 10% less than unimpacted growth rate (P(IGR<2.5)) 93
3.2.13 Overlap between impacted and unimpacted population (OI:U) 97
4 References 102

1 Introduction

Offshore wind farms potentially have a number of negative effects on seabird populations. These include displacement from preferred foraging areas, the risk of collision with turbines and the wind farm acting as a barrier to migrating or commuting birds (Garthe & Huppop 2004; Drewitt & Langston 2006; Everaert & Stienen 2007; Petersen & Fox 2007; Masden *et al* 2009; Krijgsveld *et al* 2011; Vanermen *et al* 2013; Furness *et al* 2013). As part of the consenting process, it is necessary to understand what impact these effects are likely to have at a population level. In the UK, the potential for a proposed offshore wind farm development to affect seabird populations has previously been assessed using demographic models, for example Population Viability Analysis (PVA) or Potential Biological Removal (PBR) (Wade 1998; Maclean *et al* 2007; Dillingham & Fletcher 2008; WWT 2012; Bennet 2013).

These demographic models can be used either to compare the trajectory of the population over time with and without the development, or quantify the impact of the development within a risk-based framework (for example, the probability that the population declines). To date, a range of different metrics have been used to undertake such assessments including the ratio of the predicted population size with and without the development, the ratio of the growth rates for each population, the increase in the probability of recording a growth rate less than 1 (*i.e.* a population decline) and the increase in the probability of a population decreasing by a fixed amount (*e.g.* a 50% decline over 10 years) (e.g. Green 2014; Trinder 2014). However, there is likely to be significant uncertainty and variability amongst the input parameters used for the demographic models, leading to concerns that metrics may not always allow a clear understanding of the population level consequences associated with offshore wind farms (Green 2014; Cook & Robinson 2015). The importance of capturing uncertainty when estimating the effects associated with offshore wind farms has recently been highlighted (Masden *et al* 2014; Green 2014). Without capturing this uncertainty, it is difficult to know how likely any of the scenarios put forward are, potentially posing problems for the consenting process.

The quantity and quality of data available to inform demographic models for different species is highly variable (Maclean *et al* 2007; Horswill & Robinson 2015). For some species time-specific data will be available from particular colonies of interest for at least some parameters whereas, for other species even basic estimates may be lacking. In the absence of detailed demographic data, especially at a site-specific level, for the species under consideration, it is important to understand whether these metrics are unduly sensitive to mis-specification of demographic parameters in the models used to derive them. The impact of this sensitivity may depend on the specific circumstances under consideration. For example if strong evidence is available to support estimates of adult survival rates, but the evidence underpinning the immature survival rates is less robust, metrics which may be more sensitive to the estimate of adult survival but less sensitive to estimates of immature survival would be favoured. Based on the guidance given by the steering group we set out criteria against which sensitivity to different attributes could be assessed and which metrics should be favoured based on this assessment. While this report has looked at the sensitivity of metrics, it has not explicitly considered how that sensitivity is influenced by the value chosen for the rule derived for that metric.

2 Approach

2.1 Metrics used to quantify population level consequences of effects from offshore wind farms on seabirds

As part of the Strategic Ornithological Support Service (SOSS) work programme, WWT (2012) produced guidance on the use of Population Viability Analysis (PVA) to assess the population level consequences of effects from offshore wind farms on seabirds. Using a stochastic population model, the effect of the additional mortality arising as a result of birds colliding with turbines on northern gannet *Morus bassanus* populations is assessed by considering the probability of collision mortality causing populations to decline at colonies across the North Sea. Subsequently, a broad range of metrics, have been derived from population models with which to assess population level effects (Centrica Energy 2009; Trinder 2014; Green 2014; Cook & Robinson 2015).

As part of Cook and Robinson (2015), we reviewed Habitats Regulations Assessments (HRA) undertaken for offshore wind farms currently within the planning process. We identified eleven metrics which can be derived from population models and that have been used to assess the population level effects of impacts from offshore wind farms on seabirds. These can be split into two broad categories, probabilistic approaches (e.g. the probability of the population declining) or ratio approaches (e.g. the ratio of the population size in the presence and absence of the wind farm). However, many of these approaches have been criticised as, potentially, being sensitive to both uncertainties in the demographic parameters used in the underlying population models and to uncertainties in the magnitude of the impact predicted (Green 2014). Cook and Robinson (2015) assessed the validity of these criticisms and highlighted some areas where further analyses were required in order to draw firm conclusions about the usefulness of these approaches. The purpose of this report is to use population models, to quantify how sensitive conclusions drawn from each are to uncertainty in the demographic parameters used in the population models, the structure of the population models used to derive the metrics and the magnitude of the impact considered.

Table 1. Description of metrics used to assess population responses to impacts of offshore wind farms and included in the sensitivity analysis and scale over which the metrics operate.

	Metric	Scale	Description
1	**Population growth rate** **(GR)** **Section 3.2.3**	A value of 1 indicates a stable population, a value <1 indicates a declining population and a value >1 indicates an increasing population.	By considering the growth rate of the population in the presence of an offshore wind farm, it will be possible to consider whether the population will remain stable, increase or decrease through the life time of the project. A value of 1 indicates a stable population, <1 a declining population and >1 an increasing population. Growth rate is calculated as a mean rate over the study period: $\left(\frac{End\ Population\ Size}{Start\ Population\ Size}\right)^{1/Nyears}$
2	**Ratio of median impacted to unimpacted growth rate** **(RI:U)** **Section 3.2.4**	From 0 – 1, with 1 indicating the impacted population growth rate is the same as the unimpacted growth rate (i.e. no population-level consequence) and values close to 0 indicating a large difference between the impacted and unimpacted population growth rates (i.e. a strong population-level consequence).	Considering only the growth rate of a population in the presence of an offshore wind farm enables an assessment of whether the population will remain stable, increase or decrease over time, but it does not make it possible to quantify the impact of the wind farm on that growth rate. By comparing the growth rate of the population in the presence of a wind farm to that expected in the absence of a wind farm it may be possible to demonstrate what impact the development is having on a population.

	Metric	Scale	Description
3	**Ratio of impacted to unimpacted population size** **(RI:U25)** **Section 3.2.5**	From 0 – 1, with 1 indicating the impacted population size is the same as the unimpacted growth rate (i.e. no population-level consequence) and values close to 0 indicating a large difference between the impacted and unimpacted population sizes (i.e. a strong population-level consequence).	Population models can be used to estimate the size of a population through time both with and without the impact of an offshore wind farm. Comparing the ratio of the size of these two populations offers a relatively easy to interpret statistic with which to assess the population level impact of an offshore wind farm. The ratio could be derived either from a simple deterministic model or taken from the mean or median values simulated using a more complex stochastic model. The ratio of population sizes could be estimated either at a fixed point in time, for example at the end of a project, or at a series of intervals throughout the life time of a project.
4	**Probability that growth rate <1, 0.95, 0.8** **(P(GR<1))** **Section 3.2.6**	From 0 – 1 with 0 indicating that none of the simulations from a stochastic model result in a growth rate <1 and 1 indicating that all of the simulations from a stochastic model result in a growth rate <1.	Calculated from a stochastic model based on the proportion of simulations where the population declines (i.e. has a growth rate <1). The probability of a population declining is typically assessed over the lifetime of the project. However, it would also be possible to examine the probability of the population declining at any point during the lifetime of the project. Alternatively, the metric could consider the probability of the growth rate being below other values (e.g. 0.95 or 0.8) which could be selected with reference to the status of the population concerned.
5	**Change in probability that growth rate <1, 0.95, 0.8** **(dP(GR<1))** **Section 3.2.7**	From 0 – 1, with 0 indicating that there is no likely change in the probability of the growth rate being <1 between impacted and unimpacted populations (i.e. no population-level consequence) and values approaching 1 indicating there is an almost certain change in the probability of the growth rate being <1 between the impacted and unimpacted populations (i.e. a population-level consequence).	Where simulations show that a population may already be at risk of declining in the absence of a wind farm, for example if >50% of simulations have a growth rate <1, simply quantifying the probability of a population decline in the presence of an offshore wind farm may not be meaningful. To assess the population level impact of a development it is therefore necessary to determine how much greater the probability of a decline is in the presence of an offshore wind farm than in the absence of an offshore wind farm. This could be done either at a single fixed point in time, or at intervals throughout the life time of the project.

	Metric	Scale	Description
6	**Probability that population is below initial size at any point in time** **($P(p<p_0)$)** **Section 3.2.8**	From 0 -1 with 0 indicating that none of the simulations from a stochastic model result in a population below its initial size at any point in time and 1 indicating that all of the simulations from a stochastic model result in a population below its initial size at any point in time.	After an initial impact, environmental stochasticity and density dependence may mean a population is able to recover throughout the life time of a project. This recovery would mean that over 25 years the final population size may not be smaller than starting population size.
7	**Probability of a 10, 25 or 50% population decline** **(P(ld>0.25))** **Section 3.2.9**	From 0 – 1, with 0 indicating that none of the simulations from a stochastic model show the impacted population declining by a given magnitude (i.e. no population-level consequence) and 1 indicating that all simulations show the impacted population declining by at least the given magnitude.	A metric to assess the population level impact of a development could be derived by estimating the proportion of simulations for a population in the presence of a wind farm in which a decline of a given magnitude was recorded.
8	**Change in probability of a 10, 25 or 50% decline** **(dP(ld>0.25))** **Section 3.2.10**	From 0 – 1, with 0 indicating that there is no change in the probability of the population decreasing by a given magnitude between the impacted and unimpacted populations (i.e. no population-level consequence) and values approaching 1 indicating there is a large change in the probability of the population decreasing by a given magnitude between the impacted and unimpacted populations (i.e. a population-level consequence).	At many colonies throughout the UK, seabird populations are already declining (JNCC 2013). As a consequence, the presence of a wind farm may not increase the probability of the population size at these colonies being <1, if all simulations from the baseline scenario already have a population size less than starting population size. However, the presence of the wind farm may cause a further reduction in population size. It may, therefore, be more meaningful to consider the change in probability of population size decreasing by a given magnitude, for example a 10% increase in the probability of a 5% decline.

	Metric	Scale	Description
9	**Probability of a population being a given magnitude below the median size predicted in the absence of an impact** **P(I<25)** **Section 3.2.11**	From 0 – 1, with 0 indicating that none of the simulations from a stochastic model show the impacted population being a given magnitude below the unimpacted population (i.e. no population-level consequence) and 1 indicating that all simulations show the impacted population a given magnitude below the unimpacted population.	A metric to assess the population level impact of a development could be derived by estimating a median size for a population in the absence of an offshore wind farm and calculating the proportion of simulations for a population in the presence of a wind farm which were either below this median population size, or a given magnitude below this median population size.
10	**Probability that impacted population growth rate is 2.5, 5 or 10% less than unimpacted growth rate** **(P(IGR<2.5))** **Section 3.2.12**	From 0 – 1, with 0 indicating that none of the simulations from a stochastic model show the impacted population growth rate being a given magnitude below the unimpacted population (i.e. no population-level consequence) and 1 indicating that all simulations show the impacted population growth rate a given magnitude below the unimpacted population.	With growth rates simulated from stochastic models, it may be desirable to estimate a mean or median value for the unimpacted population and calculate the proportion of simulations in which the growth rate of the impacted population is lower, or a given percentage lower, than this value. This approach has the advantage of allowing a probabilistic forecast of the impact of the offshore wind farm on a population, e.g. there is a 50% chance that the wind farm will reduce the population growth rate by 10%.
11	**Overlap of Impacted and Unimpacted Populations** **(OI:U)** **Section 3.2.13**	From 0 – 1, with 0 indicating that none of the simulated population sizes after 25 years from the stochastic model of the impacted population overlap with the simulated population sizes after 25 years from the unimpacted population and 1 indicating that all of the simulated population sizes after 25 years from the stochastic model of the impacted population overlap with the simulated population sizes after 25 years from the unimpacted population.	Using stochastic models, the population size at a fixed point in time (i.e. at the end of a project lifetime) may be expressed as a distribution. In these circumstances, it may be desirable to compare the distributions of the impacted and unimpacted populations. Where there is greater overlap between the two populations, impacts may be deemed less significant.

2.2 Sensitivity Analysis

2.2.1 Baseline Scenario

Initially, each metric listed above was derived for a baseline scenario, against which sensitivity to mis-specification of demographic parameters, model structure and the magnitude of any impacts could be considered.

Table 2. Parameters used in population models for r-selected and K-selected seabird species with stable, increasing or decreasing population trends (± 1SD).

	R-selected			**K-selected**
	Increasing	**Stable**	**Decreasing**	**Stable**
Age at first breeding	4			9
Initial Population Size	10,000 Breeding adults			
Sex Ratio	0.5			
Adult Survival	0.89 (± 0.085)	0.89 (± 0.085)	0.866 (± 0.024)	0.953 (± 0.030)
Immature Survival	0.850 (± 0.200)	0.741 (± 0.200)	0.741 (± 0.206)	0.845 (± 0.150)
First year Survival	0.441 (± 0.200)	0.441 (± 0.200)	0.358 (± 0.219)	0.845 (± 0.150)
Productivity	1.590 (± 0.175)	1.030 (± 0.175)	0.920 (± 0.175)	0.540 (± 0.089)

Rather than consider any particular species, we focused on a generic “r-selected” species and a generic “K-selected” species, with suitable demographic rates informed by a recent review of seabird demography (Horswill & Robinson 2015). Whilst we acknowledge that, in general, seabirds are K-selected species, there is variation in life history across the group as a whole. For example some, such as terns, may be considered to be more r-selected (lower survival rates, higher productivity rates), whilst others, for example fulmar or gannet, may be considered more K-selected (higher survival rates, lower productivity rates). For simplicity throughout this report we refer to these two groups as r-selected and K-selected respectively. We based demographic parameters for the r-selected species on those presented for terns and parameters for the K-selected species on those presented for northern gannet and northern fulmar *Fulmarus glacialis*, these species reflecting opposing ends of the life history spectrum occupied by seabirds.

This baseline scenario considered a stochastic population model for a stable population of an r-selected seabird species with the demographic parameters given in Table 2 and informed by a recent review of demography (Horswill & Robinson 2015). Following the guidance given in Horswill and Robinson (2015), for the stochastic models we sampled demographic parameters from distributions based on the mean values given in Table 2 and bounded by one standard deviation. Each metric is derived using a “matched runs” approach, as specified in WWT (2012) and Green (2014), whereby stochasticity is applied to the population, but the survival and productivity rates used for the impacted and unimpacted populations at each time step are the same, prior to any impact from an offshore wind farm being applied.

Table 3. Sources of uncertainty considered as part of sensitivity analysis of metrics used to quantify population level impacts of offshore wind farms on birds.

Population Trajectory	**R/K-selected species**	**Type of model**	**Parameter affected**	**Demographic parameter varied**	**Low (10%)/moderate (20%)/high (40%) impact**
Stable	R-selected	Deterministic	Survival	Adult survival	Low
					Moderate
					High
				Immature Survival	Low
					Moderate
					High
				Chick Survival	Low
					Moderate
					High
				Productivity	Low
					Moderate
					High
			Productivity	Adult survival	Low
					Moderate
					High
				Immature Survival	Low
					Moderate
					High
				Chick Survival	Low
					Moderate
					High
				Productivity	Low
					Moderate
					High
		Stochastic	Survival	Adult survival	Low
					Moderate
					High
				Immature Survival	Low
					Moderate
					High
				Chick Survival	Low
					Moderate
					High
				Productivity	Low
					Moderate
					High
			Productivity	Adult survival	Low
					Moderate
					High
				Immature Survival	Low
					Moderate
					High
				Chick Survival	Low
					Moderate
					High
				Productivity	Low
					Moderate
					High
		Density dependent impact on	Survival	MaxF	Low
					Moderate
					High

Population Trajectory	**R/K-selected species**	**Type of model**	**Parameter affected**	**Demographic parameter varied**	**Low (10%)/moderate (20%)/high (40%) impact**
		survival		Shape parameter (b)	Low
					High
		Density dependent impact on Productivity	Survival	MaxF	Low
					Moderate
					High
				Shape parameter (b)	Low
					Moderate
					High
Increasing	R-selected	Stochastic	Survival	NA	High
					Moderate
					Low
			Productivity	NA	High
					Moderate
					Low
Decreasing	R-selected	Stochastic	Survival	NA	High
					Moderate
					Low
			Productivity	NA	High
					Moderate
					Low
Stable	K-selected	Stochastic	Survival	NA	High
					Moderate
					Low
			Productivity	NA	High
					Moderate
					Low

Following discussion with the project steering group, we derived metrics from stochastic population models run over a 25 year time period for 1,000 iterations. It was not feasible to test every conceivable combination of impact, impact magnitude, demographic parameter, population trend, life history strategy and model structure. We therefore selected 77 scenarios (Table 3) from which general inferences could be drawn about the relationship between each metric and parameters to which they may be sensitive.

2.2.2 Deterministic or stochastic models

In a deterministic population model, each of the demographic parameters is assumed to have a single value, which is constant over time, whilst in a stochastic model each parameter is drawn from a distribution, with a different value prevailing in each simulated year. It has been argued that where there is significant uncertainty surrounding demographic parameters and the magnitude of impacts predicted from offshore wind farms, using deterministic models may be a more “honest” approach than using stochastic models (WWT 2012). This is because the confidence intervals presented surrounding the outputs from a stochastic model may imply a level of precision that the underlying data do not justify.

Initial simulations by Green (2014) suggest that there is little difference between metrics derived from deterministic models and equivalent metrics derived from stochastic models. However, stochastic models are inherently more conservative than deterministic models as environmental stochasticity causes the long-run growth rate to be below the mean growth rate (Lande *et al* 2003). Given the preference of some authors for deterministic models as a result of the uncertainty associated with demographic parameters (WWT 2012; Green 2014) it is important to understand the extent to which they may be less conservative than stochastic models.

Deterministic models do not produce the distribution of potential results necessary to estimate the probabilistic metrics. Therefore, comparisons between deterministic and stochastic models are restricted to the ratio based metrics derived from a stable population of an r-selected species. For each model we consider a 10% or 20% increase in mortality or a 10% or 20% decrease in productivity.

2.2.3 Sensitivity to impact

Whilst collisions would be expected to affect seabird survival rates, displacement may affect either survival or productivity rates. For example, displacement from a preferred feeding area may mean birds are unable to meet their energy requirements, resulting in a reduction in the survival rate (e.g. Searle *et al* 2014). Alternatively, if birds are unable to meet their energy requirements, they may abandon breeding attempts in the year concerned, resulting in an overall reduction in productivity rates. As K-selected species, seabird populations are thought to be more resilient to impacts on productivity than impacts on, especially adult, survival. For this reason we modelled impacts on survival and productivity separately. Following discussion with the project steering group, we considered impacts arising as a result of the presence of an offshore wind farm of up to a 40% increase in the mortality rate or up to a 40% reduction in the productivity rate, in line with the magnitude of impacts predicted for some offshore wind farms. Note that, in contrast to previous work (e.g. Searle *et al* 2014) these figures relate to a percentage of the mortality rate, rather than survival rates. Also note that it considers relative, rather than absolute increases in mortality or decreases in productivity, i.e. if baseline mortality were 10%, a 40% increase in mortality would give a total mortality rate of 14 % (i.e. 10% + 40% of 10%), not 50% (i.e. 10% + 40%).

A reduction in the productivity rate of 40% would lead to a change from 1.030 chicks fledging per nest in the absence of the wind farm, to 0.618 chicks/nest fledging in the presence of the wind farm. Assuming a stable population of an r-selected species with a starting size of 10,000 breeding adults, the baseline mortality rate (i.e. mortality in the absence of an offshore wind farm) would be 0.11, or 1,100 adult birds per annum. A 40% increase in the mortality rate would lead to an additional 440 deaths per annum and a total annual mortality of 1540 adult birds per annum. Under this scenario the annual mortality rate would increase from 0.11 to 0.15 and the survival rate would reduce from 0.89 to 0.85 (see below for calculations).

Population size:	10,000 breeding adults
Annual mortality:	(1-0.89) * 10,000 = 1,100 adults/year
40% increase in mortality:	1,100 * 1.40 = 1,540 adults/year
New mortality rate:	1,540/10,000 = 0.15
New survival rate:	1 – 0.15 = 0.85

Increased mortality rates were calculated on an annual basis, as using a single value for additional mortality (i.e. adding the additional mortality predicted for year 1 to each subsequent time step) would mean that mortality would not vary in proportion with the population size at each time step. As a consequence, additional mortality will vary from year to year across each simulation. In reality, population-level impacts will be greater than the 440 birds per annum given in the above example as this figure only relates to breeding adults and not juvenile, sub-adult or non-breeding adult birds. However, this approach is consistent with the way in which Habitats Regulations Assessments (HRA) are currently applied. HRA considers the impact of a development on a designated population which, at present, typically relates to the number of breeding adults at a protected site.

These initial analyses were used to investigate how each metric varied in response to up to a 40% increase in mortality and up to a 40% reduction in productivity.

2.2.4 Sensitivity to population trend

A key criticism made of metrics used to assess the population level consequence of impacts from offshore wind farms is that they are sensitive to the population trends of the species concerned (Green 2014). This may mean that decisions about whether or not the impacts associated with a wind farm may be deemed acceptable may be based on the population trend prior to construction (i.e. whether it was increasing, decreasing or stable) rather than the magnitude of the population-level consequences associated with the wind farm.

In order to evaluate how each metric varied in response to current population status we adjusted the population models using biologically plausible values (Table 2) determined from the review of seabird demography by Horswill and Robinson (2015) in order to give increasing and declining trends. We compare the metrics derived from populations with increasing and declining trends with those derived from a stable population using stochastic models and assuming a 10% or 20% increase in mortality or decrease in productivity. Ideally metrics would have an identical value for a given magnitude of impact regardless of whether a population was increasing, stable or declining, prior to the assumed effect of the offshore wind farm.

2.2.5 Sensitivity to life history strategy

As described above, whilst seabirds are primarily K-selected species they cover a spectrum from species such as terns, with lower survival rates and higher productivity rates, to species like northern fulmar and northern gannet, with higher survival rates and lower productivity rates. Therefore, it is important to understand how the metrics may reflect differences in life history strategies.

To test this we compare the metrics derived using a stable r-selected species to those derived using a stable K-selected species with the demographic characteristics given in Table 2 and using stochastic models.

2.2.6 Sensitivity to mis-specification of demographic parameters

There is often significant uncertainty surrounding the demographic parameters used in the population models from which each metric is derived (Robinson & Horswill 2015). As a consequence, concerns have been raised that the metric may be highly sensitive to mis-specification of these parameters (Green 2014), and that small changes in the demographic rates considered may result in relatively large changes in the metric derived. Ideally, changes in the metric should primarily be driven by changes in the magnitude of the impact as opposed to mis-specification of the parameters used to derive the metric.

We consider the impact of mis-specifying adult survival, first year survival, immature survival and productivity by 1% in relative terms, to give a measure of the sensitivity of the metric to each parameter. We do this for both stochastic and deterministic models (where appropriate), assuming a stable population of an r-selected species and considering a 10% or 20% increase in mortality or decrease in productivity. We vary each parameter in turn by 1% and calculate the percentage change in the metric (regardless of whether it is an increase or decrease). Ideally, mis-specification of any of the demographic parameters should result in minimal change to the metric concerned and we assess this in relation to a subjective threshold of 1% of the parameter value.

2.2.7 Sensitivity to density dependence

Where seabird population sizes are reduced as a result of the effects from offshore wind farms, density dependent responses may partially compensate for any losses through increases in survival or productivity. In these circumstances, the inclusion of density dependence in any population models may lead to metrics which are less precautionary than those derived from population models which do not incorporate density dependence. Furthermore, whilst there is strong evidence for density dependent population responses in some seabirds (Horswill & Robinson 2015), there is considerable uncertainty about the form and strength of these relationships, as they will generally depend on processes acting at a site specific level. As a consequence, it is important to determine the extent to which the use of density independent models when deriving the metrics is a precautionary approach and, if density dependent models are to be used, the sensitivity of the metrics to assumptions about the form of that density dependence. Ideally, if density dependent models are to be used, metrics should be relatively insensitive to assumptions about its form.

In order to assess the impact of incorporating density dependence on the metrics we updated our population models for a stable population of an r-selected seabird species to incorporate density dependent regulation of productivity or survival. Using this approach, we estimated density dependent responses of productivity and survival to population size within a stochastic model. It was assumed that density dependent impacts on survival would apply only to adults at their breeding colonies where they are constrained as central place foragers (Thaxter *et al* 2012) and therefore less able to make use of alternative foraging habitats.

A variety of functions can be used to represent density dependent responses (Horswill & Robinson 2015), however, the Weibull function (Eq. 1) has been found to be a realistic representation across a variety of species (Cury *et al* 2011).

Equation 1. $D = maxD * \exp(-a * N^b)$

Where D is the demographic parameter under consideration (productivity or adult survival), $maxD$ is the biologically plausible maximum value for this parameter, informed by Horswill and Robinson (2015), N is the population size, a is a scale parameter and b is a shape parameter. We consider the sensitivity of each metric to both $maxD$ and b. The scale parameter, a, is estimated with reference to b, consequently it is inappropriate to consider sensitivity of the metrics to a in isolation. The relationship between the population size and productivity or survival for different values of the shape parameter and $maxD$ are shown in Figures 1 and 2.

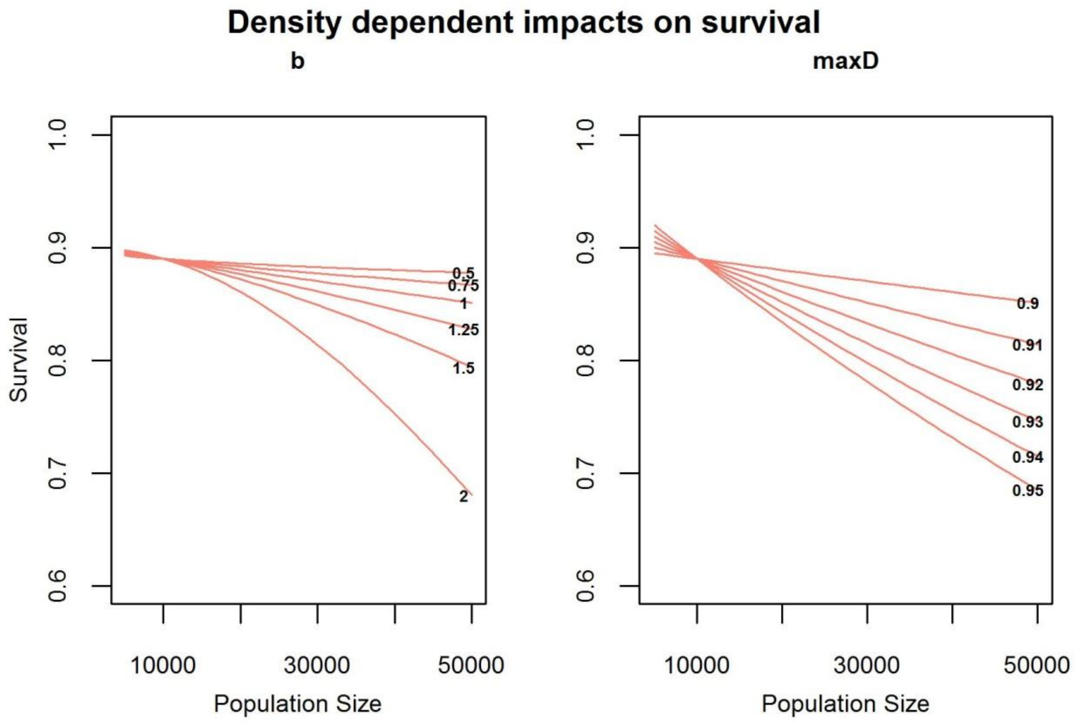

Figure 1. Density dependent relationship between survival and population size (number of breeding adults) for different values of the shape parameter, b (0.5, 0.75, 1, 1.25, 1.5, 2), assuming a maximum survival rate of 0.9 and the maximum survival rate (0.90, 0.91, 0.92, 0.93, 0.94, 0.95), assuming a value of 1 for the shape parameter.

Figure 1 shows how the adult survival rate changes for different values of *b* and *maxD*. This plot assumes a stable population with a carrying capacity of 10,000 breeding adults. Where the population drops below the carrying capacity, there are increases in the survival rate to compensate. Where the population rises above carrying capacity, the survival rate declines through mechanisms such as increased competition. The strength of the relationship between the survival rate and the population size is determined by both the shape parameter, *b*, and the maximum value permitted for survival, *maxD*. As the value assumed for the shape parameter *b* increases, the survival rate responds more quickly to changes in population size. Similarly, as the maximum value allowed for survival increases, so too does the strength of the relationship between population size and survival rate. Where the survival rate assumed in the population models is closer to the maximum allowable survival rate, there is less potential for it to increase and therefore less variability in relation to population size. Figure 2 shows how the population changes through time assuming density dependent regulation of survival with different values assumed for *b* and *maxD*. Over time, the population rises towards an asymptote, which reflects the carrying capacity of the population concerned. The shape parameter, *b*, determines the approximate size of the population at carrying capacity (and is therefore effectively the strength of the density dependent relationship) whilst the maximum allowable survival rate, *maxD*, influences variation around this population size.

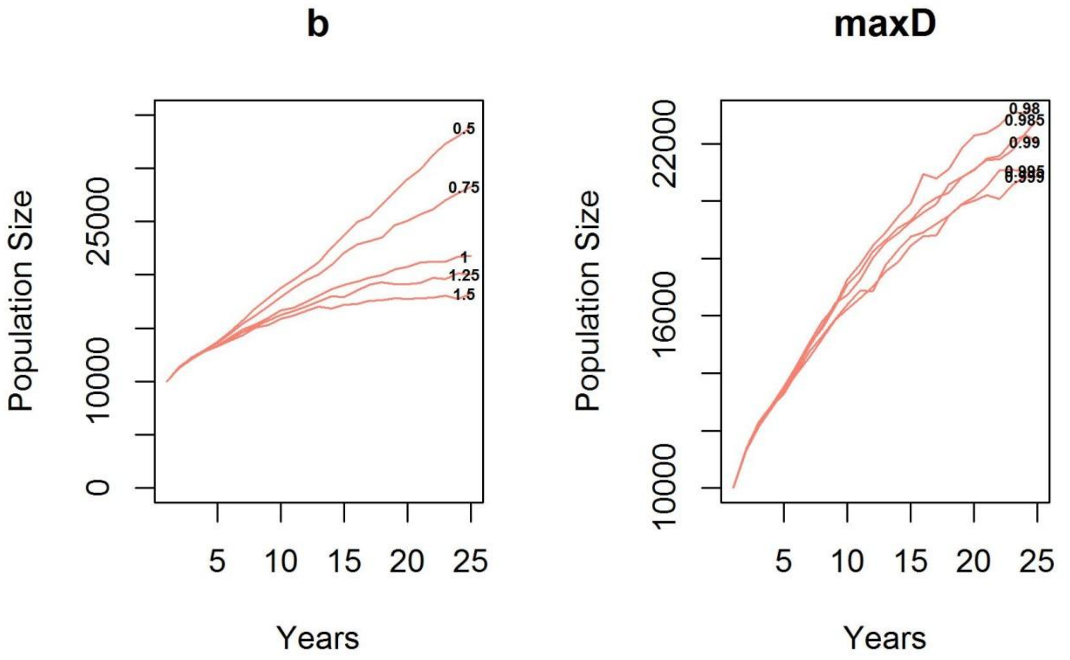

Figure 2. Influence of density dependent regulation of survival on population size through time. Models assume an increasing population based on the demographic parameters in Table 2. Left hand graph shows population trajectory for different values of the shape parameter *b* (0.5, 0.75, 1, 1.25 and 1.5) assuming a maximum survival rate of 0.98. Right hand graph shows population trajectory for different maximum survival rates (0.98, 0.985, 0.99, 0.995, 0.999) assuming a shape parameter of 1.

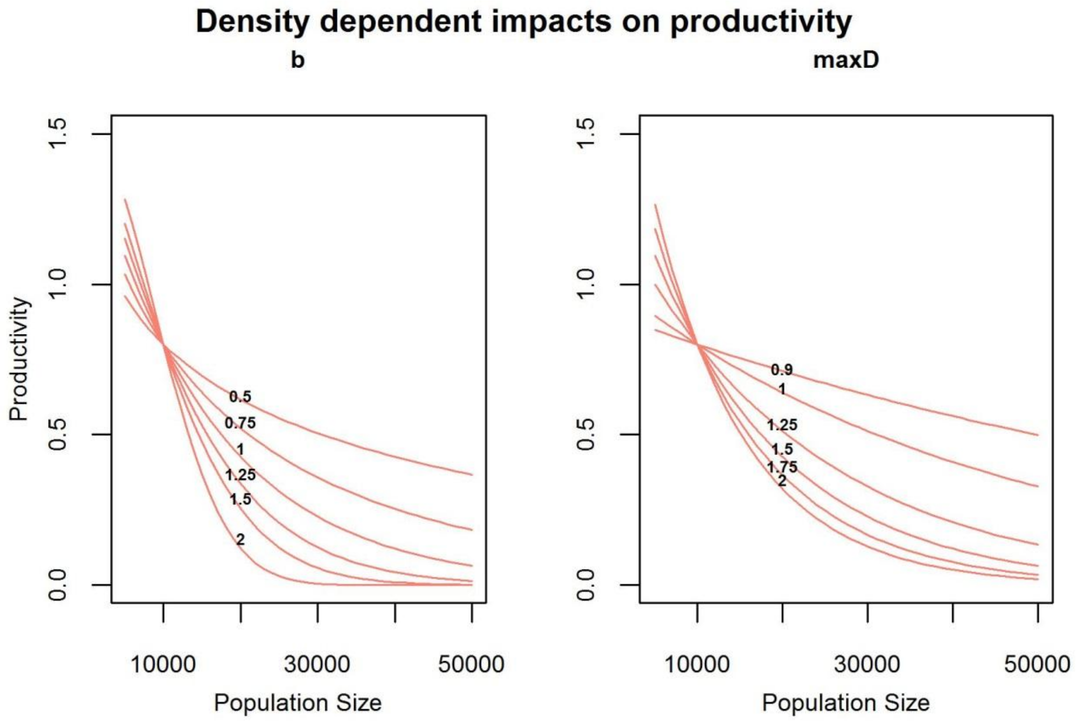

Figure 3. Density dependent relationship between productivity and population size for different values of the shape parameter, b (0.5, 0.75, 1, 1.25, 1.5, 2), assuming a maximum productivity rate of 1.5, and maximum productivity (0.9, 1 1.2, 1.3, 1.5, 1.75, 2), assuming a value of 1 for the shape parameter.

Figure 3 shows how the productivity rate varies in response to changes in population size. As with survival, where the population drops below its carrying capacity, there is an increase in productivity to compensate. Similarly, where the population size exceeds the carrying capacity, there is a drop in the productivity rate as a result of factors such as increased competition for food, nest sites or nest predation from con-specifics. However, it is noticeable that the density dependent relationship between productivity and population size is much more pronounced than that for survival (Fig. 1). This pattern is likely to reflect the fact that productivity rates are more variable than survival rates (Horswill and Robinson 2015). For higher values of *b* and *maxD*, as the population size rises above the carrying capacity, the productivity rate quickly declines to 0, suggesting that, in these cases, density dependence means large populations may fail to produce any chicks in a given year. Figure 4 shows how the population changes through time assuming density dependent regulation of productivity with different values assumed for *b* and *maxD*. Over time, the population rises towards an asymptote, which reflects the carrying capacity of the population concerned. The shape parameter, *b*, determines the approximate size of the population at carrying capacity whilst the maximum allowable productivity rate, *maxD*, influences variation around this population size.

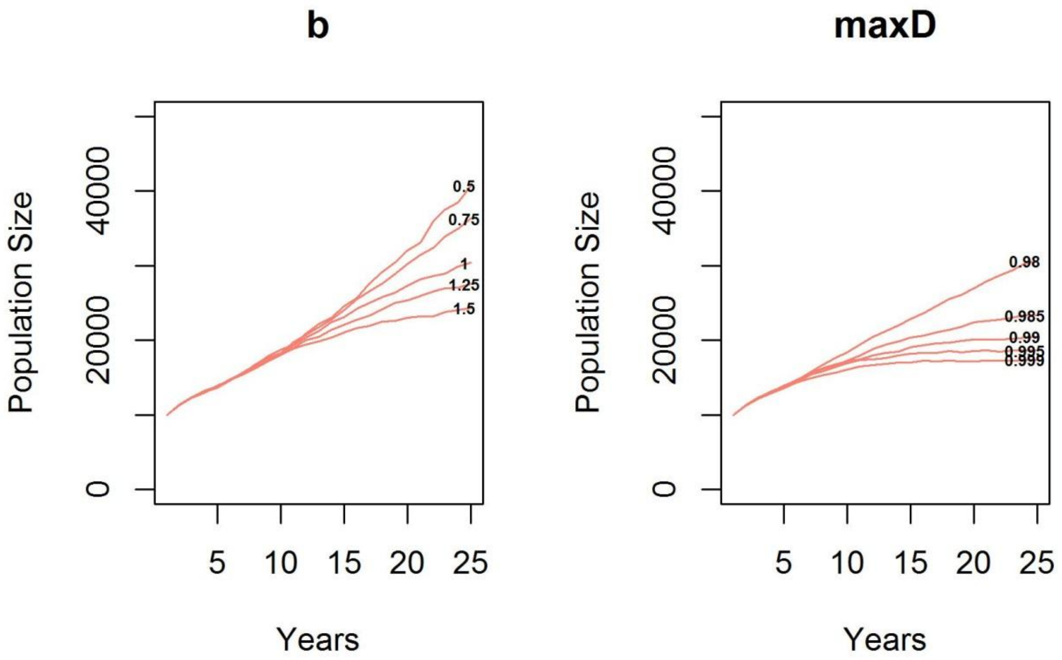

Figure 4. Influence of density dependent regulation of productivity on population size through time. Models assume an increasing population based on the demographic parameters in Table 2. Left hand graph shows population trajectory for different values of the shape parameter *b* (0.5, 0.75, 1, 1.25 and 1.5) assuming a maximum survival rate of 0.98. Right hand graph shows population trajectory for different maximum survival rates (0.98, 0.985, 0.99, 0.995, 0.999) assuming a shape parameter of 1.

To test the influence of density dependence on the metrics we consider, we compare metrics derived from density dependent stochastic models of an r-selected seabird with a stable population size to metrics derived from density independent stochastic models of the same population. We consider density dependent regulation of survival and productivity separately. We also consider sensitivity to assumptions about the shape parameter and maximum value selected for each demographic parameter.

2.3 Population Models

In order to test sensitivity to each of the factors listed above, we built seven different population models based on the demographic parameters set out in Table 2:

- a deterministic population model for a seabird with the characteristics of an r-selected species with a stable population
- a stochastic population model for a seabird with the characteristics of an r-selected species with an increasing population
- a stochastic population model for a seabird with the characteristics of an r-selected species with an stable population
- a stochastic population model for a seabird with the characteristics of an r-selected species with a declining population
- a stochastic population model for a seabird with the characteristics of a K-selected species with a stable population
- a stochastic population model with a density dependent response to productivity for a seabird with the characteristics of an r-selected species
- a stochastic population model with a density dependent response to survival for a seabird with the characteristics of an r-selected species

The purpose of these analyses was to examine general patterns and trends in each of the metrics as opposed to considering sensitivity to every conceivable combination of parameters. We use a stochastic population model for a stable r-selected population as a basis for comparing the sensitivity of each metric to demographic parameters. Useful metrics would be expected to respond in a similar fashion across different models, for example metrics derived from a declining population of a K-selected species would be expected to show a similar pattern to metrics from a declining population of an r-selected species. By restricting the analyses to a limited subset of models and extrapolating across them, we aim to simplify the interpretation of the results, aiding clarity by drawing broad conclusions about expected patterns in the metrics as opposed to a detailed discussion covering every possible combination of sources of sensitivity.

As described above, following discussions with the project steering group about selecting realistic levels for simulated effects arising as a result of impacts from offshore wind farms, we considered up to a 40% increase in mortality and up to a 40% reduction in productivity. It is worth noting that, in absolute terms, these figures reflect a greater effect on productivity than on survival. For example, assuming a stable population of an r-selected species (Table 2), a 40% decrease in productivity would result in a change from 1.030 chicks/nest to 0.618 chicks/nest. In contrast, a 40% increase in adult mortality would result in a decrease in the adult survival rate from 0.890 (1,100 deaths per year assuming a population of 10,000 adults) to 0.846 (1,540 deaths per year assuming a population of 10,000 adults). However, the purpose of these metrics is to determine what impact these changes have at a population level.

2.3.1 Deterministic population model for r-selected species

Population trends were simulated over a typical 25 year life time of an offshore wind farm using Leslie Matrix Models. Based on the review of Horswill and Robinson (2015), for the r-selected species we considered a model with four age-classes with annual survival transition probabilities between the ages of 0-1, 1-2, 2-3 and for an adult age class (Matrix *a*). Reproduction was confined to the adult age class:

$$a = \begin{Bmatrix} 0 & 0 & 0 & 0.515 \\ 0.441 & 0 & 0 & 0 \\ 0 & 0.741 & 0 & 0 \\ 0 & 0 & 0.741 & 0.890 \end{Bmatrix}$$

Matrix *a* assumes a stable population of an r-selected species with four age-classes. The top row reflects the annual productivity rate for each age class and is derived from half the productivity rate in Table 2, to give per individual productivity as opposed to a per pair productivity. The values on the diagonal give the survival probability for each of the immature age classes, and the final value the adult survival rate, i.e. the rate at which adults continue to be (living) adults.

This model can be thought of as a post-breeding census of the population concerned, with the first age class giving the number of birds that fledged per breeding individual that calendar year. For the unimpacted population, each bird has the probability of surviving until the next calendar year given in the diagonal of matrix *a*, where each adult will raise the number of chicks given in row 1, column 4 to fledging. For the impacted population, at each 1-year time step, impacts of an additional mortality of between 0 and 40% across all age classes or a reduction in productivity of between 0 and 40% were applied.

2.3.2 Stochastic population model for r-selected species

The format of the stochastic population models is similar to that given above in matrix *a* for the deterministic model. The key difference is that an element of random variation is introduced into the model by sampling each demographic parameter from a distribution for each iteration (year) of the model, rather than assuming a fixed value across all iterations. The model is then run many times (in our case, 1000) in order to give an indicative trend for the population concerned and an estimate of the uncertainty surrounding that trend.

Two types of stochasticity can be incorporated within the models, demographic stochasticity and/or environmental stochasticity. Demographic stochasticity can be considered to be variation between individuals (e.g. variation in individual quality), which affects likelihood of transition between states (age classes). Environmental stochasticity can be considered to be variation arising as a result of changes in the environment (e.g. between year differences in weather conditions) affecting all individuals within a group. Environmental stochasticity is considered to be more important than demographic stochasticity, particularly in the case of large populations (Lande 1993; Fox & Kendall 2002); for this reason, in our analyses we only consider environmental stochasticity.

Environmental stochasticity was incorporated into the models by considering one standard deviation around the mean values given for each parameter (Table 2). The survival rate must be bounded by 0 and 1; therefore it was sampled using a logit-link. Similarly, productivity cannot be less than 0; consequently it was sampled using a log-link. A matched runs approach was used to compare the impacted and unimpacted populations. For each iteration, a productivity rate and a survival rate for each age class was simulated. These productivity and survival rates were then used to estimate the size of the unimpacted population. To estimate the size of the impacted population, as described above for the deterministic model, impacts of a 0-40% increase in mortality or reduction in productivity were then applied to these simulated rates.

2.3.3 Stochastic population model for increasing or decreasing r-selected species

In order to extend these models to consider how the metrics responded to populations that were increasing or decreasing, we adjusted the demographic parameters given in matrix *a* above using biologically plausible values identified in Horswill and Robinson (2015). Through trial and error, we aimed to identify a combination of demographic parameters that would result in a moderate increase of roughly 5% per year and a decrease of roughly 5% per year; which would result in the population doubling, or halving, in approximately 14 years. This was achieved using matrix *b* for an increasing population and matrix *c* for a declining population.

$$b = \left\{\begin{matrix} 0 & 0 & 0 & 0.795 \\ 0.441 & 0 & 0 & 0 \\ 0 & 0.850 & 0 & 0 \\ 0 & 0 & 0.850 & 0.890 \end{matrix}\right\}$$

$$c = \left\{\begin{matrix} 0 & 0 & 0 & 0.460 \\ 0.358 & 0 & 0 & 0 \\ 0 & 0.741 & 0 & 0 \\ 0 & 0 & 0.741 & 0.866 \end{matrix}\right\}$$

We incorporated stochasticity as described above, and considered impacts of a 0-40% increase in mortality or decrease in productivity.

2.3.4 Stochastic population model for an r-selected species incorporating density dependent impacts on survival or productivity

In order to extend these models to incorporate the density dependent regulation of survival or productivity, we used the Weibull function (Equation 1), as described above, to estimate productivity and survival rates given the estimated size of the impacted and unimpacted populations at each time step. As described above, in the case of the unimpacted populations these values were used to estimate population size. In the case of the impacted populations, an additional mortality of between 0 and 40% or a reduction in productivity of between 0 and 40% was then applied before estimating population size. For simplicity, it was assumed that density dependent regulation of survival would only occur in adult birds as other age classes may be less constrained in their foraging areas and are therefore, less likely to be affected by competition.

2.3.5 Stochastic Population Model for K-selected species

In order to consider how the metrics may change in response to a more K-selected species we used Horswill and Robinson (2015) to identify a range of biologically plausible values for a species at the opposite end of the seabird life history spectrum from those considered above. Based on this review, we consider a nine age class model with higher survival rates and lower productivity rates than described above (matrix *d*).

$$d = \left\{ \begin{matrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.270 \\ 0.845 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.845 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.845 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.845 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.845 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.845 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.845 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.845 & 0.953 \end{matrix} \right\}$$

2.3.6 Additional Analyses

For promising metrics, we undertook some further analyses to allow us to more carefully consider their suitability. Concern has been raised that the value estimated for a metric may be determined by uncertainty surrounding the demographic parameters used in the population models (Green 2014). Non-biological factors, such as sampling variance, may make a significant contribution to the total variance associated with demographic parameters (Gould & Nichols 1998). In addition, these parameters may not be estimated over a sufficient time period in which to capture the true variability of any population (Lande *et al* 2003). We recalculate these metrics based on distributions of adult survival rates using a fixed mean estimate (0.89, see Table 2) and a range of values for the standard deviation informed by the review of Horswill and Robinson (2015). The resulting distributions are shown in Figure 5. Ideally, the metrics calculated should have similar values, regardless of the distribution used to estimate adult survival, indicating that populations are responding to the impacts associated with offshore wind farms, rather than uncertainty in demographic rates.

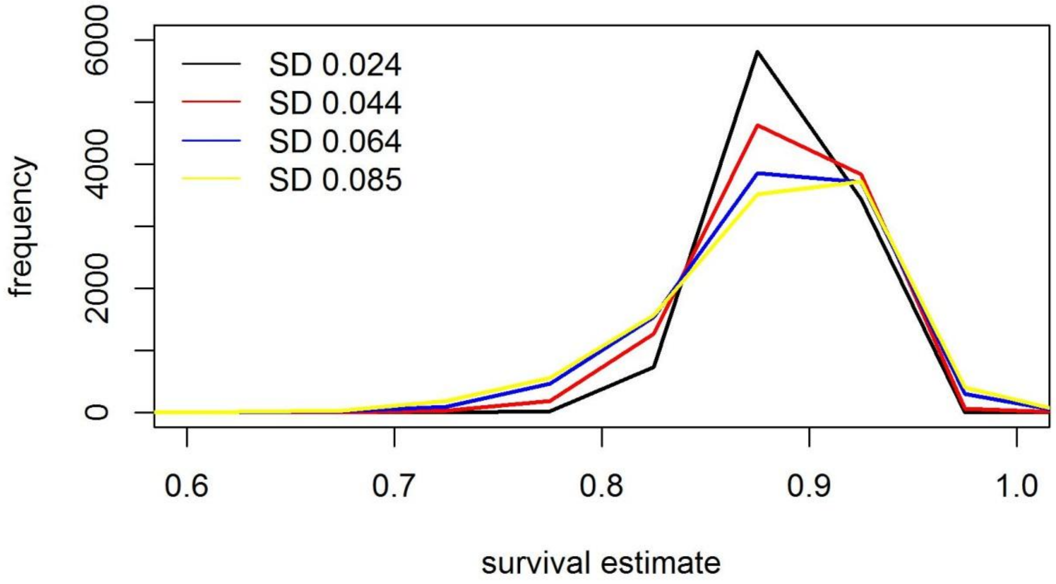

Figure 5. Frequency distributions estimated for adult survival rates based on a mean of 0.89 and standard deviations of 0.024, 0.044, 0.064 and 0.085.

Metrics may be calculated at different points in time (e.g. five years post-construction, 10 years post-construction etc.) meaning it is possible to have a snapshot of what population level impacts are likely to be at any point in the lifetime of the wind farm. However, it is unclear whether sensitivity of the metrics to demographic parameters may vary in time. For example, over a longer time period, variation in demographic parameters may average out meaning metrics would be expected to be less sensitive to mis-specification of demographic parameters at the end of a project lifetime than at earlier stages of the project. We test this for periods of five and 10 years post-construction in relation to adult survival, and compare these values to those obtained in the earlier analyses for 25 years post-construction.

Finally, we more closely examine how incorporating density dependence into population models influences the final metrics. Firstly, we consider how sensitive density dependent models are to mis-specification of adult survival, following the approach take in section 2.2.6. If density dependent models are to be used, then ideally they should be no more sensitive to mis-specification of adult survival than density independent models.

Density dependence may also influence a metric’s sensitivity to population trend, for example where a population is increasing, density dependent processes may cause growth rates of impacted and unimpacted populations to be equalised. We therefore consider the sensitivity of selected metrics to population trend, when derived from a density dependent model. Lastly, we consider how incorporating density dependence influences the metrics through time.

2.4 Assessing the value of metrics

In order to determine how robust different metrics are to uncertainty, it is important identify key criteria against which each metric should be assessed. Following a discussion with the project steering group, it was agreed the criteria for assessing the metrics should be:

- Have a consistent response to the magnitude of the estimated impact (i.e. the relationship between the magnitude of the impact and the metric should be linear)
- Have a clear relationship with the magnitude of the impact (i.e. there should be a noticeable change in the metric in response to impacts of increasing magnitude)
- Insensitive to mis-specification of the input demographic parameters (see section 2.2.6)
- Insensitive to population trend (see section 2.2.4)
- Insensitive to the incorporation of density dependence (see section 2.2.7)
- Insensitive to uncertainty in the form of density dependence (see section 2.2.7)
- Insensitive to whether it is derived from a deterministic or stochastic model (see section 2.2.2)

Ideally, metrics should have a clear and consistent relationship with the magnitude of the estimated impact in order to help interpret the population-level consequences of any impact. Such a relationship will help decision makers understand what the extent of the risk of over or underestimating the severity of any population level effect is. For example, in Figure 6, we consider two possible relationships between a metric and the magnitude of the impact under consideration. If there is a consistent linear trend between the metric and the magnitude of the impact under consideration, it is easier to predict what the effect at a population level will be of an increase or decrease in the magnitude of the predicted impact. In contrast, if there is a curved relationship between the metric and the magnitude of the impact, extrapolating the metric value for an increase or decrease in the impact will be less straightforward as the rate of change will differ between high and low impacts.

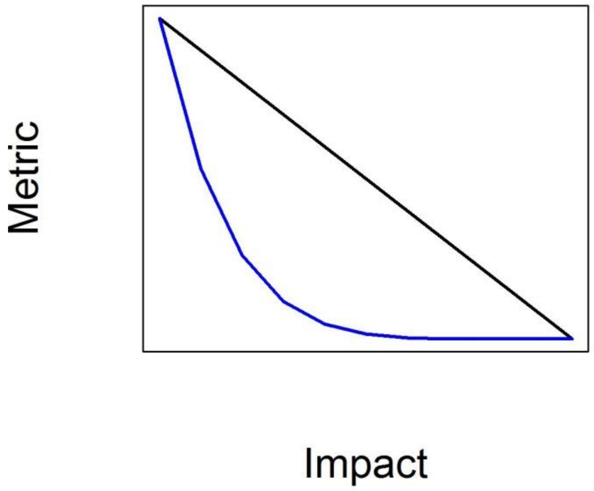

Figure 6. Possible linear or non-linear relationships between metrics used to assess the population-level consequences of impacts from offshore wind farms and the magnitude of the impacts concerned.

Given the uncertainties in the data used to derive these metrics, it is important the relationship between the metric and the magnitude of the impact is clear. For example, in the case of the straight line in Figure 6, this should have a steep gradient. If the gradient is less steep, then the limited range of values over which the metric operates may mean that significant effects at a population level are masked by relatively minor changes in the metric value. Additionally, it may be difficult to determine the extent to which any change results from an increase in the magnitude of the impact as opposed to uncertainty in the demographic parameters used in the population models. Linked to this, it is important that the metrics are insensitive to mis-specification of the demographic parameters used in population models. If metrics are sensitive to mis-specification of demographic parameters, it may lead to inappropriate conclusions, or not, as a result of incomplete knowledge of the demography of the species concerned. Metrics may also be sensitive to the degree of uncertainty surrounding estimates of demographic parameters. Whilst it is important to understand this sensitivity, we felt that it was less important than the sensitivity to the mis-specification of the demographic parameters themselves. For this reason, we restricted analysis of the sensitivity to the level of uncertainty surrounding demographic parameters to metrics which had performed strongly in relation to other criteria.

Seabird populations are known to be affected by immigration (the recruitment of breeding birds from elsewhere) and emigration (the loss of breeding birds to other populations). Metrics used to assess the population consequences of impacts from offshore wind farms may be sensitive to these changes. However, immigration and emigration will be reflected at a population level by changes in the number of breeding adults present. These changes would be similar to an increase (immigration) or decrease (emigration) in the adult survival rate. For this reason, we felt it would be more appropriate to focus on changes in survival as part of our sensitivity analysis, rather than considering immigration or emigration directly.

The purpose of these metrics is to understand what the population level impact of the wind farm is, after all other factors have been accounted for. For this reason, it is important that metrics are insensitive to population trend so that the metric reflects the impact of the wind farm, as opposed to the status of the population concerned. This means that, for impacts of a similar magnitude, metrics for a population that was increasing prior to the construction of the wind farm should have the same value as those for a population that was decreasing prior to the construction of the wind farm. However, such an approach does not preclude taking population trends into account when assessing the impact of a development at a population level. For example, it would be possible to specify that a more severe population level effect was permissible if that population were increasing, rather than stable or declining.

For similar reasons it is desirable that metrics should be insensitive to the incorporation of density dependence and the form of any density dependence assumed. The latter is particularly important given uncertainty over the forms of density dependence that may be present in seabird populations (Horswill & Robinson 2015). For example, if density dependence were depensatory (reduction in survival/productivity in response to reductions in population density) this would mean that impacted populations would be expected to decline more quickly than unimpacted populations.

Finally, ideally metrics should be unaffected by whether they are derived from a deterministic or stochastic population model to minimise the uncertainty which may arise if one approach suggests an impact may be acceptable and the other approach suggests that it is not. As described above, the metrics should focus on the population effects of offshore wind farms, once all other factors have been accounted for. This means that ideally, where the same demographic parameters are used, and impacts are of the same magnitude, the metrics derived should be the same, regardless of whether a stochastic or a deterministic model is used. However, it is important to note that probabilistic metrics cannot be derived from deterministic models.

2.5 R Code

All models were developed in the R statistical package (R-project 2015), and the code used is available as an electronic appendix to this report. The code used for the population models was written in consultation with the BTO Ecological Statistician, Dr Alison Johnston.

3 Results

Each of the metrics described in Table 1 was derived from a population model. The population models used to derive these metrics are presented below in section 3.1. The metrics themselves and their sensitivity to different parameters, population trends and model structures are then presented in section 3.2, with the key findings and recommendations presented in sections 3.2.1 and 3.2.2. The first metric text (Section 3.2.3) contains guidance on how to interpret the results presented in assessment of each metric.

3.1 Population Models

3.1.1 Deterministic population model for a seabird with the characteristics of an r-selected species with a stable population

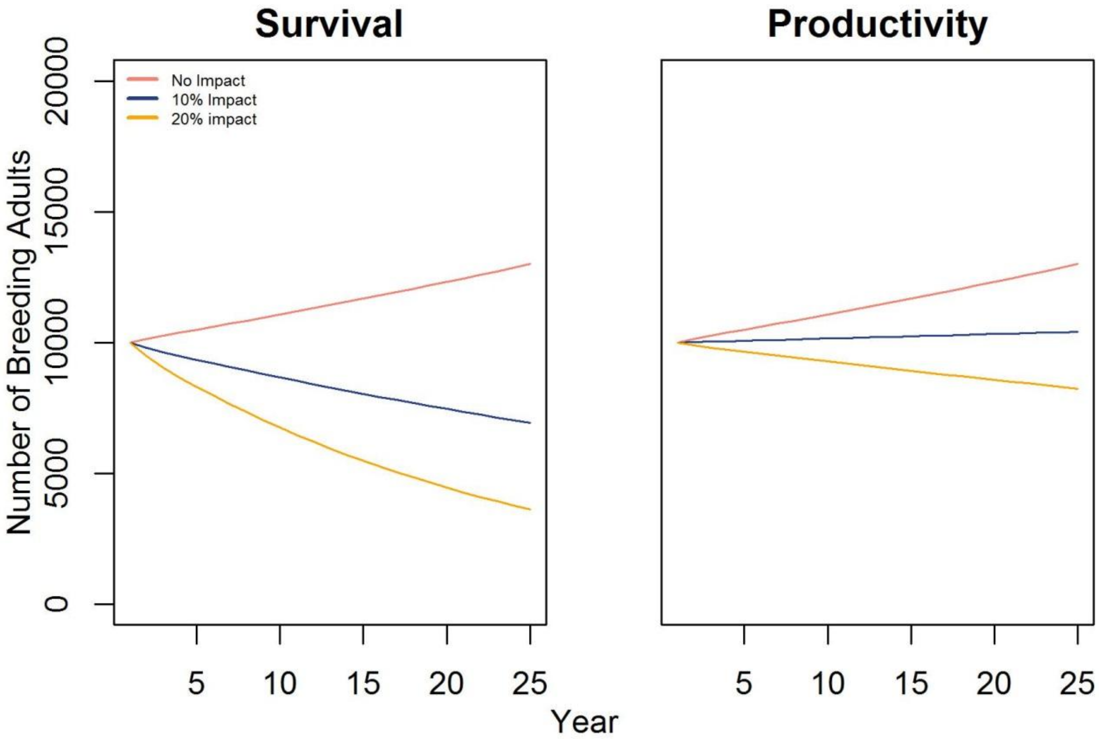

Figure 7. Deterministic population model for an r-selected seabird species with a stable population over 25 years. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph). Note that deterministic models are naturally less precautionary than stochastic models (Lande *et al* 2003).

Using a deterministic model, the growth rate of the unimpacted population was 1.010. Following a 10% increase in mortality, the growth rate fell to 0.985 and following a 20% increase in mortality the growth rate fell to 0.959. For impacts on productivity, a 10% reduction led to the growth rate falling to 1.001 and a 20% reduction led to the growth rate falling to 0.992 (Fig. 7, Table 4). Whilst a 10% reduction in productivity results in a growth rate that is closer to 1 than the baseline scenario, the baseline demographic parameters were selected as they resulted in both the deterministic and stochastic models having a growth rate close to 1 (i.e. essentially stable). Stochastic models naturally result in more conservative estimates of population size as the impact of environmental stochasticity generally causes the long-term growth rate to be less than the mean growth rate (Lande *et al* 2003). Consequently, parameters resulting in a slight increase in population size with a deterministic model would result in a slight decrease for a stochastic model. In order to compare metrics derived from deterministic and stochastic models, with all other factors being equal, we therefore selected demographic parameters that would result in a growth rate as close to 1 (i.e. a stable population) as possible.

Table 4. Population growth rates obtained from different models and different levels of offshore wind farm impact (95% CIs for Stochastic models).

	No Impact	Impact on Survival			Impact on Productivity		
		10%	20%	40%	10%	20%	40%
Deterministic, Stable, r-selected	1.010	0.985	0.959	0.908	1.001	0.992	0.971
Stochastic, Stable, r-selected	0.996 (0.961 – 1.028)	0.969 (0.933 – 1.004)	0.942 (0.907 - 0.976)	0.889 (0.843 – 0.928)	0.988 (0.958 – 1.016)	0.980 (0.951 – 1.008)	0.962 (0.935 – 0.987)
Stochastic, Increasing, r-selected	1.073 (1.037 – 1.109)	1.044 (1.006 – 1.080)	1.012 (0.966 – 1.053)	0.944 (0.881 – 1.001)	1.061 (1.027 – 1.095)	1.049 (1.017 - 1.082)	1.022 (0.993 – 1.051)
Stochastic, Declining, r-selected	0.952 (0.923 – 0.982)	0.922 (0.888 – 0.957)	0.891 (0.851 – 0.927)	0.829 (0.778 – 0.875)	0.945 (0.913 – 0.974)	0.938 (0.907 – 0.966)	0.922 (0.894 – 0.949)
Stochastic, Stable, K-selected	0.998 (0.978 – 1.017)	0.987 (0.966 – 1.007)	0.978 (0.957 – 0.998)	0.958 (0.935 – 0.979)	0.995 (0.977 – 1.014)	0.992 (0.975 – 1.011)	0.987 (0.971 – 1.003)
Stochastic, Stable, r-selected, Density dependent survival	1.002 (0.961 – 1.041)	0.986 (0.944 – 1.029)	0.972 (0.925 – 1.018)	0.939 (0.987 – 0.874)	0.997 (0.960 – 1.039)	0.993 (0.958 – 1.033)	0.984 (0.945 – 1.023)
Stochastic, Stable, r-selected, Density dependent productivity	0.997 (0.975 – 1.020)	0.983 (0.958 – 1.007)	0.965 (0.933 – 0.994)	0.916 (0.857 – 0.961)	0.994 (0.972 – 1.016)	0.990 (0.969 – 1.009)	0.982 (0.962 – 0.999)

3.1.2 Stochastic population model for a seabird with the characteristics of an r-selected species with a stable population

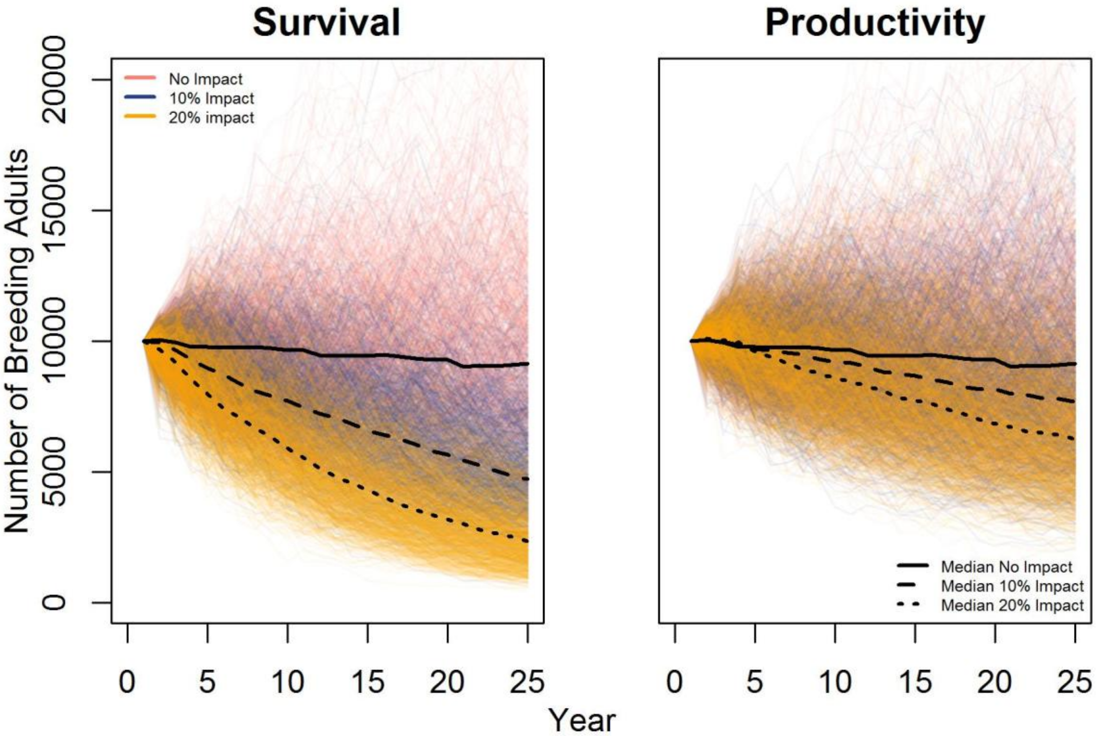

Figure 8. Stochastic population model (1000 bootstraps) for an r-selected seabird species with a stable population over 25 years. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph).

Stochastic population models were run over 1000 bootstraps. Each coloured line in Figure 8, above, represents population changes in a single model bootstrap run over 25 years. The red lines indicate populations exposed to no impact from offshore wind farms, the blue lines reflect a 10% impact from offshore wind farms and the orange lines reflect a 20% impact. Where effects have a strong impact at a population level, the red, blue and orange lines would be clearly distinguishable, as is the case for the plot on the left. Where the effects have a less severe impact at a population level, the lines would be less clearly distinguishable, as is the case for the plot on the right. In addition to each bootstrap, the black lines in Figure 6 show the median population trajectories under each scenario (solid lines = no impact, dashed line = 10% impact, dotted line = 20% impact). These roughly correspond to the median population growth rates shown in Table 4. The variance around these population trajectories can be inferred with reference to the individual bootstraps for each scenario; darker areas indicate more frequent population trajectories, paler areas those represented by fewer bootstrap runs. They show for example, that although impacts on productivity can result in reduced population sizes, with reasonable environmental variation the differences may be hard to distinguish. Even when there are relatively large impacts on survival the impacts may not be consistently manifested for several years, highlighting the need for consistent post-consent monitoring.

Using a stochastic model, the population growth rate of the stable population was 0.996. Following a 10% increase in mortality, this rate fell to 0.969 and 0.942 in response to a 20% increase in mortality. For a 10% reduction in productivity, the population growth rate fell to 0.988 and 0.980 in response to a 20% reduction in productivity. As explained above (section 3.1.1), using demographic parameters equivalent to those used in the deterministic model results in a relatively minor rate of decline, in comparison to the relatively minor rate of increase observed in the deterministic model. Based on the criteria described above, any metrics used to quantify the population level effects of impacts from an offshore wind farm would be insensitive to such differences.

3.1.3 Stochastic population model for a seabird with the characteristics of an r-selected species with an <u>increasing population</u>

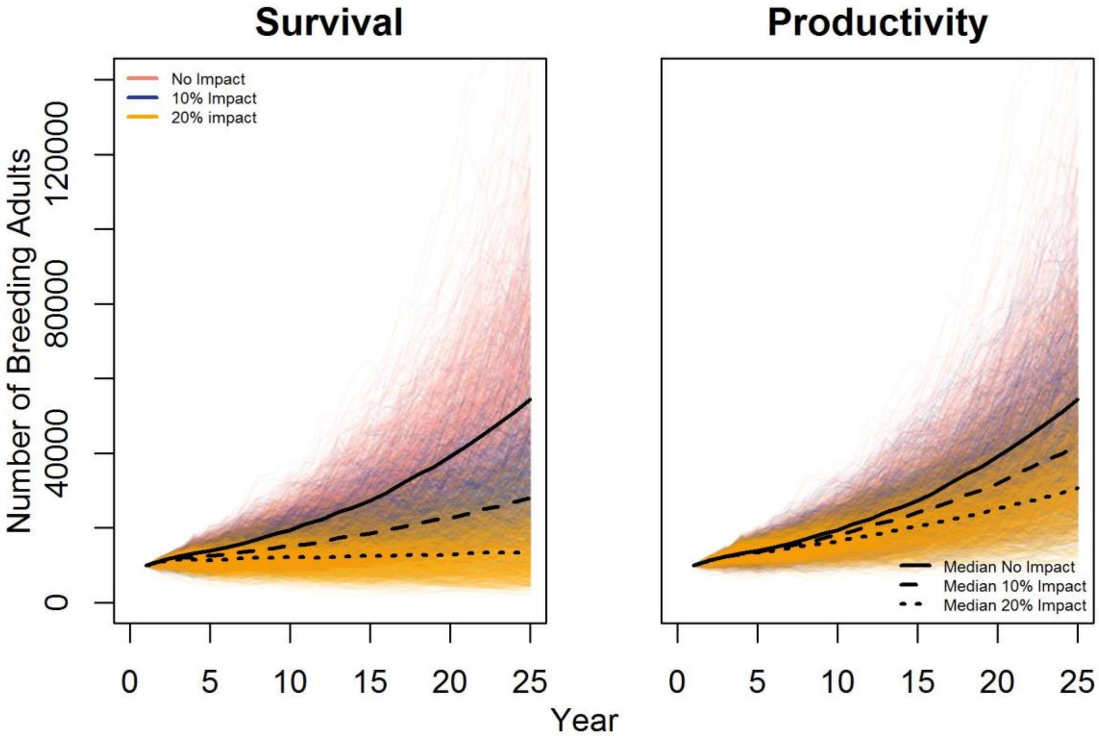

Figure 9. Stochastic population model (1000 bootstraps) for an r-selected seabird species with an increasing population over 25 years. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph).

Using a stochastic model, the population growth rate of the increasing population was 1.073 (Fig. 9). Following a 10% increase in mortality, this rate fell to 1.044 and 1.012 in response to a 20% increase in mortality. For a 10% reduction in productivity, the population growth rate fell to 1.061 and 1.049 in response to a 20% reduction in productivity.

3.1.4 Stochastic population model for a seabird with the characteristics of an r-selected species with a declining population

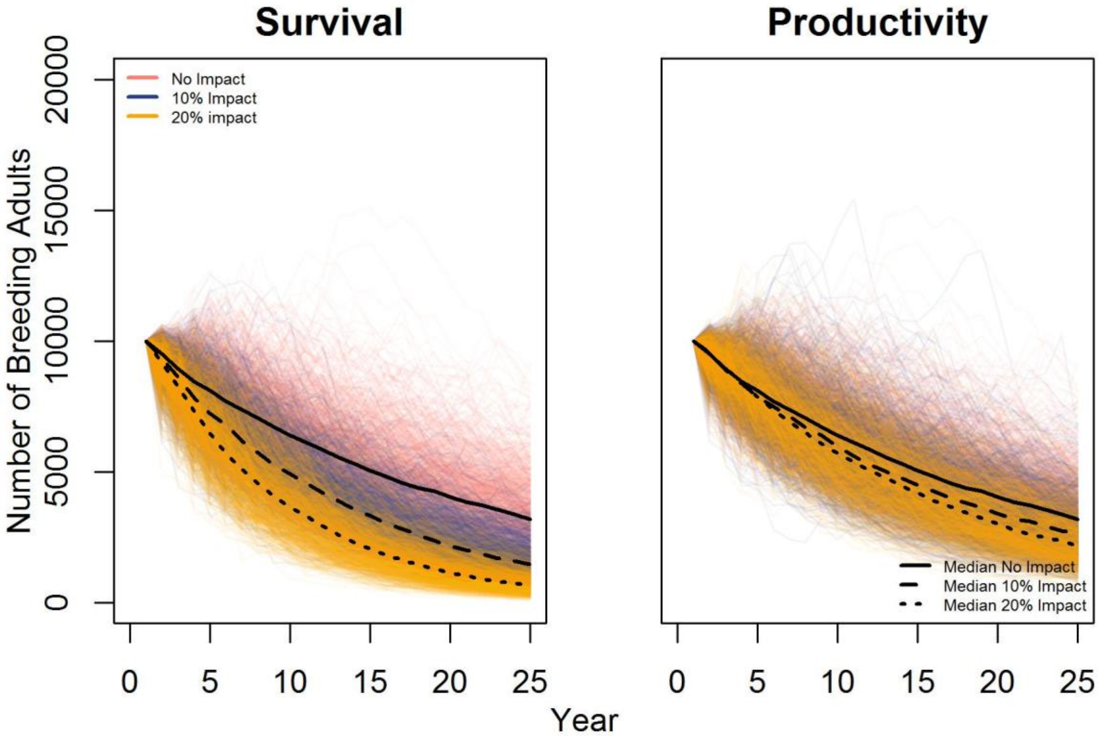

Figure 10. Stochastic population model (1000 bootstraps) for an r-selected seabird species with a declining population over 25 years. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph).

Using a stochastic model, the population growth rate of the decreasing population was 0.952 (Fig. 10). Following a 10% increase in mortality, this rate fell to 0.922 and 0.891 in response to a 20% increase in mortality. For a 10% reduction in productivity, the population growth rate fell to 0.945 and 0.938 in response to a 20% reduction in productivity.

3.1.5 Stochastic population model for a seabird with the characteristics of a K-selected species with a stable population

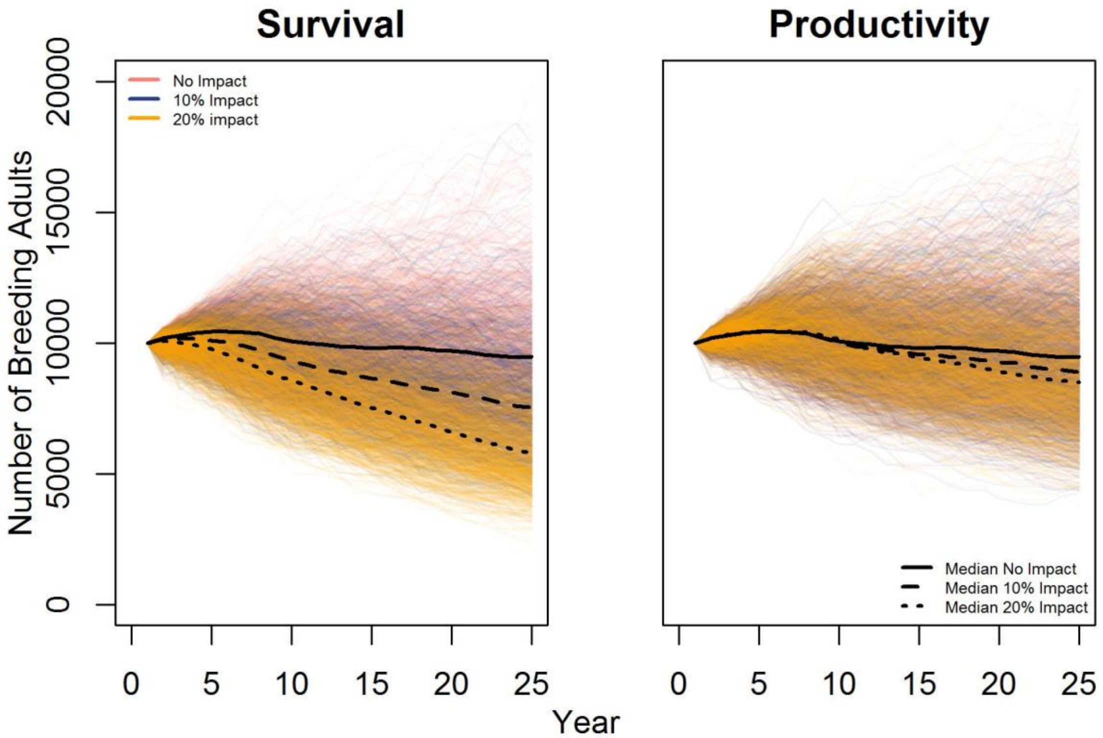

Figure 11. Stochastic population model (1000 bootstraps) for a K-selected seabird species with a stable population over 25 years. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph).

Using a stochastic model, the population growth rate of the stable K-selected population was 0.998 (Fig. 11). Following a 10% increase in mortality, this rate fell to 0.987 and 0.978 in response to a 20% increase in mortality. For a 10% reduction in productivity, the population growth rate fell to 0.995 and 0.992 in response to a 20% reduction in productivity. The greater overlap in the bootstrap population trajectories, indicate that impacts on productivity may be harder to detect than impacts on survival.

In comparison to a stable population of an r-selected species, populations of the K-selected species appear to be less affected by changes in survival and productivity. This means that the growth rate of the impacted K-selected species is likely to decline less than the growth rate of the impacted r-selected species. It is also worth noting that the longer generation times of the K-selected species mean that where productivity, rather than survival, is impacted, these changes will not become evident for a longer period than they would for an r-selected species.

3.1.6 Stochastic population model with a density dependent response to productivity for a seabird with the characteristics of an r-selected species

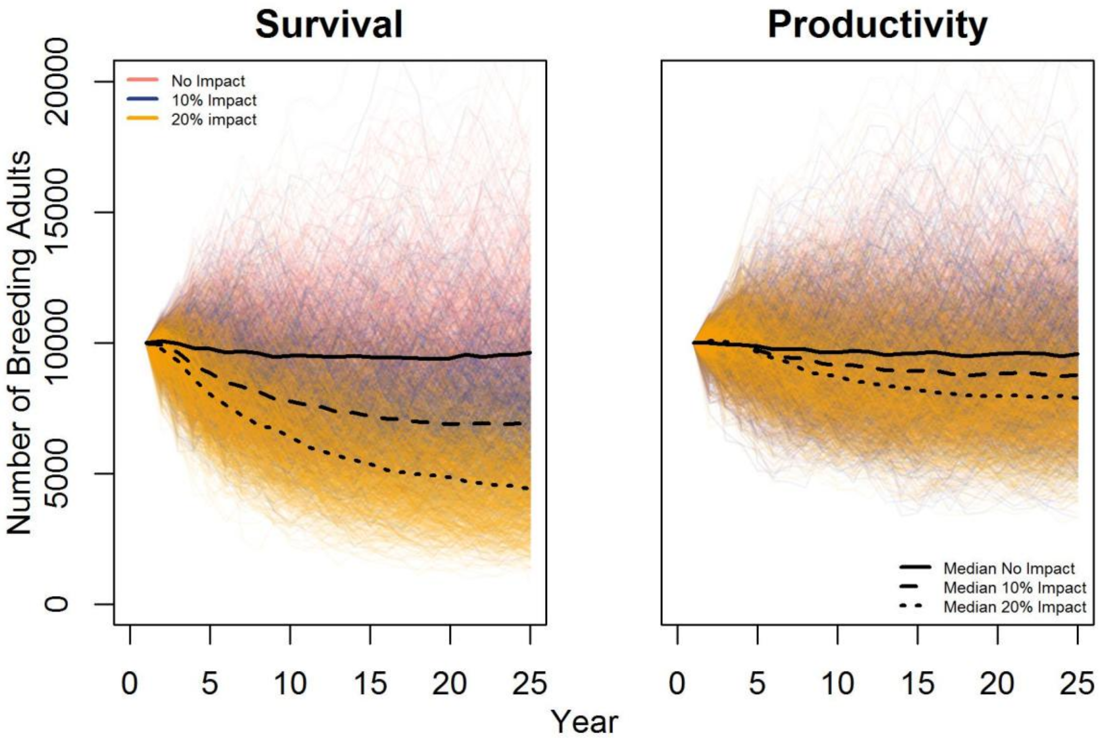

Figure 12. Stochastic population model (1000 bootstraps) for an r-selected seabird species with a stable population over 25 years assuming density dependent productivity. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph).

Assuming density dependent regulation of the population growth rate, changes in the population size are compensated for by changes in the productivity rate. As a consequence, when the population size decreases, for example as a result of the impacts arising from offshore wind farms, the productivity rate increases so that the population growth rate is maintained at a higher level than for a density independent model.

Using a stochastic model, the population growth rate over the 25 years of the study period for a stable population with density dependent regulation of productivity was 0.997 (Fig. 12), assuming a maximum productivity rate (maxD) of 1.5 chicks/nest and a shape parameter (*b*) of 1. Following a 10% increase in mortality, this rate fell to 0.983 and 0.965 in response to a 20% increase in mortality. For a 10% reduction in productivity, the population growth rate fell to 0.994 and 0.990 in response to a 20% reduction in productivity. For the reasons set out above, these growth rates are higher than were recorded for the density independent model of a stable r-selected seabird population (see section 3.1.2).

3.1.7 Stochastic population model with a density dependent response to survival for a seabird with the characteristics of an r-selected species

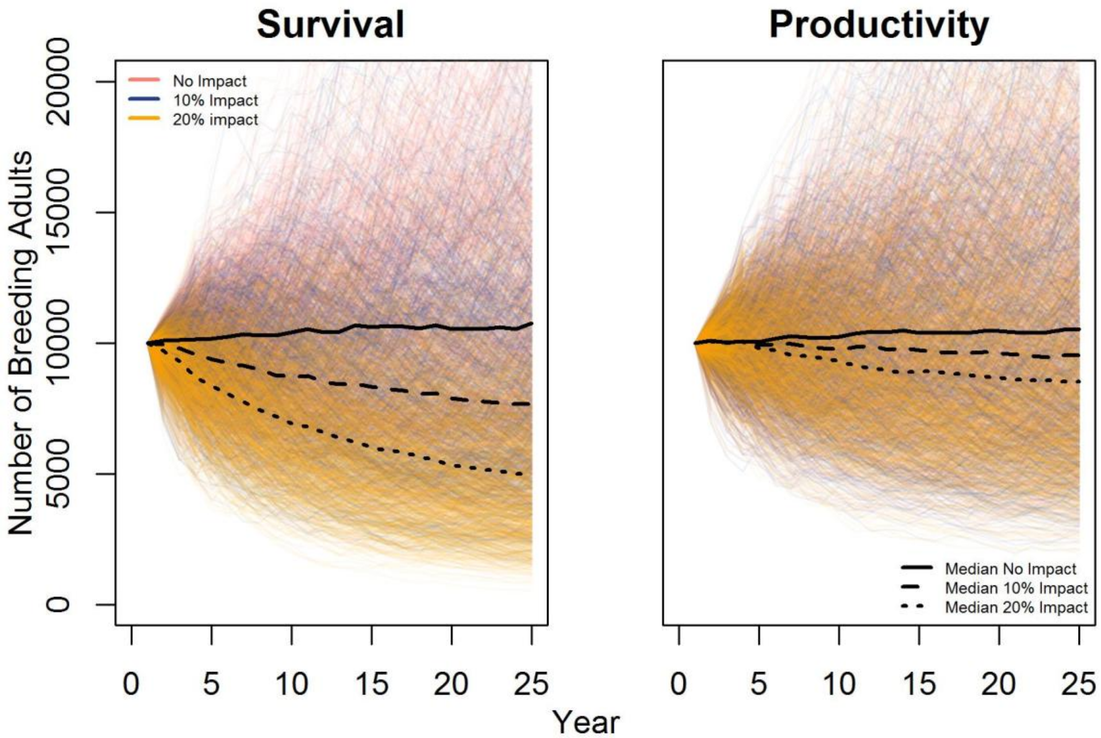

Figure 13. Stochastic population model (1000 bootstraps) for an r-selected seabird species with a stable population over 25 years assuming density dependent survival. Plots show the baseline (i.e. no impact scenario) as well as the impact of a 10% or 20% increase in mortality (left hand graph) and a 10% or 20% decrease in productivity (right hand graph).

Assuming density dependent regulation of the survival rate, changes in the population size are compensated for by changes in the survival rate. As a consequence, when the population size decreases, for example as a result of the impacts arising from offshore wind farms, the survival rate increases so that the population growth rate is maintained at a higher level than for a density independent model.

Using a stochastic model, the population growth rate of a stable population with density dependent regulation of survival was 1.002 (Fig. 13), assuming a maximum survival rate (maxD) of 0.98 and a shape parameter (*b*) of 1. Following a 10% increase in mortality, this rate fell to 0.986 and 0.972 in response to a 20% increase in mortality. For a 10% reduction in productivity, the population growth rate fell to 0.997 and 0.993 in response to a 20% reduction in productivity. For the reasons set out above, these growth rates are higher than were recorded for the density independent model of a stable r-selected seabird population (see section 3.1.2).

For both the density dependent scenarios, but especially where survival is density-dependent, in the face of environmental stochasticity, determining the consequences of the impacts becomes more difficult as there is less separation between bootstraps from each scenario (Fig’s 12 and 13).

3.2 Metrics for Population Level Impacts

3.2.1 Assessing the metrics

This section summarises the key findings from the sensitivity analysis of the eleven metrics listed in section 2.1.4, a more detailed summary of the results from the sensitivity analysis of each of these metrics is provided below in sections 3.2.3 – 3.2.12.

The metrics considered indicated that where effects of a similar magnitude operated on survival or productivity (e.g. a 20% reduction in productivity or a 20% increase in mortality), impacts on survival had a more significant impact at a population level. In reality, the life history strategies of seabirds mean that indirect impacts on survival (through displacement or barrier effects) are likely to be of a lower magnitude than effects on productivity as seabirds are likely to abandon breeding attempts in sub-optimal conditions and thus minimise impacts on survival (e.g. Monaghan *et al* 1989; Aebischer & Wanless 1992; Klomp & Furness 1992). Such situations may occur if birds are displaced from favoured foraging areas in response to the presence of an offshore wind farm. As a consequence, where impacts are on survival, metrics may reflect the lower end of the range of impacts considered here, whereas for impacts on productivity metrics may be towards the upper end of those considered.

Of the metrics we considered in this sensitivity analysis, none showed both a clear and a consistent response to impacts of increasing magnitudes (Table 5). A clear response makes it more straightforward to distinguish between population level consequences arising from impacts of differing magnitudes. For example, if metrics vary only over a limited range then relatively small changes in their value may mask more severe changes at a population level. Additionally, if metrics do not show a clear response to impacts arising as a result of offshore wind farms, it may be difficult to discern any effects from what would be expected in response to natural variation in the population concerned. However, this may be partly addressed through the use of matched runs, as advocated by Green (2014) and WWT Consulting (2012), in our analyses.

A consistent response facilitates understanding the relationship between the metric and the impact at a population level. It also allows us to more easily understand what the consequences of under or over-estimating the magnitude of any impact at a population level would be. For example, if there is a linear relationship between the metric and the magnitude of the impact, it is possible to quickly determine what the implications are of under or over-estimating the impact. This is less straightforward for a curved relationship as the implications of under of over-estimating the impact will depend on the magnitude of the impact predicted (see Figure 6), making the conclusion more vulnerable to mis-specification of the model parameters.

Of the metrics considered, only the population growth rate and the ratio of the impacted to unimpacted population growth rate showed a consistent linear relationship with impacts of increasing magnitude (Table 5). However, the confidence intervals associated with these metrics, in combination with the range over which they operate, meant that impacts arising as a result of the presence of an offshore wind farm could not be clearly detected unless they were particularly severe. In contrast, the ratio of the impacted to unimpacted population size after 25 years showed a clear response to the range of impacts considered. However, this response was asymptotic. Where an asymptote is reached, it can be difficult to distinguish between population level impacts of differing magnitudes. These metrics were similar regardless of whether they were derived from deterministic or stochastic models. None of the probabilistic metrics gave responses which were clear or consistent (Table 5).

Ideally the metrics should be able to separate the population level consequences of impacts from offshore wind farms from the underlying trend of the population concerned. For this reason, it is desirable that metrics should give the same value for a similar magnitude of impact, regardless of whether the population is stable, increasing or declining. Of the metrics considered, only probability of the population growth rate of the impacted population being 2.5% less than the population growth rate of the unimpacted population was insensitive to population trend (Table 5). However, this metric had no clear and consistent relationship with the magnitude of the impact concerned, making it more difficult to draw conclusions about the population consequence of any impact, and was particularly sensitive to mis-specification of the adult survival rate (Table 5).

Of the remaining metrics, most showed clear differences between populations which were stable and those that were declining and/or increasing. For example, the probability of a population growth rate being less than 1 changes from 0.968, for a 10% increase in mortality in a stable population, to 0.029 for a 10% increase in mortality in an increasing population (Section 3.2.6 Table 22), meaning it was not possible to separate the impact of the offshore wind farm from the underlying trend of the population concerned with this metric. However, these differences were less pronounced for the ratio of the impacted to unimpacted population growth rate and the ratio of the impacted to unimpacted population size after 25 years (Table 5). For the ratio of the impacted to unimpacted growth rate the values of this ratio for stable and increasing populations were the same (0.973) for a 10% increase in mortality, but decreased to 0.966 for a declining population (Section 3.2.4 Table 10). Whilst such a change may appear small, the resultant change in the growth rate over the lifetime of the project is likely to have a significant impact at a population level. For the ratio of the impacted to unimpacted population size after 25 years, for a 10% increase in mortality values for an increasing and stable population are similar (0.509 and 0.515 respectively), but decrease substantially (to 0.460) for a declining population (Section 3.2.5 Table 16).

Of the demographic parameters considered, all metrics were most sensitive to mis-specification of adult survival. As is often the case in long-lived species, variation in adult survival has the greatest impact on population growth rates (Lande *et al* 2003). However, the uncertainty surrounding estimates of adult survival can be lower than the uncertainty surrounding estimates of other demographic parameters, such as recruitment rates, as adult survival is generally easier to measure (Horswill & Robinson 2015). This greater uncertainty means other parameters are more likely to be mis-specified than adult survival and, as a result, it is desirable that metrics should be considerably less sensitive to them than to adult survival. This was true for every metric with the exception of the change in the probability of the population growth rate being <1 (Table 5). Even when considered over a realistic range (defined by the observed mean and standard deviation of each parameter, so accounting for the fact that adult survival rates are known more precisely) in percentage terms, mis-specification of adult survival still has a more significant effect on the final value than other demographic parameters for all metrics, with the exception of the probability of the change in the population growth rate being <1 (Table 5). Consequently, every effort should be made to obtain accurate and representative estimates of adult survival for the species concerned.

In general, the sensitivity of each metric to mis-specification of the parameters used in demographic models increases with the magnitude of the impact considered. This means that where impacts are likely to have a greater magnitude, there is likely to be greater uncertainty in the conclusions drawn about the population level consequences associated with the offshore wind farms. As the parameters used in the demographic models are mean values, mis-specification means that these impacts are as likely to under-estimated as over-estimated. Therefore, the values presented throughout this report reflect the impact of mis-specification in either direction.

Of the metrics considered, only population growth rate and the ratio of the impacted to unimpacted population growth rate were relatively insensitive to mis-specification of adult survival (i.e. a 1% mis-specification of adult survival resulted in <1 % change in the metric) (Table 5), with a 1% mis-specification of adult survival resulting in a 0.75% and 0.12% change in the two metrics respectively, assuming a 10% increase in mortality (Tables 4 and 5). Of the remaining metrics, the ratio of the impacted to unimpacted population size after 25 years and the probability that the population drops below its initial size at any point in time are less sensitive to mis-specification of adult survival than the others (Table 5). The probability of the growth rate being <1, the change in the probability of the growth rate being <1, the probability of a 25% decline and the change in probability of a 25% decline were also sensitive to mis-specification of the immature survival rate. Of those, the last three were also sensitive to mis-specification of chick survival and productivity as well (Table 5).

As might be expected, most metrics were sensitive to the incorporation of density dependence in the population models. The exceptions to this were the probability that the population was below its initial size at any point in time and the probability that the growth rate of the impacted population was 2.5% less than the unimpacted population (Table 5). Of the remaining metrics, sensitivity to density dependence reflected the range of values over which they operated. This meant that population growth rate, the ratio of the impacted to unimpacted population growth rate, the change in probability of the growth rate being <1 and the change in probability of a 25% decline were less sensitive to the incorporation of density dependence than the ratio of the impacted to unimpacted population size after 25 years, the probability of the growth rate being <1 and the probability of a 25% population decline. However, the metrics appeared to be relatively insensitive to the form of density dependence assumed, with similar population level consequences predicted regardless of the values assumed for the shape parameter, *b*, and the maximum level set for each demographic parameter. These results suggest that where there is good evidence about the presence and direction of any density dependent relationship in seabirds, it can be incorporated into population models and metrics generated may not be unduly sensitive to mis-specification of either the shape parameter or the maximum value for the demographic rate under consideration. However, it is important to note that density dependent relationships appear to operate on a highly site-specific basis and cannot be assumed to be present at all sites (Horswill & Robinson 2015).

Table 5. Assessment of metrics used to determine the population level effects of impacts from offshore wind farms on seabird populations. Colour indicates how well each metric matches each criterion – Light gray indicates close match, Dark gray indicates moderate match, black indicates poor match. Note that probabilistic metrics cannot be calculated from deterministic models, so the comparison between stochastic and deterministic models is not applicable for these metrics. Of the factors assessed, a clear and consistent relationship between the magnitude of the impact and the metric was considered to be key (highlighted by black outline around columns).

Metric (Acronym)	**Consistent** – see Figure 6, light gray indicates linear relationship, dark gray = curved relationship, black = stepped relationship	**Clear** – light gray, clear difference between metrics for impacts of increasing magnitude, dark gray, metric varies over a very narrow range, black the metric quickly reaches an asymptote when compared to impacts of increasing magnitude	**Insensitive to population trend** – light gray metrics identical regardless of population trend, dark gray <10 percentage change in metric in relation to population trend, black >10 percentage change in metric in relation to population trend	**Insensitive to Adult Survival** – light gray sensitivity to misspecification <1% for 10%l impacts on survival/productivity, dark gray sensitivity <5% for 10% impacts, black sensitivity >5% for 10 % impacts	**Insensitive to Immature Survival** – light gray sensitivity to misspecification <1% for 10%l impacts on survival/productivity, dark gray sensitivity <5% for 10% impacts, black sensitivity >5% for 10 % impacts	**Insensitive to Chick Survival** – light gray sensitivity to misspecification <1% for 10%l impacts on survival/productivity, dark gray sensitivity <5% for 10% impacts, black sensitivity >5% for 10 % impacts	**Insensitive to Productivity** – light gray sensitivity to misspecification <1% for 10%l impacts on survival/productivity, dark gray sensitivity <5% for 10% impacts, black sensitivity >5% for 10 % impacts	**Insensitive to incorporation of density dependence** – light gray median values the same for density dependent and independent, Dark gray <10 percentage change in metric between density dependent/independent, Black >10% change	**Insensitive to form of density dependence** – Light gray straight line regardless of values for *b* or maxD, dark gray wavy line, black clear +ve or –ve relationship	**Insensitive to Stochastic / deterministic model** – light gray median values the same for each model, dark gray <10% change between models, black >10% change between models
Population Growth Rate (GR)	░	▓	▓	░	░	░	░	▓	░	▓
Ratio of Impacted to unimpacted population growth rate (RI:U)	░	▓	▓	░	░	░	░	▓	░	▓
Ratio of impacted to unimpacted population size after 25 years (RI:U25)	▓	░	▓	▓	░	░	░	█	█	▓
Probability of growth rate being <1 P(GR<1)	▓	█	█	▓	▓	░	░	█	▓	
Change in probability of growth rate being <1 dP(GR<1)	▓	█	█	█	▓	▓	▓	█	▓	
Probability that population is below initial size at any point in time P(p<p$_0$)	▓	█	█	▓	░	░	░	▓	░	
Probability of a 25% population decline P(ld<0.25)	▓	█	█	▓	▓	▓	▓	█	█	
Change in Probability of a 25% population decline P(ld<0.25)	▓	█	█	█	▓	▓	▓	█	█	
Probability impacted population 50% below unimpacted population(P(I<25))	▓	█	█	▓	▓	▓	▓	█	█	
Probability that impacted population growth rate is 2.5% less than unimpacted population growth rate P(lgr>2.5)	▓	█	█	▓	▓	▓	▓	█	█	
Overlap of Impacted and Unimpacted Populations (OI:U)	▓	█	█	█	█	█	█	█	▓	

3.2.2 Recommendations

Our analyses suggest that metrics derived from deterministic models consistently predict lower population level consequences associated with the impacts of offshore wind farms than those derived from stochastic models. Given the differences between population level consequences predicted using deterministic and stochastic models and the fact that stochastic models are likely to be more realistic (Lande *et al* 2003), we suggest that metrics should be derived using stochastic models.

Incorporating compensatory density dependence into the population models can be considered to make the resulting metrics less precautionary. Horswill & Robinson (2015) found that density dependent effects were highly site-specific. For this reason, we suggest that compensatory density dependence should only be incorporated into models where there is sufficient evidence for it operating on the population concerned. Given our modelling suggests that predicted impacts may be reasonably robust to mis-specification of the relationship, the form of that relationship may not, necessarily, be important. Where density dependent processes are incorporated in population models, metrics should be estimated for the end of the project life cycle, so that the compensatory mechanisms of density dependence are accounted for. However, in small populations, depensatory density dependence may operate (Horswill & Robinson 2015). It is important that, where applicable, depensatory processes are incorporated into the population models in order to ensure any metrics are suitably precautionary.

We found that none of the metrics fulfil all of the criteria set out in section 2.4. Whilst we suggest that some metrics are better than others, we recognise that the selection of a metric with which to examine the population level consequences of an offshore wind farm may depend on the specific circumstances of the site concerned. With this in mind, in Table 6, we list each metric we have examined and outline the strengths and weaknesses of each approach, as well as suggesting how each should be used.

Notwithstanding the issues highlighted in Table 6, based on our analyses, we recommend that the ratio of impacted to unimpacted population growth rate (RI:U) and the ratio of impacted to unimpacted population size after 25 years (RI:U25) are likely to be the most generally useful metrics. However, RI:U varies over a limited range, meaning it may be difficult to distinguish between the between the population level consequences arising from impacts of different magnitudes, and RI:U25 has a non-linear relationship with impacts of increasing magnitude, making it harder to understand the consequences of incorrectly predicting the magnitude of any impact. For this reason, when assessing the population level consequences of impacts from offshore wind farms, we suggest referencing both metrics: the ratio of growth rates to quantify the consequence of impacts at a population level and the ratio of population sizes to present these impacts in an easily understandable context, for example:

“The impacts associated with *Offshore Wind Farm X* are predicted to result in the annual population growth rate at *Breeding Colony Y* declining from 0.994 to 0.967, a ratio of impacted to unimpacted population growth rate of 0.973. This means that after the 25 year life time of *Offshore Wind Farm X*, the population size of *Breeding Colony Y* is expected to be 51.5% of what it would have been in the absence of *Offshore Wind Farm X*.”

These metrics should be derived using stochastic population models. Density dependence should only be incorporated into these models where there is suitable evidence of it acting on the population concerned at a site-specific level.

Table 6. Strengths, weaknesses and guidance on the usage of metrics presented in this report.

METRIC	STRENGTHS	WEAKNESSES	HOW TO USE/INTERPRET
Population Growth Rate (GR)	Easy to interpret. Relatively insensitive to mis-specification of demographic parameters.	No comparison with an unimpacted population means that, on its own, the metric cannot be used to assess the population level effects associated with impacts from offshore wind farms. Variability around estimates of population growth rate mean that it can be difficult to distinguish between the impact of an offshore wind farm and variation in the baseline population growth rate.	On its own, the population growth rate is not a meaningful metric with which to assess the population level effects of impacts arising from offshore wind farms. If selected, the population growth rate of the impacted population should be compared to the population growth rate of the unimpacted population. Care must be taken when comparing the growth rates of impacted and unimpacted populations. The overlapping confidence intervals may make it difficult to distinguish between the two, but a lack of a significant difference between impacted and unimpacted population growth rates does not necessarily reflect no population-level consequence over the 25 year life time of an offshore wind farm.

METRIC	STRENGTHS	WEAKNESSES	HOW TO USE/INTERPRET
Ratio of Impacted to unimpacted population growth rate (RI:U)	Consistent relationship between metric and the magnitude of any impact, making it easier to assess what the likely implication of incorrectly predicting the magnitude of any impact will be at the population level. Insensitive to mis-specification of demographic parameters and relatively insensitive to estimates of uncertainty surrounding these parameters. Insensitive to population trend, meaning that metric reflects only the impact of the offshore wind farm and not the status of the population concerned.	The metric varies over a limited numeric range, which combined with the overlapping confidence intervals of the two population GR's, may make it harder to infer population level effects from impacts of different magnitudes. The limited range of the metric makes it harder to assess what the effect of the offshore wind farm means in a population context.	RI:U can be used to assess the population level effect of impacts arising from offshore wind farms regardless of population status or trend. The metric should be presented as a median value with 95% confidence intervals. Thresholds for determining whether or not an impact is deemed acceptable will be subjective, but could be set with reference to the status or trend of the population concerned.
Ratio of impacted to unimpacted population size after 25 years (RI:U25)	Metric is easy to interpret in a population context. Clear relationship between metric and the magnitude of any impact making it easier to assess what the population level effects of any impact will be. Relatively insensitive to the estimate of uncertainty surrounding demographic parameters.	Sensitive to whether population is declining rather than stable/increasing. More sensitive to mis-specification of demographic parameters than GR or RI:U.	On its own, RI:U25 can be used to assess the population level effects of impacts arising from offshore wind farms for stable or increasing populations. However, the metric may also offer a useful context for the RI:U metric, regardless of population trend. The metric should be presented as a median value with 95% confidence intervals. Thresholds for determining whether or not an impact is deemed acceptable will be subjective, but could be set with reference to the status or trend of the population concerned.

METRIC	STRENGTHS	WEAKNESSES	HOW TO USE/INTERPRET
Probability of growth rate being <1 P(GR<1)	Produces a metric which is intuitive and easy to understand.	No comparison with an unimpacted population means that, on its own, the metric cannot be used to assess the population level effects associated with impacts from offshore wind farms. Sensitive to mis-specification of adult survival rate. Sensitive to whether population is increasing or stable/declining. Where population is stable/declining the metric only varies over a limited range, making it more difficult to discern population level effects associated with different impacts.	Needs comparison with an unimpacted population to understand the population level effect associated with any wind farm. Only suitable for use in situations where population was increasing prior to the construction of offshore wind farms. If the metric is to be used, robust data describing adult survival rates, at a site specific level, are required. Thresholds for determining whether or not an impact is deemed acceptable will be subjective, but could be set with reference to the status or trend of the population concerned.
Change in probability of growth rate being <1 dP(GR<1)	Easy to understand metric that quantifies the change in probability of a population declining as a result of an offshore wind farm.	Sensitive to population trend. Sensitive to mis-specification of demographic parameters.	Not suitable for use in populations where the populations were declining prior to the construction of an offshore wind farm, where the P(GR<1) is already close to 1. If metric is to be used, robust, site-specific data describing demographic parameters are required. Thresholds for determining whether or not an impact is deemed acceptable will be subjective, but could be set with reference to the status or trend of the population concerned.

METRIC	**STRENGTHS**	**WEAKNESSES**	**HOW TO USE/INTERPRET**
Probability that population is below initial size at any point in time $P(p<p_0)$	Takes into account the fact that populations may recover from initial declines over the lifetime of an offshore wind farm.	No comparison with an unimpacted population means that, on its own, the metric cannot be used to assess the population level effects associated with impacts from offshore wind farms. Sensitive to whether population is increasing or stable/declining prior to offshore wind farm construction. Sensitive to mis-specification of adult survival rate.	Needs comparison with an unimpacted population to understand the population level effect associated with any wind farm. Only suitable for use in situations where population was increasing prior to the construction of offshore wind farms. If the metric is to be used, robust data describing adult survival rates, at a site specific level, is required. Thresholds for determining whether or not an impact is deemed acceptable will be subjective, but could be set with reference to the status or trend of the population concerned.
Probability of a 25% population decline $P(ld<0.25)$	Relatively easy to understand metric which could, potentially, be related to established conservation assessments (e.g. Birds of Conservation Concern Red/Amber lists – Eaton *et al* 2009).	No comparison with an unimpacted population means that, on its own, the metric cannot be used to assess the population level effects associated with impacts from offshore wind farms. Sensitive to whether population is increasing or stable/declining prior to offshore wind farm construction. Sensitive to mis-specification of demographic parameters.	Needs comparison with an unimpacted population to understand the population level effect associated with any wind farm. Only suitable for use in situations where population was increasing prior to the construction of offshore wind farms. If the metric is to be used, robust data describing adult survival rates, at a site specific level, is required. Thresholds for determining whether or not an impact is deemed acceptable will be subjective, but could be set with reference to the status or trend of the population concerned.

METRIC	STRENGTHS	WEAKNESSES	HOW TO USE/INTERPRET
Change in probability of a 25% population decline P(Id<0.25)	Easy to understand metric that quantifies the change in probability of a population declining by 25% as a result of an offshore wind farm.	Sensitive to whether population is stable or increasing/declining prior to offshore wind farm construction. Sensitive to mis-specification of demographic parameters.	Not suitable for use in populations where the populations were declining prior to the construction of an offshore wind farm, where the P(GR<1) is already close to 1. If metric is to be used, robust, site-specific data describing demographic parameters are required.
Probability impacted population 25% below unimpacted population (P(I<25))	Straightforward, easy to understand comparison of impacted and unimpacted populations. Can be easily related to criteria used to assess conservation status of species (i.e. Birds of Conservation Concern – Eaton *et al* 2009).	Some sensitivity to underlying population trend. Sensitive to mis-specification of demographic parameters.	A difference of 25% between the impacted and unimpacted populations is a subjective threshold. Careful consideration should be given as to whether this is an appropriate threshold for the population concerned, drawing on information about the importance and status of the population concerned. If metric is to be used, robust, site-specific data describing demographic parameters are required. Sensitivity to inclusion and form of density dependence, mean density dependent models should only be used where there is strong, clear evidence for it in the population.

METRIC	STRENGTHS	WEAKNESSES	HOW TO USE/INTERPRET
Probability that impacted population growth rate is 2.5% less than unimpacted population growth rate P(lgr>2.5)	Metric which assesses the impacted population growth rate relative to the unimpacted population growth rate.	May be difficult to understand in a population context. In practice it may be statistically difficult to detect a 2.5% drop in the population growth between the impacted and unimpacted populations. It is possible to consider a greater change, but more severe impacts would be required to detect such a change. Sensitive to whether population is stable/increasing or declining prior to offshore wind farm construction. Sensitive to mis-specification of demographic parameters.	Not suitable for use in populations where the populations were declining prior to the construction of an offshore wind farm. If metric is to be used, robust, site-specific data describing demographic parameters are required. Sensitivity to inclusion and form of density dependence, mean density dependent models should only be used where there is strong, clear evidence for it in the population.

METRIC	STRENGTHS	WEAKNESSES	HOW TO USE/INTERPRET
Overlap of Impacted and Unimpacted Populations (OI:U)	Straightforward comparison which enables understanding of how similar the outputs from models of the impacted and unimpacted populations are.	Sensitive to population trend. Sensitive to mis-specification of demographic parameters. Sensitive to estimates of uncertainty surrounding the demographic parameters. Value may depend on the number of simulations used in the demographic models used to derive metric.	Sensitivity to population trend means that the metric should only be used where there is a clear understanding of the status of the population concerned. If metric is to be used, robust, site-specific data describing demographic parameters, and the uncertainty surrounding these parameters, are required. Sensitivity to inclusion and form of density dependence, mean density dependent models should only be used where there is clear evidence for it in the population. Careful analysis is needed to ensure sufficient simulations are used in demographic models.

Clarifying the direction of sensitivity could be an important consideration for those wishing to decide how appropriate it is to use the metric. In this report, the results for the population growth rate metric provide a detailed account of how to interpret the presentation of the sensitivity analyses. Subsequent metrics are presented in a more concise manner.

3.2.3 Population Growth Rate (GR)

By considering the growth rate of the population in the presence of an offshore wind farm, it will be possible to consider whether the population will remain stable, increase or decrease through the lifetime of the project. A value of 1 indicates a stable population, <1 a declining population and >1 an increasing population.

Growth rate is calculated as a mean rate over the study period:

$$\left(\frac{End\ Population\ Size}{Start\ Population\ Size}\right)^{1/Nyears}$$

Mean annual growth rate over the study period is used in preference to the year-specific figures because, as a result of year to year variation in demographic parameters influencing population size, this approach gives a value that is more representative of any impacts at a population level. This definition is used for all subsequent metric which rely on a population growth rate. With this metric, a value of 1 indicates a stable population, a value <1 indicates a declining population and a value >1 indicates an increasing population.

Initial Results

Outputs from the sensitivity analyses of each metric are presented in a series of graphs and tables. Graphs are purposefully presented on the same scale for each metric in order to aide comparison between different methods. The first plots in each section (Fig. 14) show how the metric changes in response to impacts ranging from a 0 – 40% increase in mortality and a 0 – 40% reduction in productivity.

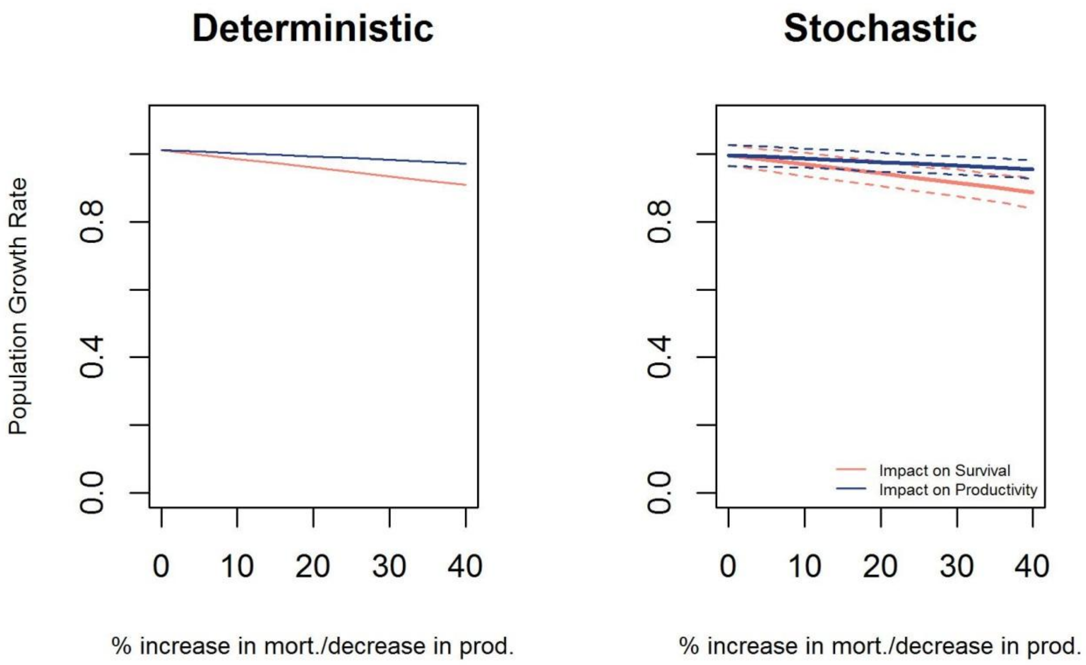

Figure 14. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the growth rate of a population of seabirds with an r-selected life history strategy and a stable population trajectory derived from deterministic and stochastic models (95% CIs for the latter given by broken lines).

Where appropriate, these figures are presented for the metric derived from both deterministic and stochastic models. If metrics are based on mean or median values, plots illustrating those derived from stochastic models are bounded by the 95% confidence intervals (shown by broken lines). In these plots, red illustrates the metric derived when an increase in mortality is considered, whilst blue illustrates the metric derived when a reduction in productivity is considered. Ideally, these plots should show a linear response to impacts of increasing magnitude, with a strong gradient. A non-linear response may make it harder to infer what the consequences of inaccurately estimating the impact arising from an offshore wind farm would be as this would depend on the magnitude of the impact concerned.

As might be expected, increases in mortality or decreases in productivity cause the population growth rate (GR) to decline over the life time of an offshore wind farm (Fig. 14). This decline is more severe when the impact is on survival than when the impact is on productivity, consistent with what would be expected amongst a group of species with high survival and relatively low productivity. Consistent with the finding that stochastic models are likely to result in more severe declines than deterministic models (Lande *et al* 2003), predicted GR over 25 years declined from 1.010 to 0.903 using a deterministic model and assuming up to a 40% increase in mortality, and from 0.994 (95% CIs 0.96 – 1.03) to 0.877 (95% CIs 0.82 – 0.92) using a stochastic model. Assuming up to a 40% decrease in productivity, GR would decline to 0.971 using a deterministic model and 0.954 (95% CIs 0.92 – 0.98) using a stochastic model. It should be noted that the one standard deviation around the population growth rate assuming no offshore wind farm impact overlaps with one standard deviation around a population with up to a 20% increase in mortality, suggesting that using population growth rate to estimate the population level impact of a development may only be possible where these impacts are large (>20% increase in mortality).

Sensitivity to life history strategy, population trend and density dependence

The following table, Table 7, illustrates how the metric would change (assuming a 10 or 20% increase in mortality or reduction in productivity) if populations were stable, increasing, decreasing, regulated by density dependence or based on a stable population of a K-selected species rather than an r-selected species. Ideally, values of the metric should be identical for similar levels of impact, regardless of whether the population concerned is increasing, decreasing or stable. The metric should also be similar when density dependent regulation of productivity or survival is introduced into the population models. It is expected that the metric would differ between stable populations of r or K-selected species, reflecting the different life history strategies of these species.

As might be expected, if a population were increasing prior to any wind farm impact, GR is higher for an impacted population than would be the case if the population were stable prior to the wind farm impact. Similarly, were the population already declining prior to the wind farm impact, the impacted GR is lower than would be the case if the population were stable prior to the wind farm impact (Table 7). As expected, if density dependent processes operate on the population this may mitigate the any impacts arising from the wind farm (Table 7). It appears to make relatively little difference whether density dependence is assumed to operate on productivity or survival. These results confirm that where there is uncertainty over density dependent processes in a population, assuming no density dependence is present is likely to be the most precautionary assumption, unless there is a depensatory density dependent relationship.

Changes in GR appear to be more pronounced for species which have a more r-selected life history than for those which have a more K-selected strategy (Table 7). This may be linked to the generation times of the respective species meaning that there is a greater chance of changes in populations of r-selected species (which have shorter generation times) becoming apparent over the 25 year lifetime of an offshore wind farm than is the case for K-selected species (which have longer generation times) in response to a given magnitude of impct.

Table 7. Population growth rates (95% CIs) resulting from a 10%, 20% or 40% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Unimpacted population	Survival			Productivity		
		10%	20%	40%	10%	20%	40%
Increasing	1.073 (1.037 – 1.109)	1.044 (1.006 – 1.080)	1.012 (0.966 – 1.053)	0.944 (0.881 – 1.001)	1.061 (1.027 – 1.095)	1.049 (1.017 - 1.082)	1.022 (0.993 – 1.051)
Stable	0.996 (0.961 – 1.028)	0.969 (0.933 – 1.004)	0.942 (0.907 - 0.976)	0.889 (0.843 – 0.928)	0.988 (0.958 – 1.016)	0.980 (0.951 – 1.008)	0.962 (0.935 – 0.987)
Decreasing	0.952 (0.923 – 0.982)	0.922 (0.888 – 0.957)	0.891 (0.851 – 0.927)	0.829 (0.778 – 0.875)	0.945 (0.913 – 0.974)	0.938 (0.907 – 0.966)	0.922 (0.894 – 0.949)
K selected	0.998 (0.978 – 1.017)	0.987 (0.966 – 1.007)	0.978 (0.957 – 0.998)	0.958 (0.935 – 0.979)	0.995 (0.977 – 1.014)	0.992 (0.975 – 1.011)	0.987 (0.971 – 1.003)
Density Dependent Survival	1.002 (0.961 – 1.041)	0.986 (0.944 – 1.029)	0.972 (0.925 – 1.018)	0.939 (0.987 – 0.874)	0.997 (0.960 – 1.039)	0.993 (0.958 – 1.033)	0.984 (0.945 – 1.023)
Density Dependent Productivity	0.997 (0.975 – 1.020)	0.983 (0.958 – 1.007)	0.965 (0.933 – 0.994)	0.916 (0.857 – 0.961)	0.994 (0.972 – 1.016)	0.990 (0.969 – 1.009)	0.982 (0.962 – 0.999)

Sensitivity to mis-specification of demographic parameters

The next figure (Fig. 15) and tables (Tables 8 and 9) illustrate how sensitive each metric is to the mis-specification of each demographic parameter in the models. For this, we consider a 1 percentage change in each parameter and what change this makes, in percentage terms, to the value of the metric. Figure 13, illustrates this graphically. It is important to note that the y-axis of this barchart is **not** linear. To aid interpretation, we use a horizontal, red line to illustrate the point at which a 1% mis-specification of the demographic parameter concerned would correspond to a 1 percentage change in the metric (this is purely to help interpretation, and should not be taken to imply this represents any sort of threshold, acceptable or otherwise). Tables 8 and 9 tabulate the values in this figure. Ideally, each of these values should be close to 0, indicating that mis-specification of the input parameters has little impact on the value of the derived metric. Where appropriate, Tables 8 and 9 and Figure 15 are shown for both the deterministic and stochastic models.

Of the demographic parameters considered, GR appears to be most sensitive to the mis-specification of the adult survival rate (Fig. 13 and Tables 8 and 9). However, this sensitivity is relatively minor, with a mis-specification of 1% in the adult survival rate resulting in less than a 1 percentage change in the population growth rate (Fig. 13 & Tables 8 and 9). However, the sensitivity of GR to the adult survival rate appears to increase as the magnitude of the impact increases (Tables 8 and 9). These results are consistent, regardless of whether a deterministic or stochastic model is used.

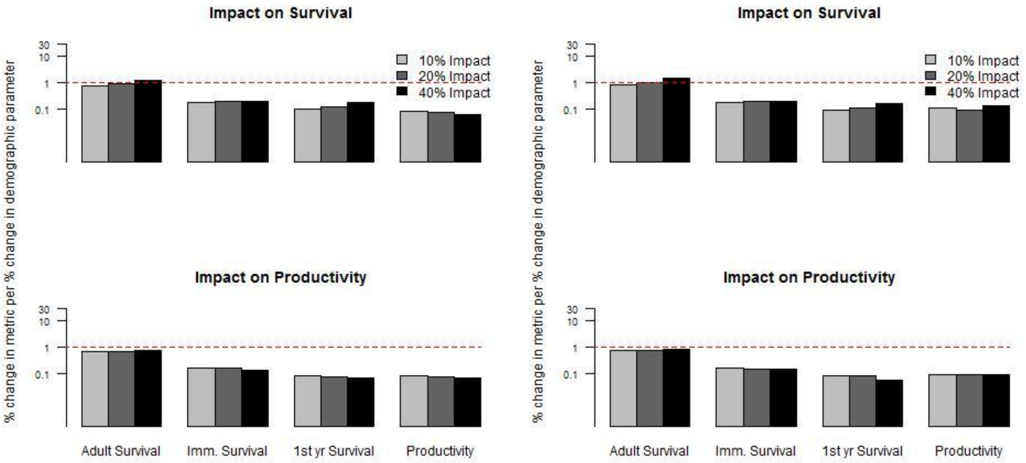

Figure 15. Percentage change in population growth rate per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from deterministic (left) and stochastic (right) models. Note that the Y-axis is on a non-linear scale. Data tabulated in Tables 8 and 9.

Table 8. Influence of a 1% mis-specification of each demographic parameter on the growth rate of an r-selected seabird species estimated from deterministic and stochastic models (assessed as % change in metric), assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 15.

	Deterministic			Stochastic		
	10%	20%	40%	10%	20%	40%
Adult Survival	0.75	0.89	1.25	0.84	0.97	1.32
Immature Survival	0.18	0.19	0.20	0.18	0.19	0.16
Chick Survival	0.12	0.12	0.17	0.10	0.10	0.13
Productivity	0.08	0.08	0.06	0.08	0.08	0.10

Table 9. Influence of a 1% mis-specification of each demographic parameter on the growth rate (as assessed by % change in metric) of an r-selected seabird species estimated from deterministic and stochastic models, assuming a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 15.

	Deterministic			Stochastic		
	10%	20%	40%	10%	20%	40%
Adult Survival	0.65	0.68	0.75	0.74	0.75	0.80
Immature Survival	0.17	0.17	0.14	0.16	0.16	0.14
Chick Survival	0.08	0.08	0.07	0.09	0.08	0.06
Productivity	0.08	0.08	0.07	0.09	0.09	0.06

Sensitivity to form of density dependence

The final figure, Figure 16, illustrates the impact of mis-specifying the parameters used to estimate the density dependent response of survival or productivity on the value of the metric derived. Here, ideally, the lines on each plot should be flat, indicating that an error in estimating these parameters has little or no impact on the value of the metric derived.

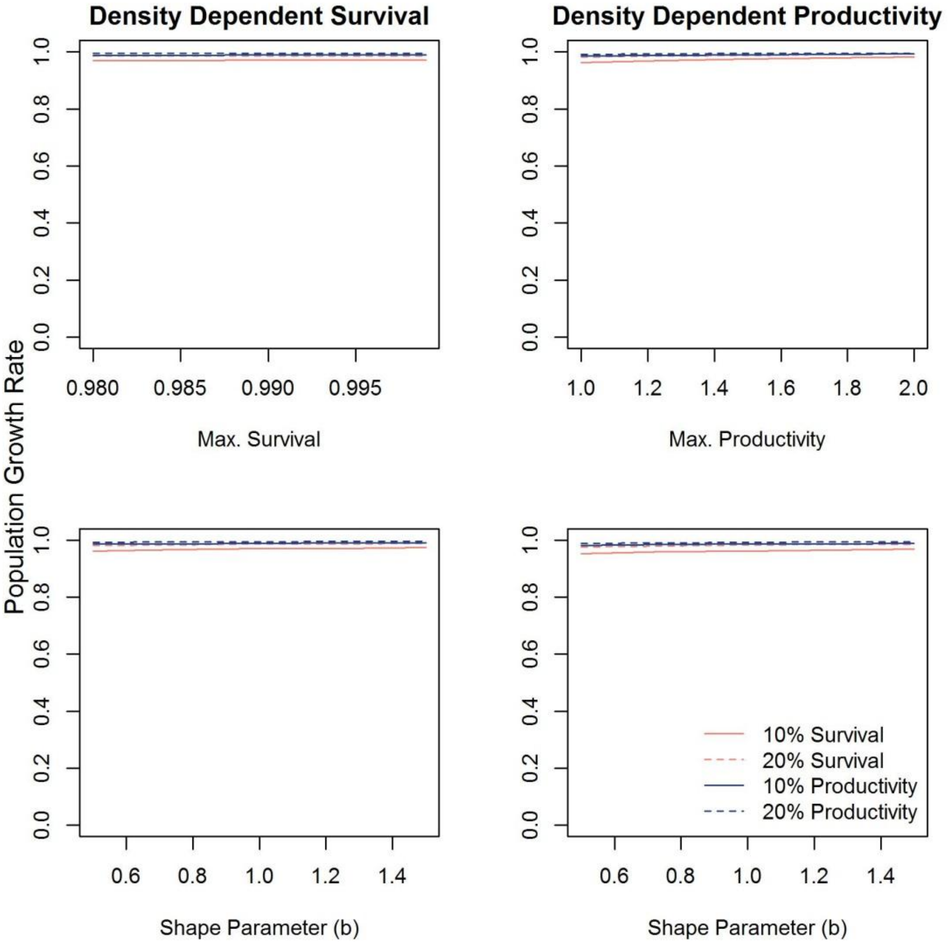

Figure 16. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

If density dependence is introduced into the models, the impacted GR does not appear to be particularly sensitive to either mis-specification of the shape parameter or mis-specification of the maximum survival or productivity rate.

Metric overview

GR shows a consistent decline as the magnitude of any impact increases. This decline is more severe where survival is impacted than where productivity is impacted. Stochastic and deterministic models produce similar results although stochastic models may be more precautionary as they result in stronger declines. Whilst growth rates derived from stochastic models are lower than those derived from deterministic models, they may better reflect biological reality by accounting for the changeable nature of the environment in which these species live. However, when using stochastic models it is only possible to clearly distinguish between the growth rates of an impacted and unimpacted population when the predicted impacts of an offshore wind farm are relatively severe. This means that more moderate changes in the population growth rate, which may still have a significant population level impact over the lifetime of a project, may not be identified. GR, as a metric, is relatively insensitive to mis-specification of the input demographic parameters using either a deterministic or stochastic model and regardless of whether density dependence is incorporated.

3.2.4 Ratio of the Median Impacted to Unimpacted Population Growth Rate (RI:U)

Considering only the growth rate of a population in the presence of an offshore wind farm enables an assessment of whether the population will remain stable, increase or decrease over time, but it does not make it possible to quantify the impact of the wind farm on that growth rate. By comparing the growth rate of the population in the presence of a wind farm to that expected in the absence of a wind farm it may be possible to demonstrate what impact the development is having on a population.

This metric is on a scale from 0 – 1, with 1 indicating the impacted population growth rate is the same as the unimpacted growth rate (i.e. no population-level consequence) and values close to 0 indicating a large difference between the impacted and unimpacted population growth rates (i.e. a strong population-level consequence). Changes in the metric reflect increases or decreases in the impacted population growth rate.

Initial Results

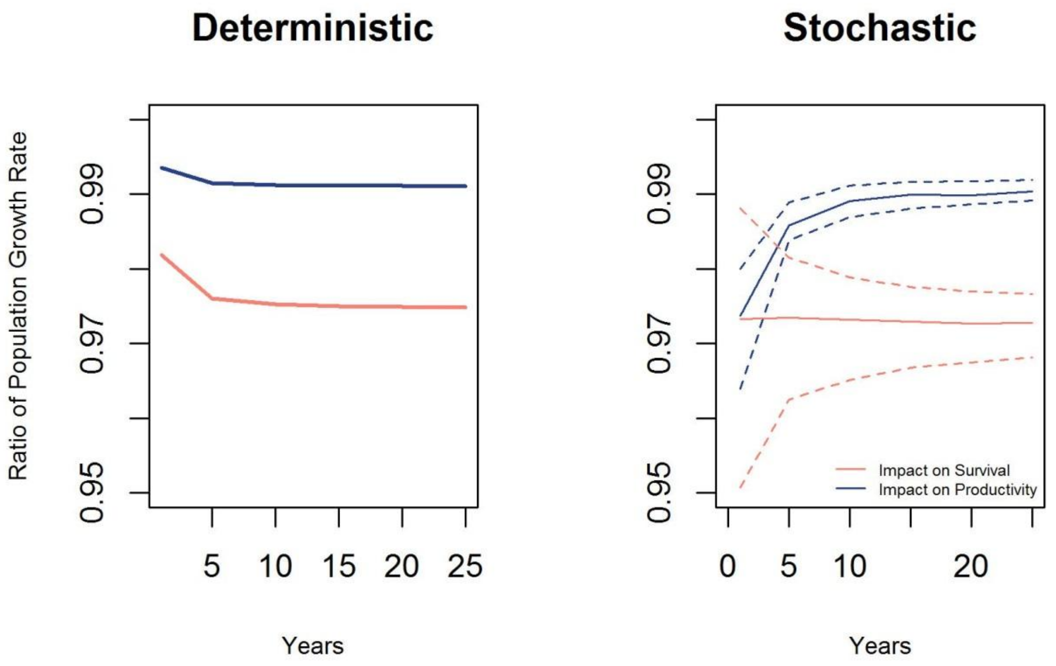

Figure 17. Change in value of the ratio of the impacted to unimpacted population growth rate through time calculated using a deterministic (left) and stochastic (right) model and assuming a 10% increase in mortality or a 10% reduction in productivity. Broken lines indicate 95% confidence intervals. Note, first point is shown for year 1, not year 0.

The ratio of the median impacted to unimpacted population growth rate (RI:U) can be calculated for any point over the lifetime of a development. As time increases, the ratio of the impacted to unimpacted population growth rate stabilises, suggesting a new stable age-structure is reached (Fig. 17). Impacts on survival result in a larger change than those on productivity. Using the stochastic model, the uncertainty surrounding the ratio appears to decrease through time as a result of regression to the mean. Given this, it makes sense to use the ratio estimated at the end of the lifetime of the project, in this case after 25 years, when predicted impacts will be at their greatest. For this reason, subsequent discussion of the metric is based on RI:U after 25 years. Apparent differences in the value of the metric derived from different models relate to the fact the stochastic value comes from multiple simulations whereas the deterministic value comes from a single calculation. Furthermore, as described above, values from stochastic models are slightly lower than those from deterministic models as a result of accounting for variation in demographic rates.

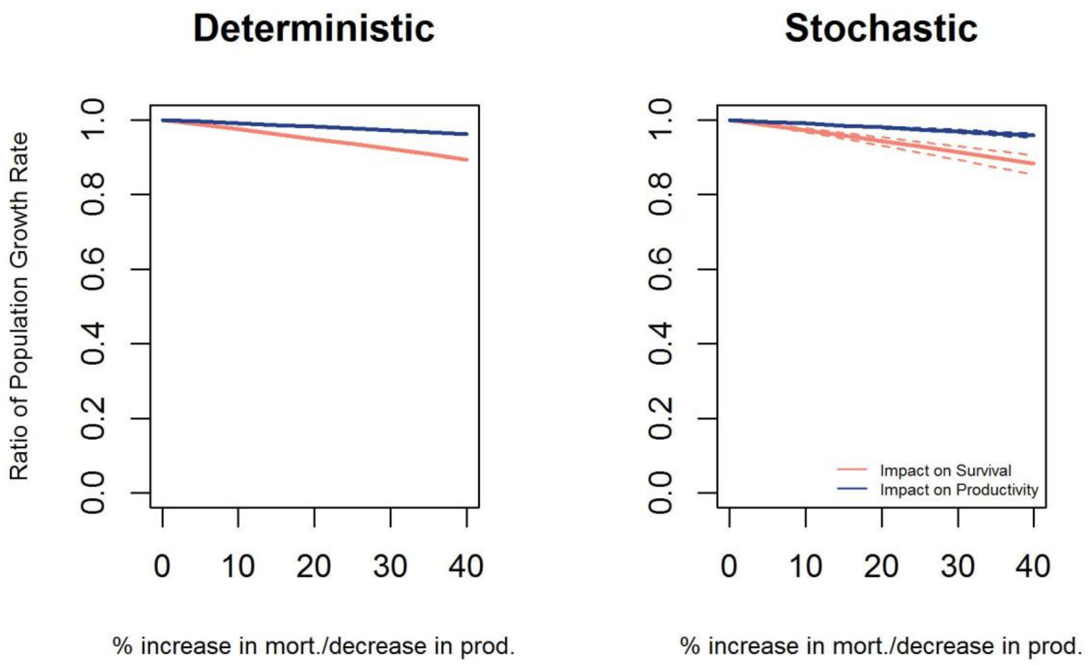

Figure 18. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the ratio of the median growth rate of an impacted and unimpacted population of seabirds with an r-selected life history strategy and a stable population trajectory derived from deterministic and stochastic models (95% CIs given by broken lines).

RI:U decreases as the magnitude of any impact increases (Fig. 18). Ratios are similar, regardless of whether a stochastic or deterministic model is used. Assuming a 40% increase in mortality results in a ratio of 0.894 using the deterministic model and 0.882 using the stochastic model. However, given that the growth rates of impacted and unimpacted populations estimated from the stochastic models overlap for impacts of up to 20% on survival or up to 40% on productivity (see above, section 3.2.1 Table 7), these values must be interpreted with caution.

Sensitivity to life history strategy, population trend and density dependence

In contrast to GR, RI:U appears to be relatively insensitive to the underlying population trend, with extremely similar values obtained for increasing and stable populations, and only a small change where the population is decreasing (Table 10). As expected, if density dependent processes operate on the population this may mitigate the impact of any impacts arising from the wind farm (Table 10). It appears to make relatively little difference whether density dependence is assumed to operate on productivity or survival. These results confirm that where there is uncertainty over density dependent processes in a population, assuming no density dependence is present is likely to be the most precautionary assumption.

Table 10. Ratio of impacted to unimpacted population growth rates (95% CIs) resulting from a 10%, 20% or 40% increase in mortality or a 10%, 20% or 40% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity. Values close to 1 indicate no impact from offshore wind farm, values close to 0 indicate strong impact from offshore wind farm.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.973 (0.966 – 0.978)	0.945 (0.929 – 0.956)	0.882 (0.840 – 0.908)	0.988 (0.987 – 0.989)	0.975 (0.973 – 0.977)	0.946 (0.941 – 0.951)
Stable	0.973 (0.965 – 0.976)	0.943 (0.931 – 0.953)	0.881 (0.851 – 0.903)	0.990 (0.989 – 0.991)	0.980 (0.977 – 0.982)	0.958 (0.952 – 0.963)
Decreasing	0.966 (0.971 – 0.958)	0.930 (0.912 – 0.942)	0.853 (0.801 – 0.881)	0.991 (0.989 – 0.991)	0.981 (0.978 – 0.983)	0.959 (0.952 – 0.965)
K selected	0.989 (0.987 – 0.990)	0.978 (0.974 – 0.981)	0.958 (0.949 – 0.964)	0.995 (0.994 – 0.996)	0.990 (0.989 – 0.992)	0.980 (0.976 – 0.984)
Density Dependent Survival	0.985 (0.983 – 0.991)	0.969 (0.961 – 0.980)	0.933 (0.896 – 0.948)	0.994 (0.994 – 0.995)	0.988 (0.987 – 0.990)	0.972 (0.969 – 0.976)
Density Dependent Productivity	0.989 (0.978 – 0.994)	0.971 (0.949 – 0.986)	0.934 (0.874 – 0.965)	0.996 (0.993 – 0.997)	0.991 (0.987 – 0.994)	0.984 (0.977 – 0.988)

As highlighted previously (section 3.2.1), the growth rates of K-selected seabird species appear to be more resilient to impacts from offshore wind farms as the RI:U is higher than that for r-selected species (Table 10).

Sensitivity to mis-specification of demographic parameters

Of the demographic parameters considered, RI:U appears to be most sensitive to the mis-specification of the adult survival rate (Fig. 19 & Tables 11 and 12). However, this sensitivity is relatively minor, with a mis-specification of 1% in the adult survival rate resulting in less than a 1 percentage change in the population growth rate (Fig. 19 & Tables 11 and 12). However, the sensitivity of the ratio of population growth rate to the adult survival rate appears to increase as the magnitude of the impact increases (Tables 11 and 12). These results are consistent, regardless of whether a deterministic or stochastic model is used.

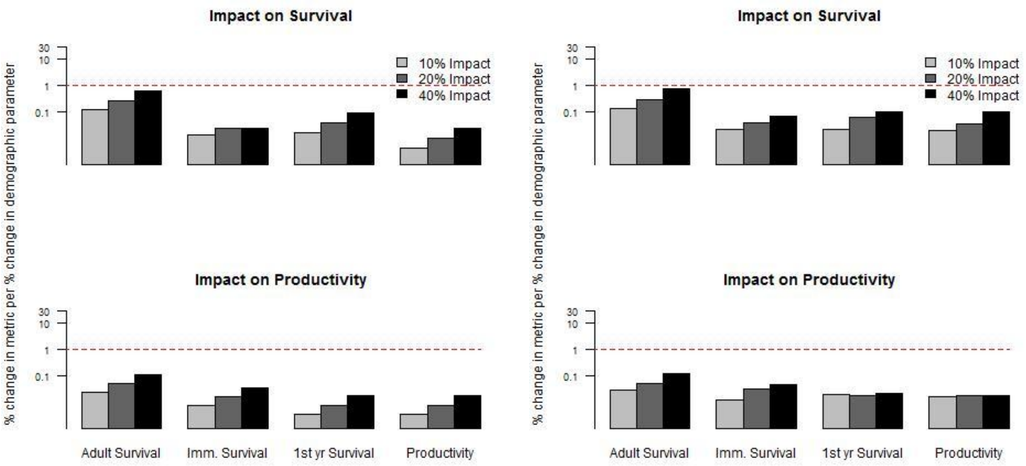

Figure 19. Percentage change in the ratio of impacted to unimpacted population growth rate per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from deterministic (left) and stochastic (right) models. Note that the Y-axis is on a non-linear scale. Data tabulated in Tables 10 and 11.

Table 11. influence of a 1% mis-specification of each demographic parameter on the ratio of the growth rate of an impacted to unimpacted population (as assessed by % change in metric) of an r-selected seabird species estimated from a deterministic and stochastic model, assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 19.

	Deterministic			Stochastic		
	10%	20%	40%	10%	20%	40%
Adult Survival	0.12	0.26	0.62	0.14	0.30	0.74
Immature Survival	0.01	0.01	0.02	0.02	0.04	0.07
Chick Survival	0.02	0.04	0.09	0.02	0.06	0.10
Productivity	<0.01	0.01	0.02	0.02	0.04	0.11

Table 12. Influence of a 1% mis-specification of each demographic parameter on the ratio of the growth rate of an impacted to unimpacted population (as assessed by % change in metric) of an r-selected seabird species estimated from a deterministic and stochastic model, assuming a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 19.

	Deterministic			Stochastic		
	10%	20%	40%	10%	20%	40%
Adult Survival	0.02	0.05	0.11	0.03	0.05	0.11
Immature Survival	<0.01	0.01	0.04	0.01	0.03	0.04
Chick Survival	<0.01	0.01	0.02	0.02	0.02	0.02
Productivity	<0.01	0.01	0.02	0.02	0.02	0.03

Sensitivity to form of density dependence

If density dependence is introduced into the models, RI:U does not appear to be particularly sensitive to either mis-specification of the shape parameter or mis-specification of the maximum survival or productivity rate (Fig. 20).

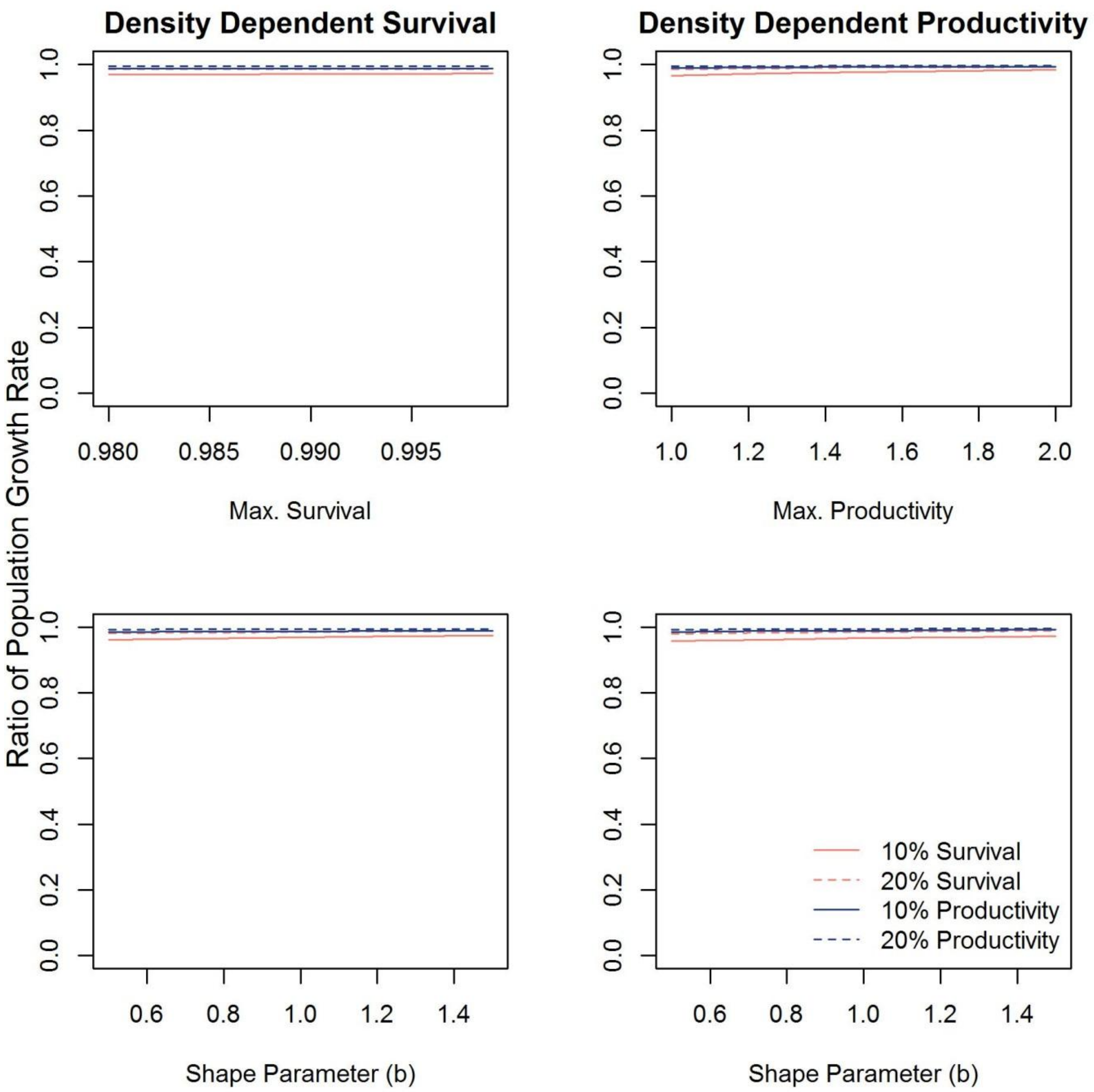

Figure 20. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Additional Analysis

Since initial results suggested that this metric may be of use in estimating the population level effects of impacts arising from offshore wind farms, additional analyses were undertaken.

RI:U can be estimated at any point over the lifetime of a project. However, it is unclear whether sensitivity to mis-specification of demographic parameters is constant through time, i.e. if we estimate RI:U after 5 or 10 years, is it more important that we use accurate survival estimates than if we estimate it after 25 years. In order to understand this, we investigate how mis-specification of adult survival rates may affect the metric at different points in time (5 and 10 years post-construction). These results suggest that the sensitivity of the metric to mis-specification of demographic parameters is likely to be broadly similar regardless of when in a project’s lifetime it is calculated (Fig. 21 & Table 13). These results imply that the metric may be interpreted with the same degree of confidence regardless of whether it is estimated 5, 10 or 15 years post-construction.

Table 13. Impact of a 1% mis-specification of adult survival rate on the ratio of the growth rate of an impacted to unimpacted population after 5 or 10 years for an r-selected seabird species estimated from a stochastic model, assuming a 10%, 20% or 40% increase in mortality or a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 19.

	Impact on Survival			Impact on Productivity		
	10%	20%	40%	10%	20%	40%
After 5 years	0.12	0.27	0.59	0.04	0.06	0.13
After 10 Years	0.13	0.28	0.67	0.03	0.06	0.12

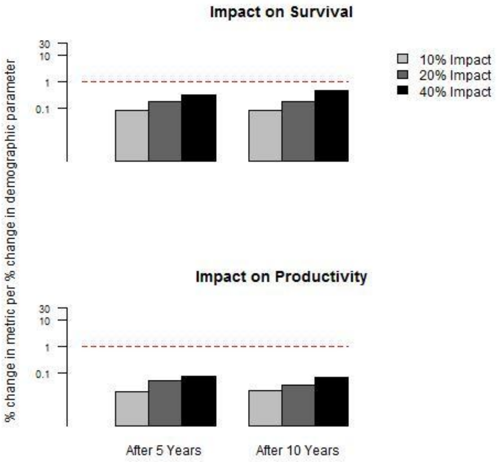

Figure 21. Percentage change in the ratio of impacted to unimpacted population growth after 5 and 10 years rate per percentage change in adult survival for offshore wind farm impacts on survival and productivity from a stochastic model. Note that the Y-axis is on a non-linear scale. Data tabulated in Table 13.

Additional analyses revealed that RI:U showed some sensitivity to the extent of uncertainty surrounding the demographic parameters used in population models (Fig. 22). However, this sensitivity did not appear to be greater than the sensitivity of the metric to mis-specification of demographic parameters. These analyses show that in populations where there is greater uncertainty surrounding the demographic parameters, RI:U is lower, implying a stronger population-level consequence, than is the case where there is less uncertainty surrounding the demographic parameters. This is because the wider confidence intervals surrounding the demographic parameters enable more extreme values to be selected. In the case of adult survival rates, 0.89 in this analysis, there is more scope for lower values to be selected than higher values (as the maximum possible rate is 1). Consequently, when averaged over multiple simulations the population with the wider confidence limits surrounding adult survival will show a greater impact than the population with narrower confidence limits.

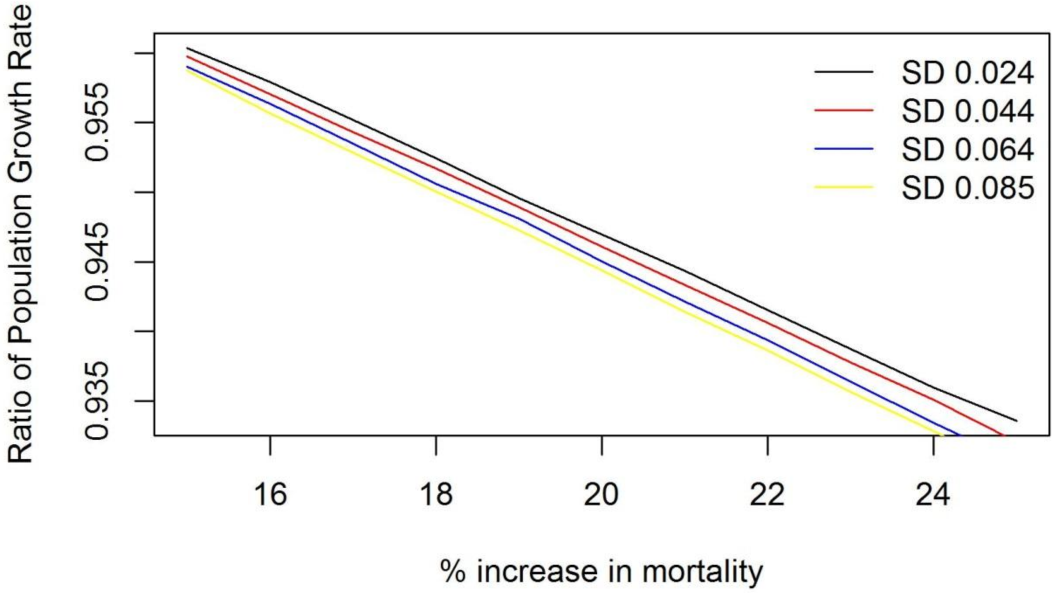

Figure 22. Impact of 15% to 25% increase in mortality on the ratio of impacted to unimpacted population growth rate for a population of seabirds with an r-selected life history strategy and a stable population trajectory, assuming an adult survival rate of 0.89 and standard deviations of 0.024, 0.044, 0.064 and 0.085.

Sensitivity to population trend may vary depending on whether or not density dependence is incorporated in the population models used to estimate RI:U. We therefore estimated this metric using a model assuming a density dependent impact on productivity and increasing, stable and declining populations. As with density independent models, when derived from density dependent models, RI:U is insensitive to whether the population is stable or increasing, but does appear to be sensitive to whether the population is declining (Table 14), i.e. including a density dependent response does not change how the metric behaves.

Table 14. Sensitivity of the ratio of impacted to unimpacted population growth rate after 25 years to population trend, derived from stochastic models of an r-selected seabird assuming stable, increasing or declining populations with density dependent regulation of productivity.

	Impact on survival			Impact on productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.989 (0.982 – 0.993)	0.976 (0.958 – 0.985)	0.932 (0.866 – 0.962)	0.994 (0.992 – 0.995)	0.988 (0.984 – 0.991)	0.977 (0.967 – 0.982)
Stable	0.989 (0.978 – 0.994)	0.971 (0.949 – 0.986)	0.934 (0.874 – 0.965)	0.996 (0.993 – 0.997)	0.991 (0.987 – 0.994)	0.984 (0.977 – 0.988)
Declining	0.977 (0.966 – 0.986)	0.950 (0.922 – 0.968)	0.865 (0.446 – 0.916)	0.996 (0.995 – 0.997)	0.993 (0.990 – 0.995)	0.986 (0.980 – 0.990)

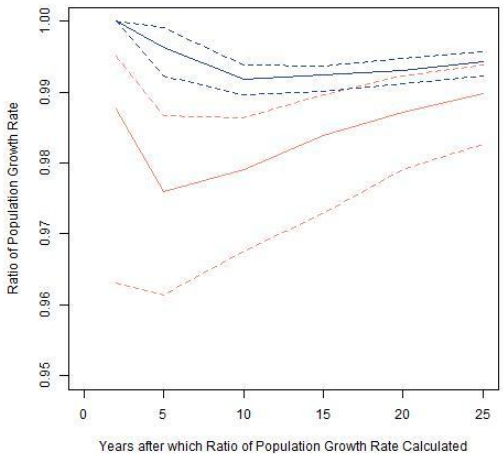

Figure 23. Change in value of the ratio of the impacted to unimpacted population growth rate through time calculated using a stochastic model with density dependent regulation of productivity and assuming a 10% increase in mortality (red lines) or a 10% reduction in productivity (blue lines). Broken lines indicate 95% confidence intervals.

In contrast to density independent models, when using a density dependent model (Fig. 23), after an initial decrease in RI:U over the first five years of a project lifetime, the metric increases again over the remaining time period. This suggests that, over time, density dependent mechanisms are compensating for the impacts associated with the offshore wind farm and that, as a result, the growth rates of the impacted and unimpacted populations become more similar (i.e. the metric takes values closer to one).

RI:U can be estimated from a density dependent model at any point over the lifetime of a project. However, it is unclear how incorporating density dependence into the models will affect sensitivity to mis-specification of demographic parameters. To test this, we focus on adult survival rate, which previous analyses showed was the parameter the metric was most sensitive to, and consider the sensitivity of the metric to mis-specification after 5, 10 and 25 years using a stochastic model with density dependent regulation of productivity. These results suggest that when density dependence is incorporated into population models, the metric may be less sensitive to mis-specification of demographic parameters than is the case for density independent models. These results are consistent regardless of whether the metric is estimated 5,10 or 25 years post-construction (Table 15, Figure 24).

Table 15. Influence of a 1% mis-specification of adult survival rate on the ratio of the growth rate (as assessed using by % change in metric) of an impacted to unimpacted population after 5, 10 or 25 years for an r-selected seabird species estimated from a stochastic model with density dependent regulation of productivity, assuming a 10%, 20% or 40% increase in mortality or a 10%, 20% or 40% reduction in productivity.

	Impact on Survival			Impact on Productivity		
	10%	20%	40%	10%	20%	40%
After 5 years	0.07	0.17	0.44	0.02	0.03	0.08
After 10 Years	0.09	0.22	0.54	0.02	0.03	0.05
After 25 Years	0.08	0.22	0.67	0.02	0.03	0.04

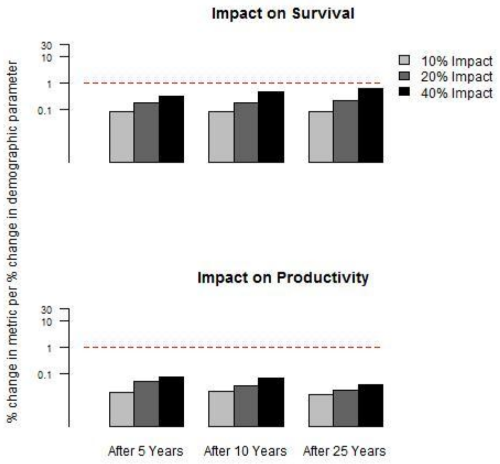

Figure 24. Percentage change in the ratio of impacted to unimpacted population growth after 5, 10 and 25 years rate per 1 percentage change in adult survival for offshore wind farm impacts on survival and productivity from a stochastic model with density dependent regulation of productivity. Note that the Y-axis is on a non-linear scale.

Metric overview

RI:U shows a consistent decline as the magnitude of any impact increases. This decline is more severe where survival is impacted than where productivity is impacted. Stochastic and deterministic models produce similar results, although stochastic models may be more precautionary as they predict stronger declines. However, as highlighted previously this metric must be interpreted with caution given the overlapping confidence intervals recorded in the population growth rates of unimpacted populations and populations exposed to moderate impacts as a result of an offshore wind farm (see Figure 14, section 3.2.3). This may make interpreting the outputs of this metric difficult, particularly when combined with the fact that it only varies over a fairly limited range. Despite this, it is important to note that the metric is relatively insensitive to mis-specification of demographic parameters. Where there is greater uncertainty surrounding the appropriate values for these parameters, this is reflected by the metric predicting a more severe population-level consequence. The metric can be estimated using a density dependent model, and this approach is no more sensitive to assumptions about the underlying population trend or to mis-specification of demographic parameters than is the case for density independent models. However, incorporating density dependence into the models means that RI:U does not remain constant through time, as is the case for density independent models. Consequently, if this approach is taken, it is only appropriate to estimate RI:U at the end of the project lifetime (in the above example, after 25 years).

3.2.5 Ratio of Impacted to Unimpacted Population Size (RI:U25)

Population models can be used to estimate the size of a population through time both with and without the impact of an offshore wind farm. Comparing the ratio of the size of these two populations offers a relatively easy to interpret statistic with which to assess the population level impact of an offshore wind farm. The ratio could be derived either from a simple deterministic model or taken from the mean or median values simulated using a more complex stochastic model with matched runs for impacted and unimpacted populations. The ratio of population sizes could be estimated either at a fixed point in time, for example at the end of a project, or at a series of intervals throughout the life time of a project.

The metric is on a scale from 0 – 1, with 1 indicating the impacted population size is the same as the unimpacted growth rate (i.e. no population-level consequence) and values close to 0 indicating a large difference between the impacted and unimpacted population sizes (i.e. a strong population-level consequence).

Initial Results

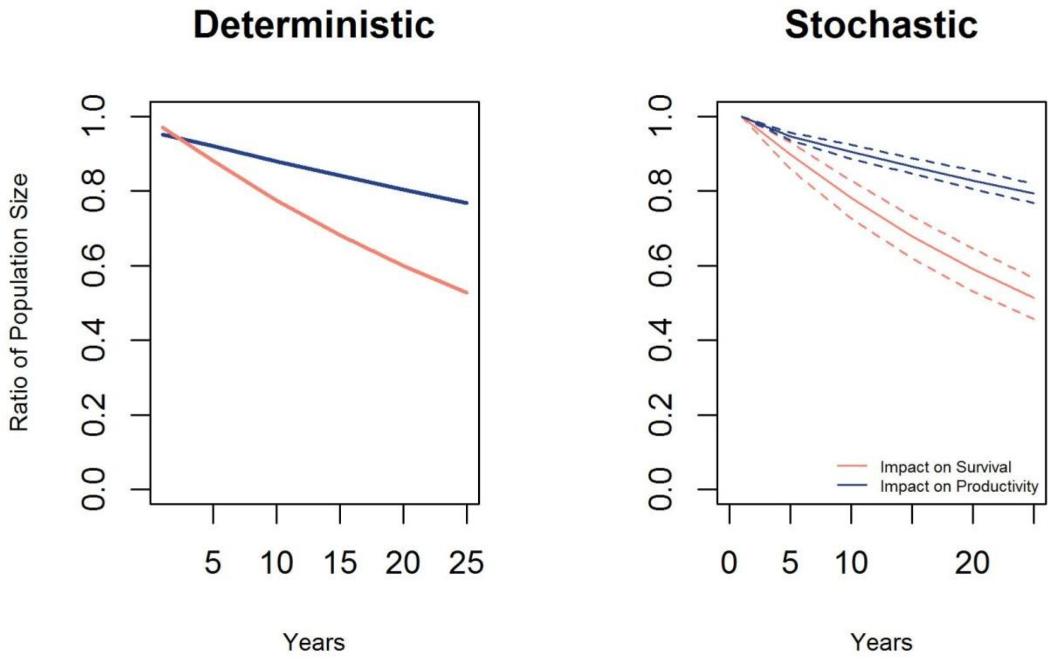

Figure 25. Change in value of the ratio of the impacted to unimpacted population size through time calculated using a deterministic (left) and stochastic (right) model and assuming a 10% increase in mortality or a 10% reduction in productivity. Broken lines show 95% Confidence Intervals.

The ratio of the impacted to unimpacted population size can be calculated for any point over the lifetime of a development. As time increases, the ratio of the impacted to unimpacted population decreases (Fig. 25). As with previous metrics, impacts on survival result in a more significant impact than those on productivity. Using the stochastic model, after the first 5 years the uncertainty surrounding the ratio appears relatively constant. Given this, it makes sense to use the ratio estimated at the end of the lifetime of the project, in this case after 25 years, when predicted impacts will be at their greatest. For this reason, subsequent discussion of the metric is based on the ratio of the impacted to unimpacted population size after 25 years (RI:U25).

RI:U25 decreases with increasing magnitude of the impact resulting from the offshore wind farm (Fig. 26). The metric is similar for both stochastic and deterministic models (Fig. 26). Using a deterministic model, RI:U25, assuming a 40% increase in mortality, is 0.07, in comparison to a value of 0.06 (± 0.02) from a stochastic model. For a 40% reduction in productivity the equivalent figures are 0.32 based on a deterministic model and 0.37 (0.03) based on a stochastic model. However, it is important to note that the relationship between the metric and the magnitude of the impact is not linear and approaches an asymptote where predicted offshore wind farm impacts are most severe (Fig. 26). This is an inevitable feature of the metric because as the population declines towards extinction the value of the metric cannot go below 0. As a consequence, whist distinguishing between low-moderate impacts is likely to be relatively straightforward, this distinction may be more difficult when predicted impacts are severe.

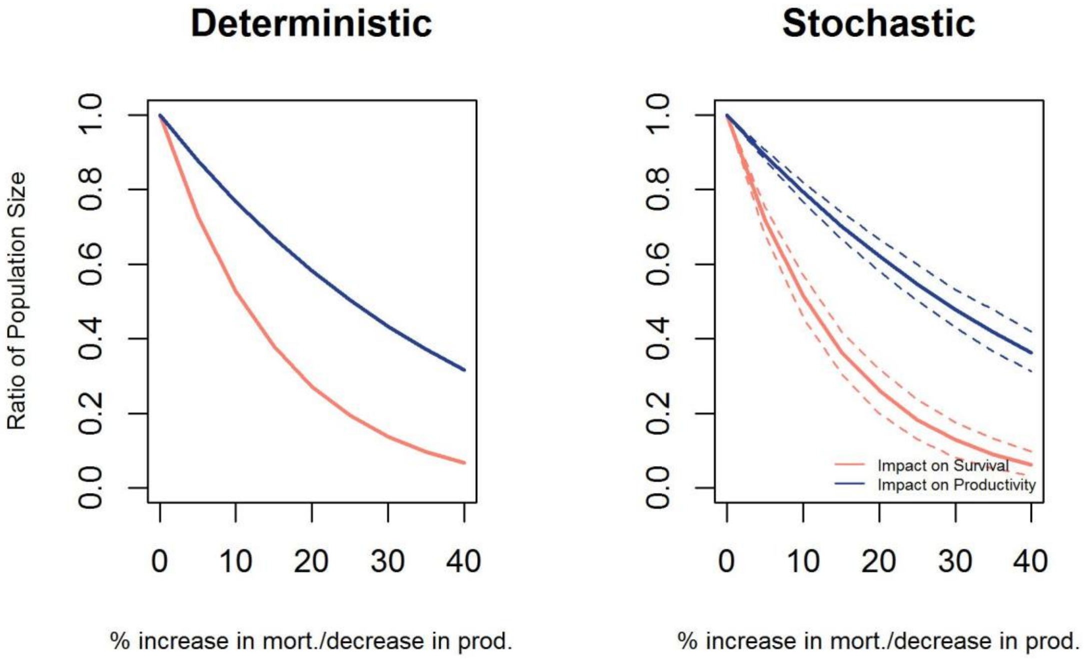

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Figure 26. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the ratio of the population size after 25 years for an impacted and unimpacted population of seabirds with an r-selected life history strategy and a stable population trajectory derived from deterministic and stochastic models (95% CIs given by broken lines).

Sensitivity to life history strategy, population trend and density dependence

There appears to be relatively little difference between RI:U25 estimated for populations which are stable or increasing (Table 16). However, there is a more noticeable difference between the ratios estimated from stable and decreasing populations, suggesting that despite impacts of a similar magnitude, they may have a more significant effect on a declining population. Considering a species which may have a more K-selected life history strategy results in significantly higher values for the ratio of the impacted to unimpacted population size (Table 16), implying that these species may be better able to withstand these impacts on their populations. As expected, if density dependent processes operate on the population this may mitigate the impact of any impacts arising from the wind farm (Table 16). It appears to make relatively little difference whether density dependence is assumed to operate on productivity or survival. These results confirm that where there is uncertainty over density dependent processes in a population, assuming no density dependence is present is likely to be the most precautionary assumption.

Table 16. Ratio of impacted to unimpacted population size after 25 years (95% CIs) resulting from a 10% or 20% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.509 (0.437 – 0.565)	0.248 (0.171 – 0.319)	0.050 (0.017 – 0.089)	0.738 (0.716 – 0.761)	0.532 (0.499 – 0.564)	0.255 (0.222 – 0.292)
Stable	0.515 (0.452 –	0.263 (0.202 -	0.061 (0.032 –	0.795 (0.768 –	0.624 (0.579 –	0.365 (0.313 –

	0.567)	0.319)	0.095)	0.821)	0.667)	0.427)
Decreasing	0.460 (0.397 – 0.517)	0.204 (0.144 – 0.261)	0.036 (0.011 – 0.061)	0.809 (0.778 – 0.833)	0.647 (0.600 – 0.692)	0.395 (0.334 – 0.460)
K selected	0.773 (0.740 – 0.801)	0.599 (0.549 – 0.643)	0.363 (0.307 – 0.418	0.897 (0.879 – 0.915)	0.798 (0.767 – 0.836)	0.620 (0.568 – 0.687)
Density Dependent Survival	0.742 (0.671 – 0.802)	0.528 (0.409 – 0.623)	0.195 (0.091 – 0.282)	0.883 (0.867 – 0.898)	0.773 (0.741 – 0.801)	0.522 (0.471 – 0.575)
Density Dependent Productivity	0.755 (0.594 – 0.883)	0.503 (0.299 – 0.717)	0.213 (0.049 – 0.430)	0.904 (0.862 – 0.932)	0.814 (0.729 – 0.866)	0.685 (0.587 – 0.765)

Sensitivity to mis-specification of demographic parameters

In comparison to the metrics based on population growth rate, this metric is more sensitive to mis-specification of adult survival, but not to mis-specification of other demographic parameters. There was strong evidence that this sensitivity varied with the magnitude of the predicted impact. With a 10% increase in mortality, a 1% mis-specification of adult survival led to a 2.45 percentage change in the ratio based on a deterministic model, or a 2.81% change based on a stochastic model (Fig. 27 & Tables 17 and 18). Were mortality to increase by 20%, the sensitivity to this mis-specification increases to 5.30% and 6.10% respectively. These patterns likely reflect the non-linear relationship between the metric and the magnitude of the predicted impact.

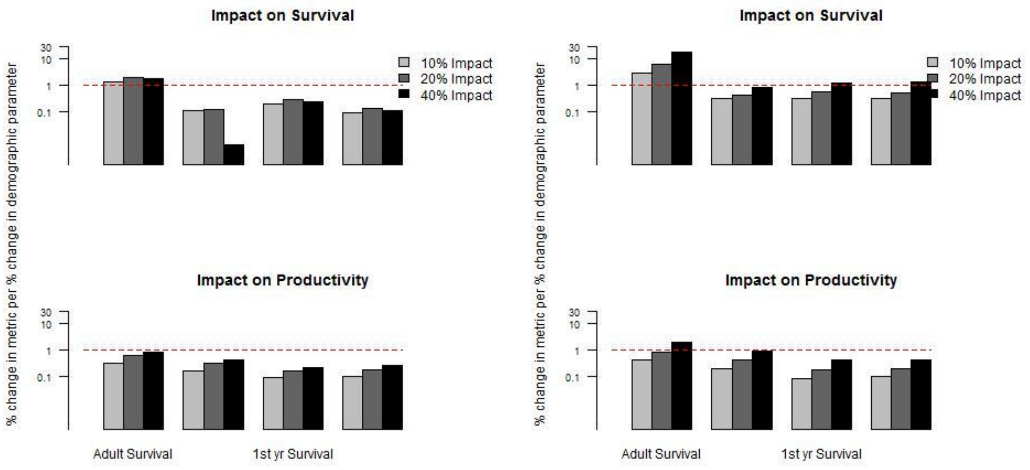

Figure 27. Percentage change in the ratio of impacted to unimpacted population size after 25 years per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from deterministic (left) and stochastic (right) models. Note that the Y-axis is on a non-linear scale. Data tabulated in Tables 17 and 18.

Table 17. Influence of a 1% mis-specification of each demographic parameter on the ratio of the population's size after 25 years (as assessed by % change in metric) of an impacted to unimpacted population of an r-selected seabird species estimated from a deterministic and stochastic model, assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 27.

	Deterministic			Stochastic		
	10%	20%	40%	10%	20%	40%
Adult Survival	2.45	5.30	13.73	2.81	6.07	16.34
Immature Survival	0.16	0.41	0.04	0.28	0.50	0.86
Chick Survival	0.37	0.78	1.76	0.29	0.59	1.51
Productivity	0.17	0.36	0.82	0.22	0.54	1.25

Table 18. Influence of a 1% mis-specification of each demographic parameter on the ratio of the population's size after 25 years (as assessed by % change in metric) of an impacted to unimpacted population of an r-selected seabird species estimated from a deterministic and stochastic model, assuming a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 27.

	Deterministic			Stochastic		
	10%	20%	40%	10%	20%	40%
Adult Survival	0.43	0.89	2.01	0.42	0.88	1.98
Immature Survival	0.12	0.29	1.03	0.17	0.36	0.89
Chick Survival	0.11	0.24	0.55	0.08	0.18	0.46
Productivity	0.13	0.27	0.61	0.11	0.21	0.53

Sensitivity to form of density dependence

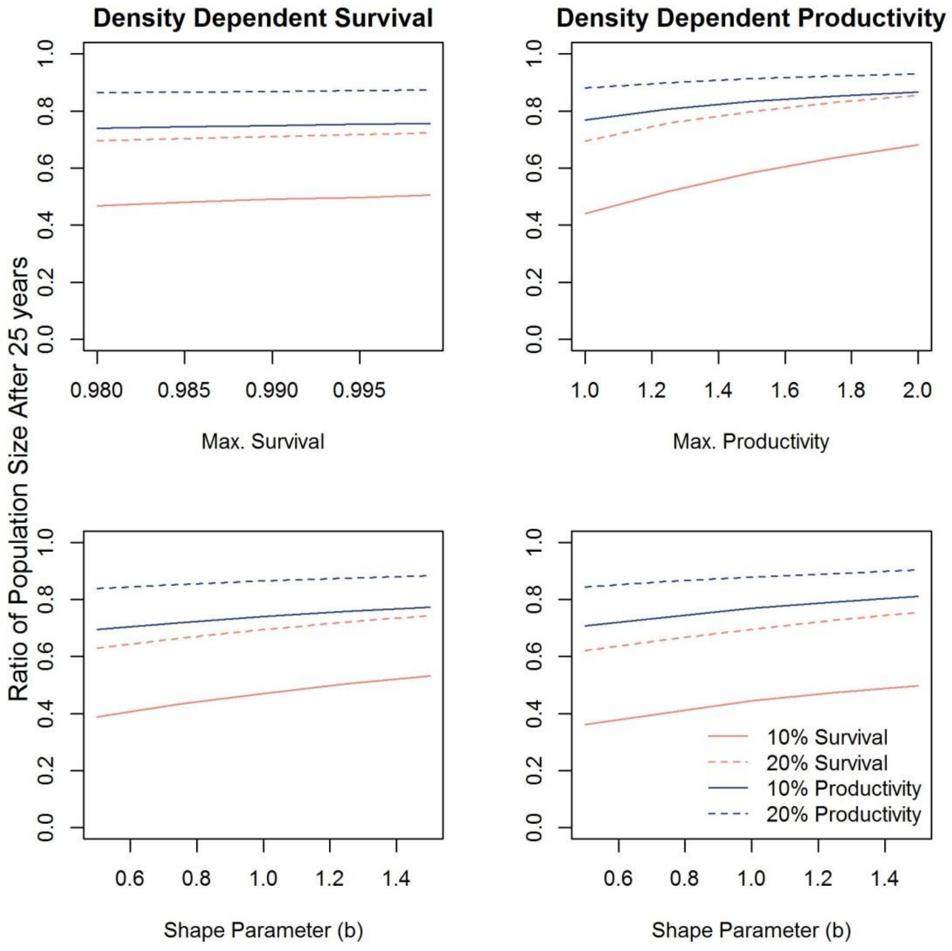

Figure 28. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

RI:U25 is more sensitive to the shape parameter and the maximum productivity rate when estimated from a density dependent model than is the case for either GR or RI:U (Fig’s 16, 20, and 28). Where survival is regulated, the maximum survival rate has little effect on RI:U25. However, as the shape parameter increases, the metric also increases. Where it is productivity that is regulated by density dependence, increases in both the maximum productivity rate and the shape parameter result in increases in RI:U25.

Additional Analysis

Since initial results suggested that this metric may be of use in estimating the population level effects of impacts arising from offshore wind farms, additional analyses were undertaken.

RI:U25 can be estimated at any point over the lifetime of a project. However, it is unclear whether sensitivity to mis-specification of demographic parameters is constant through time, i.e. if we estimate RI:U25 after 5 or 10 years, is it more important that we use accurate survival estimates than if we estimate it after 25 years. In order to understand this, we investigate how mis-specification of adult survival rates may affect the metric at different points in time (5 and 10 years post-construction). In contrast to the ratio of population growth rates (section 3.2.4), it appears that the ratio of impacted to unimpacted population size becomes more sensitive to mis-specification of demographic parameters over time (Fig. 29 & Table 19). This is because the population size in any given year is a product of the population size in the previous year and a matrix of the demographic parameters. As a consequence, any mis-specification of the demographic parameters becomes magnified through time, leading to a noticeable change in the metric value.

Table 19. Influence of a 1% mis-specification of adult survival rate on the ratio of the growth rate (as assessed by % change in metric) of an impacted to unimpacted population after 5 or 10 years for an r-selected seabird species estimated from a deterministic and stochastic model, assuming a 10%, 20% or 40% increase in mortality or a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 28.

	Impact on Survival			Impact on Productivity		
	10%	20%	40%	10%	20%	40%
After 5 years	0.42	0.87	1.94	0.05	0.10	0.23
After 10 Years	1.00	2.11	4.85	0.14	0.30	0.68

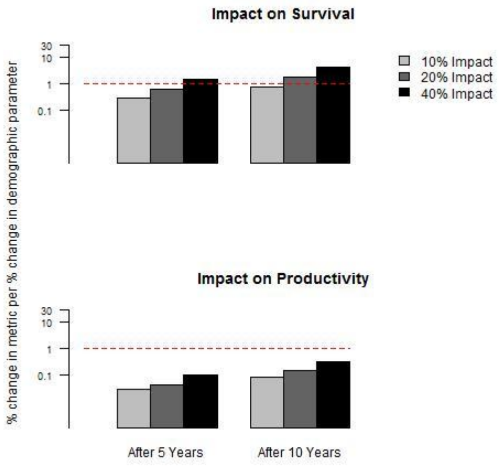

Figure 29. Percentage change in the ratio of impacted to unimpacted population size after 5 and 10 years rate per percentage change in adult survival for offshore wind farm impacts on survival and

productivity from a stochastic model. Note that the Y-axis is on a non-linear scale. Data tabulated in Table 18.

Additional analyses revealed that RI:U25 showed some sensitivity to the extent of uncertainty surrounding the demographic parameters used in population models (Fig. 30). However, this sensitivity did not appear to be greater than the sensitivity of the metric to mis-specification of demographic parameters. These analyses show that in populations where there is greater uncertainty surrounding the demographic parameters, RI:U is lower, implying a stronger population-level consequence, than is the case where there is less uncertainty surrounding the demographic parameters.

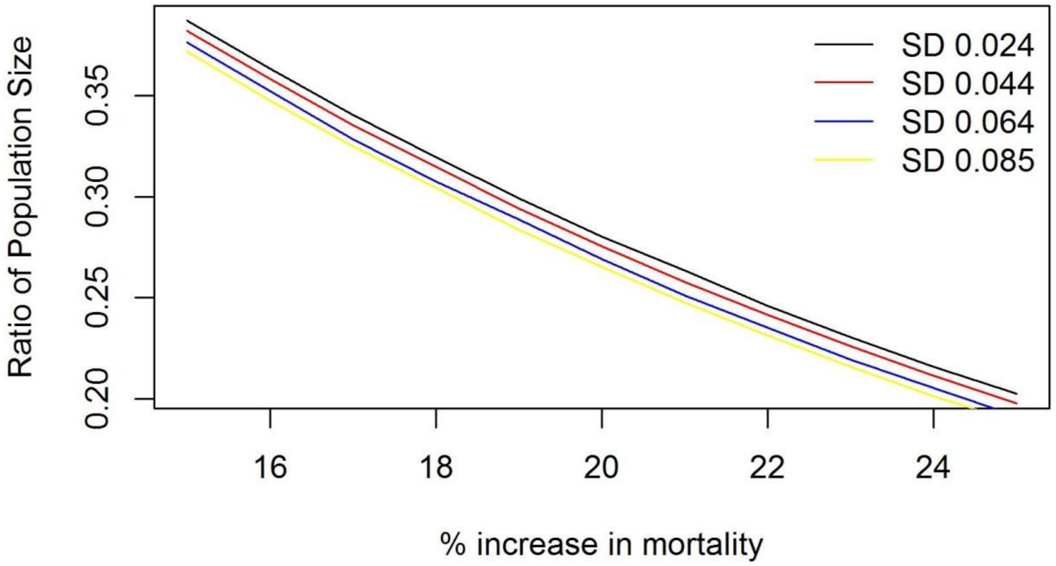

Figure 30. Impact of 15% to 25% increase in mortality on the ratio of impacted to unimpacted population size for a population of seabirds with an r-selected life history strategy and a stable population trajectory, assuming an adult survival rate of 0.89 and standard deviations of 0.024, 0.044, 0.064 and 0.085.

Sensitivity to population trend may vary depending on whether or not density dependence is incorporated in the population models used to estimate RI:U25. We therefore estimated this metric using a model assuming a density dependent impact on productivity and increasing, stable and declining populations. As with density independent models, when derived from density dependent models, where the impact is on survival, RI:U25 is insensitive to whether the population is stable or increasing, but does appear to be sensitive to whether the population is declining. Where the impact is on productivity, the metric is sensitive to whether the population is stable, declining or increasing (Table 20).

Table 20. Sensitivity of the ratio of impacted to unimpacted population size after 25 years to population trend, derived from stochastic models of an r-selected seabird assuming stable, increasing or declining populations with density dependent regulation of productivity.

	Impact on survival			Impact on productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.768 (0.652 – 0.860)	0.550 (0.361 – 0.703)	0.193 (0.037 – 0.388)	0.865 (0.821 – 0.901)	0.748 (0.673 – 0.808)	0.560 (0.441 – 0.660)
Stable	0.755	0.503	0.213	0.904	0.814	0.685

	(0.594 – 0.883)	(0.299 – 0.717)	(0.049 – 0.430)	(0.862 – 0.932)	(0.729 – 0.866)	(0.587 – 0.765)
Declining	0.600 (0.465 – 0.724)	0.314 (0.167 – 0.471)	0.049 (0 – 0.138)	0.924 (0.896 – 0.945)	0.852 (0.803 – 0.892)	0.722 (0.623 – 0.800)

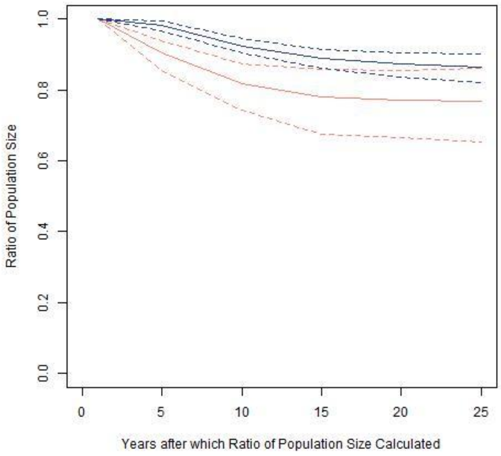

Figure 31. Change in value of the ratio of the impacted to unimpacted population size through time calculated using a stochastic model with density dependent regulation of productivity and assuming a 10% increase in mortality or a 10% reduction in productivity.

In contrast to density independent models, when using a density dependent model (Fig. 31), after an initial decrease in the ratio of impacted to unimpacted population size over the first 10 years of a project lifetime, the metric stabilises over the remaining time period. This suggests that, over time, density dependent mechanisms are compensating for the impacts associated with the offshore wind farm and that, as a result, an asymptote is reached in the ratio of impacted to unimpacted population size.

The ratio of impacted to unimpacted population growth size can be estimated from a density dependent model at any point over the lifetime of a project. However, it is unclear how incorporating density dependence into the models will affect sensitivity to mis-specification of demographic parameters. To test this, we focus on adult survival rate, which previous analyses showed was the parameter the metric was most sensitive to, and consider the sensitivity of the metric to mis-specification after 5, 10 and 25 years using a stochastic model with density dependent regulation of productivity. These results suggest that density dependent models may not be any more sensitive to mis-specification of demographic parameters than density independent models (Table 21, Figure 32).

Table 21. Influence of a 1% mis-specification of adult survival rate on the ratio of the population size (as assessed by % change in metric) of an impacted to unimpacted population after 5, 10 or 25 years for an r-selected seabird species estimated from a stochastic model with density dependent regulation of productivity, assuming a 10%, 20% or 40% increase in mortality or a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 32.

	Impact on Survival			Impact on Productivity		
	10%	20%	40%	10%	20%	40%
After 5 years	0.28	0.62	1.46	0.03	0.06	0.15
After 10 Years	0.73	1.69	4.12	0.07	0.14	0.31
After 25 Years	1.91	4.54	14.36	0.25	0.47	0.84

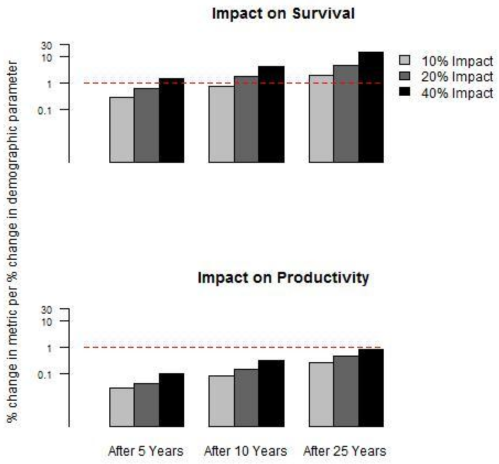

Figure 32. Percentage change in the ratio of impacted to unimpacted population size after 5, 10 and 25 years rate per percentage change in adult survival for offshore wind farm impacts on survival and productivity from a stochastic model with density dependent regulation of productivity. Note that the Y-axis is on a non-linear scale. Data tabulated in Table 21.

Metric overview

RI:U25 shows a clear and consistent relationship with increasing impacts resulting from offshore wind farms. However, the non-linear relationship between the magnitude of any impact and the metric may make interpreting the metrics more complicated when the impacted population size after 25 years is small. This metric appears to be more sensitive to mis-specification of demographic parameters, notably adult survival rate, than either GR, or RI:U. It also appears to be more sensitive to assumptions about density dependence than either of the preceding metrics. As with the preceding metrics, similar conclusions are reached about sensitivity to population trends and mis-specification of demographic parameters regardless of whether stochastic or deterministic models are used.

3.2.6 Probability of population growth rate being <1, 0.95 or 0.8 (P(GR<1))

Calculated from a stochastic model based on the proportion of simulations where the population growth rate is less than 1 (i.e. declining) or less than 0.95 or 0.8 (indicating more severe declines. The probabilities are typically assessed over the lifetime of the project. However, it would also be possible to examine these probabilities at any point during the lifetime of the project.

The metric is on a scale from 0 – 1 with 0 indicating that none of the simulations from a stochastic model result in a growth rate <1, 0.95 or 0.8 and 1 indicating that all of the simulations from a stochastic model result in a growth rate <1, 0.95 or 0.8.

Initial Results

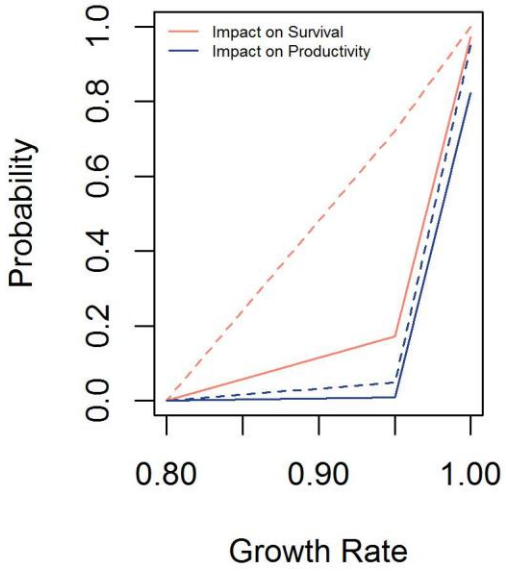

Figure 33. Probability of growth rate being less than 0.8, 0.95 or 1 assuming a stable population of an r-selected seabird species and a 10% (solid lines) or 20% (broken lines) increase in mortality or reduction in productivity.

Probabilistic metrics are estimated from the population growth rates estimated in simulations from a stochastic model. For this reason they cannot be derived from a deterministic model. The probability of the population growth rate of an impacted population being less than 0.8, 0.95 or 1 was considered (Fig. 33). For a stable population, in the absence of any impact, the probability of the population growth rate being <1 should be close to 0.5. Once an impact from an offshore wind farm was applied to the population, this probability would be expected to rise towards 1, depending on the magnitude of the impact. Initial trials suggested that, for a stable population, an increase of 20% in mortality would result in a noticeable increase in the probability of the population growth rate being less than 0.95 or less than 1. However, the clearest response for either a 10% or 20% increase in mortality or reduction in productivity is for the probability of the growth rate being less than 1. For this reason, subsequent discussion focuses the metric of the probability of the growth rate being less than 1 (P(GR<1)). It is likely that any issues raised by this metric will be equally applicable to a metric of the probability of the growth rate being less than 0.95 or less than 0.8.

If the median growth rate of the population under consideration were precisely 1, the probability of the growth being <1 would be approximately 0.5 as half of the simulations from the stochastic model would have a growth rate <1 and half would have a growth rate >1. However, as the median growth rate of this population is slightly less than 1 (see section 3.2.3), there is greater probability of the unimpacted population having a growth rate <1, in this case 0.598 (Fig. 34). As the magnitude of the impact on survival or productivity increases, P(GR<1) approaches one (Fig. 34). Less severe impacts are required on survival before the probability of the growth rate being less than 1 reaches 1, than is the case for impacts on productivity. A 15% increase in mortality results in a probability of the growth rate being less than 1 of 0.998. In contrast, a 30% reduction in productivity is required before a 0.996 probability of the growth rate being less than one is estimated.

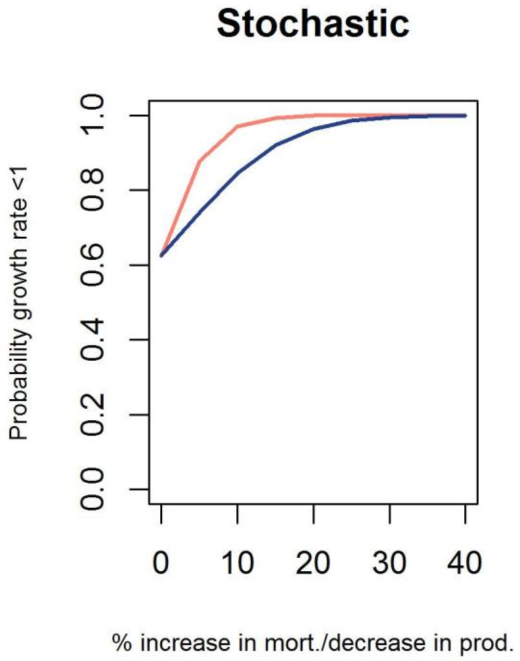

Figure 34. Impact of up to a 40% increase in mortality (red line) or up to a 40% decrease in productivity on the probability (blue line) of the growth rate of a population of seabirds with an r-selected life history strategy and a stable population trajectory.

Sensitivity to life history strategy, population trend and density dependence

There are clear differences between P(GR<1) for increasing and stable populations (Table 22). Differences are also evident between stable and decreasing populations although these narrow as the magnitude of the predicted impact increases. Species which have a more K-selected life history strategy appear to be more resilient to impacts than those with an r-selected strategy and the probability of a stable population of these species having a growth rate of less than 1 is lower for an equivalent impact level than is the case for an r-selected species (Table 22).

Table 22. Probability of population growth rate being less than one resulting from a 10% or 20% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.009	0.296	0.970	<0.001	0.001	0.064
Stable	0.963	0.998	1.000	0.792	0.910	0.999
Decreasing	1.000	1.000	1.000	1.000	1.000	1.000
K selected	0.901	0.982	1.000	0.677	0.777	0.931
Density Dependent Survival	0.730	0.876	0.990	0.537	0.653	0.809
Density Dependent Productivity	0.901	0.989	1.000	0.725	0.835	0.975

As might be expected, density dependent processes appear to mitigate the impacts arising from offshore wind farms on seabirds. Density dependent regulation of survival appears to more effectively regulate against any impacts than density dependent regulation of productivity (Table 22).

Sensitivity to mis-specification of demographic parameters

P(GR<1) is more sensitive to mis-specification of input parameters than the metrics discussed previously (Fig. 35, Tables 23 and 24, and see sections 3.2.1 - 3.2.3 above). As previously, the metric is most sensitive to mis-specification of adult survival. However, in contrast to these preceding metrics, it may also be fairly sensitive to mis-specification of other demographic parameters, particularly when productivity is affected by a development. The sensitivity of the metric to mis-specification of demographic parameters declines with the magnitude of the predicted impact, and for a 40% increase in mortality the sensitivity to mis-specification of demographic parameters other than adult survival is 0. This is because, for the stable, r-selected population considered, an increase in mortality of 40% will, almost always, result in a growth rate less than 1 regardless of the value assumed for immature or first year survival or productivity. It is worth noting that, in contrast to previous metrics (see sections 3.2.3 – 3.2.5), there is less scope for this metric to vary as it cannot exceed 1, and for no impact, the probability of a population growth rate of <1 is 0.6, meaning the metric must be bound by these two values.

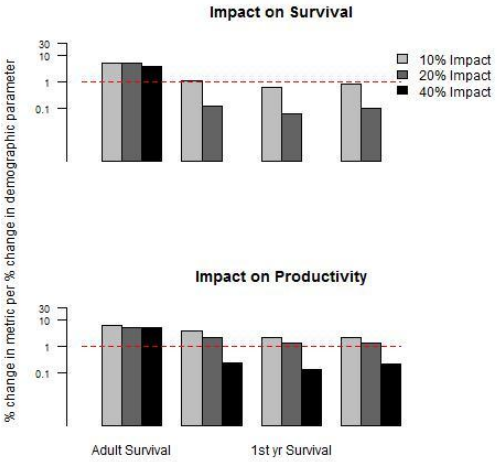

Figure 35. Percentage change in the probability of the population growth rate being less than 1 per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from deterministic (left) and stochastic (right) models. Note that the Y-axis is on a non-linear scale. Data tabulated in Tables 23 and 24.

Table 23. Influence of a 1% mis-specification of each demographic parameter on the probability of the population growth rate being less than 1 (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 35.

	Stochastic		
	10%	20%	40%
Adult Survival	5.19	5.00	3.77
Immature Survival	1.21	0.19	<0.01
Chick Survival	0.76	0.13	<0.01
Productivity	0.90	0.15	<0.01

Table 24. Influence of a 1% mis-specification of each demographic parameter on probability of the population growth rate being less than 1 (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 35.

	Stochastic		
	10%	20%	40%
Adult Survival	6.26	5.45	5.01
Immature Survival	3.82	2.20	0.22
Chick Survival	2.18	1.29	0.10
Productivity	2.42	1.17	0.14

Sensitivity to form of density dependence

If density dependence is introduced into the models, P(GR<1) appears to show some sensitivity to mis-specification of the shape parameter and mis-specification of the maximum survival or productivity rate (Fig. 36), with some variation in the metric when alternative values are assumed for each parameter.

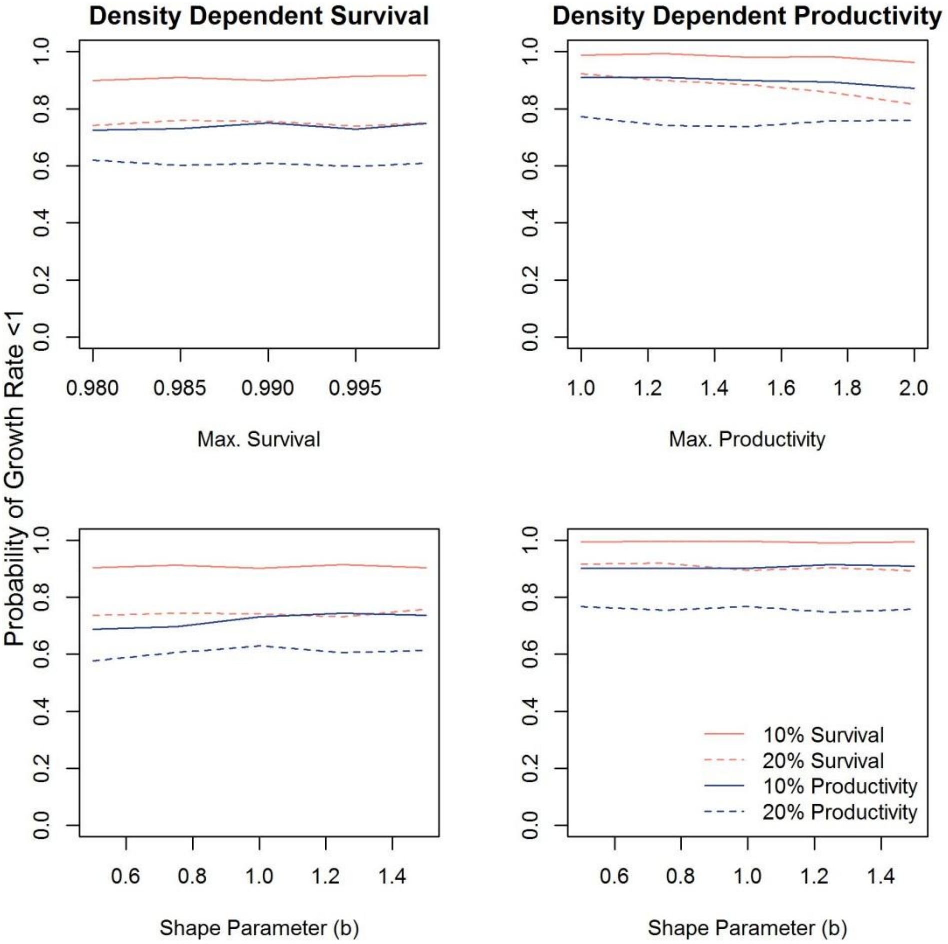

Figure 36. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Metric overview

P(GR<1) reaches an asymptote (Fig. 34), making it harder to understand differences in the population level effects of a development when impacts are moderate to severe, particularly in the case of impacts on survival. The metric appears to be more sensitive to mis-specification of demographic parameters than those discussed previously. As with previous metrics it is most sensitive to mis-specification of adult survival. However, there are also indications that it may be sensitive to mis-specification of other demographic parameters. Whilst incorporating density dependent regulation of survival and/or productivity into the models reduces the value estimated for this metric, it appears to have some sensitivity to assumptions about the form of this density dependence (Fig. 36).

3.2.7 Change in the probability of the population growth rate being <1, 0.95 or 0.8 (dP(GR<1))

Where simulations show that a population may already be at risk of declining in the absence of a wind farm, for example if >50% of simulations have a growth rate <1, simply quantifying the probability of a population decline in the presence of an offshore wind farm may not be meaningful. To assess the population level impact of a development it is therefore necessary to determine how much greater the probability of a decline is in the presence of an offshore wind farm than in the absence of an offshore wind farm. This could be done either at a single fixed point in time, or at intervals throughout the life time of the project.

The metric is on a scale from 0 – 1, with 0 indicating that there is no change in the probability of the growth rate being <1, 0.95 or 0.8 between impacted and unimpacted populations (i.e. no population-level consequence) and values approaching 1 indicating there is a change in the probability of the growth rate being <1, 0.95 or 0.8 between the impacted and unimpacted populations (i.e. a population-level consequence).

Initial Results

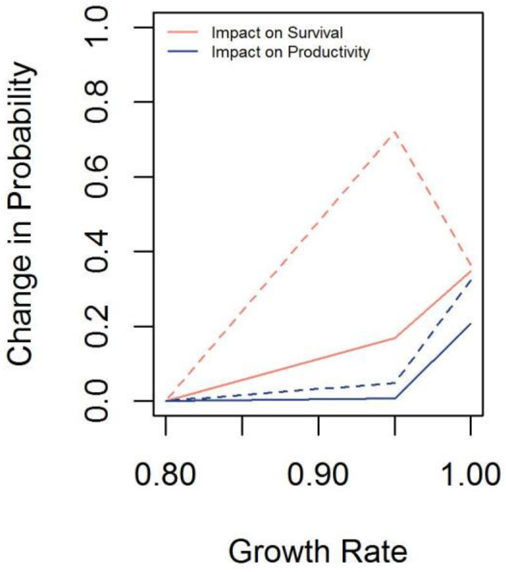

Figure 37. Change in probability of growth rate being less than 0.8, 0.95 or 1 assuming a stable population of an r-selected seabird species and a 10% (solid lines) or 20% (broken lines) increase in mortality or reduction in productivity.

Initial trials suggested that, for a stable population, the change in probability of the growth rate being 0.8, 0.95 or 1 peaked at different points depending on the magnitude of the impact considered (Fig. 37). The probability of the population growth rate being <1 for a stable population in the absence of impacts from an offshore wind farm should be close to 0.5. As a consequence, once impacts from an offshore wind farm are applied to a population, the maximum value possible for the change in probability of the population growth rate being <1 is 0.5 (i.e. the impact associated with an offshore wind farm causes the probability of the growth rate being <1 to increase from 0.5 to 1.0). Under the scenarios considered in Figure 37 a 10% impact on mortality or a 20% impact on survival or mortality causes the probability of the population growth rate being <1 to increase by between 0.35 and 0.4 (i.e. from a probability of 0.5 for a stable population in the absence of any offshore wind farm impact to 0.85-0.90 for the same population in the presence of an offshore wind farm impact). Similarly, for a stable population, the probability of a growth rate of <0.95 or <0.80 should be close to 0. Therefore, there is greater scope for a change in the probability of the growth rate being lower than either of these two values than is the case for a growth rate of <1. Figure 37 demonstrates that a severe impact on survival can result in a large change in the probability of the growth rate being <0.95. However, even with a 20% increase in mortality, the probability of the population growth rate being <0.8 was still close to 0. For this reason, subsequent discussion focuses on the probability of the population growth rate being less than 1 (dP(GR<1)). It is likely that this discussion would be equally applicable to metrics of the change in probability of the population growth rate being less than 0.95 or 0.8. Based on the stable population of an r-selected seabird considered in this report, the minimum value for P(GR<1) is 0.598 (see section 3.2.6, above). As a consequence, the maximum value for dP(GR<1), assuming a stable population, is 0.402 as 1 is the upper limit on P(GR<1). As the magnitude of the impact on survival or productivity increases, the change in the probability of the population growth rate being less than 1 reaches an asymptote at approximately 0.40 (Fig. 38). Less severe impacts are required on survival before the probability of the growth rate being less than 1 reaches an asymptote, than is the case for impacts on productivity. A 15% increase in mortality results in the change in the probability of the growth rate being less than 1 of 0.389. In contrast, a 30% reduction in productivity is required before this value is reached.

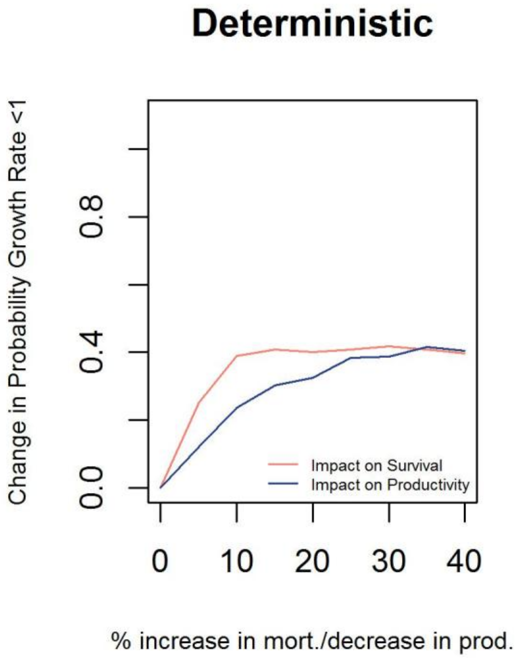

Figure 38. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the change in the probability of the growth rate being less than 1 for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

Sensitivity to life history strategy, population trend and density dependence

dP(GR<1) appears to be sensitive to the underlying trajectory of the population concerned. Where a population is stable, the metric may indicate the impact of any development relatively clearly. However, where the population is increasing or decreasing, the metric is less capable of detecting any impact when these impacts are less severe. In the case of an increasing population, dP(GR<1) is 0.98 for a 40% impact on survival, indicating that the growth rate from the simulations for the unimpacted population was almost always >1, but almost always <1 for the impacted population.

Species which have a more K-selected life history strategy appear to be more resilient to impacts than those with an r-selected strategy and the probability of a stable population of these species having a growth rate of less than 1 is lower for an equivalent impact level than is the case for an r-selected species (Table 25).

Table 25. Change in probability of population growth rate being less than 1 after 25 years resulting from a 10% or 20% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.017	0.296	0.980	<0.001	0.005	0.074
Stable	0.383	0.379	0.400	0.185	0.328	0.400
Decreasing	0.001	0.002	0.002	<0.001	0.001	0.001
K selected	0.263	0.325	0.333	0.146	0.250	0.340
Density Dependent Survival	0.241	0.456	0.516	0.077	0.170	0.333
Density Dependent Productivity	0. 298	0.405	0.403	0.162	0.236	0.391

As might be expected, density dependent processes appear to largely mitigate the impacts arising from offshore wind farms on seabirds. However, in contrast to previous metrics, it appears that when impacts on survival are more severe, incorporating density dependence into the model may indicate a more severe impact at a population level. This is likely to be because the growth rate of the unimpacted populations is slightly higher when density dependence is incorporated (see Table 25), meaning a lower proportion of simulations will have a growth rate <1 than would be the case for density independent populations. Consequently, there is more scope for dP(GR<1) to increase when the density dependence is incorporated into the models.

Sensitivity to mis-specification of demographic parameters

As with previous metrics dP(GR<1) is most sensitive to adult survival (Fig. 39 and Tables 26 and 27). However, the change in probability of the population growth rate being less than one is also extremely sensitive to mis-specification of each of the other demographic parameters.

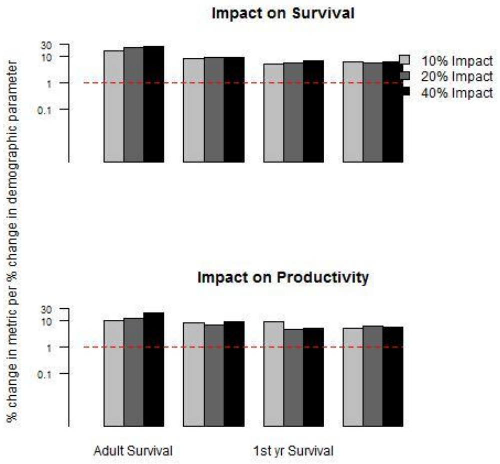

Figure 39. Percentage change in the change in probability of the population growth rate being less than 1 per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity stochastic models. Data tabulated in Tables 26 and 27.

Table 26. Influence of a 1% mis-specification of each demographic parameter on the change in the probability of the population growth rate being less than 1 (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 39.

	Stochastic		
	10%	20%	40%
Adult Survival	16.88	23.03	23.75
Immature Survival	7.54	9.06	10.01
Chick Survival	5.18	5.99	6.03
Productivity	6.02	6.40	6.68

Table 27. Influence of a 1% mis-specification of each demographic parameter on the change in the probability of the population growth rate being less than 1 (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 39.

	Stochastic		
	10%	20%	40%
Adult Survival	13.37	14.79	20.28
Immature Survival	10.40	8.63	8.81
Chick Survival	5.83	7.61	5.86
Productivity	6.22	6.36	7.19

Sensitivity to form of density dependence

If density dependence is introduced into the models, dP(GR<1) appears to have some sensitivity to both mis-specification of the shape parameter and mis-specification of the maximum survival or productivity rate (Fig. 40), with some variation in the metric when alternative values are assumed for each parameter.

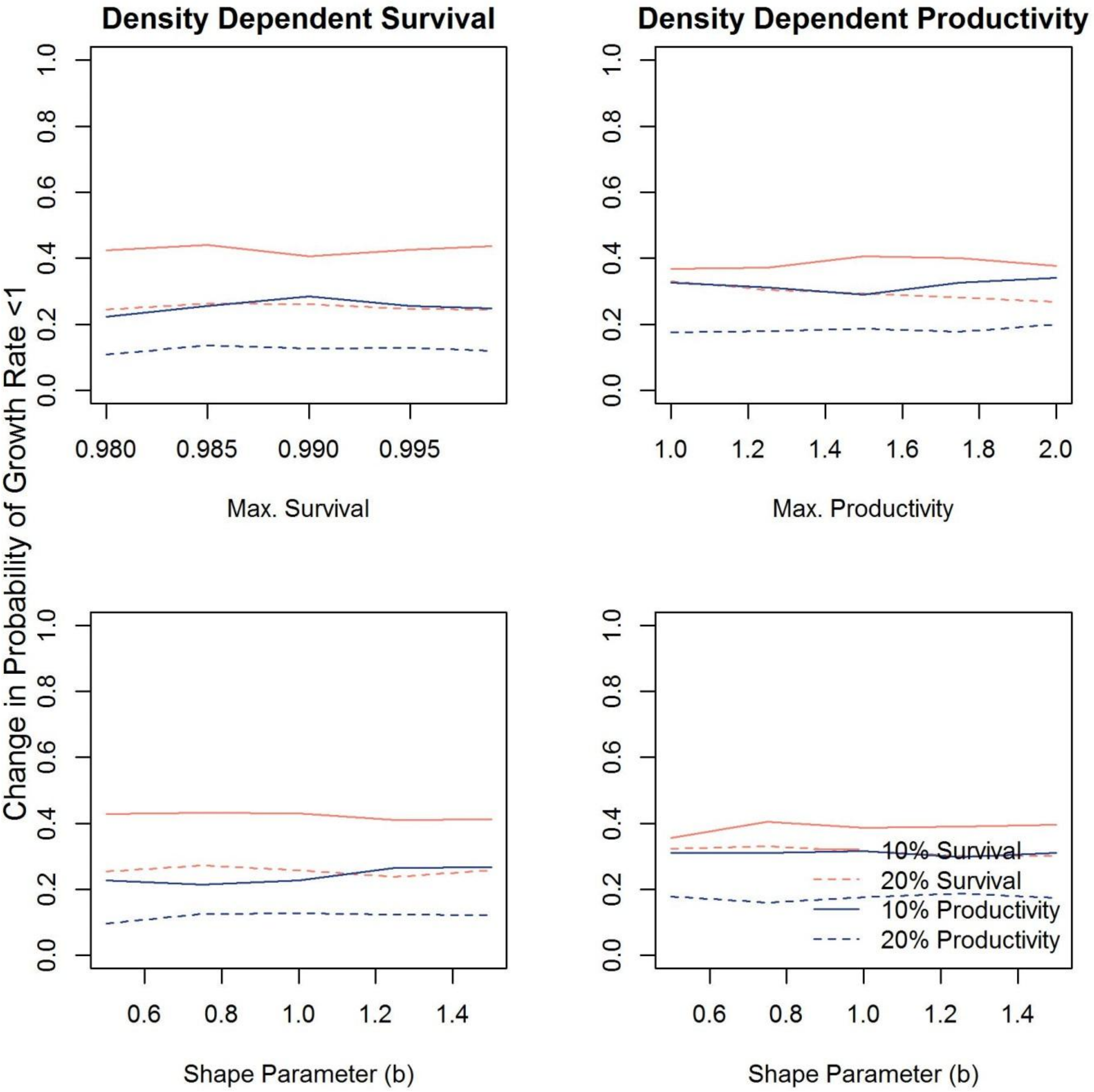

Figure 40. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Metric overview

dP(GR<1) quickly reaches an asymptote (Fig. 38), making it harder to understand differences in the population level effects of a development when impacts are moderate to severe, particularly in the case of impacts on survival. The metric appears to be more sensitive to mis-specification of demographic parameters than those discussed previously. As with previous metrics it is most sensitive to mis-specification of adult survival. However, there are also indications that it is also sensitive to mis-specification of other demographic parameters. Incorporating density dependent regulation of survival and/or productivity into the models reduces the value estimated for this metric, it also appears to have some sensitivity to assumptions about the form of this density dependence (Fig. 40).

3.2.8 Probability of the population declining below its initial size at any point in time ($P(p<p_0)$)

After an initial impact, environmental stochasticity and density dependence may mean a population is able to recover throughout the life time of a project. This recovery would mean that over 25 years the final population size may not be smaller than starting population size.

The metric is on a scale from 0 -1 with 0 indicating that none of the simulations from a stochastic model result in a population below its initial size at any point in time and 1 indicating that all of the simulations from a stochastic model result in a population below its initial size at any point in time.

Initial Results

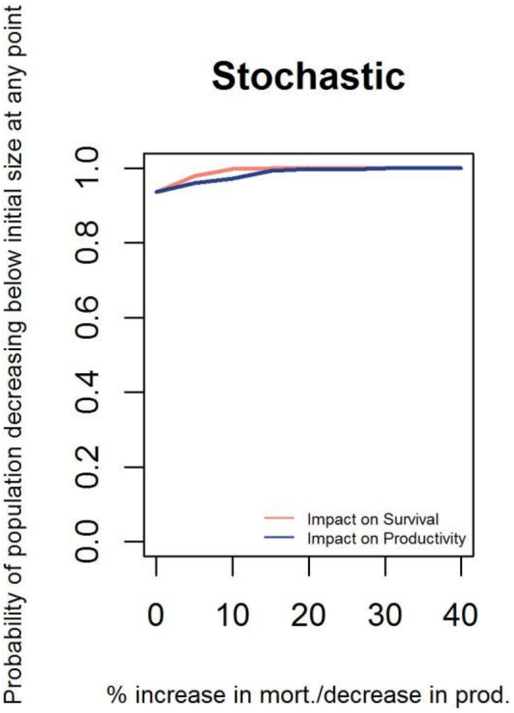

Figure 41. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the probability of the population dropping below its initial size at any point in time for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

In contrast to the previous metrics, this considers the probability of a population deceasing below its initial size at any point in time ($P(p<p_0)$), as opposed to being below its initial size at the end of the project lifetime (i.e. has an average population growth rate <1). Therefore, this metric allows for the possibility that the impact from a development may initially cause a population to decline, but that it may then recover over the lifetime of the project. Assuming a stable population, this metric is at, or close to, 1 regardless of the magnitude of impact a population experiences (Fig. 41).

Sensitivity to life history strategy, population trend and density dependence

There are clear differences between $P(p<p_0)$ for increasing and stable populations (Table 28). However, differences are less clear for stable or decreasing populations. Species which have a more K-selected life history strategy appear to be more resilient to impacts than those with an r-selected strategy and the probability of a stable population of these species

having P($p<p_0$) is lower for an equivalent impact level than is the case for an r-selected species (Table 28).

As might be expected, density dependent processes mitigate against the impact of any impacts from development. Density dependent regulation of survival appears to more effectively mitigate the impacts of any development than density dependent regulation of productivity (Table 28).

Table 28. Probability of a population decreasing below its initial size at any point in time resulting from a 10% or 20% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.617	0.865	1.000	0.517	0.710	1.000
Stable	0.997	1.000	1.000	0.980	0.997	1.000
Decreasing	1.000	1.000	1.000	1.000	1.000	1.000
K selected	0.989	0.999	1.000	0.980	0.998	1.000
Density Dependent Survival	0.967	0.990	0.998	0.914	0.974	0.995
Density Dependent Productivity	0.994	1.000	1.000	0.989	0.996	1.000

Sensitivity to mis-specification of demographic parameters

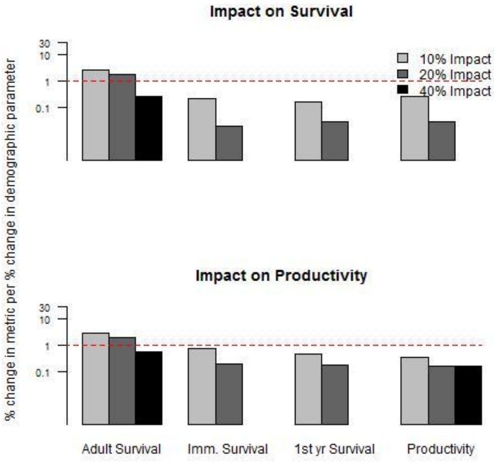

Figure 42. Percentage change in the change in probability of a population decreasing below its initial size at any point per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from stochastic models. Data tabulated in Tables 29 and 30.

As with previous metrics, P(p<p0) is most sensitive to mis-specification of adult survival. However, it is relatively insensitive to mis-specification of other parameters (Fig. 42 and Tables 29 and 30). Sensitivity to mis-specification of the demographic parameters varied according to the magnitude of the impact predicted, and the metric was less sensitive to mis-specification when more severe impacts were estimated.

Table 29. Influence of a 1% mis-specification of each demographic parameter on the probability of a population decreasing below its initial size at any point (as assessed by % change in metric) in time for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Data illustrated graphically in Figure 42.

	Stochastic		
	10%	20%	40%
Adult Survival	2.73	1.70	0.26
Immature Survival	0.22	0.02	<0.01
Chick Survival	0.16	0.03	<0.01
Productivity	0.25	0.03	<0.01

Table 30. Influence of a 1% mis-specification of each demographic parameter on the probability of a population decreasing below its initial size at any point in time (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% reduction in productivity. Data illustrated graphically in Figure 42.

	Stochastic		
	10%	20%	40%
Adult Survival	2.80	1.98	0.58
Immature Survival	0.75	0.20	<0.01
Chick Survival	0.16	0.03	<0.01
Productivity	0.33	0.16	<0.01

Sensitivity to form of density dependence

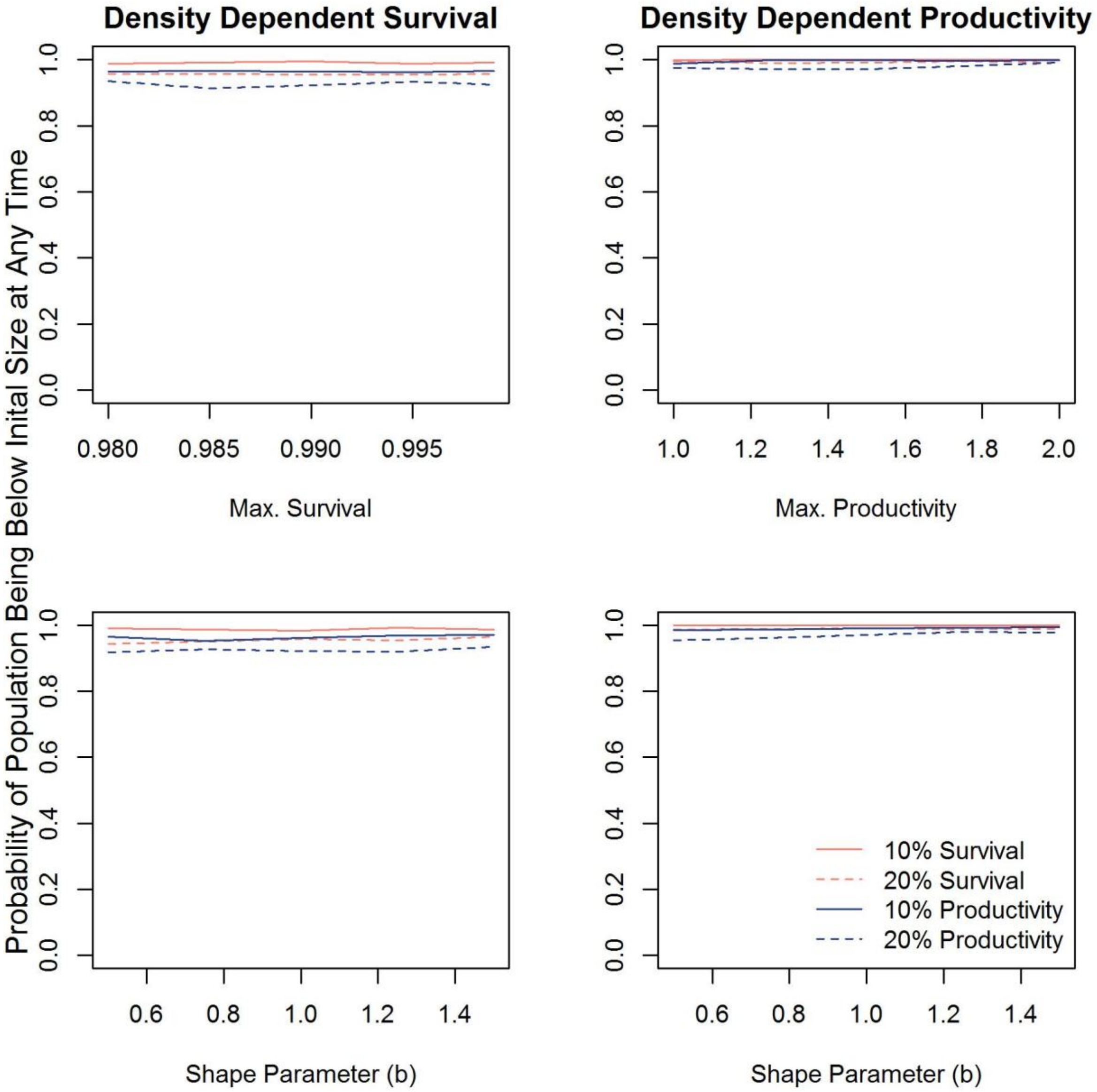

Figure 43. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

If density dependence is introduced into the models, $P(p<p_0)$ does not appear to be particularly sensitive to either mis-specification of the shape parameter or mis-specification of the maximum survival or productivity rate (Fig. 43).

Metric overview

The metric is sensitive to the underlying trend of the population concerned, with clear differences when calculated for increasing or stable/decreasing populations. Where the pre-impact population at a site is stable, $P(p<p_0)$ rapidly plateaus at 1, regardless of whether impacts are on productivity or survival. However, the metric is relatively insensitive to mis-specification of demographic parameters and the assumptions made about density dependence.

3.2.9 Probability of a 10, 25 or 50% population decline (P(Id>0.25))

A metric to assess the population level impact of a development could be derived by estimating the proportion of simulations for a population in the presence of a wind farm which in which a decline of a given magnitude was recorded.

The metric is on a scale from 0 – 1, with 0 indicating that none of the simulations from a stochastic model show the impacted population declining by a given magnitude (i.e. no population-level consequence) and 1 indicating that all simulations show the impacted population declining by a given magnitude.

Initial Results

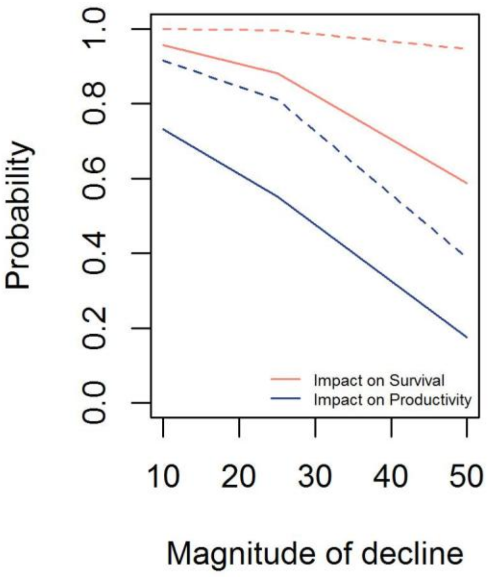

Figure 44. Probability of a decline of 10, 25 or 50% assuming a stable population of an r-selected seabird species and a 10% (solid lines) or 20% (broken lines) increase in mortality or reduction in productivity.

This metric considered the probability of a population declining by 10, 25 or 50% as a result of the impacts associated with an offshore wind farm after the 25 year life time of a wind farm (Fig. 44). Assuming a 20% increase in mortality, the metric is close, or equal, to 1 regardless of whether a 10, 25 or 50% decline is under consideration. For a 10% increase in mortality or a 10 or 20% decrease in productivity, the probability of detecting changes of these magnitudes declines sharply. Further discussion of this metric focusses on 25% decline, although these comments are likely to be equally applicable to a 10 or 50% decline.

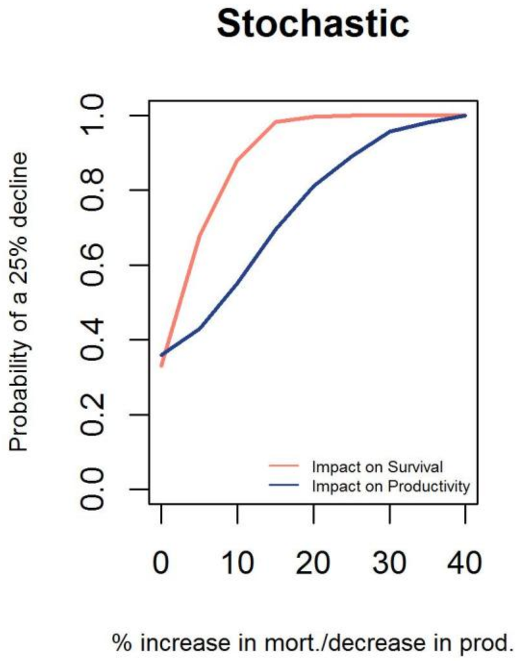

Figure 45. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the probability of a decline of 25% for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

The probability of a population decline of 25% (P(Id>0.25)) reaches an asymptote at 1 for a 20% increase in mortality. Therefore, this metric may be unable to distinguish between the population-level consequences of medium (20% mortality) and large (40% mortality) magnitude impacts. If the impact is on productivity, the probability of a population decline of 25% rises more gradually before also reaching 1 after a 40% decrease in productivity (Fig. 45).

Sensitivity to life history strategy, population trend and density dependence

There are clear differences between P(Id<0.25) for populations which are increasing and for those that are stable (Table 31). There are also clear differences between stable and decreasing populations where there is a 10% increase in mortality or a 10 or 20% impact on productivity. However, where there are more severe increases in mortality, these differences are less clear. Species which have a more K-selected life history strategy appear to be more resilient to the impacts of offshore wind farms.

As might be expected, density dependent regulation of the population can mitigate the impacts arising as a result of offshore wind farms. It appears that density dependent regulation of productivity more effectively mitigates population level effects than density dependent regulation of productivity (Table 31).

Table 31. Probability of a population decline of 25% resulting from a 10% or 20% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	<0.001	0.170	0.944	<0.001	<0.001	0.059
Stable	0.882	0.994	1.000	0.594	0.798	1.000
Decreasing	1.000	1.000	1.000	1.000	1.000	1.000
K selected	0.596	0.884	0.997	0.354	0.589	0.916
Density Dependent Survival	0.512	0.804	0.978	0.372	0.524	0.765
Density Dependent Productivity	0.450	0.841	0.997	0.221	0.327	0.732

Sensitivity to mis-specification of demographic parameters

As with previous metrics, P(Id<0.25) is most sensitive to mis-specification of the adult survival rate. However, it is also sensitive to mis-specification of other demographic parameters, particularly when impacts are predicted to affect productivity (Fig. 46 and Tables 32 and 33).

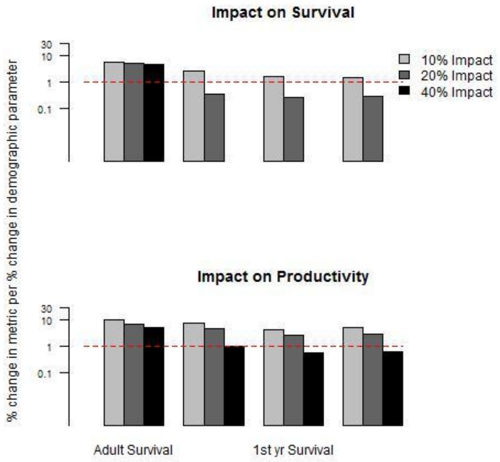

Figure 46. Percentage change in the probability of the population declining by 25% per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from stochastic models. Data tabulated in Tables 32 and 33.

Table 32. Influence of a 1% mis-specification of each demographic parameter on the probability of a population decreasing by 25% (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 46.

	Stochastic		
	10%	20%	40%
Adult Survival	5.86	5.02	4.47
Immature Survival	2.76	0.43	<0.01
Chick Survival	1.51	0.19	<0.01
Productivity	1.64	0.19	<0.01

Table 33. Influence of a 1% mis-specification of each demographic parameter on the probability of a population decreasing by 25% (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% reduction in productivity. Illustrated graphically in Figure 46.

	Stochastic		
	10%	20%	40%
Adult Survival	9.41	6.54	5.02
Immature Survival	7.07	3.60	0.37
Chick Survival	4.58	1.97	0.29
Productivity	4.30	2.23	0.31

Sensitivity to form of density dependence

Where a population has density dependent regulation of survival, P(Id>0.25) is relatively insensitive to assumptions about the maximum survival rate and the shape parameter (Fig. 47). However, where productivity is regulated by density dependence, P(Id>0.25) is sensitive to both of these parameters. This is because density dependence triggers an increase in the productivity rate of the impacted population, reducing the proportion of simulations in which it undergoes a 25% decline.

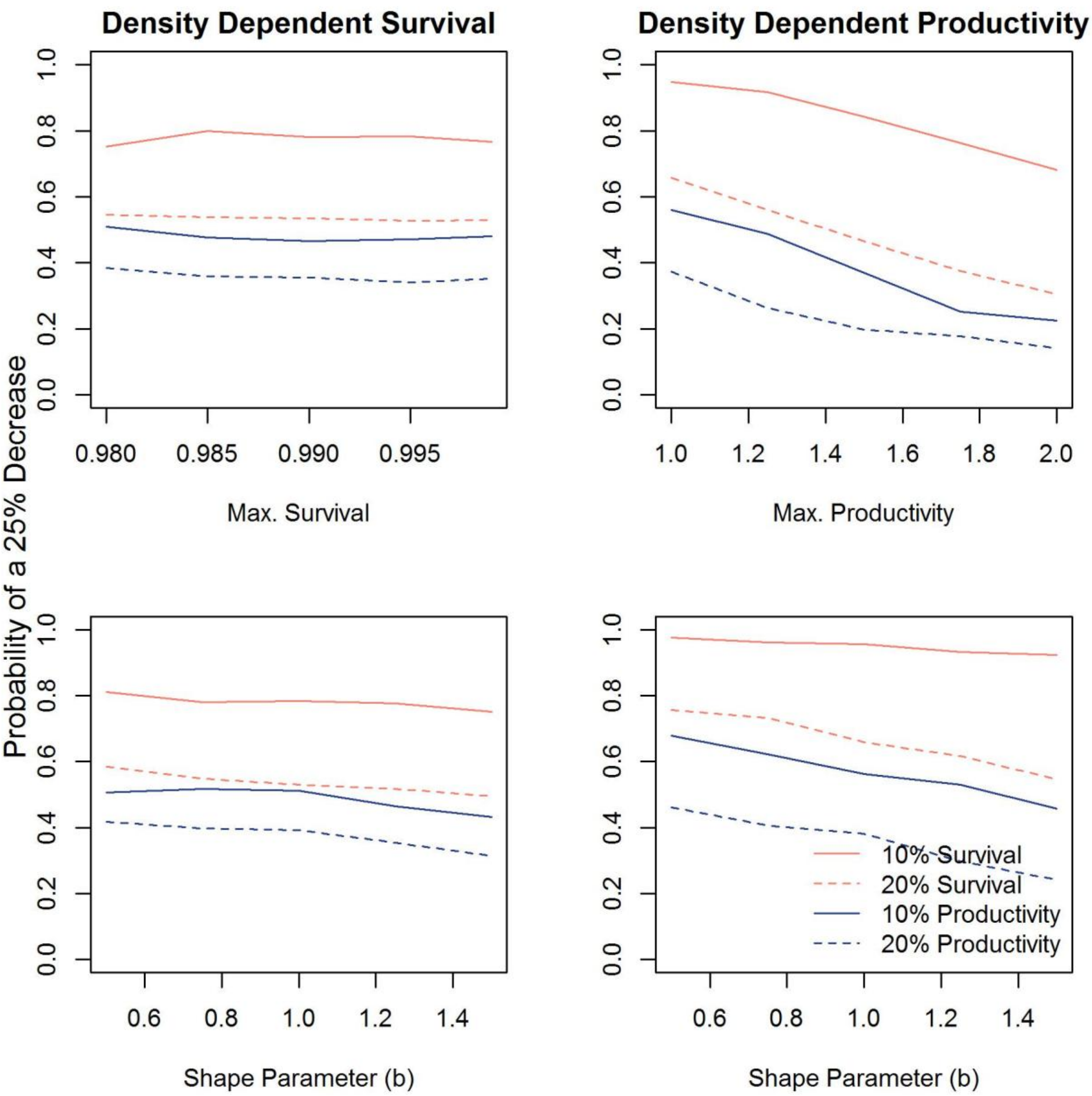

Figure 47. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Metric overview

P(Id>0.25) reaches an asymptote, making it difficult to distinguish the population level effects of more severe impacts, particularly in relation to increases in mortality. The metric appears to be sensitive to assumptions about the underlying trend of the population concerned and to the demographic parameters used in the population models, particularly when impacts are on productivity. The metric is also sensitive to assumptions about the density dependent regulation of productivity.

3.2.10 Change in probability of a 10, 25 or 50% decline (dP(Id.0.1), dP(Id>0.25), dP(Id>0.5))

At many colonies throughout the UK seabird populations are already declining (JNCC 2013). As a consequence, the presence of a wind farm may not increase the probability of the population size at these colonies being <1, if all simulations from the baseline scenario already have a population size less than starting population size. However, the presence of the wind farm may cause a further reduction in population size. It may, therefore, be more meaningful to consider the change in probability of population size decreasing by a given magnitude, for example a 10% increase in the probability of a 5% decline.

From 0 – 1, with 0 indicating that there is no change in the probability of the population decreasing by a given magnitude between the impacted and unimpacted populations (i.e. no population-level consequence) and values approaching 1 indicating there is a large change in the probability of the population decreasing by a given magnitude between the impacted and unimpacted populations (i.e. a population-level consequence).

Initial Results

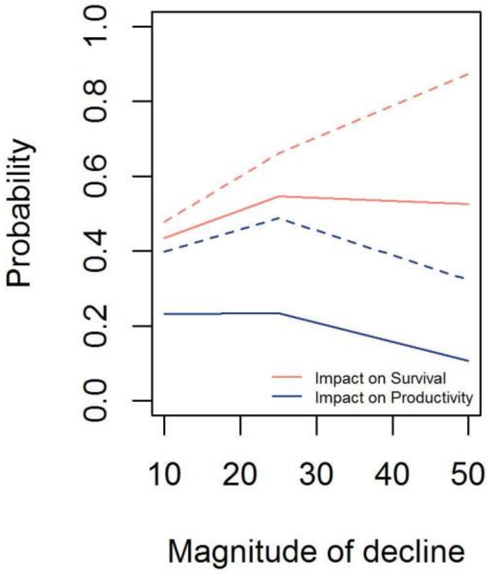

Figure 48. Change in probability of a decline of 10, 25 or 50% assuming a stable population of an r-selected seabird species and a 10% (solid lines) or 20% (broken lines) increase in mortality or reduction in productivity.

When considering the probability of a population decline of 10, 25 or 50% (dP(Id>0.1), dP(Id>0.25), dP(Id>0.5)), the relationship between the probability and the magnitude varies according to the level of impact predicted (i.e. 10% or 20%) and whether survival or productivity is affected (Fig. 48). For a 20% increase in mortality, the change in probability increases between dP(Id>0.1) and dP(Id>0.5). In contrast, for a 10% reduction in productivity, the change in probability decreases over this range. For a 10% increase in mortality, or a 20% decrease in productivity, the change in probability appears to peak at dP(Id>0.25). The reason for this peak is that whilst a 10 % increase in mortality, or up to a 20% decrease in productivity, are sufficient to increase the proportion of simulations showing a 25% decline for an impacted population relative to the unimpacted population, these impacts are not severe enough to cause a similar increase in the proportion of simulations showing a 50% decline. Consequently, further discussion of this metric is focussed on the change in probability of a 25% decline (dP(Id>0.25).

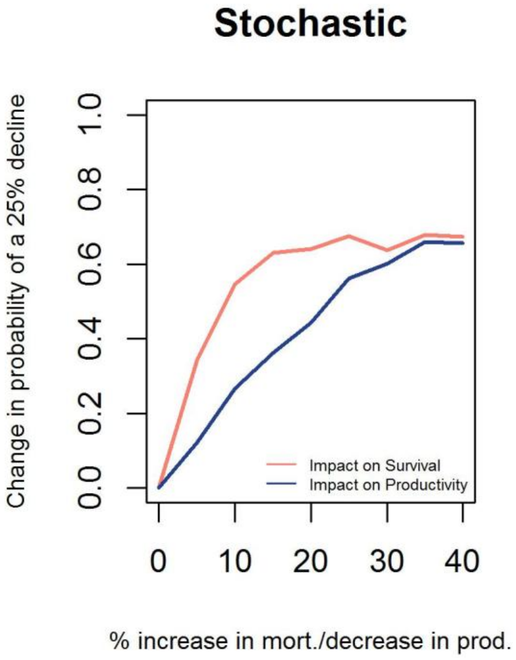

Figure 49. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the change in probability of a decline of 25% for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

dP(ld>0.25) reaches an asymptote at around 0.65 for a 20% increase in mortality. If the impact is on productivity, the probability of a population decline of 25% rises more gradually before also reaching 0.65 after a 40% decrease in productivity (Fig. 49). It is worth noting that dP(ld>0.25) cannot exceed 0.65 as P(ld>0.25) in an unimpacted population is approximately 0.35 (Fig. 44) and cannot exceed 1.

Sensitivity to life history strategy, population trend and density dependence

dP(ld>0.25) appears to be sensitive to the underlying trajectory of the population concerned as there is limited scope for the metric to change in stable and declining populations. Where a population is increasing the metric may indicate the impact of any development relatively clearly. However, where the population is increasing or decreasing, the metric is less capable of detecting any impact, particularly when these impacts are less severe. Species which have a more K-selected life history strategy appear to be more resilient to impacts than those with an r-selected strategy and the probability of a stable population of these species having a growth rate of less than 1 is lower for an equivalent impact level than is the case for an r-selected species (Table 34).

As might be expected, density dependent processes appear to largely mitigate the impacts arising from offshore wind farms on seabirds. However, in contrast to previous metrics, it appears that when impacts on survival are more severe, incorporating density dependence into the model may indicate a more severe impact at a population level (Table 34).

Table 34. Change in probability of a population decline of 25% resulting from a 10% or 20% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.007	0.187	0.944	<0.001	<0.001	0.059
Stable	0.552	0.667	0.677	0.255	0.471	0.695
Decreasing	0.016	0.012	0.014	0.007	0.015	0.014
K selected	0.380	0.618	0.762	0.156	0.325	0.680
Density Dependent Survival	0.276	0.504	0.730	0.112	0.233	0.524
Density Dependent Productivity	0.333	0.722	0.899	0.102	0.249	0.643

Sensitivity to mis-specification of demographic parameters

As with previous metrics, dP(Id>0.25) is most sensitive to mis-specification of the adult survival rate. However, it is also sensitive to mis-specification of other demographic parameters (Fig. 50 and Tables 35 and 36)

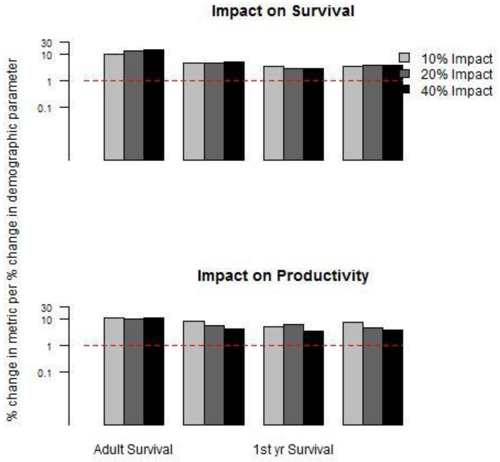

Figure 50. Percentage change in the change in probability of the population declining by 25% per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from stochastic models. Data tabulated in Tables 35 and 36.

Table 35. Influence of a 1% mis-specification of each demographic parameter on the change in probability of a population decreasing by 25% (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Data illustrated graphically in Figure 50.

	Stochastic		
	10%	20%	40%
Adult Survival	10.49	13.14	13.44
Immature Survival	4.90	4.80	4.71
Chick Survival	3.21	2.55	2.72
Productivity	4.04	3.03	2.97

Table 36. Influence of a 1% mis-specification of each demographic parameter on the change in probability of a population decreasing by 25% (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% reduction in productivity. Data illustrated graphically in Figure 50.

	Stochastic		
	10%	20%	40%
Adult Survival	10.54	9.97	12.33
Immature Survival	5.57	5.93	4.67
Chick Survival	5.12	2.53	2.99
Productivity	7.06	3.27	2.89

Sensitivity to form of density dependence

Where a population has density dependent regulation of survival, dP(ld>0.25) is relatively insensitive to assumptions about the maximum survival rate and the shape parameter. However, where productivity is regulated by density dependence, the metric is sensitive to both of these parameters (Fig. 51).

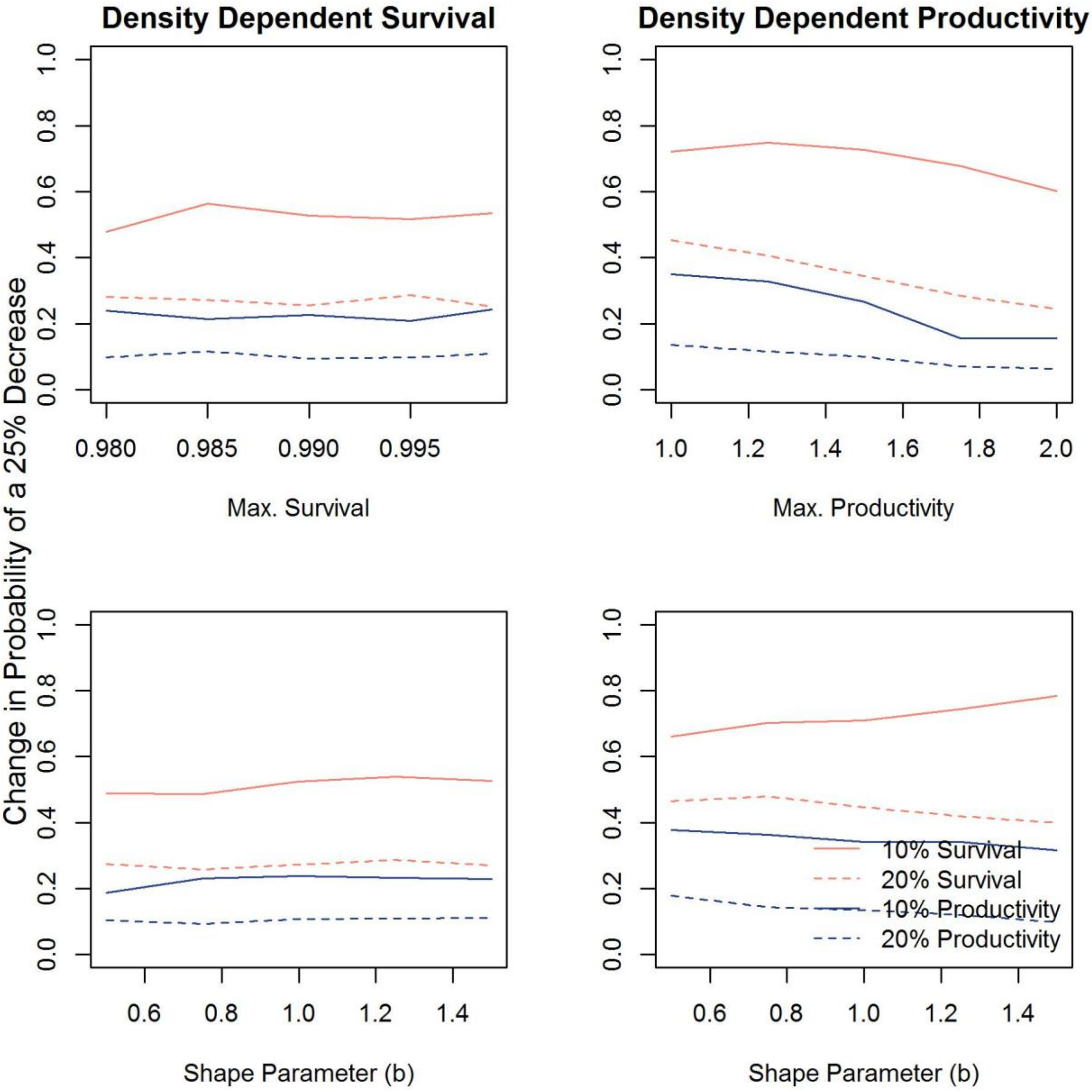

Figure 51. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Metric overview

dP(Id>0.25) reaches an asymptote, making it difficult to distinguish the population level effects of more severe impacts, particularly in relation to increases in mortality. The metric appears to be sensitive to assumptions about the underlying trend of the population concerned and to the demographic parameters used in the population models, particularly when impacts are on productivity. The metric is also sensitive to assumptions about the density dependent regulation of productivity.

3.2.11 Probability of an impacted population being a given magnitude below the median size predicted in the absence of an impact (P(I<25))

A metric to assess the population level impact of a development could be derived by estimating a median size for a population in the absence of an offshore wind farm and calculating the proportion of simulations for a population in the presence of a wind farm which were either below this median population size, or a given magnitude below this median population size.

The metric is on a scale from 0 – 1, with 0 indicating that none of the simulations from a stochastic model show the impacted population being a given magnitude below the unimpacted population (i.e. no population-level consequence) and 1 indicating that all simulations show the impacted population a given magnitude below the unimpacted population.

Initial Results

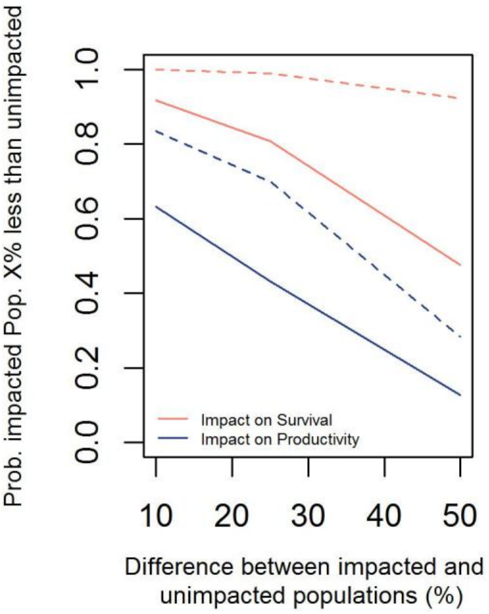

Figure 52. Probability of the impacted population being 10, 25 or 50% less than the unimpacted population after 25 years, assuming a stable population of an r-selected seabird species and a 10% (solid lines) or 20% (broken lines) increase in mortality or reduction in productivity.

When considering whether a population impacted by an offshore wind farm is 10, 25 or 50% less than it would be in the absence of the offshore wind farm, a range of probabilities are obtained for each value depending on the magnitude of the impact considered (Fig. 52).

However, for a 20% increase in mortality, the probability of a 10% change is similar to the probability of a 25% change. For this reason further discussion here focuses on the probability of a 25% decline (P(I<25)).

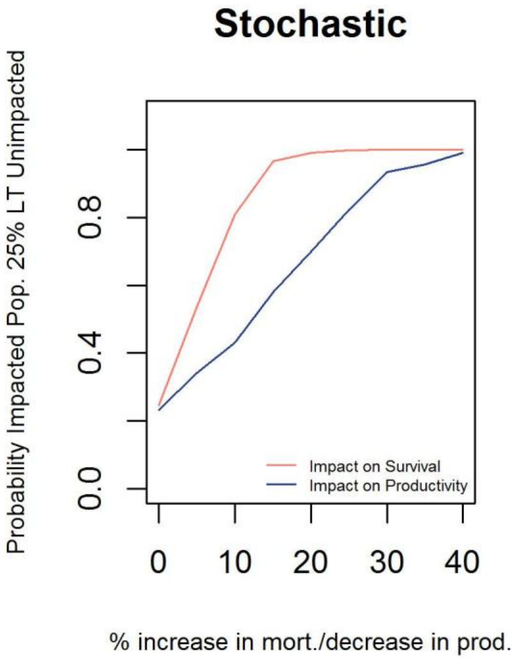

Figure 53. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the probability that the impacted population is 25% less than the unimpacted population after 25 years for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

The probability of an impacted population being 25% less than an unimpacted population (P(I<25)) approaches an asymptote at 1 for a 20% increase in mortality. If the impact is on productivity, P(IGR<2.5) appears to have a more linear relationship with the magnitude of the impact under consideration, reaching 1 for a 40% reduction in productivity (Fig. 53).

Sensitivity to life history strategy, population trend and density dependence

P(I<25) is sensitive to whether the population is declining, rather than increasing or stable (Table 37). There is also evidence to suggest that P(I<25) is more sensitive to population trend if productivity, rather than survival, is affected. Using this metric, K-selected species are far less likely to reveal any population-level impact than r-selected species. As might be expected, incorporating density dependence into the model reduces the magnitude of the population level effect.

Table 37. Probability of the impacted population being 25% less than the unimpacted population resulting from a 10%, 20% or 40% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.833	0.985	1.000	0.468	0.730	0.992
Stable	0.829	0.988	1.000	0.391	0.607	0.947
Decreasing	0.853	0.996	1.000	0.383	0.562	0.915
K selected	0.433	0.782	0.991	0.180	0.231	0.458
Density Dependent Survival	0.533	0.746	0.971	0.365	0.441	0.622
Density Dependent Productivity	0.561	0.900	1.000	0.216	0.320	0.622

Sensitivity to mis-specification of demographic parameters

P(I<25) is sensitive to the demographic parameters incorporated in the models (Fig. 54 and Tables 38 and 39). Sensitivity appears to decrease as the magnitude of the impact increases. Sensitivity appears to be greatest where impacts are on productivity, rather than survival.

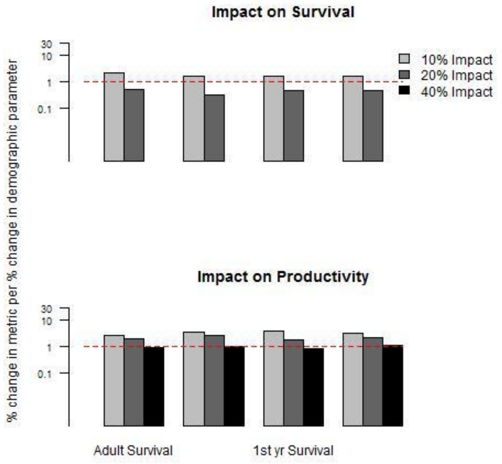

Figure 54. Percentage change in the probability of the impacted being 25% less than the impacted population after 25 years per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from stochastic models. Data tabulated in Tables 38 and 39.

Table 38. Influence of a 1% mis-specification of each demographic parameter on the probability of the impacted population being 25% less than the impacted population after 25 years (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 54.

	Stochastic		
	10%	20%	40%
Adult Survival	2.49	0.45	<0.01
Immature Survival	1.95	0.37	<0.01
Chick Survival	1.53	0.38	<0.01
Productivity	1.08	0.39	<0.01

Table 39. Influence of a 1% mis-specification of each demographic parameter on the probability of the impacted population being 25% less than the impacted population after 25 years (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10% and 20% reduction in productivity. Illustrated graphically in Figure 54.

	Stochastic		
	10%	20%	40%
Adult Survival	3.84	2.29	0.89
Immature Survival	3.68	1.88	0.76
Chick Survival	2.52	2.43	0.98
Productivity	2.95	1.82	0.86

Sensitivity to form of density dependence

P(I<25) appears to be more sensitive to the form of density dependence assumed than previous metrics. As the maximum value allowable for productivity and the shape parameter increase, the probability of the impacted population being 25% less than the unimpacted population decreases (Fig. 55). This is likely to reflect the density dependent mechanisms acting to increase the growth rate of the impacted population, whilst the unimpacted population remains relatively stable.

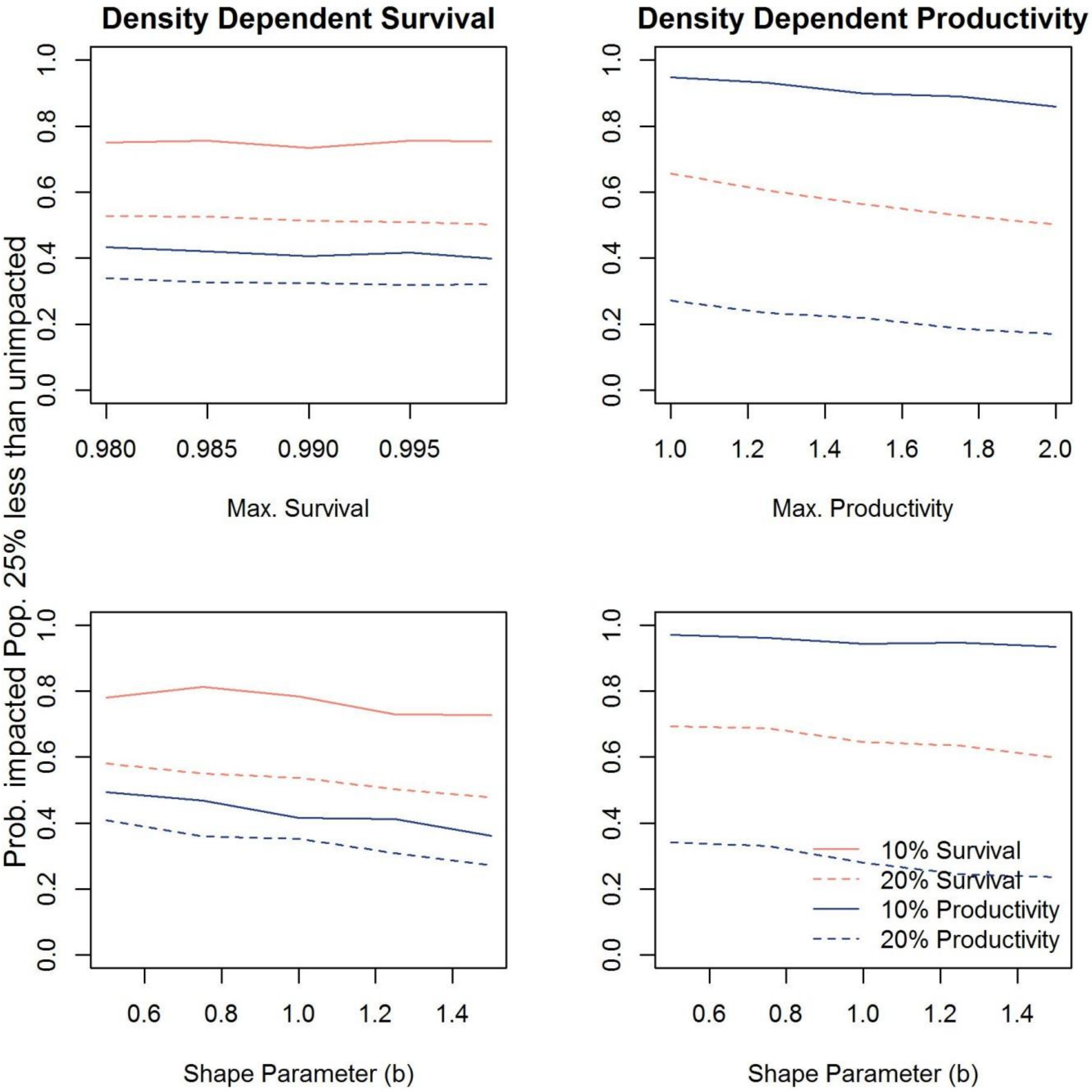

Figure 55. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Metric overview

P(I<25) reaches an asymptote, making it difficult to distinguish the population level effects of more severe impacts, particularly in relation to increases in mortality. The metric appears to be sensitive to assumptions about the underlying trend of the population concerned and to the demographic parameters used in the population models, particularly when impacts are on productivity. The metric is also sensitive to assumptions about the form of density dependence used in any models.

3.2.12 Probability that impacted population growth rate is 2.5, 5 or 10% less than unimpacted growth rate (P(IGR<2.5))

With growth rates simulated from stochastic models, it may be desirable to estimate a mean or median value for the unimpacted population and calculate the proportion of simulations in which the growth rate of the impacted population is lower, or a given percentage lower, than this value. This approach has the advantage of allowing a probabilistic forecast of the impact of the offshore wind farm on a population, e.g. there is a 50% chance that the wind farm will reduce the population growth rate by 10%.

The metric is on a scale from 0 – 1, with 0 indicating that none of the simulations from a stochastic model show the impacted population growth rate being a given magnitude below the unimpacted population (i.e. no population-level consequence) and 1 indicating that all simulations show the impacted population growth rate a given magnitude below the unimpacted population.

Initial Results

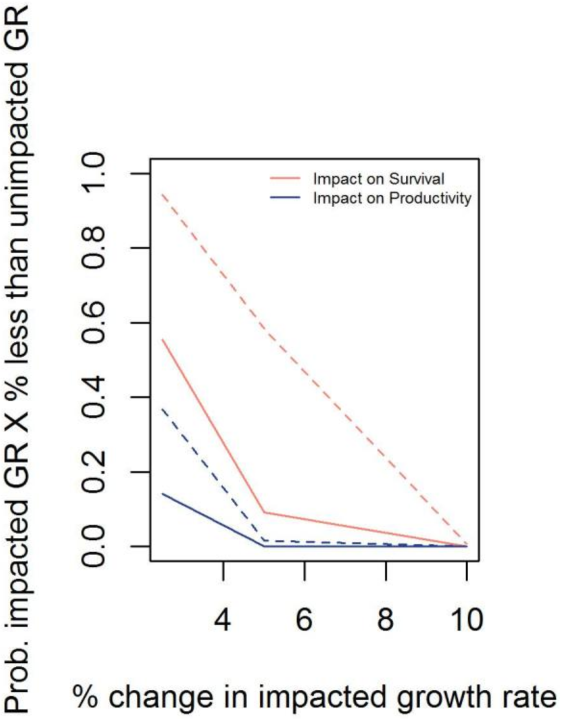

Figure 56. Probability of the growth rate of the impacted population being 2.5, 5 or 10% less than the growth rate of the unimpacted population assuming a stable population of an r-selected seabird species and a 10% (solid lines) or 20% (broken lines) increase in mortality or reduction in productivity.

When considering whether the growth rate of a population impacted by an offshore wind farm it is not possible to detect the population level effect of the impacts considered here when they are assessed against the probability of a 10% reduction in the impacted population growth rate (Fig. 56). Similarly, it is not possible to detect population level effects of the impacts on productivity considered when assessed against the probability of a 5% decline in the growth rate. For this reason, further analysis here focuses on the probability of a 2.5% decline in the population growth rate, which shows a range of values for the different impacts considered here (Fig. 56).

The probability of a change in population growth rate of 2.5% (P(IGR<2.5)) approaches an asymptote at 1 for a 25% increase in mortality. If the impact is on productivity, P(IGR<2.5) appears to have a more linear relationship with the magnitude of the impact under consideration, rising to 0.881 for a 40% reduction in productivity (Fig. 57). However, it should be noted that the confidence limits associated with the population growth rate (see section 3.2.3) may make it hard to detect a 2.5 percentage change in population growth rate with confidence.

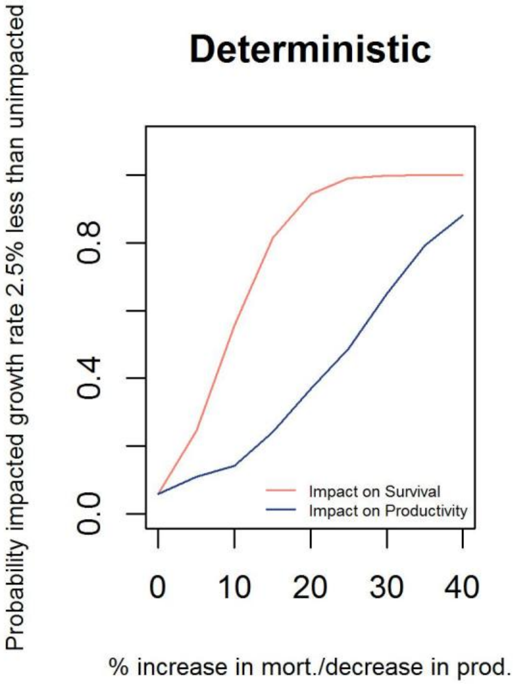

Figure 57. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the probability that the impacted population growth rate is 2.5% less than the unimpacted population growth rate for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

Sensitivity to life history strategy, population trend and density dependence

P(IGR>2.5) is sensitive to population trend with different values recorded for low impacts depending on whether the population is declining or stable/increasing (Table 40). Using this metric, K-selected species are far less likely to reveal any population-level impact than r-selected species. As might be expected, incorporating density dependence into the model reduces the magnitude of the population level effect.

Table 40. Probability of a P(GR) decreasing >2.5% resulting from a 10%, 20% or 40% increase in mortality or a 10% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.561	0.944	1.000	0.171	0.406	0.945
Stable	0.541	0.954	1.000	0.126	0.277	0.752
Decreasing	0.647	0.979	1.000	0.140	0.238	0.647
K selected	0.073	0.333	0.896	0.012	0.013	0.048
Density Dependent	0.289	0.556	0.917	0.145	0.200	0.361

Survival						
Density Dependent Productivity	0.207	0.664	0.995	0.029	0.049	0.150

Sensitivity to mis-specification of demographic parameters

P(IGR>2.5) is sensitive to the demographic parameters incorporated in the models (Fig. 58 and Tables 41 and 42). Sensitivity appears to be greater for more moderate impacts and also where productivity is affected.

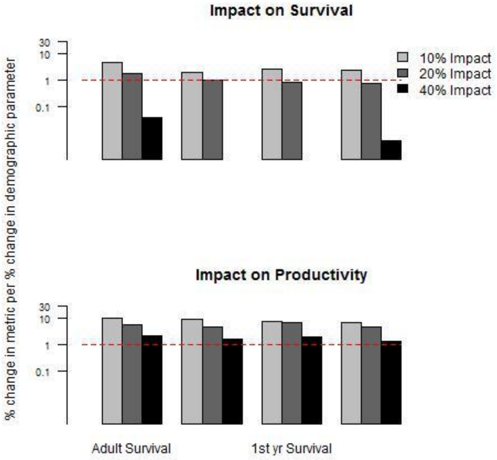

Figure 58. Percentage change in the probability of the impacted population growth rate being 2.5% less than the impacted population growth rate per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity from deterministic (left) and stochastic (right) models. Note that the Y-axis is on a non-linear scale. Data tabulated in Tables 40 & 41.

Table 41. Influence of a 1% mis-specification of each demographic parameter on the probability of the impacted population growth rate being 2.5% less than the impacted population growth rate (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality. Illustrated graphically in Figure 58.

	Stochastic		
	10%	20%	40%
Adult Survival	5.02	1.72	0.04
Immature Survival	2.59	0.83	<0.01
Chick Survival	1.89	0.75	0.01
Productivity	2.28	0.99	0.01

Table 42. Influence of a 1% mis-specification of each demographic parameter on the probability of the impacted population growth rate being 2.5% less than the impacted population growth rate (as assessed by % change in metric) for an r-selected seabird species estimated from a stochastic model assuming a 10% and 20% reduction in productivity. Illustrated graphically in Figure 58.

	Stochastic		
	10%	20%	40%
Adult Survival	9.69	5.49	2.54
Immature Survival	6.88	2.84	1.65
Chick Survival	8.06	2.92	2.02
Productivity	6.06	3.82	1.43

Sensitivity to form of density dependence

P(IGR<2.5) appears to be more sensitive to the form of density dependence assumed than previous metrics. As the maximum value allowable for productivity and the shape parameter increase, the probability of the growth rate of the impacted population being 2.5% less than the unimpacted population decreases (Fig. 59). This is likely to reflect the density dependent mechanisms acting to increase the growth rate of the impacted population, whilst the unimpacted population remains relatively stable.

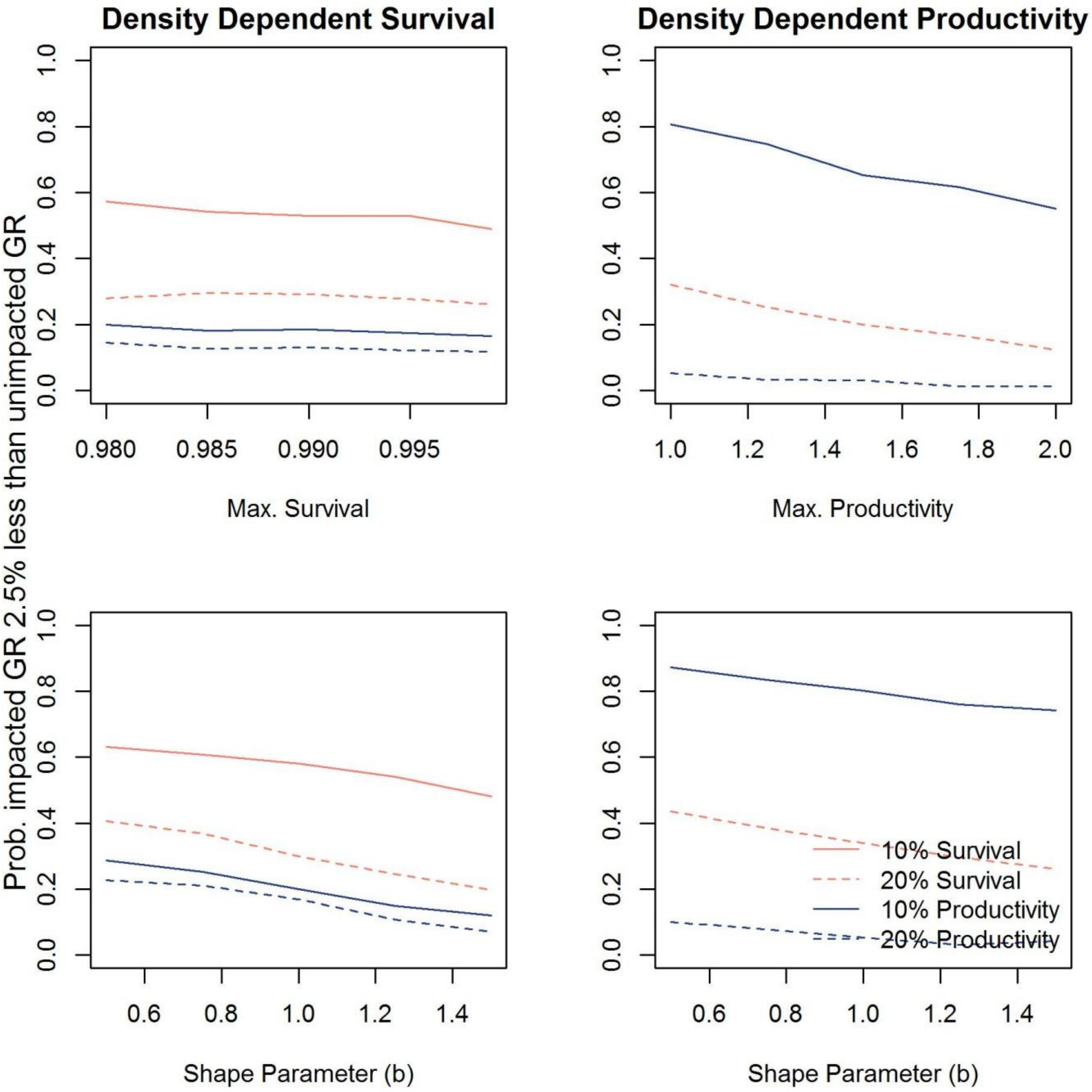

Figure 59. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Metric overview

Overall P(IGR>2.5) is sensitive to mis-specification of the input demographic parameters and assumptions about the underlying population trend. Furthermore, given the uncertainty which is associated with population growth rates as a result of stochasticity, it is likely to be difficult to determine whether a change of 2.5% in the population growth rate is actually statistically significant. Whilst, it may be possible to consider a similar metric, based on a greater change in the growth rate, initial simulations suggested that it was difficult to detect a population level effect using these values as the probability of detecting such a change declined dramatically (see Figure 56).

3.2.13 Overlap between impacted and unimpacted population (OI:U)

Using stochastic models, the population size at any fixed point in time (e.g. at the end of a project lifetime) may be expressed as a distribution. In these circumstances, it may be desirable to compare the distributions of the impacted and unimpacted population trajectories. Where there is greater overlap between the two trajectories, impacts may be deemed less significant. This metric may be expressed as a rule, for example Acceptable Biological Change (ABC, Bennet 2013), whereby impacts are deemed acceptable if the median impacted population after 25 years is predicted to be greater than the 33% quantile of the unimpacted population (i.e. >50% of the simulations from the model of an impacted population result in a population size that is equal to, or greater than, that predicted by the 33% quantile of the unimpacted population). For the purposes of this sensitivity analysis, we compared the overlap of the whole distribution of the impacted and unimpacted populations, without the use of confidence intervals.

The metric is on a scale from 0 – 1, with 0 indicating that none of the simulated population sizes after 25 years from the stochastic model of the impacted population overlap with the simulated population sizes after 25 years from the unimpacted population.

Initial results

The percentage overlap between the impacted and unimpacted populations declines rapidly as impacts on mortality increase. Where mortality is predicted to increase by more than 35%, there is close to zero overlap between the two population sizes after 25 years (Figure 60). If the impact is on productivity, the population sizes after 25 years remain similar for reductions in productivity of up to 25%. A note of caution should be applied to this metric. From the initial analysis of decreases in productivity presented in Figure 60, following a decrease in the metric value between a 25 and 30% decrease in productivity, the metric value then increases again between a 30 and 35% decrease in productivity. This is likely to be an artefact of the number of simulations used to derive the metric and it is likely that an increase in the number of simulations used would remove this apparent discrepancy. Nevertheless, it is important to highlight the potential sensitivity of this metric to the number of simulations used in the population models.

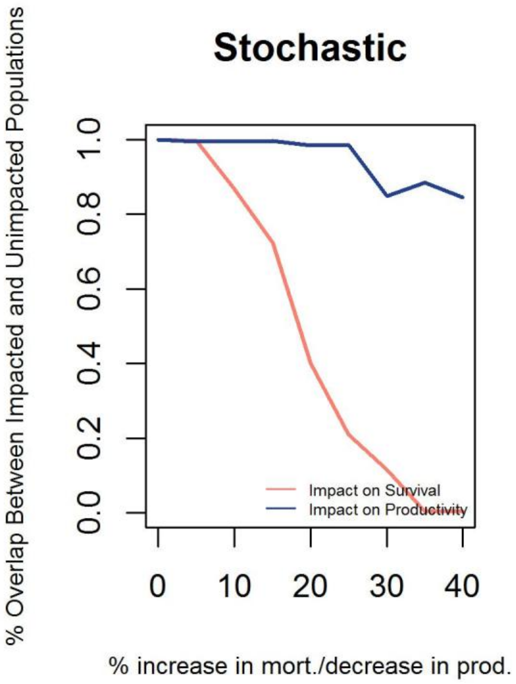

Figure 60. Impact of up to a 40% increase in mortality or up to a 40% decrease in productivity on the % overlap between the impacted and unimpacted population size after 25 years for a population of seabirds with an r-selected life history strategy and a stable population trajectory.

Sensitivity to life history strategy, population trend and density dependence

OI:U is sensitive to population trend with different values recorded for low impacts depending on whether the population is increasing or stable/declining (Table 43). Using this metric, K-selected species are far less likely to reveal any population-level impact than r-selected species. As might be expected, incorporating density dependence into the model reduces the magnitude of the population level effect.

Table 43. Overlap of the impacted and unimpacted population size after 25 years for a 10%, 20% or 40% increase in mortality or a 10%, 20% or 40% decrease in productivity estimated from a stochastic model and assuming an increasing, stable or decreasing population of an r-selected seabird species, a stable population of a K-selected seabird species and a stable population of an r-selected species with density dependent regulation of survival or productivity.

	Survival			Productivity		
	10%	20%	40%	10%	20%	40%
Increasing	0.976	0.497	0.003	0.998	0.991	0.829
Stable	0.840	0.488	0.008	0.999	0.991	0.960
Decreasing	0.840	0.600	<0.001	0.999	0.998	0.901
K selected	0.986	0.911	0.289	0.999	0.999	0.995
Density Dependent Survival	0.999	0.952	0.569	0.999	0.999	0.999
Density Dependent Productivity	0.997	0.827	0.079	0.999	0.999	0.999

Sensitivity to mis-specification of demographic parameters

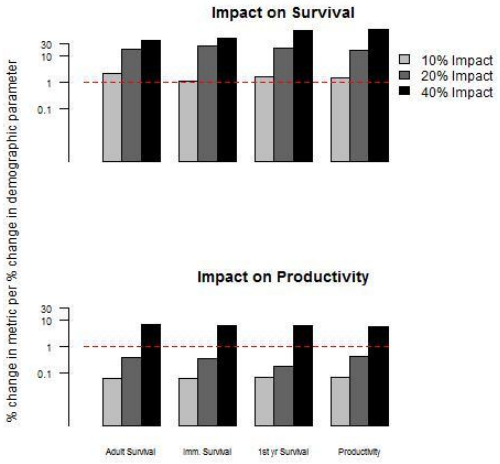

Figure 61. Percentage change in the overlap between the impacted and unimpacted populations per percentage change in adult survival, immature survival, first year survival and productivity for offshore wind farm impacts on survival and productivity. Note that the Y-axis is on a non-linear scale. Data tabulated in Tables 44 and 45.

OI:U is sensitive to the mis-specification of demographic parameters. (Figure 61, Tables 44 and 45). This sensitivity increases as magnitude of the predicted impact increases. This is particularly noticeable for impacts on chick survival and productivity.

Table 44. Impact of a 1% mis-specification of each demographic parameter on overlap between impacted and unimpacted population sizes after 25 years for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% increase in mortality.

	Stochastic		
	10%	20%	40%
Adult Survival	2.17	18.57	38.50
Immature Survival	1.13	23.60	48.31
Chick Survival	1.61	18.82	87.71
Productivity	1.40	15.91	100.00

Table 45. Impact of a 1% mis-specification of each demographic parameter on the change in probability of a population decreasing by 25% for an r-selected seabird species estimated from a stochastic model assuming a 10%, 20% or 40% reduction in productivity.

	Stochastic		
	10%	20%	40%
Adult Survival	0.06	0.37	0.68
Immature Survival	0.06	0.35	0.09
Chick Survival	0.07	0.17	0.49
Productivity	0.07	0.40	0.74

Sensitivity to form of density dependence

If density dependence is introduced into the models, OI:U does not appear to be particularly sensitive to either mis-specification of the shape parameter or mis-specification of the maximum survival or productivity rate (Fig. 62), if density dependence is assumed to influence survival. However, where density dependence is assumed to influence productivity, OI:U may be sensitive to the mis-specification of both the shape parameter and the maximum productivity rate where smaller impacts on survival are predicted.

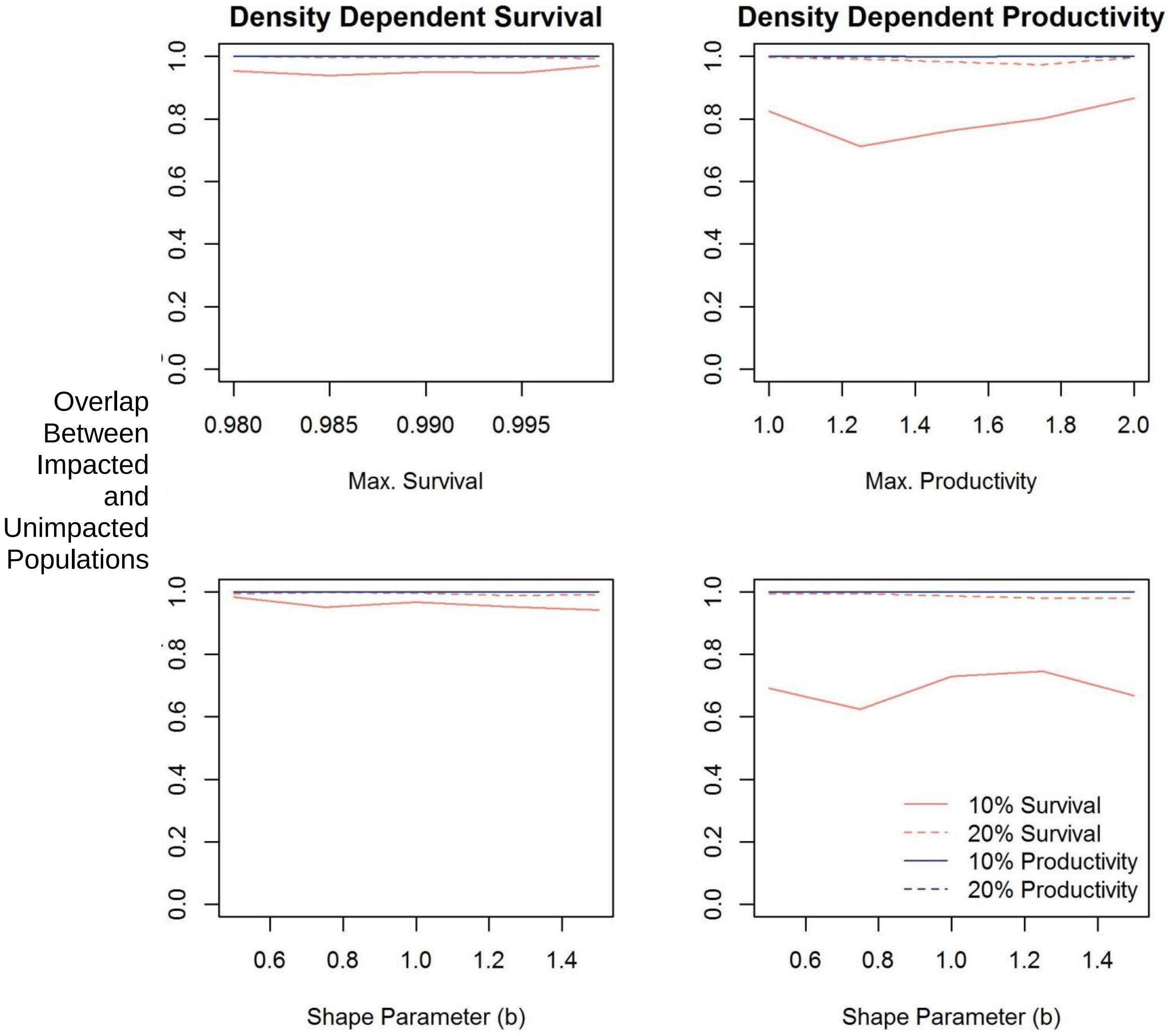

Figure 62. Impact of mis-specifying the shape parameter and maximum survival or productivity rate in a stable population of an r-selected seabird when using a stochastic model with density dependent regulation of survival or productivity.

Additional Analysis

Additional analyses revealed that OI:U showed sensitivity to the extent of uncertainty surrounding the demographic parameters used in population models (Fig. 62). These analyses show that in populations where there is greater uncertainty surrounding the demographic parameters, OI:U is higher, implying a lower population-level consequence, than is the case where there is less uncertainty surrounding the demographic parameters. This is because the wider confidence intervals surrounding the adult survival rate lead to simulations with a greater range of population sizes for both the impacted and unimpacted populations. As non-biological sources (e.g. variability due to sampling error) of variability can constitute a significant proportion of the total observed variability (Gould & Nicholls 1998), ideally, all four distributions should have a similar overlap between impacted and unimpacted populations. This is of concern as it leads to the possibility that an impact might be deemed acceptable simply as a result of a lack of knowledge of the demography of the population concerned, which may be a common occurrence in relation to seabird populations (Maclean *et al* 2007; Robinson & Ratcliffe 2010; Horswill & Robinson 2015).

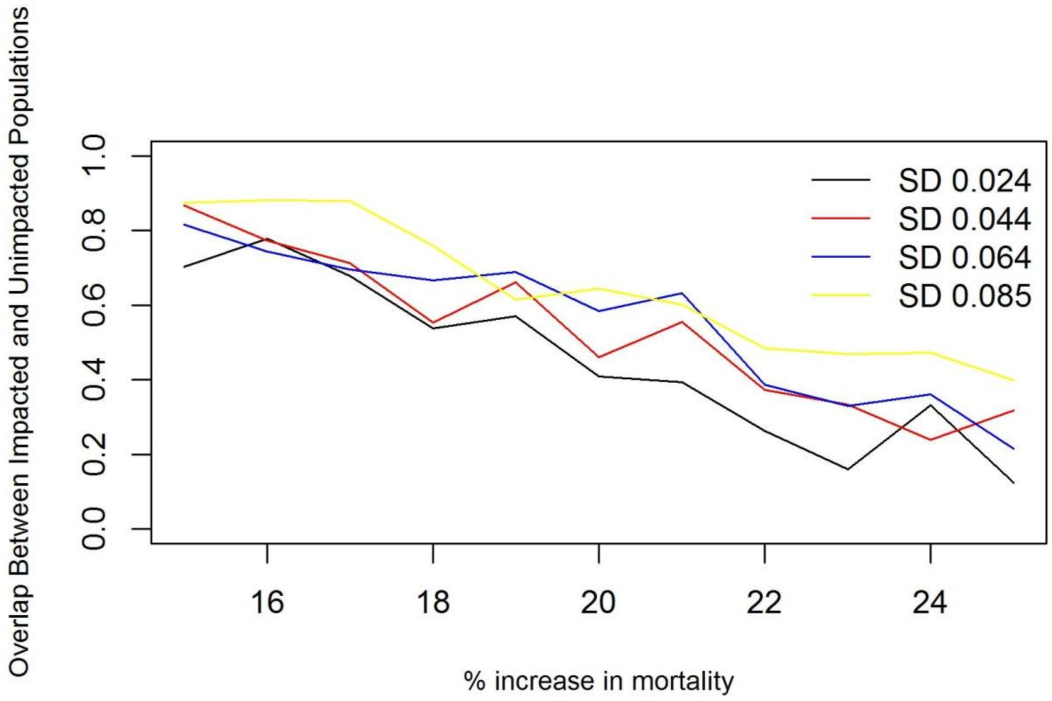

Figure 62. Impact of 15% to 25% increase in mortality on the overlap of impacted and unimpacted population sizes after 25 years for a population of seabirds with an r-selected life history strategy and a stable population trajectory, assuming an adult survival rate of 0.89 and standard deviations of 0.024, 0.044, 0.064 and 0.085.

Metric overview

It appears that OI:U is sensitive to both the demographic parameters used in the population models and to the underlying trend of the population concerned. It is less sensitive to mis-specification of the form of density-dependence, at least where this affects survival rates. Given the relatively high sensitivity of this metric, greater consideration of the value applied by a rule may be required because of its potential influence on the conclusions. There are some signs that OI:U may be sensitive to the number of simulations used in demographic models from which it is derived. In addition, this metric appears to be sensitive to the degree of uncertainty surrounding the parameters of the population models from which it is derived. This may reduce the ability to identify wind farm impacts on a population if knowledge of the demographic parameters is poor.

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