An Initial Analysis of the Power of Monitoring certain Indices to Determine the Effect of Fishing on Penguin Reproductive Success from an Experiment where Pelagic Fishing is Prohibited in the Neighbourhood of Robben Island, but Continues around Dassen Island

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ABSTRACT

Historical data on fledging success and the breeders per adult moulter ratio for penguins at the Robben and Dassen island colonies are analysed using General Linear Modelling (GLM) to provide the basis for a simulation evaluation of the power of an experiment which closes a neighbourhood (about 20 km radius perhaps) around Robben Island to detect a statistically significant (5% level) impact of the (assumed multiplicative) effect of fishing on penguin reproductive output. Process error for each index is estimated to be about 20%. For an actual effect size of 30% (corresponding to a change in the population growth rate of about 3% p.a.), the experiment would have to continue for some 10 years for a better than 50:50 chance of such detection for the breeders per adult moulter index, and at least 20 years for fledging success. An initial GLM analysis to determine the direction and magnitude of the effect of pelagic catches on penguin reproductive output in terms of the two indices and colonies considered suggests that these catches enhanced this output in all four instances (a potential consequence of the hypothesis that fishing scatters large shoals, thus increasing the probability of natural predators finding their prey), though none of the estimates is statistically significant at the 5% level.

INTRODUCTION

Sensibly, experiments planned to ascertain the possible effect of the pelagic fishery on African penguin populations should be such that they have a reasonable chance of detecting any appreciable real effect if present, and within a realistic time-period.

This was recognised by the July 2007 international stock assessment workshop, which recommended in regard to such possible experiments (see EAFWG/OCT2007/STG/05) that general “best practice” guidelines should be followed, with these including an evaluation of experimental power. More specifically, the workshop recommended a structured approach to developing such experiments, with this to include addressing the following questions:

1) What are the specific alternative hypotheses?
2) What are the predictions under each hypothesis?
3) What past data are available for the case under investigation?
4) What size of an effect would be considered “of consequence” and what is the desirable probability of detecting an effect of this size?
5) What needs to be monitored to detect an effect?
6) How can past data inform the amount of process[1] and observation error for each variable that could be monitored?

[1] Process error reflects inter-colony variation in the underlying value of an index each year (in contrast to the observation error that results from sampling effects) due to factors other than that hypothesised to have an effect on the index.

This paper seeks to follow these guidelines in considering a possible experiment involving closure of a neighbourhood of Robben (or Dassen) island to pelagic fishing. In respect of questions 1) and 2) in the list above, there are probably three hypotheses about the effects of pelagic fishing on penguin populations (as it would affect reproductive success or survival rates through impacting prey availability):

i) the fishery overall reduces pelagic fish populations below the levels that would otherwise occur, thus reducing the amount of prey available to predators such as penguins;

ii) pelagic fishing in the neighbourhood of a penguin breeding colony reduces the local density of prey available to penguins, this being deleterious to breeding birds which have a limited foraging range; and

iii) pelagic fishing in the neighbourhood of a penguin colony breaks up shoals (for these fish larger shoals offer effectively better protection against natural predators by reducing the per capita probability of a predator finding a forage fish), and thus increases prey detectability.

Under hypotheses i) and ii) penguin reproductive success and survival rates would decrease given (additional) fishing, whereas under hypothesis iii) the reverse would occur.

The remaining questions are addressed later in this document. The Data section addresses questions 3) and 5). Question 4) is addressed under Results, and question 6) under Methods. The estimated power of the experiment considered is presented and discussed in the final sections of the document.

DATA

Only two indices have been selected for power evaluation in this document (fledging success and the breeders per adult moulter ratio, both of which would be expected to increase given greater food availability, hence improving reproductive output), and for only two island colonies (Robben and Dassen). Annual counts have not been considered as their analysis in this context would first require the finalisation of population models for which residuals of model fits could be taken as independent in checking for correlations with the effects of fishing. Survival rate estimates are potential candidates, but time series of colony-specific estimates are first required to enable estimation of the associated process error (see below).

It thus seems from consideration of the available data series (see Plaganyi and Butterworth, 2007) that the two indices and two island colonies chosen reflect the only current possibilities for power analysis. The associated data for periods for which values are available for both colonies are listed in Table 1 (taken from Plaganyi and Butterworth, 2007). These would all seem to be instances where monitoring could be continued in the future (see question 5) above).

Table 1 also includes data on the annual combined sardine and anchovy catch in the neighbourhood of these two colonies. This information is as kindly provided by Jan van der Westhuizen (MCM), and reflects catches in grid cells 4953, 4943, 4952, 4903 and half of 4902 around Robben island, and cells 4931, 4932, and half each of 4921, 4830, 4941 and 4942 around Dassen; these regions we understand to reflect an approximate 20 km radius around these islands.

METHODS

Appendix A details the methods applied in this study. A General Linear Model (GLM) has been applied to the historical data for the two islands for each of the indices considered so as to provide an estimate of the magnitude of process error (which is taken to dominate any observation error for which variance might differ from year to year). The indices are log-transformed for the analysis, so that the effects of year, colony[2] and fishing (taken here to be Boolean: either present or absent) are assumed to be multiplicative. Clearly alternative assumptions for how these effects inter-relate are possible, but a multiplicative approach seems the simplest and most obvious starting point. Note that the estimate of the magnitude of the process error is not the MLE, but rather effectively a REML estimate as it takes due account of degrees of freedom effects. The parameter estimates provided by this GLM are then used to generate simulated future data (with fishing continuing around Dassen but not Robben island), to which a GLM is then again applied to determine the power with which the effects of fishing can be detected over various periods. This is carried out for inputs of different underlying effect sizes (multiplicative effects of 0, 15 and 30% on reproductive output).

In a further analysis, the historical data for the indices together with the data on annual pelagic catches in the neighbourhood of each of the Robben and Dassen island colonies (Table 1) are analysed using a GLM to estimate the direction and magnitude of the effect of catches on reproductive success. The details are again provided in Appendix A. For this analysis, the multiplicative effect of such catches is assumed to be proportional to the catch in tons. Again more complex models could be conceived, involving different functional forms and also including fish abundance indices, but at this stage the intention is simply to provide an initial analysis.

RESULTS AND DISCUSSION

Question 4) above requires the specification of the size of an effect considered to be “of consequence”. Appendix B provides an analysis relating the impact of multiplicative changes in penguin reproductive output to population growth rate. Results in Table B.1 indicate that typically the multiplicative effect sizes of 15 and 30% in the reproductive parameters that are considered would correspond to changes of about 1.5 and 3% respectively in the penguin population annual growth rate. Given that penguin growth rates in the Western Cape appear to have approached 10% p.a. in the recent past, the effect sizes considered would indeed seem to be “of consequence” in a conservation context.

The GLMs provide estimates of process error (σ_e) of about 20% for both indices considered (see Table A.1). The results of the simulation-based estimation of the power of an experiment involving closure of the neighbourhood of Robben but not Dassen island to pelagic fishing in future are reported in Table 2, with distributions of the estimates of the ω parameter that quantifies the effect of fishing shown in Figs 1 and 2 for the fledging success and breeders per adult moulter ratio indices respectively.

As might be expected, the spreads of the distributions of the estimates of ω around their true values decrease as the duration of the experiment is extended (Figs 1 and 2). Detection power is better for the breeders per adult moulter ratio than for fledging success (presumably reflecting the longer time series of historical data available for the former), but nevertheless

[2] Note that colony-specific effects would be expected, for example because the moulter count at Dassen island is not as comprehensive as that at Robben island.

is generally poor (Table 1)[3]. Only for an effect size of 30% does the probability of a result significant at the 5% level reach 50% (after some 10 years for the breeders per adult moulter ratio, but scarcely after 20 for the fledging success index). For an effect size of 15%, after 10 years there remains a 10% chance that the effect size estimated will be in the wrong direction.

Table 3 provides results for the GLM analysis that attempts to estimate both the direction and magnitude of the impact of the amount of fishing in the neighbourhood of Robben and Dassen islands on penguin reproductive output from the historical data for the two indices considered. In all four cases penguin reproductive output is estimated to have ***increased*** for larger catches, but none of these results is statistically significant at the 5% level.

CONCLUSIONS

The power of an experiment to detect a statistically significant (5% level) impact of the effect of fishing on penguin reproductive output through closing the neighbourhood of Robben island to pelagic fishing is poor. For an actual effect size of 30% (corresponding to a change in the population growth rate of about 3% p.a.), the experiment would have to continue for some 10 years for a better than 50:50 chance of such detection for the breeders per adult moulter index, and at least 20 years for fledging success.

An initial analysis to determine the direction and magnitude of the effect of pelagic catches on penguin reproductive output in terms of the two indices and colonies considered suggests that this is positive in all four instances, though not significantly so at the 5% level in any.

ACKNOWLEDGEMENTS

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REFERENCE

Plaganyi, E. and Butterworth, D. 2007. Summary of available data for modelling African penguin *Spheniscus demersus* populations. MCM document MCM/2007/MAY/SWG/PEL06a (also ASWS/JUL07/PENG/DAT/1). 20pp.

[3] Results of ***decreasing*** power for longer experimental periods shown in Table 1 for an effect size of 15% may seem strange. They arise because for shorter periods, large negative values of ω may be estimated and are evaluated as significant at the 5% level. For longer periods, estimates of this size become less frequent, so that instances of significance and hence power may decrease.

Table 1. Available data on the fledging success of penguins, the breeders per adult moulter ratio and total sardine and anchovy catches in a 20 km neighbourhood of the penguin colonies considered in the analyses presented in this paper (see text for sources).

Year	Fledging success of penguins		Breeders per adult moulter ratio		Total sardine and anchovy catch (t)	
	Robben	Dassen	Robben	Dassen	Robben	Dassen
1995	0.380	0.650	0.287	0.792	8974	16879
1996	0.650	0.805	0.472	0.777	8041	17119
1997	0.970	0.929	0.595	0.668	14580	5509
1998	0.750	1.057	0.399	0.670	9116	12122
1999	0.600	1.083	0.468	0.707	20205	35407
2000	—	—	0.485	0.622	11706	21676
2001	—	—	0.503	0.820	12608	33084
2002	—	—	0.441	0.893	28817	37864
2003	—	—	0.437	0.903	42812	34052
2004	—	—	0.489	1.415	14931	18515
2006	—	—	0.556	1.240	8295	39860

Table 2. Simulation results of the power of the (one-tailed) test to find a fishing effect that is significantly different from zero at the 5% level for future survey periods of 5, 10 and 20 years, when an effect size δ of 0, 0.15 and 0.30 is assumed for the island at which no fishing occurs when generating future data (and applied for the historical data). The proportion of occurrences in which a positive fishing effect is estimated for the island around which fishing took place is also given. Results are shown when fitting to both fledging success and breeders per adult moulter ratio data.

a) Fledging success.

		5 years	10 years	20 years
Power	**Effect size = 0.00**	0.026	0.004	0.000
	Effect size = 0.15	0.104	0.100	0.032
	Effect size = 0.30	0.356	0.408	0.498
Proportion of positive estimates	**Effect size = 0.00**	0.472	0.440	0.458
	Effect size = 0.15	0.182	0.102	0.040
	Effect size = 0.30	0.052	0.010	0.000

b) Breeders per adult moulter ratio.

		5 years	10 years	20 years
Power	**Effect size = 0.00**	0.056	0.026	0.008
	Effect size = 0.15	0.176	0.226	0.202
	Effect size = 0.30	0.462	0.632	0.762
Proportion of positive estimates	**Effect size = 0.00**	0.478	0.470	0.476
	Effect size = 0.15	0.220	0.106	0.040
	Effect size = 0.30	0.050	0.016	0.000

Table 3. Parameter estimates (and standard errors) for the effect of the amount of catch taken around each island on fledging success of penguins or the breeders per adult moulter ratio. None of these estimates is statistically significant at the 5% level.

Parameter	Fledging success of penguins	Breeders per adult moulter ratio
λ_{Robben}	+0.258 (0.270)	+0.009 (0.172)
λ_{Dassen}	+0.417 (0.179)	+0.417 (0.238)

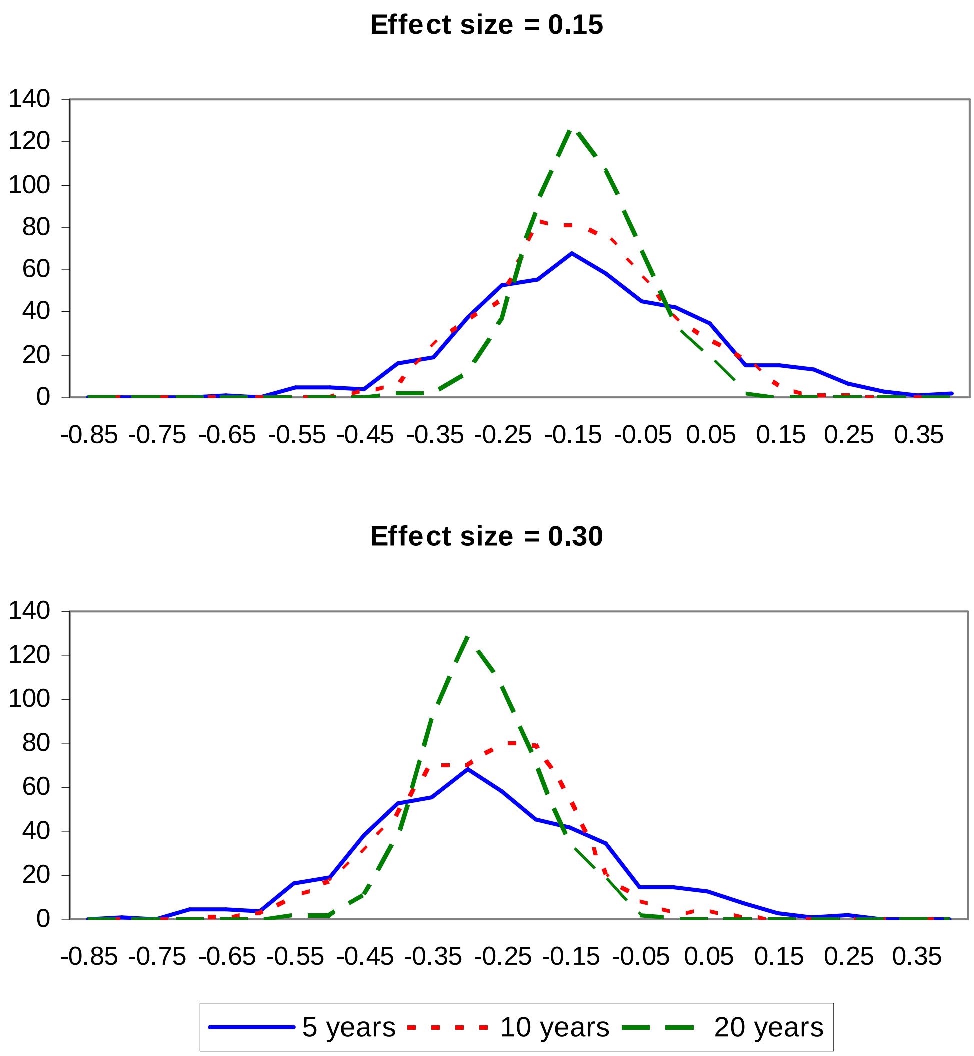

Figure 1. Distribution of the parameter estimate for the fishing effect ω when fitting to fledging success data and when an effect size δ of 0.15 and 0.30 has been assumed for the island around which no fishing occurs when generating future data. Results are shown for future survey periods 5, 10 and 20 years. (Note: effectively ω is $-\delta$).

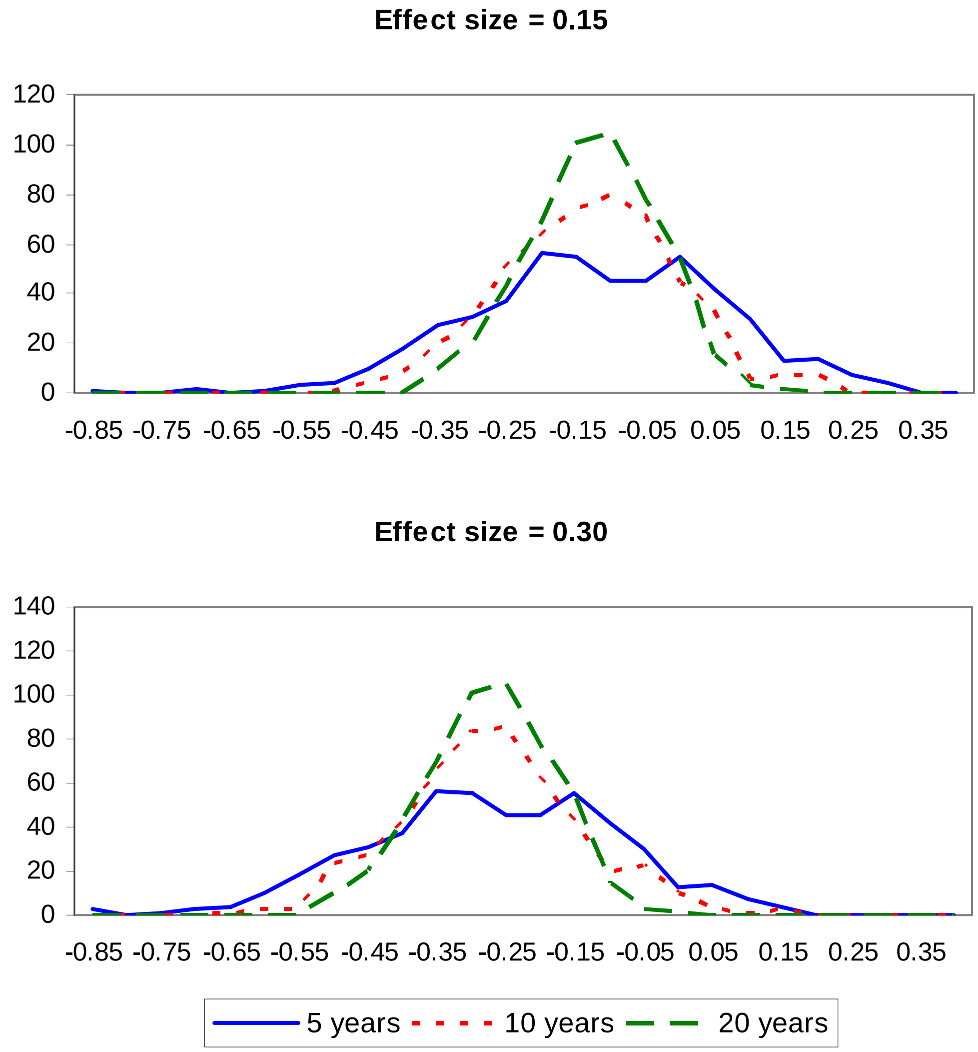

Figure 2. Distribution of the parameter estimate for the fishing effect when fitting to breeders per adult moulter ratio data and when an effect size δ of 0.15 and 0.30 has been assumed for the island around which no fishing occurs when generating future data. Results are shown for future survey periods 5, 10 and 20 years. (Note: effectively ω is -δ).

APPENDIX A

GENERAL LINEAR MODELS

General Linear Models (GLMs) that account for island and year effects are applied to fledging success and to breeders per adult moulter data. A GLM is fitted to historical data (where fishing took place every year around both islands) to obtain parameter estimates to be used to then generate future data. These future data are generated in such a way that fledging success of penguins (or the breeders per adult moulter ratio) for the island around which no future fishing takes place is increased by an effective size (δ) that is to be estimated (in this paper two values have been used for δ: 15 and 30%). A further GLM is then fitted to the combined historical and future data to estimate the effect of fishing around an island. These GLMs are detailed below. Although the GLMs are described in terms of fledging success, the same models apply to the breeders per adult moulter ratio data with the only difference being that historical data are now available for the years 1995–2006 instead of only 1995 to 1999.

GLM for Historical Data

The General Linear Model (GLM) considered for the historical fledging success data is given by:

$$\ln(F^h_{y,i}) = \alpha_i + \beta_y + \varepsilon_{y,i} \qquad \text{(A1)}$$

where:

$F^h_{y,i}$	is the historical fledging success of penguins in year y at island i,
i	is a factor with 2 levels associated with each of the islands Robben and Dassen,
y	is a factor with 5 levels associated with the years 1995–1999, and
ε	is an error term assumed to be normally distributed and with constant variance (i.e. process error is taken to dominate over observation error which could vary over time in relation to sampling intensity).

GLM for Historical and Future Data

The GLM applied to the combined historical and future fledging success data is given by:

$$\ln(F^c_{y,i}) = \alpha_i + \beta_y + \omega_f + \varepsilon_{y,i} \qquad \text{(A2)}$$

where:

$F^c_{y,i}$	is the historical and future fledging success of penguins in year y at island i,
i	is a factor with 2 levels associated with each of the islands Robben and Dassen,
y	is a factor associated with the years 1995–(1999+γ), where γ represents the number of future years for which data are generated (5, 10 and 20 year periods are considered in this paper),
f	is a factor with 2 levels associate with whether fishing around an island occurred or not (the value of ω reported is that for Dassen island (with fishing) less that for Robben island (without fishing), i.e. $\omega = -\delta$), and
ε	is an error term assumed to be normally distributed as above.

Simulation Algorithm

For each effective size (δ) and number of future years for which data are to be generated (γ), the following steps are taken:

1. Generate future fledging success of penguins $F^f_{y,i}$, for year *y* and island *i*.
2. Append future data to historical data ($F^c_{y,i}$).
3. Fit GLM given by equation (A2) to get parameter estimate for δ and its standard error.
4. Perform a one-tailed t-test to determine whether this estimate is significantly less than zero ("less than zero" applies here because of the way that the GLM has been parameterised in this analysis: viz. the estimate obtained corresponds to the island around which fishing continues in the future).
5. Repeat steps (1) to (4) 500 times.
6. Compute power.

Data Generation

Future fledging success (or breeders per adult moulter ratio) data are generated using the results from the GLM fitted by equation (A1). No future fishing is assumed for one of the islands (Robben in this analysis), while fishing is assumed to continue around the other island (Dassen). Thus the future data generated are given by:

$$\ln\left(F^f_{y,i}\right) = \begin{cases} \hat{\alpha}_i + \hat{\beta}_y + \delta + \hat{\varepsilon} & \text{if } i \text{ denotes Robben} \\ \hat{\alpha}_i + \hat{\beta}_y + \hat{\varepsilon} & \text{if } i \text{ denotes Dassen} \end{cases}, \quad \text{(A3)}$$

where $\hat{\alpha}_i$ is the estimated effect for island *i* (Table A.1), $\hat{\beta}_y$ is the future year effect which is generated from a uniform distribution whose parameters encompass the range of the year effect estimates obtained from historical data, $\hat{\varepsilon}$ is generated from a normal distribution with mean zero and standard deviation given by the standard error of the observation (σ_e) when the GLM of equation (A1) is fitted to historical data (Table A.1), and δ is the effect size of fishing assumed (15 or 30% for this analysis).

Simulation Power Analysis

The power to detect a fishing effect is given by the number of times a statistically significant fishing effect is estimated in the simulations, divided by the number of simulations carried out.

GLM TO CONSIDER CATCH DATA

The following GLM is applied to historical data of fledging success of penguins (or breeders per adult moulter ratio), which takes into consideration the total catch of sardine and anchovy around each island as a fraction of the average catch around the island over the time period considered:

$$\ln(F^{h}_{y,i}) = \alpha_i + \beta_y + \lambda_i \, C_{y,i}\big/\bar{C}_i + \varepsilon_{y,i} \qquad \text{(A4)}$$

where:

$C_{y,i}$ is the total catch of sardine and anchovy taken around island i and in year y,

$\bar{C}_i$ is the mean annual catch over the period considered taken around island i, and

λ_i is a parameter relating the effect of the extent of catch around island i to the fledging success of penguins (or breeders per adult moulter ratio).

Table A.1: Parameter estimates (and standard errors) when fitting the GLM of equation (A1) to historical data. These estimates are then used in the generation of future data for the simulation analyses of experiment power.

Parameter	Fledging success	Breeders per moulters ratio
α_{Robben}	0.000	0.000
α_{Dassen}	0.328 (0.115)	0.625 (0.085)
β_{1995}	-0.863 (0.141)	-1.053 (0.154)
β_{1996}	-0.488 (0.141)	-0.814 (0.154)
β_{1997}	-0.216 (0.141)	-0.774 (0.154)
β_{1998}	-0.280 (0.141)	-0.972 (0.154)
β_{1999}	-0.380 (0.141)	-0.865 (0.154)
β_{2000}	—	-0.912 (0.154)
β_{2001}	—	-0.755 (0.154)
β_{2002}	—	-0.778 (0.154)
β_{2003}	—	-0.778 (0.154)
β_{2004}	—	-0.496 (0.154)
β_{2005}	—	-0.499 (0.154)
β_{2006}	—	-0.605 (0.154)
Uniform distribution range for *year* effect	-0.9; -0.2	-1.1; -0.4
σ_e	0.182	0.209

APPENDIX B

RELATIONSHIP BETWEEN EFFECT SIZE AND PENGUIN POPULATION GROWTH RATE

In a steady growth situation, the penguin population growth rate is governed by the equation:

$$(1+R)^{T} = (1+R)^{T-1} S + \mu S^{T-1} \quad \text{(B1)}$$

where:

R	is the annual proportional increase in the population,
S	is the post-first-year annual survival rate,
T	is the age at first breeding, and
μ	is the product of the annual laying rate, proportion of chicks that are female, and first year survival rate (both pre- and post-fledging).

The factors considered in the main text as possibly impacted by fishing (i.e. fledging success and the breeders per adult moulter ratio) both relate to the parameter μ. Thus for an effect size δ:

$$\mu \to \mu e^{\delta}$$

as the model consider logs of variables.

Differentiating equation (B1) gives:

$$T\,(1+R)^{T-1}\frac{\partial R}{\partial \mu} = (T-1)(1+R)^{T-2}\, S\,\frac{\partial R}{\partial \mu} + S^{T-1}$$

so that:

$$\frac{\partial R}{\partial \mu} = S^{T-1} \Big/ \left\{T\,(1+R)^{T-1} - (T-1)(1+R)^{T-2}\, S\right\}. \quad \text{(B2)}$$

Thus for an increase in μ, $\Delta\mu = \left(e^{\delta}-1\right)\mu$, and a population maintaining current abundance (R = 0), the increase in R, ΔR, is given by :

$$\Delta R = S^{T-1}\left(e^{\delta}-1\right)\mu \Big/ \left\{T-(T-1)S\right\} \quad \text{(B3)}$$

where from equation (B1):

$$1 = S + \mu S^{T-1}$$

$$\text{i.e. } \mu = (1-S) \Big/ S^{T-1}.$$

Table B.1 below shows the change in penguin population annual growth (ΔR expressed as a percentage) that corresponds to effect sizes δ of 15% and 30% for a number of plausible combinations of the parameters S and T for penguins.

Table B.1: Change in penguin population annual growth (ΔR expressed as a percentage) that corresponds to effect sizes δ of 15% and 30% for a number of plausible combinations of the parameters S and T for penguins.

Effect size (%)	**Age at first breeding**	**Post first year survival rate**	**Change in population growth rate (%)**
15	3	0.85	1.87
		0.90	1.35
	4	0.85	1.67
		0.90	1.24
30	3	0.85	4.04
		0.90	2.92
	4	0.85	3.62
		0.90	2.69