Electronic Supplementary Material:

Bottom-up effects of a no-take zone on endangered penguin demographics

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Full methods

(a) Penguin data and chick survival rates

Between 37 and 239 nests were visited each year between mid-March and mid-October (Table S1). Visits were normally at intervals of 4–7 days but occasionally logistics imposed longer intervals of 14–28 days. Study nests comprised nests that were active at the time that monitoring commenced in a year. Further nests were added to the sample throughout the breeding season, so it was not always possible to determine whether the breeding attempts represented first or second clutches. The majority of nests were first visited during incubation (ca. 85 %) but in all years a few nests were first monitored once chicks had already hatched. Chicks were classified into five stages of development (P0 to P4) from hatching (P0) to being observed in full juvenile plumage (P4) and were considered to have fledged if they reached the final stage. This would usually be at 65 to 80 days old, but could occur at any stage between 55 and 130 days post hatching, depending on the growth rate of the chick.

Chick survival was determined using a combination of the Mayfield method and parametric survival models [1,2]. For each chick that was monitored, nestling days [1] were calculated by taking the mid-point between visits to the nest when chicks were or were not present. Data were considered right censored if the nest persisted through the end of the study period. These were used to generate annual failure rates (deaths/unit time of exposure) using the survreg function from the 'survival' package in R v3.0.2 with the nestling days as the response variable. The maximum likelihood estimate for failure (death), or the hazard

function (λ) was:

$$\lambda(t) = e^{-\alpha + \omega_i} t$$

<div align="right">(S1)</div>

where t = 74 days, the average chick-rearing period (Sherley et al. 2013), α = intercept parameter estimated from the model, i = the vector of nest identites and ω_i = a shared frailty term assumed to be normally distributed with a mean of 1 and a variance term (σ) estimated from the model. In these parametric survival models, a shared frailty is analogous to a random effect except that hierarchical structures was not possible. We used the nest identity (unique within years) as the frailty term to account for dependence in mortality rates between siblings which may occur if parents abandon a breeding attempt completely or struggle to provision both chicks in a two-chick brood.

An exponential error distribution was employed to map the hazard function (chick deaths per day of exposure) to a survival distribution, as this assumes that nests fail at a continuous rate through time. Chick survival (ϕ_c) was thus defined as:

$$\phi_c = e^{-\lambda(t)}$$

<div align="right">(S2)</div>

Even though year could have been added as a fixed effect to the survival model, we chose to analyse the data for each year independently to avoid dependence among these estimates. These analyses thus produced an estimate of chick survival at 74 days for each year, expressed as a proportion from 0 to 1, and an associated standard error (obtained via a delta-method transformation).

(b) Biomass and catch data

Anchovy recruits and adult sardine are the main targets for the local purse-seine boats, together accounting for ca. 75% of landings under two separate quotas [3,4]. In order to

manage these fisheries, the South African Department of Agriculture, Forestry and Fisheries (DAFF) conducts two hydro-acoustic surveys each year in May and in November. The May survey is conducted between the Orange River Mouth and Cape Infanta and provides an estimate of the biomass of recruit (age 0) sardine and anchovy which migrate southwards past Robben Island during the austral winter when penguins are breeding. Anchovy dominated the recruitment biomass (Hutchings et al. 2009, DAFF, unpubl. data) and generally made up >90% of the diet fed to African penguin chicks at Robben Island during the study period (Sherley et al. 2013, RJMC, unpubl. data). Thus we used the May recruit biomass of anchovy (Figure S2) to index the prey available to chick-rearing penguins during the breeding season.

The November survey is conducted between Hondeklip Bay and Port Alfred and provides an estimate of the adult biomass (excluding age 0 recruits) of anchovy and sardine. Off western South Africa, African penguins predominately feed their chicks anchovy recruits, but adult sardine may be important for adult penguins before and after breeding and moult [2]. Because the biomass surveys suggested that the majority of the sardine biomass was predominately off the South Coast for 9 of the 13 years of the present study, and so inaccessible to breeding penguins (DAFF, unpubl. data), we considered the biomass of sardine located to the west of Cape Agulhas (from Hondeklip Bay to Cape Agulhas) in the November prior to each breeding season (i.e. November 2000-2012) as an index of adult sardine availability to penguins at Robben Island (Figure S2). The location of Robben Island in relation to the biomass survey areas is shown in Figure S1 of [2] (http://www.int-res.com/articles/suppl/m473p291_supp.pdf).

The South African purse-seine industry was not required to record the geographic coordinates for each set of the nets and each catch during our study period. Thus, boat skippers assigned catches to 10' latitude × 10' longitude grid cells (approximately 10 x 10 nautical miles [4] and we obtained data on the catches of sardine and anchovy within 30

nautical miles of Robben Island from DAFF (Figure S2). Although the fishery operates throughout the year, the majority of the catch on the West Coast is taken between March and October, when the penguins are breeding.

(c) Analysis of the effect of closure on chick survival

Because it was not possible to fit a hierarchical frailty term in the parametric survival model, we used a two-stage process in which the annual chick survival estimates (on the logit scale) formed the response variable for subsequent analysis. As the survival rates were estimated rather than observed directly, we adopted an approach based on hierarchical Bayesian meta-analyses [5] to estimate the effect of the closure status ('Closed' or 'Open' to fishing) on chick survival. This meant we could both account for biases arising from the monitoring protocol (e.g. censored data, dependence in the survival rates of siblings) and to account for the uncertainty associated with the annual survival estimates.

The candidate models (see Table S2) took the basic form:

$$\text{logit}(\phi_{c,y}) = \alpha + \beta_x \times x_y + \beta_{B,s,q} \times B_{y,s,q} + \beta_{C,s} \times C_{y,s} + \varepsilon_y$$

(S3)

where $\phi_{c,y}$ is the chick survival for year y the β's are the coefficients to be estimated; x_y is a binary covariate for the closure effect ('Open' = 0. 'Closed' = 1); $B_{y,s,q}$ is the covariate vector of pelagic biomass estimates for year y, species s, where q refers to the November adult biomass west of Cape Agulhas for adult sardine (measured during the previous calendar year, $y_q = y - 1$) or the May recruit biomass for anchovy (when $y_q = y$); C_y is the covariate denoting the effect of fishery catches made in year y of species s; $\varepsilon_y \sim N(0,\sigma)$ is the residual error, with σ estimated from the data; and the survival rates were modelled as originating from a latent normal distribution using the estimates and SEs from the

4

parametric survival models so that $\text{logit}(\phi_y) \sim N(\varphi, \hat{\tau}_y)$, where φ is the unknown true mean survival and $\hat{\tau}_y$ is the SE associated with the survival estimate for year y.

The Monte-Carlo Markov Chain (MCMC) estimation was implemented in JAGS 3.01 using the 'rjags' and 'coda' libraries for R v.3.0.2 [6]. The priors were $N(0,10^6)$ for means and $U(0,100)$ for standard errors. We ran three chains of length 1 000 000 with the first 10 000 samples discarded as burn-in. Inference was drawn from the rest of the chains with no thinning. The models were checked for convergence using the Gelman-Rubin diagnostics (all < 1.01) and visual inspection of the trace plots. We favoured the use of penalized expected deviance over the DIC as the latter tends to perform poorly at estimating model complexity (the effective number of parameters, p_D), especially when p_D is not much smaller than the sample size under consideration [7]. Since our response variable consisted of 13 annual estimates, we were particularly keen to avoid over-parameterisation.

(d) Demographic model structure

Since we used census data based on the number of breeding pairs, we assumed a balanced sex ratio and that all mature birds would breed in each year. In reality, there are c. 1.2 birds that do not breed per breeding pair in African penguins. These birds would include mature adults that opt not to breed in a given year as well as birds in adult plumage that have yet to breed for the first time [8]. We used the number of breeding pairs observed at Robben Island in 2004 (see Table S1) as the starting population. First year (ϕ_j) and adult (ϕ_a) survival were based on mean estimates from a multi-state model using steel flipper-banded individuals from Robben Island between 1994 and 2012 [9]. That study found no evidence for differences in survival between immature and mature birds in adult plumage (i.e. no evidence for a sub-adult survival rate) [9]. We omitted the final estimate (for 2011/12) in [9] as recapture and survival probabilities are strongly correlated and their separate estimates

are unreliable for the final years of any survival analysis. These estimates were based on steel flipper bands, which can lower survival in penguins (see discussion in [9]). As a result, our population model may have over-estimated the proportion of losses in the number of pairs breeding attributable to annual adult mortality.

For fecundity (F), R was based on a mean clutch size of 1.86 eggs, a mean egg survival rate of 0.548 and a breeding frequency of 1.27 clutches per annum recorded at Robben Island for 1988–1995 as these values were used in previous population models for this species [10]. These long-term averages appear to be stable over time at Robben Island; the average clutch size was 1.87 for 2001–2010 and egg survival was 0.548 for 2001–2013 (R. B. Sherley unpubl. data).

Finally, we assumed that all individuals bred for the first time at 4 years of age, although African penguins may breed for the first time as young as 2 years old or as old as 7 [11]. However, in a sample of 87 birds banded as chicks and later breeding at Robben Island, only 4 had bred at 2 years old, 37% had bred by age 3 and 90% by age 5 [11].
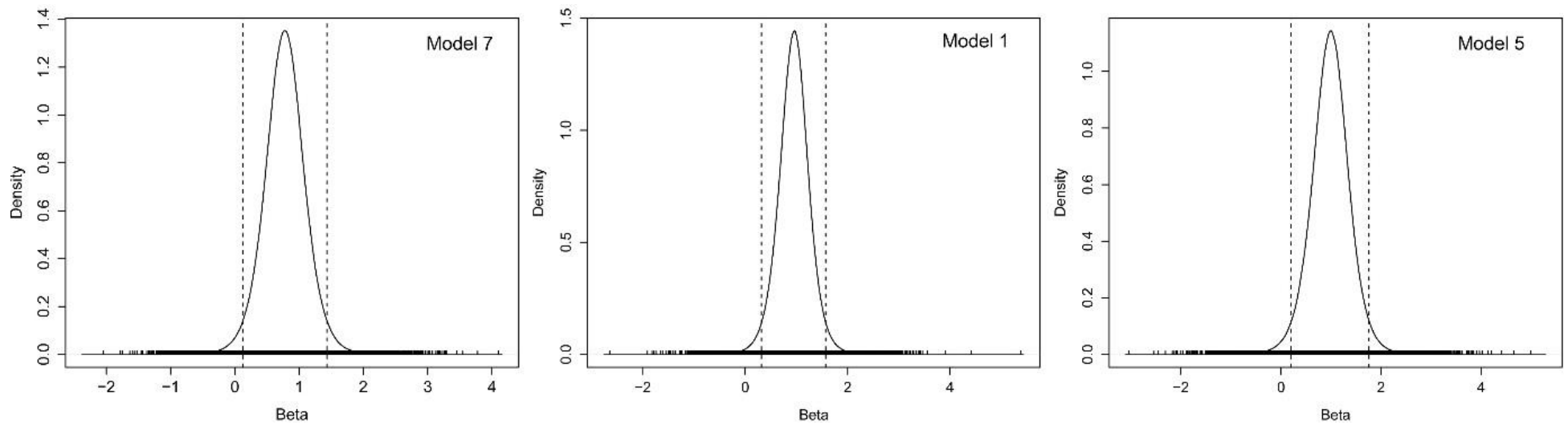
Supplementary Figures

Figure S1 Probability density function for the estimates of the closure effect (beta) from model 7 (left), model 1 (middle) and model 5 (right), Table S2. The dashed vertical lines show the 95% credible intervals.
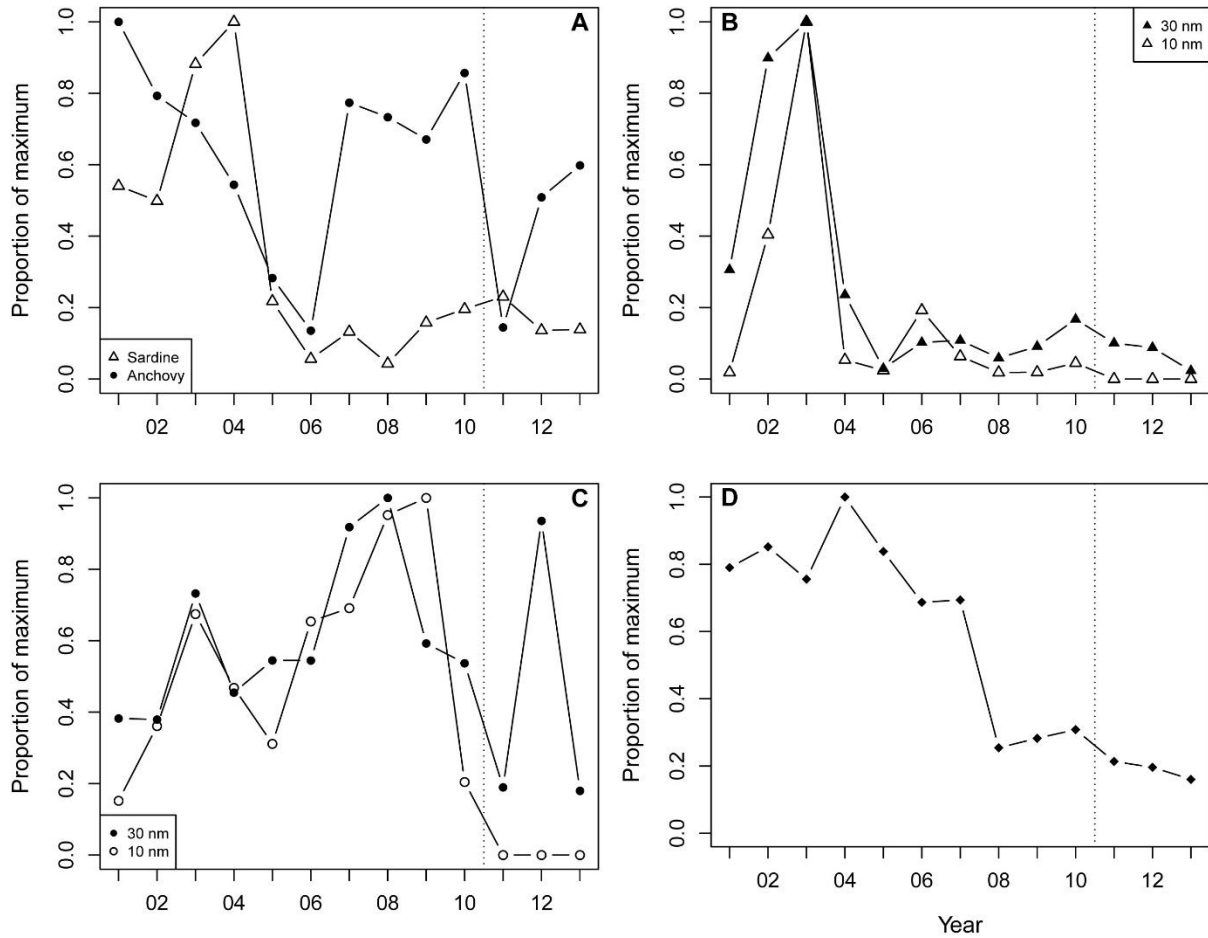
Figure S2 Time-series of the variables used in the study. A: Sardine adult biomass (white triangles) measured in the November of the previous year and anchovy recruitment biomass (black circles) measured in May of the corresponding year; B: Annual sardine catches made by the purse-seine industry within 10 nm of Robben Island (entirely encompassed by the 20 km radius closure; white triangles) and 30 nm of Robben Island (black triangles); C: Annual anchovy catches made by the purse-seine industry within 10 nm of Robben Island (white circles) and 30 nm of Robben Island (black circles); D: The number of breeding pairs estimated as breeding at Robben Island during the annual census in May each year (original values are in Table S1). Explanatory variables were expressed as a proportion of their maximum value for the statistical analysis. From 2001 to 2010 (left of the dotted vertical line), fishing was permitted around Robben Island and from 2011 to 2013 (right of the dotted vertical line) fishing was excluded within 20 km of the island. See Table S1 and Table S3 for details.

Supplementary Tables

Table S1 The time-series of penguin parameters estimated or used in this study and the number (*N*) of chicks and nests monitored each year.

Year	*N* chicks (nests) monitored	Chick survival (SE)	*N* breeding pairs
2001	63 (37)	0.399 (0.094)	6726
2002	93 (52)	0.304 (0.041)	7251
2003	113 (64)	0.250 (0.023)	6433
2004	179 (101)	0.254 (0.022)	8512
2005	131 (82)	0.569 (0.060)	7134
2006	141 (80)	0.388 (0.037)	5846
2007	197 (103)	0.701 (0.041)	5906
2008	434 (239)	0.625 (0.031)	2163
2009	285 (154)	0.527 (0.032)	2404
2010	258 (142)	0.547 (0.038)	2623
2011	312 (169)	0.634 (0.031)	1817
2012	258 (143)	0.698 (0.038)	1669
2013	245 (135)	0.799 (0.031)	1364

Table S2. The full model selection results for analysis relating African penguin chick survival at Robben Island to closure status*.

Model No.	Model	$\overline{D}$	P_{opt}	PED	ΔPED	SE	ΔPED/SE
1	AB+SB+C	-8.16	112.1	103.90	0.0	-	0.00
2	AB+AC+C	-8.90	168.2	159.30	55.4	19.88	2.79
3	AB+SC+C	-8.73	134.5	125.80	21.9	17.74	1.23
4	AB+C	-8.88	155.2	146.30	42.4	15.06	2.82
5	SB+AC+C	-8.74	122.1	113.4	9.5	10.74	0.88
6	SB+SC+C	-8.93	129.7	120.80	16.9	14.45	1.17
7	SB+C	-8.79	122.2	113.40	9.5	11.91	0.80
8	AC+SC+C	-9.05	192.4	183.40	79.5	50.44	1.58
9	AC+C	-8.97	188.5	179.60	75.7	20.13	3.76
10	SC+C	-9.13	158.7	149.60	45.7	25.61	1.78
11	C	-8.98	145.4	136.40	32.5	11.89	2.73
12	PP+AC+C	-8.82	141.7	132.90	29.0	14.20	2.04
13	PP+SC+C	-8.96	164.9	155.90	52.0	9.84	5.29
14	AB+PP+C	-8.81	148.1	139.30	35.4	18.10	1.96
15	SB+PP+C	-8.80	136.3	127.5	23.6	13.12642	1.80
16	PP+C	-8.84	138.0	129.20	25.3	11.02	2.30
17	Null model	-8.90	215.3	206.40	102.5	33.48	3.06

* Sorted by model number: $\overline{D}$ = expected deviance; P_{opt} = optimism penalty applied to each model; *PED* = penalised expected deviance ($\overline{D}$ + P_{opt}); Δ*PED* = the difference in *PED*; SE = standard error associated with the Δ*PED*; the ratio of ΔPED/SE used to indicate model support; AB = anchovy biomass; SB = sardine biomass; SC = sardine catch; AC = Anchovy catch; C = closure status; PP = penguin population size. Explanatory variable abbreviations are explained in Table S3.

Table S3

Explanatory variables used in the candidate models relating African penguin chick survival at Robben Island to closure status, fisheries catches and prey availability.

Variable abbreviation	Description
AB	Anchovy recruitment biomass: estimated biomass of young anchovy (age 0 fish) recruiting into the population from hydro-acoustic surveys conducted between the Orange River mouth and Cape Infanta in May of year y.
SB	Sardine adult biomass: estimated biomass of sardine 1 year or older west of Cape Agulhas from hydro-acoustic surveys conducted between Hondeklip Bay and Cape Agulhas during November of year $y-1$.
AC	Anchovy catch within 30 nautical miles (55.6 km) of Robben Island: catches taken during year y.
SC	Sardine catch within 30 nautical miles (55.6 km) of Robben Island: catches taken during year y.
C	Closure status: A binary covariate representing whether an area of 20 km radius around Robben Island was 'Open' (0) or 'Closed' (1) to fishing for both sardine and anchovy in year y.
PP	Penguin population size: The number of breeding pairs estimated to have nested on Robben Island in year y from the annual census data (see Table S1).

Year y denotes the year corresponding to each estimate of chick survival and $y-1$ denotes estimates from the previous November.

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