Supplementary material Appendix 1


Figure A1. Distribution of female southern elephant seal weaning mass at Marion Island, 1986 to 2012 .

Supplementary material Appendix 1

Table A1. The number of marked and weighed female southern elephant seal Mirounga leonina weaned pups entering the study population at Marion Island between 1986 and 2012. Seals were resighted until 2016 (every "Year" starts in the elephant seal breeding season [September] and ends in the winter [August $t+1$ ]). The decrease in sightings of marked females from 2013 to 2015 is neither because detection probability decreased, nor caused by a decrease in the overall population size. Rather, because pups were not entering the marked population towards the end of the study (2013-2015) there were progressively fewer individuals (especially juveniles) to be sighted from 2013 to 2015.

| Year | Females <br> marked and <br> weighed | Marked females <br> resighted |
| :---: | :---: | :---: |
| 1986 | 22 | 15 |
| 1987 | 30 | 34 |
| 1988 | 20 | 78 |
| 1989 | - | 58 |
| 1990 | - | 65 |
| 1991 | - | 67 |
| 1992 | 46 | 76 |
| 1993 | 21 | 140 |
| 1994 | 29 | 185 |
| 1995 | - | 261 |
| 1996 | - | 165 |
| 1997 | 19 | 192 |
| 1998 | 46 | 149 |
| 1999 | 45 | 191 |
| 2000 | - | 211 |
| 2001 | - | 150 |
| 2002 | 56 | 178 |
| 2003 | 26 | 267 |
| 2004 | 50 | 209 |
| 2005 | 36 | 238 |
| 2006 | 44 | 310 |
| 2007 | 53 | 358 |
| 2008 | - | 394 |
| 2009 | 51 | 386 |
| 2010 | 51 | 452 |
| 201 | 56 | 540 |
| 2012 | 45 | 526 |
| 2013 | - | 455 |
| 2014 | - | 216 |
| 2015 | - | 196 |
| Total | 746 | 6762 |
|  |  |  |
|  | - |  |

Description of elementary matrices

Five states were defined: 'pre-breeder with 2 tags' (PB2), 'pre-breeder with 1 tag' (PB1), 'breeder with 2 tags' (B2), 'breeder with 1 tag' (B1) and a 'dead' state (D), which is an absorbing state. States occupied were not directly observed, but events represent the observations following initial release that only depended on the underlying state. All individuals entered the marked population as juveniles (initial state step). Subsequent state transition probabilities were decomposed in four steps as the product of probabilities of tag loss ( $\tau^{21}$ and $\tau^{10}$ ), survival ( $S$ ) and recruitment $(R)$. The transition of pre-breeders and breeders to the 'dead' state in the tag loss step $\tau^{10}$ do not represent mortality; i.e., the transitions to the 'dead' state in $\tau^{10}$ do not contribute the estimation of mortality (or its inverse, survival rate). This representation is simply an efficient way to model the loss of both tags, since seals with zero remaining tags are never observed. We would have obtained the same results if we had specified additional and distinct unobservable states for seals with zero tags ('pre-breeder with 0 tags', and 'breeder with 0 tags').

Initial state matrix:

$$
\begin{array}{ccccc}
\text { PB2 } & \text { PB1 } & \text { B2 } & \text { B1 } & \text { D } \\
\boldsymbol{\pi}_{\boldsymbol{t}}=\left(\boldsymbol{\pi}_{\boldsymbol{P B}_{\boldsymbol{2}}}\right. & \mathbf{1}-\boldsymbol{\pi}_{\boldsymbol{P B}_{\mathbf{2}}} & \mathbf{0} & \mathbf{0} & \mathbf{0})
\end{array}
$$

Tag loss matrices:

$$
\boldsymbol{\tau}^{\boldsymbol{2 1}}{ }_{\boldsymbol{t}}=\begin{gathered}
\mathrm{PB} 2 \\
\mathrm{~PB} 1 \\
\mathrm{BB} 1 \\
\mathrm{~B} 2 \\
\mathrm{~B} 1 \\
\mathrm{D}
\end{gathered}\left(\begin{array}{ccccc}
\mathbf{1}-\boldsymbol{\tau}_{\mathbf{2 2}} & \boldsymbol{\tau}_{\mathbf{2 2}} & \mathrm{B} 1 & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{1}-\boldsymbol{\tau}_{\mathbf{2 2}} & \boldsymbol{\tau}_{\mathbf{2 2}} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1}
\end{array}\right)
$$

$$
\boldsymbol{\tau}^{\mathbf{1 0}}{ }_{\boldsymbol{t}}=\begin{gathered}
\mathrm{PB} 2 \\
\mathrm{~PB} 1 \\
\mathrm{~B} 2 \\
\mathrm{~B} 2 \\
\mathrm{~B} 1 \\
\mathrm{~B} 1 \\
\mathrm{D}
\end{gathered}\left(\begin{array}{ccccc}
\mathbf{1} & \mathrm{PB} 1 & \mathrm{~B} 2 & \mathrm{~B} 1 & \mathrm{D} \\
\mathbf{0} & \mathbf{1}-\boldsymbol{\tau}_{\boldsymbol{1 1}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \boldsymbol{\tau}_{\mathbf{1 1}} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1}-\boldsymbol{\tau}_{\boldsymbol{1 1}} & \boldsymbol{\tau}_{\boldsymbol{1 1}} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1}
\end{array}\right)
$$

Survival matrix:

$$
\boldsymbol{S}_{\boldsymbol{t}}=\begin{gathered}
\mathrm{PB} 2 \\
\mathrm{~PB} 1 \\
\mathrm{~B} 2 \\
\mathrm{~B} 1 \\
\mathrm{D}
\end{gathered}\left(\begin{array}{ccccc}
\mathrm{PB} 2 & \mathrm{~PB} 1 & \mathrm{~B} 2 & \mathrm{~B} 1 & \mathrm{D} \\
\emptyset_{\boldsymbol{P} \boldsymbol{B}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1}-\emptyset_{\boldsymbol{P} \boldsymbol{B}} \\
\mathbf{0} & \emptyset_{P \boldsymbol{B}} & \mathbf{0} & \mathbf{0} & \mathbf{1}-\emptyset_{\boldsymbol{P}} \\
\mathbf{0} & \mathbf{0} & \emptyset_{\boldsymbol{B}} & \mathbf{0} & \mathbf{1}-\emptyset_{\boldsymbol{B}} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \emptyset_{\boldsymbol{B}} & \mathbf{1}-\emptyset_{\boldsymbol{B}} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1}
\end{array}\right)
$$

Recruitment matrix:

$$
\left.\boldsymbol{R}_{\boldsymbol{t}}=\begin{array}{c}
\mathrm{PB} 2 \\
\mathrm{~PB} 1 \\
\mathrm{~B} 1 \\
\text { B1 } \\
\text { B1 } \\
\text { D }
\end{array} \left\lvert\, \begin{array}{ccccc}
\mathbf{1}-\boldsymbol{\Psi}_{\boldsymbol{P} \boldsymbol{B}-\boldsymbol{B}} & \mathrm{PB} 1 & \mathrm{~B} 2 & \mathrm{~B} 1 & \mathrm{D} \\
\mathbf{0} & \mathbf{0} & \boldsymbol{\Psi}_{\boldsymbol{P} \boldsymbol{B}-\boldsymbol{B}} & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \boldsymbol{\Psi}_{\boldsymbol{P} \boldsymbol{B}-\boldsymbol{B}} & \mathbf{0} & \boldsymbol{\Psi}_{\boldsymbol{P} \boldsymbol{B}-\boldsymbol{B}} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1} & \mathbf{0} \\
& \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{1}
\end{array}\right.\right)
$$

Event matrix:

$$
\boldsymbol{E}_{\boldsymbol{t}}=\begin{gathered}
\mathrm{PB} 2 \\
\mathrm{~PB} 1 \\
\mathrm{~B} 2 \\
\mathrm{~B} 1 \\
\mathrm{~B} 1 \\
\mathrm{D}
\end{gathered}\left(\begin{array}{ccccc}
\mathrm{PB} 2 & \mathrm{~PB} 1 & \mathrm{~B} 2 & \mathrm{~B} 1 & \mathrm{D} \\
\mathbf{1}-\boldsymbol{p}_{\boldsymbol{P} \boldsymbol{B}_{\mathbf{2}}} & \boldsymbol{p}_{\boldsymbol{P} \boldsymbol{B}_{2}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\
\mathbf{1}-\boldsymbol{p}_{\boldsymbol{P} \boldsymbol{B}_{\boldsymbol{1}}} & \mathbf{0} & \boldsymbol{p}_{\boldsymbol{P} \boldsymbol{B}_{\mathbf{1}}} & \mathbf{0} & \mathbf{0} \\
\mathbf{1}-\boldsymbol{p}_{\boldsymbol{B}_{\mathbf{2}}} & \mathbf{0} & \mathbf{0} & \boldsymbol{p}_{\boldsymbol{B}_{\boldsymbol{2}}} & \mathbf{0} \\
\mathbf{1}-\boldsymbol{p}_{\boldsymbol{B}_{\mathbf{1}}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \boldsymbol{p}_{\boldsymbol{B}_{\mathbf{1}}} \\
\mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0}
\end{array}\right)
$$

## Goodness of fit testing

No formal goodness of fit (GOF) tests are currently available for multievent- or multistate models with unidirectional transitions (Pradel et al. 2003, Pradel et al. 2005). Nevertheless, we approximated whether our data fitted the assumptions of the simpler Cormack-Jolly-Seber (CJS) model by partitioning capture history data into distinct pre-breeder and breeder components, and running available GOF tests separately for each sub-sample. First-year survival in elephant seals is low compared to subsequent survival (e.g., McMahon et al. 1999) and, because we marked and released cohorts of weaned pups, we expected that capture histories would violate the CJS assumption that every marked animal in the population immediately after time $i$ has the same probability of surviving to time $i+1$. According to Test 3.SR, 'newly marked' individuals in our sample were indeed less likely to survive (and be reencountered) than previously marked individuals (Table A2). By including age structure in the survival parameter, we could recalculate the GOF statistic without the contribution of Test 3.SR (Pradel et al. 2005). The resultant test ('Age model’, Table A2) suggested that the model fit was adequate when age-structured survival was modelled. GOF procedures were implemented in program U-CARE 2.2.2 (Choquet et al. 2009).

## References

Choquet, R., J. D. Lebreton, O. Gimenez, A. M. Reboulet, and R. Pradel. 2009. U-CARE: Utilities for performing goodness of fit tests and manipulating capture-recapture data. Ecography 32: 1071-1074.

McMahon, C. R., H. R. Burton, and M. N. Bester. 1999. First-year survival of southern elephant seals, Mirounga leonina, at sub-Antarctic Macquarie Island. Polar Biology 21: 279284.

Pradel, R., C. M. A. Wintrebert, and O. Gimenez. 2003. A proposal for a goodness-of-fit test to the Arnason-Schwarz multistate capture-recapture model. Biometrics 59: 43-53.

Pradel, R., O. Gimenez, and J. D. Lebreton. 2005. Principles and interest of GOF tests for multistate capture-recapture models. Animal Biodiversity and Conservation 28: 189-204.

Table A2. Testing the homogeneity assumptions of the Cormack-Jolly-Seber (CJS) model for pre-breeders and breeders respectively. "Test 3 " components test the assumption that marked individuals in the population immediately after time $t$ have the same probability of surviving to $t+1$. Systematic departures from model expectations might point to transience (migratory individuals leaving the sampling area after marking), or age effects (e.g., lower survival of newly marked juveniles relative to adult survival). "Test 2 " components test the assumption of equal catchability of marked individuals: every marked animal present in the population at time $t$ should have the same probability of recapture $\left(p_{t}\right)$. Here, significant $\chi^{2}$ statistics is indicative of trap-dependence or non-random temporary emigration. The "Age model", accounting for high first-year mortality of southern elephant seal pups, fitted the model assumptions.

| Test | Pre-breeders |  |  | Breeders |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | $\chi^{2}$ | df | p | $\hat{c}$ | $\chi^{2}$ | df | p | $\hat{c}$ |
| Test 3.SR | $\mathbf{3 8 . 1 4}$ | $\mathbf{1 8}$ | $\mathbf{0 . 0 0 4}$ |  | 13.11 | 22 | 0.93 |  |
| Test 3.SM | 13.64 | 14 | 0.48 |  | 2.80 | 8 | 0.95 |  |
| Test 2CT | 21.47 | 21 | 0.43 |  | 4.99 | 5 | 0.42 |  |
| Test 2L | 0.00 | 1 | 1 |  | - | - | - |  |
|  |  |  |  |  |  |  |  |  |
| CJS Model | $\mathbf{7 3 . 2 5}$ | $\mathbf{5 4}$ | $\mathbf{0 . 0 4}$ | 1.36 | 20.90 | 35 | 0.97 | 0.60 |
| Age model | 35.11 | 36 | 0.51 | 0.98 | 7.79 | 13 | 0.86 | 0.60 |

Significant $\chi^{2}$ statistics ( $\mathrm{P}<0.05$ ), indicative of violation of the homogeneity assumptions of the CJS model, are in boldface.

Supplementary material Appendix 4

Matrix population model

The population projection matrix $\boldsymbol{A}$ for females, corresponding to the stage structure in Figure 2 (main text) is:
$\left[\begin{array}{ccccccccccccc}0 & 0 & \varphi 2 \psi 2 R & \varphi 3 \psi 3 R & \varphi F 3 \delta R & \varphi 4 \psi 4 R & \varphi F 4 \delta R & \varphi B 4 \delta R & \varphi 5 \psi 5 R & \varphi F 5 \delta R & \varphi B 5 \delta R & \varphi F 6 \delta R & \varphi B \delta R \\ \varphi 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \varphi 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \varphi 2(1-\psi 2) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \varphi 2 \psi 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \varphi 3(1-\psi 3) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \varphi 3 \psi 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \varphi F 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \varphi 4(1-\psi 4) & 0 & 0 & \varphi 5(1-\psi 5) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \varphi 4 \psi 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \varphi F 4 & \varphi B 4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi 5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \varphi F 5 & \varphi B 5 & \varphi F 6 & \varphi B\end{array}\right]$

The values $a_{i j}$ of the first row in matrix $\boldsymbol{A}$ represent the contribution of each stage to female offspring. Elements on the diagonal represent the probability of surviving while staying in the same stage class, and elements on the sub-diagonals represent the probability of surviving and progressing to a subsequent stage. Parameters $\varphi_{i}, \varphi_{F i}$ and $\varphi_{B i}$ refer to age-specific survival probability of pre-breeders, first-time breeders, and experienced-breeders, respectively. Parameter $\psi_{i}$ refers to age-specific recruitment probability and $\delta_{i}$ to breeding propensity subsequent to recruitment. We set fecundity $(R)$, the number of daughters produced per breeding female, to 0.5 .

## Supplementary material Appendix 5



Figure A2. The relationship between weaning mass and probability of first-year survival of female southern elephant seals at Marion Island. Uncertainty about predicted values is given by $95 \%$ confidence intervals (shading). The distribution of weaning mass observations is indicated at the bottom of each figure.

## Supplementary material Appendix 5



Figure A3. The relationship between weaning mass and probability of second-year survival of female southern elephant seals at Marion Island. Uncertainty about predicted values is given by $95 \%$ confidence intervals (shading). The distribution of weaning mass observations is indicated at the bottom of the figure.

## Supplementary material Appendix 5

Table A3. Model selection for recapture and tag loss probabilities of southern elephant seals at Marion Island. The number of parameters (np), model deviance, $\triangle \mathrm{AICc}$ (the difference in AICc between the model with the lowest AICc value and the relevant model) and the relative support by the data of a model, in relation to the other models (AICc weight, $w_{i}$ ), is given. Models are ranked relative to models listed in Table 1 in the main text. Models shown in bold font were selected and used to model survival and recruitment probabilities (Table 1).

| Model | np | Deviance | $\Delta \mathrm{AIC}_{c}$ | $w_{i}$ |
| :---: | :---: | :---: | :---: | :---: |
| Encounter probability (p) |  |  |  |  |
| t.state.n | 146 | 4395.55 | 131.67 | 0.00 |
| t.n | 92 | 4470.51 | 85.53 | 0.00 |
| t.state | 91 | 4442.15 | 54.99 | 0.00 |
| $t$ | 64 | 4507.78 | 62.48 | 0.00 |
| state | 37 | 4520.79 | 18.84 | 0.00 |
| $i$ | 36 | 4558.48 | 54.46 | 0.00 |
| First tag loss probability ( $\tau^{21}$ ) |  |  |  |  |
| $a$ | 31 | 4533.44 | 19.10 | 0.00 |
| $a^{0, \geq 1}$ | 27 | 4535.56 | 12.99 | 0.00 |
| g. $a^{0, \geq 1}$ | 29 | 4531.37 | 12.91 | 0.00 |
| $g$ | 27 | 4543.31 | 22.79 | 0.00 |
| $i$ | 26 | 4548.08 | 23.46 | 0.00 |
| Second tag loss probability ( $\tau^{10}$ ) |  |  |  |  |
| $a^{0, \geq 1}$ | 27 | 4531.47 | 8.90 | 0.00 |
| $g$ | 27 | 4531.40 | 8.83 | 0.00 |
| $i$ | 26 | 4531.47 | 6.85 | 0.01 |

Note: Candidate models contained combinations of the following variables: intercept only (i), time variation $(t)$, breeding state (state), number of flipper tags remaining ( $n$ ), position of flipper tag $(g)$, six age classes $(0,1,2,3,4, \geq 5)(a)$, subsets of age classes (e.g., $a^{1}$ ) and weaning mass as an individual covariate (mass). The umbrella model (P1) was: $\tau^{21}$. g. $a ; \tau^{10} . g . a_{0, \geq 1} ; \varphi$. .mass $; \psi^{P B} . a_{3,4,5}$. mass ; p.t.state. $n$ where $\tau^{21}$ and $\tau^{10}$ are tag loss parameters, $\varphi$ is apparent survival probability, $\psi^{P B}$ is recruitment probability and $p$ is recapture probability (see the Methods section of the main text for details).

