

## Supplementary Methods

### Population data

#### *Steller sea lion non-pup surveys*

Surveys of Alaskan Steller sea lion populations have been conducted by the National Marine Fisheries Service and the Alaska Department of Fish and Game since 1976 as part of range-wide monitoring (Fritz and Stinchcomb 2005, NMFS 1992). During aerial surveys, photographs were taken of sea lions on all rookery and haul-out sites in the Gulf of Alaska and Aleutian Islands in approximately two weeks during the breeding season (June/July). At this time, newborns (pups) and reproductive adults are observed on rookeries where adult males defend territories and mating and birthing occur. Adults that are not breeding that year and pre-reproductive juveniles (age 1 to 3 years old) are observed on haul-out sites where sea lions predictably rest on land but where no or few pups are born. Non-pups include all juveniles and adults but not newborn pups. The National Marine Fisheries Service designates rookeries and haul-outs as trend or non-trend sites (NMFS 1992). Trend sites have been regularly surveyed since 1976, while non-trend sites have not been counted as consistently; animals on trend sites account for 60-70% of the total count. For this paper, we used the 1976-2004 total non-pup count on trend rookeries and haul-outs in the CGOA during June/July. The raw data with references are given in Supplementary Table 1.

#### *Steller sea lion pup censuses*

Pup have been counted intermittently from 1978 to 2004 at the Marmot, Sugarloaf, Chowiet, Chirokof, and Outer Island rookeries, which together contribute more than 90% of the CGOA pup production (Fritz and Stinchcomb 2005, Sease et al. 1993). For each of the years, 1978, 1979, 1984, 1986, 1989, 1990, 1991, 1992, 1993, 1994, 1997, 1998, 2000, 2001, 2002, and 2004, at least three of the five rookeries were surveyed and the other rookeries were surveyed within 2 years of those years. To create an all-CGOA pup count estimate, the pup data from each rookery was interpolated with a cubic spline and the interpolated pup time series were added together as follows:

For rookery  $i = \{\text{Marmot, Sugarloaf, Chowiet, Chirokof, Outer Island}\}$

$$P_{\text{interpolated}, i} = \text{spline}(P_{\text{raw}, i});$$

For year  $j$  in *good\_years* (below),

$$P_{\text{interpolated}, \text{all}, \text{year } j} = \sum_i P_{\text{interpolated}, i, \text{year } j}$$

else  $P_{\text{interpolated}, \text{all}, \text{year } j} = \text{"missing"}$ .

*good\_years* = [1978, 1979, 1984, 1986, 1989, 1990, 1991, 1992, 1993, 1994, 1997, 1998, 2000, 2001, 2002, 2004]

The result was that the actual counts were used for the “*good\_years*” for rookeries which had a count on those years, and for the other rookeries with counts within 1-2 years, an interpolated value was used. The estimated total pup count is given in Supplementary Table 1. Use of the pup count time series at each of the major CGOA rookeries avoided the assumption used in Holmes and York (2003) that the Marmot Island pup counts provide a temporally consistent metric of CGOA pup production. This is approximately

true, but we noticed some deviations from this assumption in key years, which could affect the analyses.

#### *A metric for the age structure*

The metric used for age structure was developed in Holmes and York (2003) from photographs of animals resting at haul-outs. We measured sea lions in the aerial photographs of haul-outs taken during the 1985, 1989, 1990, 1991, 1992, 1994, 1996, 1997, 1998, 2000, and 2002 breeding-season surveys in the CGOA. From the photographs, the longest straight-line length of every animal was measured digitally. The fraction of small animals from all haul-out photographs in a given year was used as an index of the juvenile fraction. Only haul-out, not rookery, photographs were analyzed given the low numbers of juveniles located on rookeries during the breeding season. No attempt was made to correct for curled animals; instead thousands of measurements were made and it was assumed that the mean curling rate is constant over time and that measurements of thousands of individuals would sufficiently reduce the sampling error from differences in curling tendency in small groups. The total number of measured animals for each year was 7182, 3039, 2752, 2468, 2409, 2536, 1971, 1924, 2090, 2489, and 2237 for the surveys conducted in 1985, 1989, 1990, 1991, 1992, 1994, 1996, 1997, 1998, 2000, and 2002, respectively.

The photographs provide no direct means for determining absolute size of individuals. Instead, relative size was used. Photographs were selected in which there was at least one mature adult male lying completely stretched-out. Adult males are distinctively large and light in color. The measurements of all other individuals were normalized by dividing all animal lengths in a photograph by the length of the photograph's largest mature male. Variation in the lengths of adult males is low (Calkins & Pitcher 1982), and thus they provided a natural scale. From the set of all normalized measurements, a metric,  $J/T$ , for the fraction of juveniles on haul-outs was calculated as

$$\frac{J}{T} = \frac{\text{number of animals less than 50\% of the length of the largest male}}{\text{total number of animals in a photograph}}.$$

Although when lying straight, juveniles are 60-70% of the length of large males (Calkins & Pitcher 1982), few animals in the photographs were stretched out. Cross-checking our normalized measurements with visual categorization of animals indicated that a 50% cut-off would categorize the vast majority of juveniles as juveniles while minimizing mis-categorization of adults. There is strong consistency in the  $J/T$  metric between adjacent census years (see Figure 2A in the main paper), which indicates that the metric does not show excessive year-to-year error.

#### *Relating the raw data to the model*

The life-history model models the total pup, juvenile and adult numbers while the raw data are indices that are related to the actual total pup, juvenile, and adult numbers in the population in some fashion. It was necessary to estimate the relationship between the raw indices (observed data) and the total counts (unknown).

The estimated total pup count was the most direct estimate in the sense that it was based on a census that represented a very large fraction of the actual pups each year. We

assumed a constant relationship between the pup estimates and the true total pup numbers:  $\text{Pups}_{\text{interpolated}} = \text{Pups}_{\text{true}} \times p_1 + \varepsilon$ , where  $\varepsilon$  is unknown gaussian distributed observation error. We fixed  $p_1$  at 0.95 across all model fits, thus it was never considered a free parameter. This was done after numerous test fits indicated that the maximum likelihood estimate of this parameter was relatively constant across all models, and that fixing it did not favor one model over another.

The non-pup count is less directly related to the total non-pup count because it represents only animals on trend sites and also visible at the time of the photographic census. Thus, animals on non-trend sites, those in the water, or those on trend sites but not photographed had to be accounted for in the model:  $\text{Non-pups}_{\text{trend}} = \text{Non-pups}_{\text{true}} \times p_2 + \varepsilon$ , where  $\varepsilon$  is unknown gaussian distributed observation error. We estimated  $p_2$  as a free parameter separately for each model. It did not vary greatly between models.

The J/T metric is the number of juveniles counted as juvenile in a photograph divided by the total number of animals photographed on a haul-out. We denoted by  $m_{jj}$  the fraction of juveniles in a photograph that are categorized as juveniles and denoted by  $h_j$  and  $h_a$ , respectively, the fraction of juveniles and adults that were photographed on haul-outs; only a fraction of the juvenile and adult population is photographed since some individuals are in the water, on rookeries, or on the haul-out but not photographed. The relationship between the J/T metric and the true numbers of juveniles and adults is then

$$\frac{J}{T} = \frac{m_{jj} h_j J_{\text{true}}}{h_j J_{\text{true}} + h_a A_{\text{true}}} = \frac{m_{jj} J_{\text{true}}}{J_{\text{true}} + \frac{h_a}{h_j} A_{\text{true}}}.$$

The value of  $m_{jj}$  was assumed to be 0.8 after preliminary analyses, although our results were not particularly sensitive to the exact value assumed. The constants  $h_a$  and  $h_j$  were unknown, except that  $h_a$  is considerably smaller than  $h_j$  since most adults but few juveniles are on the rookeries during the breeding season. The ratio  $h_a/h_j$  was estimated as a free parameter separately for each model. The ratio is denoted,  $p_3$ , in Eq. 3 in the main text.

### Life-history matrices

The 32 x 32 female-only age-structured life-history matrix for Steller sea lions ( $\mathbf{Y}$  in Eq. 1 in the main text) is shown in Supplementary Table 2. The matrix is a modified Leslie matrix where row 1 column  $i$  is the late-term pregnancy rate of age  $i+1$  females multiplied by the survival rate from age  $i$  to age  $i+1$  (cf. York 1994). Thus when the matrix multiplication,  $\mathbf{N}_{t+1} = \mathbf{Y} \times \mathbf{N}_t$ , is performed, the first element of  $\mathbf{N}_{t+1}$  is the pup numbers in year  $t+1$ . Rows  $i$ ,  $i > 1$ , in the matrix contain the survivorships from age  $i$  to  $i+1$ , along the diagonal. The  $s_i$  and  $f_i$  terms in the matrix have been estimated three different ways based on data from the 1970s on Marmot Island (Calkins and Pitcher 1982). The resulting three different life-history matrices are discussed below. The specific  $s_i$  and  $f_i$  terms for each matrix are given in Supplementary Table 3.

#### *Calkins and Pitcher (1982) matrix*

For this matrix, the survivorships,  $s_i$ , were those estimated originally by Calkins and Pitcher (1982) as presented in their Table 24. These estimates are from the age-distribution observed in the longitudinal sample of the population, which was done by sacrificing animals and determining age by counting the enamel layers in cross-sections of the canine teeth. Pregnancy rates were determined from pregnancy rates observed in the sampled females. The survivorships in Supplementary Table 3 are from York (1994) Table 1 with the exception of  $s_0$ ,  $s_1$  and  $s_2$ . Juvenile survivorship could not be estimated directly from the data. Instead, York (1994) and Calkins and Pitcher (1982), set juvenile survivorship such that the resulting matrix would be stable (maximum eigenvalue equals 1.0). York (1994) made juvenile survivorship equal for the 1<sup>st</sup> three years while Calkins and Pitcher (1982) had juvenile survivorship increasing with age. In this analysis, we used Calkins and Pitcher's method. Thus  $s_1$  and  $s_2$  increase linearly from  $s_0$  towards  $s_3$ , and  $s_0$  is set so that the matrix is stable. Fecundity,  $f_i$ , is based on 'percent mature' x 'birth rate' in Table 26 in Calkins and Pitcher (1982) x 0.5 sex ratio. The numbers given in Supplementary Table 3 are from York (1994), Table 1. Note that the age or  $i$  column in both York (1994) and Calkins and Pitcher (1982) is confusing. Early maturing females first become mature at age 3 but give birth at age 4, so  $f_i$  is 0 for age 0-3.

#### *York (1994) matrix*

The Calkins and Pitcher (1982) survivorships result in an equilibrium age-distribution that does not fit the observed age-distribution. York (1994) re-estimated the Calkins and Pitcher (1982) survivorships using a Weibull hazard model which is a standard model for survivorship. The re-estimated survivorships result in an age-distribution that closely matches the sampled cumulative age-distribution. The survivorships in Supplementary Table 3 are from York (1994) Table 1 with the exception of  $s_0$ ,  $s_1$  and  $s_2$ . York (1994) made juvenile survivorship equal for the 1<sup>st</sup> three year. Here, we used Calkins and Pitcher's method as above, that allowed juvenile survivorship to increase with age. Thus  $s_1$  and  $s_2$  were set to increase linearly from  $s_0$  towards  $s_3$ , and  $s_0$  adjusted so that the matrix is stable. York (1994) used the fecundity estimates directly from Calkins and Pitcher (1982). Table 1 in York (1994) gives the  $f_i$  estimates, but note that in Table 1 (York 1994), the age 'To' column represents the numbering for  $f_i$ , whereas the age 'From' column represents the numbering for  $s_i$ .

#### *Holmes et al. (2006) matrix (this paper)*

York (1994) did not re-analyze the fecundity estimates used in Calkins and Pitcher (1982), and there were a number of inconsistencies between the actual pregnancy data and the age-specific fecundity terms. In particular, Calkins and Pitcher (1982) set fecundity at a constant level after age 6; however no late-term pregnancies were observed in females over the age of 21. Data on fecundity senescence in pinnipeds is limited due to the lack of 20-year plus studies of branded individuals. The best data is from monk seals in Hawaii, northern fur seals (*Callorhinus ursinus*) on the Pribilof Islands, harp seals (*Pagophilus groenlandicus*), and grey seals (*Halichoerus grypus*) (Thea Johanos-Kam, NMFS, personal communication; Boyd 1985; Bowen et al. 1981; Lander 1981). Fecundity senescence was seen in the monk seals, harp seals and fur seals, but not in grey seals.

We revisited the raw pregnancy data from Marmot Island and re-estimated the fecundity rates as follows. We estimated late-season pregnancy rates for female Steller sea lions as the predicted values from a logistic regression model (McCullagh and Nelder 1989) of the following form:  $p_i(m) = \text{age.group}_i + a * m$ .  $p_i(m)$  is assumed to be a Bernoulli random variable with expectation equal to the logit of the estimated pregnancy rate for age group  $i$ ,  $m$  months after mating in July;  $\text{age.group}$  is one of 3, 4, 5, 6, 7-9, 10-16, 16-20, or 21-30 yr. Note  $\text{age.group}$  represents the age at which a female becomes pregnant, but she gives birth when she is one year older. We used the statistical program R (R Development Core Team 2004) for model estimation and prediction. The form of the model is conceptually different from that of Calkins and Pitcher (1982). They modeled late-season pregnancy rates as a product of an age-specific maturity rate, a constant conditional pregnancy rate given a female is mature, and a constant monthly decay rate in pregnancy rate to account for reproductive failures. Our model is an age-group specific pregnancy rate at the time of implantation with a constant monthly decay in pregnancy rate.

#### *Allowing temporal changes in the matrix*

Fecundity, juvenile survivorship (age 0-2) and adult survivorship (age 3+) were allowed to change within specific time periods. This was allowed by introducing free parameters,  $p_{f,k}$ ,  $p_{j,k}$  and  $p_{a,k}$ , for each of the  $k$  time periods. These free parameters were scaling parameters that multiplied fecundity, juvenile survivorship, and adult survivorship, respectively, across the board as shown in Supplementary Table 4. Thus, for example, for four time period changes, the model started with the base matrix (Supplementary Table 2) and then at every time period change, a new matrix (Supplementary Table 4) was used with a new set of  $p_{f,k}$ ,  $p_{j,k}$ , and  $p_{a,k}$  scaling parameters:

$$\begin{array}{ll}
 \text{For } t = 1976 : t_1 - 1, & \bar{N}_{t+1} = \mathbf{Y}_{base} \cdot \bar{N}_t \\
 \text{For } t = t_1 : t_2 - 1 & \bar{N}_{t+1} = \mathbf{Y}_1 \cdot \bar{N}_t \\
 \text{For } t = t_2 : t_3 - 1 & \bar{N}_{t+1} = \mathbf{Y}_2 \cdot \bar{N}_t \\
 \text{For } t = t_3 : t_4 - 1 & \bar{N}_{t+1} = \mathbf{Y}_3 \cdot \bar{N}_t \\
 \text{For } t = t_4 : 2004 & \bar{N}_{t+1} = \mathbf{Y}_4 \cdot \bar{N}_t
 \end{array}$$

#### **Model development, fitting and comparison**

The matrices and models were developed and estimated prior to fitting to the time series data. Note that the life history models were estimated from data that is independent from the time series data. They are estimated from age and pregnancy information from a longitudinal sample of Steller sea lions associated with the Marmot Island rookery in the 1970s. The number of parameters,  $K$ , used in the  $AIC_c$  calculations is based on the number of scaling parameters (3) times the number of time periods plus the number of fitted constants (2) and the number of fitted variances (3). Sample size,  $n$ , for the  $AIC_c$  calculation was based on the total number of data points (the circles in Figure 2a-c). The resulting  $AIC_c$  values give metric of the model fit penalized by the number of fitted parameters, however they were not used to select a model per se.

## References

- Bowen, W. D., C. K. Capstick, and D. E. Sergeant. 1981. Temporal changes in the reproductive potential of female harp seals (*Pagophilus groenlandicus*). Canadian Journal of Fisheries and Aquatic Sciences 38:495-503.
- Boyd, I. L. 1985. Pregnancy and ovulation rates in grey seals (*Halichoerus gryus*) in the British coast. Journal of Zoology 205: 265-272.
- Calkins, D. G., and K. W. Pitcher. 1982. Population assessment, ecology and trophic relationships of Steller sea lions in the Gulf of Alaska. Pages 455-546 in Environmental assessment of the Alaska continental shelf. Final report No. 19. U.S. Department of Commerce and U. S. Department of Interior, Washington, D. C.
- Fritz, L. W., and C. Stinchcomb. 2005. Aerial, ship, and land-based surveys of Steller sea lions (*Eumetopias jubatus*) in the western stock in Alaska, June and July 2003 and 2004. U. S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-153, 56 p.
- Holmes, E. E. and A. E. York. 2003. Using age structure to detect impacts on threatened populations: a case study using Steller sea lions. Conservation Biology 17:1794-1806.
- Lander, R. H. 1981. A life table and biomass estimate for Alaskan fur seals. Fisheries Research 1:55-70.
- McCullagh, P and J. A. Nelder. 1989. Generalized linear models. Chapman and Hall London, 261p.
- National Marine Fisheries Service. 1992. Final Recovery Plan for the Steller sea lion (*Eumetopias jubatus*). Prepared by the Steller sea lion Recovery Team for the National Marine Fisheries Service, Silver Spring, Maryland. 92pp.
- R Development Core Team. 2004. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL <http://www.R-project.org>.
- Sease, J. L., J. P. Lewis, D. C. McAllister, R. L. Merrick and S. M. Mello. 1993. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in Southeast Alaska, the Gulf of Alaska, and Aleutian Islands during June and July 1992. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-17.
- York, A. E. 1994. The population dynamics of northern sea lions, 1975-1985. Marine Mammal Science 10:38-51.

## Supplementary Tables

Table 1. The raw data

Table 2. The 32x32 life-history matrix

Table 3. The parameters for the three matrices

Table 4. The 32x32 life-history matrix with perturbation parameters.

Table 5. The estimated parameters and AIC<sub>c</sub> values

Supplementary Table 1. **The raw data**

Year	Non-pup count	Pup count <sup>1</sup>	J/T metric <sup>6</sup>
1976	24678 <sup>2</sup>	no data	no data
1977	no data	no data	no data
1978	no data	17835	no data
1979	no data	19886	no data
1980	no data	no data	no data
1981	no data	no data	no data
1982	no data	no data	no data
1983	no data	no data	no data
1984	no data	15019	no data
1985	19002 <sup>2</sup>	no data	0.3788
1986	no data	11598	no data
1987	no data	no data	no data
1988	no data	no data	no data
1989	8552 <sup>2</sup>	6394	0.4843
1990	7050 <sup>2</sup>	4648	0.5025
1991	6273 <sup>2</sup>	4057	0.4801
1992	5721 <sup>2</sup>	3646	0.5255
1993	no data	3176	no data
1994	4520 <sup>3</sup>	2831	0.3706
1995	no data	no data	no data
1996	3915 <sup>3</sup>	no data	0.3698
1997	3352 <sup>3</sup>	2056	0.4007
1998	3467 <sup>4</sup>	1876	0.4095
1999	no data	no data	no data
2000	3180 <sup>4</sup>	1675	0.4769
2001	no data	1540	no data
2002	3366 <sup>4</sup>	1608	0.4483
2003	no data	no data	no data
2004	3055 <sup>5</sup>	1578	no data

1. Based on Table 8 in Fritz, L. W. and C. Stinchcomb. 2005. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in the western stock in Alaska, June and July 2003 and 2004. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-153, 56 p. and Sease, J. L., J. P. Lewis, D. C. McAllister, R. L. Merrick and S. M. Mello. 1993. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in Southeast Alaska, the Gulf of Alaska, and Aleutian Islands during June and July 1992. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-17, per interpolation discussed in supplementary methods.

2. Table 4 in Sease, J. L., J. P. Lewis, D. C. McAllister, R. L. Merrick and S. M. Mello. 1993. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in Southeast Alaska, the Gulf of Alaska, and Aleutian Islands during June and July 1992. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-17.
3. Table 4 in Sease, J. L., and T. R. Loughlin. 1999. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in Alaska, June and July 1997 and 1998. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-100.
4. Table 3 in Sease, J. L., and C. J. Gudmundson. 2002. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) from the western stock in Alaska, June and July 2001 and 2002. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-100.
5. Table 4 in Fritz, L. W. and C. Stinchcomb. 2005. Aerial and ship-based surveys of Steller sea lions (*Eumetopias jubatus*) in the western stock in Alaska, June and July 2003 and 2004. U.S. Department of Commerce., NOAA Tech. Memo. NMFS-AFSC-153, 56 p. This is the raw count before adjusting for the new medium-format photography. Adjusted count would be 2944, but this lead to unrealistic pup-to-nonpup ratios.
6. The *J/T* measurement method was initially presented in Holmes and York (2003). The measurements listed here do not exactly match those in Holmes and York (2003) since more haul-out measurements were taken to supplement those used in that paper.



Supplementary Table 2. **The 32 x 32 age-structured life-history matrix**

	age 0(pup)	age 1	age 2	age 3	...	age 31
$s_i \times f_{i+1}$	$s_0 \times f_1$	$s_1 \times f_2$	$s_2 \times f_3$	$s_3 \times f_4$	...	$s_{31} \times f_{32}$
surv. age 0 to 1	$s_0$	0	0	0	...	0
surv. age 1 to 2	0	$s_1$	0	0	...	0
surv. age 2 to 3	0	0	$s_2$	0	...	0
surv. age 3 to 4	0	0	0	$s_3$	...	0
...	...	...	...	...	...	...
surv. age 30 to 31	0	0	0	0	...	0

This is a modified Leslie matrix model.  $f_i$  is fecundity or average pup production by females age  $i$ .  $s_i$  is survivorship from age  $i$  to age  $i+1$ . Line 1 is  $s_i \times f_{i+1}$  so that when the matrix multiplication is done,  $N_{0,t+1} = \sum N_{i,t} \times s_i \times f_{i+1}$  which is sum of the number of age  $i$  individuals that survive to age  $i+1$  and give birth to a pup at age  $i+1$ . When the Leslie matrix is written this way,  $N_0$  is always the pup count in the same year at the non-pup count.

Supplementary Table 3. **Specific fecundity and survivorships terms used in the three life-history matrices**

<i>i</i> age	$f_i$ CP1982	$f_i$ York 1994	$f_i$ Holmes et al 2006	$s_i$ CP1982	$s_i$ York 1994	$s_i$ Holmes et al 2006
0	0	0	0 <sup>2</sup>	0.7420 <sup>3</sup>	0.7680 <sup>3</sup>	0.7845 <sup>3</sup>
1	0	0	0	0.7840 <sup>3</sup>	0.8221 <sup>3</sup>	0.8331 <sup>3</sup>
2	0	0	0	0.8260 <sup>3</sup>	0.8761 <sup>3</sup>	0.8316 <sup>3</sup>
3	0	0	0	0.8680 <sup>1</sup>	0.9302 <sup>1</sup>	0.9302 <sup>1</sup>
4	0.1008 <sup>1</sup>	0.1008 <sup>1</sup>	0.0480	0.8790	0.9092	0.9092
5	0.17955	0.17955	0.1695	0.8880	0.8951	0.8951
6	0.26145	0.26145	0.2215	0.8930	0.8839	0.8839
7	0.315	0.315	0.27950	0.8980	0.8746	0.8746
8	0.315	0.315	0.3285	0.8740	0.8665	0.8665
9	0.315	0.315	0.3285	0.8990	0.8593	0.8593
10	0.315	0.315	0.3285	0.8930	0.8527	0.8527
11	0.315	0.315	0.3885	0.8960	0.8468	0.8468
12	0.315	0.315	0.3885	0.8950	0.8412	0.8412
13	0.315	0.315	0.3885	0.8950	0.8360	0.8360
14	0.315	0.315	0.3885	0.8950	0.8312	0.8312
15	0.315	0.315	0.3885	0.8950	0.8266	0.8266
16	0.315	0.315	0.3885	0.8950	0.8223	0.8223
17	0.315	0.315	0.2570	0.8950	0.8182	0.8182
18	0.315	0.315	0.2570	0.8950	0.8142	0.8142
19	0.315	0.315	0.2570	0.8950	0.8105	0.8105
20	0.315	0.315	0.2570	0.8950	0.8069	0.8069
21	0.315	0.315	0.2570	0.8950	0.8034	0.8034
22	0.315	0.315	0	0.8950	0.8001	0.8001
23	0.315	0.315	0	0.8950	0.7968	0.7968
24	0.315	0.315	0	0.8950	0.7937	0.7937
25	0.315	0.315	0	0.8950	0.7907	0.7907
26	0.315	0.315	0	0.8950	0.7878	0.7878
27	0.315	0.315	0	0.8950	0.7850	0.7850
28	0.315	0.315	0	0.8950	0.7822	0.7822
29	0.315	0.315	0	0.8950	0.7795	0.7795
30	0.315	0.315	0	0.8950	0.7769	0.7769
31	0.315	0.315	0	0	0	0

$f_i$  is the average number of pups produced by age  $i$  females (note age  $i$  females mate and become impregnated at age  $i-1$ ).  $s_i$  is the survivorship from age  $i$  to  $i+1$ .

1. Table 1 from York (1994). Note that in Table 1 (York 1994) the age 'To' column represents the numbering for  $f_i$ , whereas the age 'From' column represents the numbering for  $s_i$ .
2. Re-estimated in this paper from the original 1970s data. See Supplementary Methods.
3.  $s_1$  and  $s_2$  increase linearly from  $s_0$  towards  $s_3$ , and  $s_0$  is set so that the matrix is stable.

Supplementary Table 4. **The 32 x 32 age-structured life-history matrix with perturbation terms added**

	age 0(pup)	age 1	age 2	age 3	...	age 30	age 31
$s_i \times f_{i+1}$	$s_0 \times p_{j,k}$ $x f_1 \times p_{f,k}$	$s_1 \times p_{j,k} \times f_2$ $x p_{f,k}$	$s_2 \times p_{j,k}$ $x f_3 \times p_{f,k}$	$s_3 \times p_{a,k}$ $x f_4 \times p_{f,k}$	...	$s_{30} \times p_{a,k}$ $x f_{31} \times p_{f,k}$	$s_{31} \times p_{a,k}$ $x f_{32} \times p_{f,k}$
surv. age 0 to 1	$s_0 \times p_{j,k}$	0	0	0	...	0	0
surv. age 1 to 2	0	$s_1 \times p_{j,k}$	0	0	...	0	0
surv. age 2 to 3	0	0	$s_2 \times p_{j,k}$	0	...	0	0
surv. age 3 to 4	0	0	0	$s_3 \times p_{a,k}$	...	0	0
...	...	...	...	...	...	...	...
surv. age 29 to 30	0	0	0	0	...	0	0
surv. age 30 to 31	0	0	0	0	...	$s_{30} \times p_{a,k}$	0

$f_i$  is the average number of pups produced by age  $i$  females (note age  $i$  females mate and become impregnated at age  $i-1$ ).  $s_i$  is the survivorship from age  $i$  to  $i+1$ .  $p_{j,k}$ ,  $p_{a,k}$ , and  $p_{f,k}$  are the scaling terms for juvenile survivorship, adult survivorship and fecundity, respectively, at time period  $k$ .

Supplementary Table 5. **Maximum likelihood estimated historical survivorship and fecundity relative to pre-decline levels**

Model	C-III	B-III	A-III	C-II	B-II	A-II	C-I	B-I	C-IV	A-I	B-IV	A-IV
Parameters	17	17	17	14	14	14	14	14	17	14	17	17
$\Delta AIC_c$	0	2.6976	4.1328	8.6927	11.3574	21.1865	22.959	33.9089	38.6061	41.1782	46.1293	50.8704
$p_{j,1}$	0.4368	0.4856	0.7054	0.329	0.3469	0.682	0.3361	0.3615	0.37	0.6862	0.4308	0.7002
$p_{j,2}$	0.7304	0.817	0.9092	0.6772	0.8663	1.0133	0.5633	0.5972	0.6658	0.8153	0.7004	0.8518
$p_{j,3}$	0.6111	0.6702	0.8212	0.952	1.1901	1.1782	0.8571	0.8871	0.5298	0.9731	0.548	0.7559
$p_{j,4}$	0.9559	1.034	1.0209	-	-	-	-	-	0.864	-	0.8806	0.9567
$p_{f,1}$	0.8689	0.8829	0.8872	0.9529	0.9496	0.993	0.9961	1.0065	1.0077	1.0639	1.0241	1.0608
$p_{f,2}$	0.7207	0.7719	0.7795	0.7578	0.725	0.7407	0.7936	0.7082	0.7972	0.7137	0.7599	0.7844
$p_{f,3}$	0.6664	0.6658	0.6782	0.6646	0.6986	0.7467	0.7357	0.6744	0.7867	0.6561	0.7012	0.7242
$p_{f,4}$	0.6132	0.5997	0.6107	-	-	-	-	-	0.7292	-	0.659	0.6588
$p_{a,1}$	0.8995	0.8941	0.8939	1.033	1.0382	1.0155	1.0164	1.0149	1.0111	0.9897	1.0032	0.9871
$p_{a,2}$	0.9389	0.9193	0.9018	0.9984	0.9358	0.8817	1.0302	1.0012	1.0104	0.9702	0.9625	0.9328
$p_{a,3}$	1.0127	0.9913	0.9789	1.0604	1.0039	0.9399	1.0753	1.0753	1.0094	1.0753	1.005	0.9946
$p_{a,4}$	1.0753	1.055	1.0409	-	-	-	-	-	1.0753	-	1.0753	1.0753

$p_{j,k}$  is the scaling factor for juvenile survivorship in time period  $k$ . Juvenile survivorship in time period  $k$  is (pre-decline juvenile survivorship)  $\times p_{j,k}$ .  $p_{a,k}$  is the scaling factor for adult survivorship in time period  $k$ .  $p_{f,k}$  is the scaling factor for fecundity in time period  $k$ . Models A-#, B-# and C-# use the Calkins and Pitcher (1982), York (1994) and Holmes et al. (2006) life-history matrices, respectively (see supplementary methods for matrices). Models  $\alpha$ -I,  $\alpha$ -II,  $\alpha$ -III,  $\alpha$ -IV use the time periods I, II, III, and IV, respectively. Time periods I are k=1:1977-1988, k=2:1989-1997, k=3:1998-2004. Time periods II are k=1:1977-1987, k=2:1988-1997, k=3:1998-2004. Time periods III are k=1:1983-1987, k=2:1988-1992, k=3:1993-1997, k=4:1998-2004. Time periods IV are k=1:1977-1988, k=2:1989-1992, k=3:1993-1997, k=4:1998-2004.