SUPPLEMENTARY INFORMATION

King Penguins in Zoos: Relating Breeding Success to Husbandry Practices

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Supplementary Table S1. Questionnaire used to gather information of participating zoos.

Questionnaire: King Penguin (*Aptenodytes patagonicus*)

Please fill out and return this questionnaire.

Name of institution: _____

General

1.) Please attach the **ARKS/ZIMS report** for your king penguins for the years **2007-2012**.

2.) **Age of population** (years since establishment of a king penguin population): _____

3.) Please provide the **total number of eggs laid** by your king penguin population during each year.

2011: _____ 2010: _____ 2009: _____ 2008: _____ 2007: _____

Enclosure

4.) **Year** king penguins moved into current enclosure: _____

5.) Please fill out the following table about the **king penguin enclosure(s)** and **indicate m, ft, ˚C, ˚F**.

	Inside	Outside
Number of pools:		
Land area (m^2, sq ft):		
Substrate type (e.g. concrete, sand):		
Water/pool area (m^2, sq ft):		
Pool depth (m, ft):		
Water type/treatment (e.g. salt, chlorine):		
Water temperature (˚C, ˚F):		
Air temperature (˚C, ˚F):		

6.) **Other species** held in the same enclosure (please include **number of individuals** of each):

Other

7.) Please **describe any "show"** for zoo visitors the king penguins are involved in (e.g. walks) and specify **how often** this takes place:

8.) Number of **months spent outside**: _____
Number of **hours per day spent outside** during those months: _____

9.) **How often** are the following used in the enclosure?
Disinfectant: _____ Fungicide: _____

10.)Do all of your king penguins **swim regularly**? ☐ yes ☐ no

11.)Do you **provide snow or ice** in your exhibit? ☐ yes ☐ no

12.)Does the enclosure have any **incoming natural light**? ☐ yes ☐ no

13.)Is the **lighting varied** between winter and summer? ☐ yes ☐ no

14.)Are **incubating** king penguins **fed by keepers**? ☐ yes ☐ no

15.)**Who incubates the egg**? ☐ parent ☐ incubator

16.)**How are chicks reared?** ☐ parent ☐ hand

Supplementary Table S2. Data of the 39 transition matrices from the Basel Zoo colony.

Year	Total	Ratio	m	f	s	c	f_{t+1}	s_{t+1}	c_{t+1}	c -> s	s -> f	P_{13}	P_{21}	P_{22}	P_{32}	P_{33}
1972	4	0.75	3	1	0	0	1	0	0	0	0	0	0	0	0	1
1973	4	0.75	3	1	0	0	1	0	0	0	0	0	0	0	0	1
1974	4	0.75	3	1	0	0	2	0	0	0	0	0	0	0	0	1
1975	7	0.71	5	2	0	0	3	0	0	0	0	0	0	0	0	1
1976	8	0.62	5	3	0	0	3	0	0	0	0	0	0	0	0	1
1977	8	0.62	5	3	0	0	3	0	0	0	0	0	0	0	0	1
1978	8	0.62	5	3	0	0	3	0	0	0	0	0	0	0	0	1
1979	8	0.62	5	3	0	0	3	0	0	0	0	0	0	0	0	1
1980	8	0.62	5	3	0	0	3	0	1	0	0	0.33	0	0	0	1
1981	9	0.62	5	3	0	1	1	1	2	1	0	0.67	1	0	0	0.33
1982	9	0.83	5	1	1	2	1	2	1	2	0	1	1	0	0	1
1983	8	0.80	4	1	2	1	1	3	1	1	0	1	1	1	0	1
1984	9	0.80	4	1	3	1	2	2	1	1	1	1	1	0.50	0.50	1
1985	10	0.71	5	2	2	1	3	2	1	1	1	0.50	1	0.50	0.50	1
1986	11	0.62	5	3	2	1	3	2	0	1	0	0	1	1	0	1
1987	11	0.67	6	3	2	0	4	1	3	0	1	1	0	0.50	0.50	1
1988	13	0.56	5	4	1	3	5	0	1	0	1	0.25	0	0	1	1
1989	10	0.44	4	5	0	1	5	1	1	1	0	0.20	1	0	0	1
1990	11	0.44	4	5	1	1	5	2	0	1	0	0	1	1	0	1
1991	11	0.44	4	5	2	0	6	1	0	0	1	0	0	0.50	0.50	1
1992	11	0.40	4	6	1	0	6	0	2	0	0	0.33	0	0	0	1
1993	13	0.46	5	6	0	2	6	1	2	1	0	0.33	0.50	0	0	1
1994	14	0.46	5	6	1	2	6	3	4	2	0	0.67	1	1	0	1
1995	17	0.40	4	6	3	4	6	5	3	4	0	0.50	1	0.50	0	1
1996	19	0.46	5	6	5	3	5	6	0	3	0	0	1	0.75	0	0.83
1997	17	0.55	6	5	6	0	5	0	3	0	0	0.60	0	0.00	0	1
1998	15	0.58	7	5	0	3	4	3	2	3	0	0.40	1	0	0	0.80
1999	16	0.64	7	4	3	2	3	5	2	2	0	0.50	1	1	0	0.75
2000	17	0.70	7	3	5	2	3	2	0	1	1	0	0.50	0.50	0.50	0.67
2001	9	0.57	4	3	2	0	4	1	0	0	1	0	0	0.50	0.50	1
2002	9	0.50	4	4	1	0	5	0	2	0	1	0.50	0	0	1	1
2003	11	0.44	4	5	0	2	5	2	1	2	0	0.20	1	0	0	1
2004	12	0.44	4	5	2	1	4	3	0	1	0	0	1	1	0	0.80
2005	11	0.50	4	4	3	0	5	1	0	0	1	0	0	0.50	0.50	1
2006	11	0.50	5	5	1	0	5	0	2	0	0	0.40	0	0	0	1
2007	13	0.55	6	5	0	2	5	0	2	0	0	0.40	0	0	0	1
2008	13	0.55	6	5	0	2	6	2	3	2	0	0.60	1	0	0	1
2009	17	0.50	6	6	2	3	6	0	2	0	0	0.33	0	0	0	1
2010	15	0.54	7	6	0	2	6	0	1	0	0	0.17	0	0	0	1

Transition matrix

0	0	P_{13}
P_{21}	P_{22}	0
0	P_{32}	P_{33}

Mean matrix

	c	s	f
c	0	0	0.30
s	0.44	0.28	0
f	0	0.14	0.95

	P_{13}	P_{21}	P_{22}	P_{32}	P_{33}
mean	**0.30**	**0.44**	**0.28**	**0.14**	**0.95**
SD	**0.33**	**0.49**	**0.38**	**0.28**	**0.13**

Lambda = 0.981

The term ‘Total’ refers to the total colony size including males (m), females (f), subadults (s), and chicks (c). ‘Ratio’ is the adult sex ratio (m/(m+f)). ‘c -> s’ refers to the number of chicks becoming subadults and ‘s -> f’ is the number of subadults becoming females that year. P_{13} is the rate at which a female will produce a chick, P_{21} the probability at which a chick becomes a subadult, and so on.

Supplementary Table S3. Results of statistical tests analysing husbandry measures in 12 zoos.

Linear regressions

Dependent variable	*Independent variable*	r^2	*Statistic*	*P*
Egg productivity	King penguin density[1]	0.40	$F_{1,9} = 6.0$	0.037
Hatching success	King penguin density[1]	0.011	$F_{1,9} = 0.10$	0.76
Chick survival	King penguin density[1]	0.17	$F_{1,9} = 1.8$	0.21
Chick productivity	King penguin density[1]	0.27	$F_{1,9} = 3.3$	0.10
Egg productivity	Total density[1]	0.34	$F_{1,9} = 4.7$	0.058
Hatching success	Total density[1]	0.0016	$F_{1,9} = 0.014$	0.91
Chick survival	Total density[1]	0.25	$F_{1,9} = 3.0$	0.12
Chick productivity	Total density[1]	0.14	$F_{1,9} = 1.4$	0.26
Egg productivity	Dev. from even sex ratio[2]	0.59	$F_{1,8} = 11$	0.0096
Hatching success	Dev. from even sex ratio[2]	0.021	$F_{1,8} = 0.17$	0.69
Chick survival	Dev. from even sex ratio[2]	0.23	$F_{1,8} = 2.5$	0.16
Chick productivity	Dev. from even sex ratio[2]	0.18	$F_{1,8} = 1.8$	0.22

[1] In density analyses, Wuppertal was excluded as its population switched enclosures in the midst of the study.

[2] Vienna and Wuppertal were excluded from sex ratio analyses, as they did not have all of the penguins sexed.

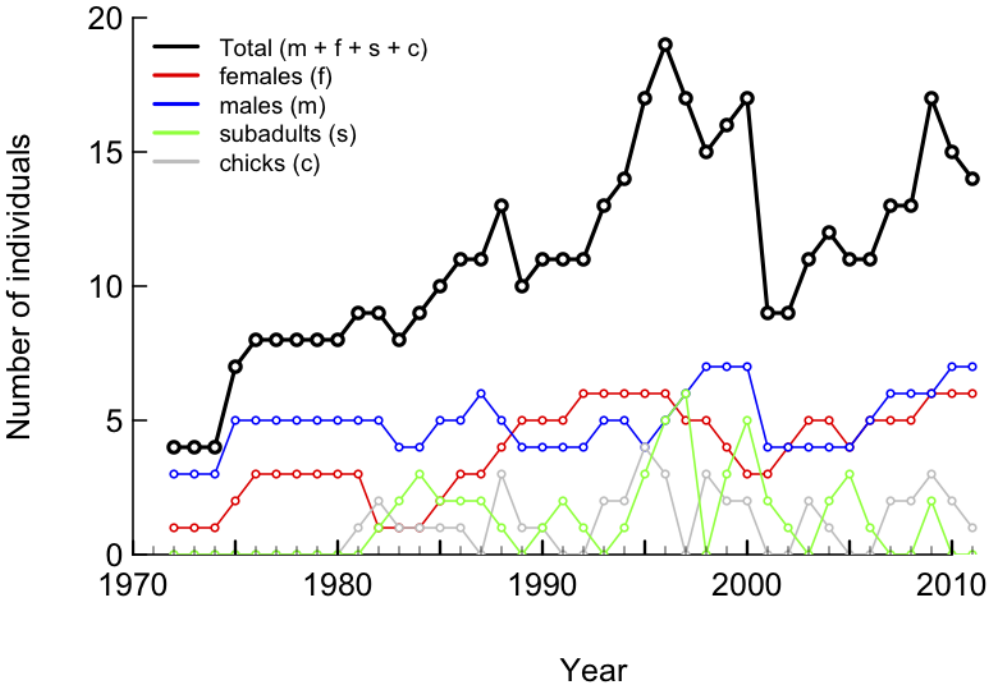
Wilcoxon rank sum tests

Dependent variable	*Comparison*	*Statistic*	*P*
Hatching success	Incubated by parent (n = 9) / incubated artificially (n = 3)	W = 14	1
Chick survival	Raised by parent(s) (n = 10) / raised by hand (n = 2)	W = 14	0.45
Egg productivity	Interactive show (n = 5) / no interactive show (n = 7)	W = 24	0.34
Hatching success	Interactive show (n = 5) / no interactive show (n = 7)	W = 26	0.19
Chick survival	Interactive show (n = 5) / no interactive show (n = 7)	W = 25.5	0.22
Chick productivity	Interactive show (n = 5) / no interactive show (n = 7)	W = 30	0.051
Egg productivity	Outside walk (n = 4) / no outside walk (n = 8)	W = 18	0.81
Hatching success	Outside walk (n = 4) / no outside walk (n = 8)	W = 29	0.028
Chick survival	Outside walk (n = 4) / no outside walk (n = 8)	W = 19	0.67
Chick productivity	Outside walk (n = 4) / no outside walk (n = 8)	W = 25	0.15
Egg productivity	Swim regularly (n = 8) / some or all never swim (n = 4)	W = 14	0.81
Hatching success	Swim regularly (n = 8) / some or all never swim (n = 4)	W = 25	0.15
Chick survival	Swim regularly (n = 8) / some or all never swim (n = 4)	W = 21	0.44
Chick productivity	Swim regularly (n = 8) / some or all never swim (n = 4)	W = 19.5	0.61
Egg productivity	Fungicide use (n = 3) / no fungicide used (n = 9)	W = 23	0.1
Hatching success	Fungicide use (n = 3) / no fungicide used (n = 9)	W = 15	0.86
Chick survival	Fungicide use (n = 3) / no fungicide used (n = 9)	W = 14	1
Chick productivity	Fungicide use (n = 3) / no fungicide used (n = 9)	W = 21	0.19
Egg productivity	Disinfectant use (n = 6) / no disinfectant used (n = 6)	W = 22	0.59
Hatching success	Disinfectant use (n = 6) / no disinfectant used (n = 6)	W = 16	0.82
Chick survival	Disinfectant use (n = 6) / no disinfectant used (n = 6)	W = 16.5	0.87
Chick productivity	Disinfectant use (n = 6) / no disinfectant used (n = 6)	W = 20	0.81
Egg productivity	Natural light (n = 7) / no natural light (n = 5)	W = 10	0.27
Hatching success	Natural light (n = 7) / no natural light (n = 5)	W = 21	0.64
Chick survival	Natural light (n = 7) / no natural light (n = 5)	W = 14	0.62
Chick productivity	Natural light (n = 7) / no natural light (n = 5)	W = 10.5	0.29
Egg productivity	Salt water (n = 7) / only freshwater (n = 5)	W = 13	0.53
Hatching success	Salt water (n = 7) / only freshwater (n = 5)	W = 9	0.20
Chick survival	Salt water (n = 7) / only freshwater (n = 5)	W = 21.5	0.57
Chick productivity	Salt water (n = 7) / only freshwater (n = 5)	W = 14.5	0.68

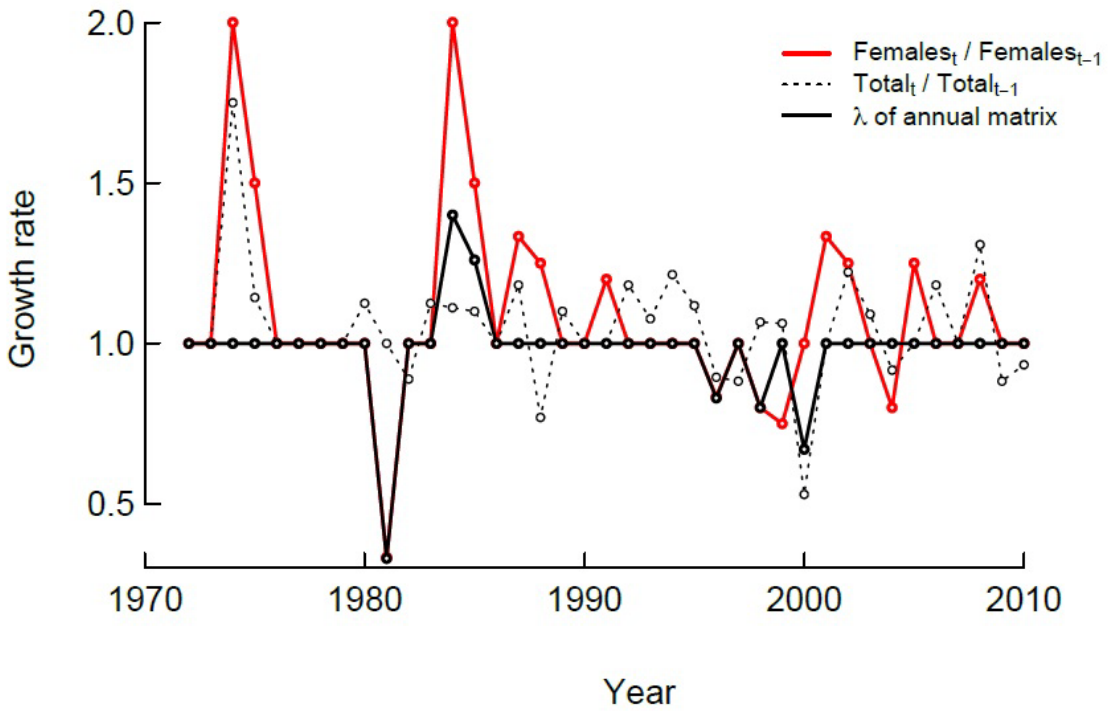
Supplementary Table S4. Growth rates of the king penguin colony at Basel Zoo for average matrix over 31 annual transitions and average matrices of years with different colony sizes and adult sex ratios (excluding first eight years with no reproduction)

	n	Deterministic λ	Stochastic approximate λ	Stochastic simulated λ	95% confidence interval
Mean matrix	31	0.999	0.986	0.977	0.970 – 0.983
Colony size > 15	6	0.913	0.910	0.905	0.900 – 0.910
Colony size 10 to 15	18	1.016	1.012	1.008	1.003 – 1.013
Colony size < 10	7	1.039	1.002	0.981	0.972 – 0.990
Equal sex ratios	4	1.000	1.000	1.000	0.996 – 1.004
Male biased	17	0.999	0.979	0.963	0.955 – 0.970
Female biased	10	0.980	0.976	0.975	0.970 – 0.979

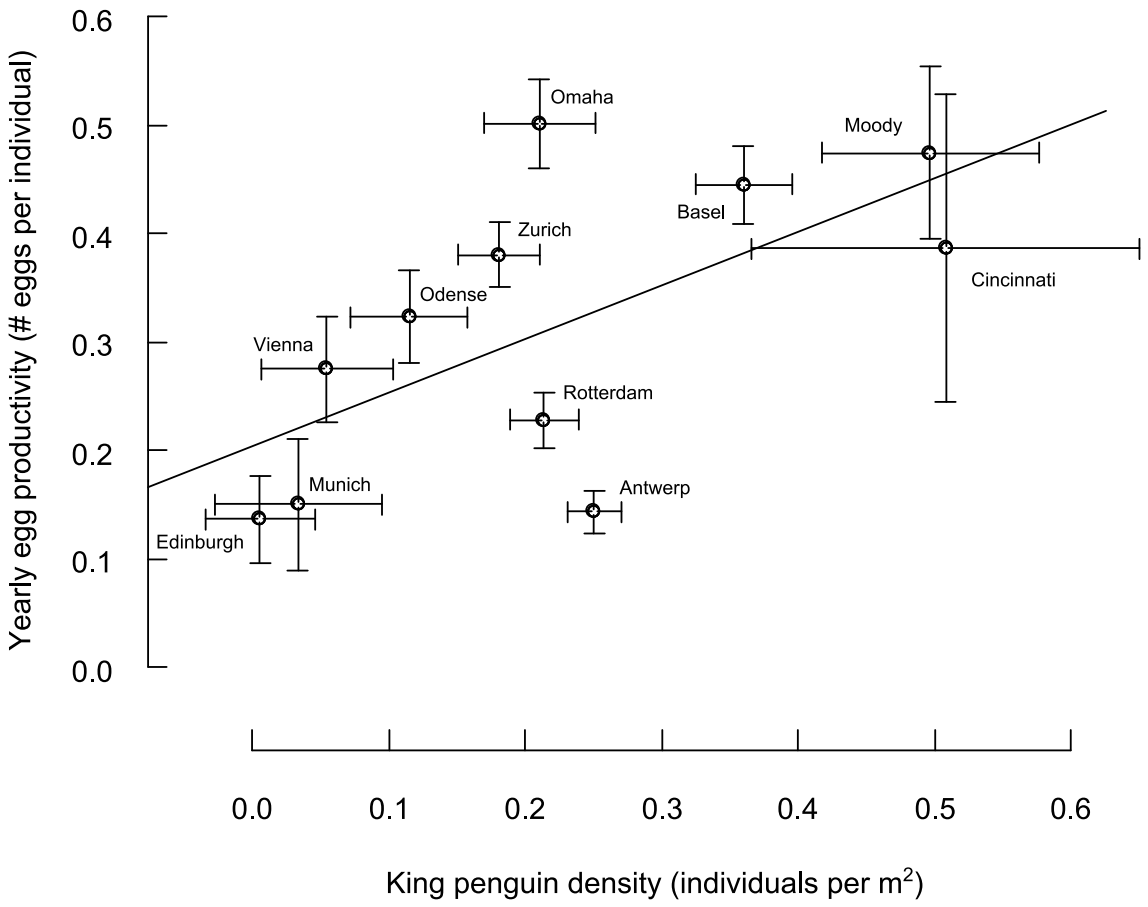
n = number of matrices, λ = growth rate, 95% confidence interval based on 10,000 simulations



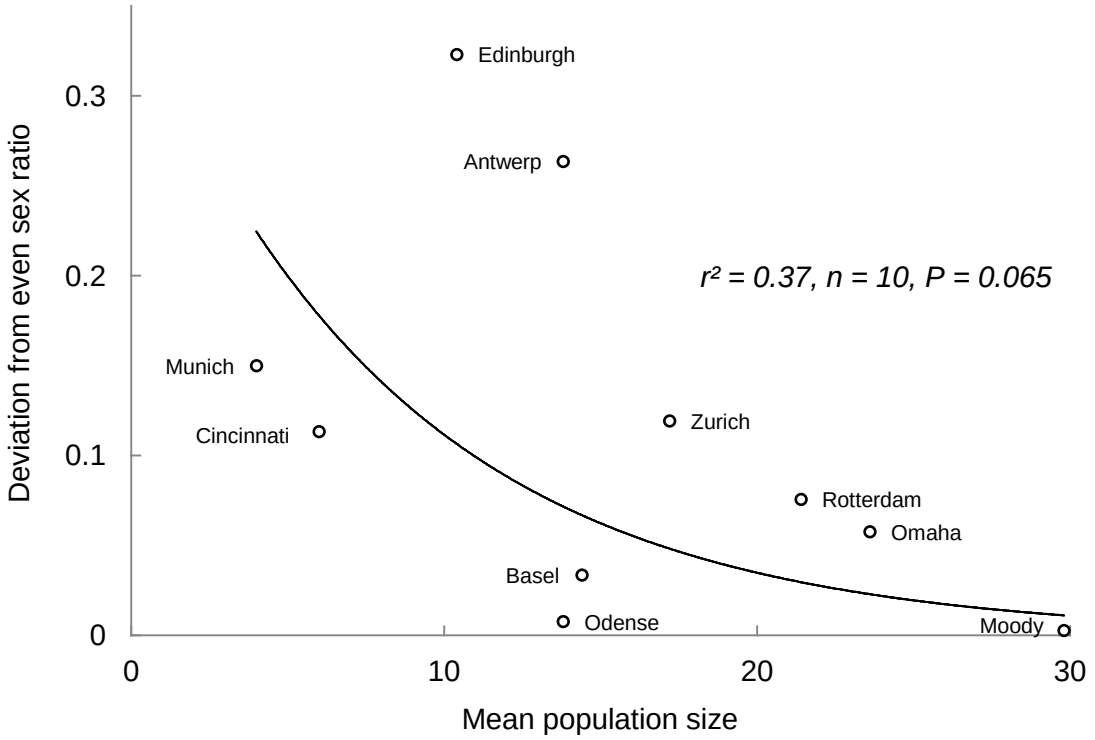
Supplementary Figure S1. Colony size development at Basel Zoo (1972–2011). The decrease in number of individuals in the year 2001 is due to an outbreak of Aspergillosis.



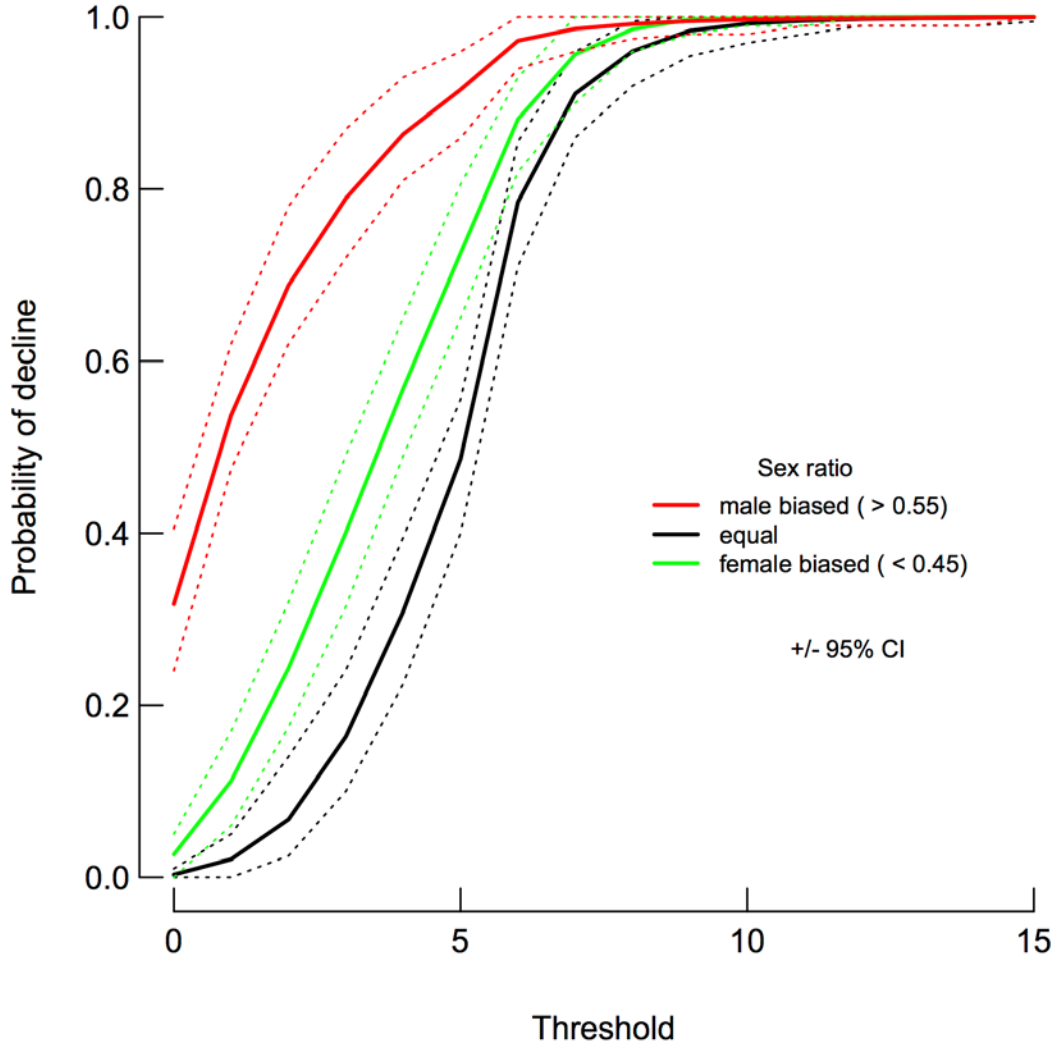
Supplementary Figure S2. Annual growth rates at Basel Zoo (1972–2011). Lambda (λ) is the growth rate at stable stage distribution while N_t / N_{t-1} is the currently observed rate of growth. The relatively large deviations in 1974 and 1984, along with most smaller ones, are due to incoming females and subadults maturing to females.



Supplementary Figure S3. Detailed relationship between mean egg productivity and king penguin density for the 11 zoos considered. The crosses show 95% confidence intervals.



Supplementary Figure S4. Relation between the deviation from an even sex ratio and mean population size over five years in king penguins at 10 zoos. The line shows a marginally significant exponential ($y = 0.358e^{-0.117\,x}$) fit.



Supplementary Figure S5. Risk of decline for populations simulated over 25 years with demographic and environmental stochasticity, based on populations with equal (black line), male-biased (red line), and female-biased (green) sex ratios. The y-axis gives the probability that the population size will fall below a certain threshold on the x-axis. Dotted lines give approximate 95% confidence intervals constructed by replicating sets of 100 stochastic simulations 100 times.