Supplementary material

Survival improvements of marine mammals in zoological institutions mirror historical advances in human longevity

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Table S1. Life expectancy and lifespan equality from one year of age for both sexes of harbour seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), polar bear (*Ursus maritimus*), and common bottlenose dolphin (*Tursiops truncatus*) for zoo-held and wild populations (Figures 2 and S5). Credible intervals could not be calculated for wild populations. The proportional relationship between the wild estimates and the mean estimates of the latest period (2005-2020) from ZIMS are depicted in the Improv. column. These are calculated as [*1+((value recent period–value oldest period)/value oldest)*] period for comparing periods, and [*1+((value zoo–value wild)/value wild)*] for comparison with the wild.

Species	Population	Sex	Period	N	Life expectancy (years)			Lifespan equality	
					Mean	95%CI	Improv.	Mean	95%CI
P. vitulina	Zoos	Female	1877-1989	438	11.52	9.97;13.41		0.169	-0.061;0.375
			1990-2004	487	18.91	16.86;21.09		0.528	0.363;0.690
			2005-2020	428	20.91	18.96;22.88	1.81	0.660	0.658;0.510
	Wild[1]		2002	1,003	7.04		2.97	0.539	
	Wild[2]		2000-2007	166	8.76		2.39	0.174	
	Zoos	Male	1877-1989	353	11.27	9.57;13.25		0.113	-0.104;0.313
			1990-2004	424	16.31	14.29;18.50		0.406	0.234;0.571
			2005-2020	386	19.02	16.93;21.15	1.69	0.574	0.398;0.748
	Wild[1]		2002	1,142	7.04		2.70	0.539	
	Wild[2]		2000-2007	181	6.11		3.11	-0.105	
Z. californianus	Zoos	Female	1875-1974	692	6.05	5.36;6.76		-0.045	-0.147;0.054
			1975-1989	737	11.39	10.41;12.46		0.272	0.161;0.371
			1990-2004	788	16.21	15.12;17.28		0.746	0.632;0.862
			2005-2020	832	18.17	17.20;19.10	3.00	0.986	0.862;1.108
	Wild[3]		1981-2006	94	11.00		1.65	0.423	
	Wild[4]		1987-2015	6,833	5.75		3.16	0.290	
	Zoos	Male	1875-1974	514	4.69	4.04;5.37		-0.140	-0.261;-0.015
			1975-1989	516	10.55	9.41;11.77		0.297	0.125;0.428
			1990-2004	606	15.37	14.15;16.57		0.751	0.617;0.890
			2005-2020	688	15.91	14.77;17.08	3.40	0.705	0.589;0.828
	Wild[3]		1981-2006	96	8.98		1.77	0.220	
	Wild[4]		1987-2015	4,465	5.75		2.77	0.290	
U. maritimus	Zoos	Female	1829-1974	569	22.68	21.00;24.40		0.947	0.735;1.144
			1975-1989	512	20.02	18.16;21.89		0.664	0.499;0.829
			1990-2004	355	21.29	19.28;23.13		0.981	0.772;1.188
			2005-2020	243	25.08	23.17;26.75	1.11	1.407	1.162;1.638
	Wild[5]		1984-2011	~1,500	8.44		2.97	0.000	
	Zoos	Male	1829-1974	467	20.23	18.55;22.03		0.843	0.647;1.053
			1975-1989	415	17.44	15.49;19.33		0.659	0.483;0.839
			1990-2004	281	19.22	17.34;21.05		0.892	0.703;1.075
			2005-2020	220	21.11	19.18;22.88	1.04	1.109	0.889;1.323
	Wild[5]		1984-2011	~1,500	7.04		3.00	0.142	
T. truncatus	Zoos	Female	1947-1989	175	9.56	5.48;13.82		-0.130	-0.592;0.348
			1990-2004	236	25.66	21.72;30.01		0.738	0.378;1.067
			2005-2020	301	30.68	26.73;35.25	3.21	0.748	0.439;1.008
	Wild[6]		1978-1997	78	8.63		3.55	0.172	
	Wild[7]		1986-2003	42	9.48		3.24	0.319	
	Zoos	Male	1947-1989	138	9.44	6.66;12.32		-0.030	-0.366;0.276
			1990-2004	205	20.88	16.84;15.68		0.428	0.026;0.711
			2005-2020	271	30.22	24.37;41.50	3.20	0.459	0.011;0.800
	Wild[6]		1978-1997	125	9.33		3.24	0.279	
	Wild[7]		1986-2003	69	9.48		3.19	0.319	

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Table S2. Proportional hazards effects of wild-born origin on survival. We provide the mean estimates, their standard errors (SE), and the lower and upper 95% credible intervals. Bayesian survival trajectory analyses were conducted on each sex and species for individuals in zoological institutions between 1990 and 2020. The potential scale reduction factor (PSRF) is an estimated factor by which the scale of the distribution for the target distribution might be reduced if the simulations were continued for an infinite number of iterations; PSRF declines to 1 as the number of iterations approaches infinity.

Species	Sex	Mean	SE	2.50%	97.50%	PSRF
Harbour seal	Female	-0.205	0.161	-0.519	0.106	1.007
Phoca vitulina	Male	0.301	0.167	-0.037	0.611	1.008
California sea lion	Female	-0.003	0.108	-0.222	0.212	1.000
Zalophus californianus	Male	0.086	0.139	-0.194	0.348	1.000
Polar bear	Female	-0.253	0.143	-0.535	0.025	1.000
Ursus maritimus	Male	-0.322	0.177	-0.666	0.018	1.000
Common bottlenose dolphin	Female	0.751	0.231	0.304	1.211	1.018
Tursiops truncatus	Male	0.838	0.208	0.433	1.240	1.001

Table S3. Calibrated Kulback-Leibler discrepancies between the posterior densities of life expectancy and lifespan equality in the last period (2005-2020) and those of the previous periods for all four species. A value of 0 implies that the two distributions are identical, and a value of 1 implies that they are entirely different (complete information loss if we use the posterior density from the previous periods to predict that of the last period). As a reference, values below 0.25 are highlighted in boldface. Survival analyses were carried out from birth (Fig. S3), from age one (Fig. S4), and from age at sexual maturity (Fig. S5).

Analysis from	Variable	Sex	Species	< 1975	< 1990 or 1975-1989	1990-2004
birth	Life exp.	Female	*Phoca vitulina*	-	1	0.96
			Zalophus californianus	1	1	1
			Ursus maritimus	1	1	1
			Tursiops truncatus	-	1	0.99
		Male	*Phoca vitulina*	-	1	1
			Zalophus californianus	1	1	0.98
			Ursus maritimus	1	1	0.98
			Tursiops truncatus	-	1	1
	Lifesp. eq.	Female	*Phoca vitulina*	-	1	0.83
			Zalophus californianus	1	1	1
			Ursus maritimus	1	1	1
			Tursiops truncatus	-	1	0.76
		Male	*Phoca vitulina*	-	1	1
			Zalophus californianus	1	1	0.86
			Ursus maritimus	1	1	0.97
			Tursiops truncatus	-	0.89	0.64
age one	Life exp.	Female	*Phoca vitulina*	-	1	0.87
			Zalophus californianus	1	1	1
			Ursus maritimus	0.97	1	1
			Tursiops truncatus	-	1	0.91
		Male	*Phoca vitulina*	-	1	0.96
			Zalophus californianus	1	1	0.35
			Ursus maritimus	0.35	1	0.86
			Tursiops truncatus	-	1	0.93
	Lifesp. eq.	Female	*Phoca vitulina*	-	1	0.77
			Zalophus californianus	1	1	1
			Ursus maritimus	1	1	1
			Tursiops truncatus	-	1	**0.03**
		Male	*Phoca vitulina*	-	1	0.83
			Zalophus californianus	1	1	0.26
			Ursus maritimus	0.94	1	0.86
			Tursiops truncatus	-	0.91	**0.10**
age at sexual maturity	Life exp.	Female	*Phoca vitulina*	-	1	0.95
			Zalophus californianus	1	1	1
			Ursus maritimus	0.72	1	1
			Tursiops truncatus	-	1	0.87
		Male	*Phoca vitulina*	-	1	0.97
			Zalophus californianus	1	1	0.39
			Ursus maritimus	**0.11**	1	0.90
			Tursiops truncatus	-	1	0.90
	Lifesp. eq.	Female	*Phoca vitulina*	-	1	0.77
			Zalophus californianus	1	1	1
			Ursus maritimus	1	1	0.99
			Tursiops truncatus	-	0.66	**0.01**
		Male	*Phoca vitulina*	-	1	0.96
			Zalophus californianus	1	1	0.51
			Ursus maritimus	0.99	1	0.94
			Tursiops truncatus	-	0.57	**0.10**

Table S4. Calibrated Kullback-Leibler discrepancies (K-L) between the life expectancy and lifespan equality posterior densities of females and that of males from age one (see Figure S8). The K-L values measure the loss of information if we were to predict the female posterior density from the male's. These K-L values are standardised such that a value of 0 implies that both posterior densities are equal, and 1.00 that they are entirely different. As a reference, values below 0.25 are highlighted in boldface.

Species	Variable	< 1975	< 1990 or 1975-1989	1990-2004	2005-2020
Phoca vitulina	Life expectancy	-	**0.04**	0.94	0.83
	Lifespan equality	-	**0.11**	0.65	0.46
Zalophus californianus	Life expectancy	1.00	0.72	0.69	1.00
	Lifespan equality	0.83	**0.22**	**0.03**	1.00
Ursus maritimus	Life expectancy	0.98	0.97	0.90	1.00
	Lifespan equality	0.39	**0.01**	0.30	0.95
Tursiops truncatus	Life expectancy	-	**0.13**	0.91	0.49
	Lifespan equality	-	**0.19**	0.79	0.88

Table S5. Quantile of the wild value on the posterior densities of life expectancy (Life expect.) and lifespan equality (Lifesp. eq.) for all periods for the analyses from age one and from age at sexual maturity. In bold, we highlighted values outside the 95% credible intervals. We italicised values below the lower 95% credible interval, indicating that the value obtained for the wild population falls on the lower end of the posterior distribution, and can therefore be assumed to be considerably lower than the posterior density average from the ZIMS population for the given period.

Analysis from	Species	Sex	Variable	Study	< 1975	< 1990 or 1975-1989	1990-2004	2005-2020
Age one	*P. vitulina*	Female	Life exp.	Harkonen (2007)	-	***< 0.001***	***< 0.001***	***< 0.001***
				Hasting (2012)	-	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Harkonen (2007)	-	**0.999**	0.555	0.060
				Hasting (2012)	-	0.517	***< 0.001***	***< 0.001***
		Male	Life exp.	Harkonen (2007)	-	***< 0.001***	***< 0.001***	***< 0.001***
				Hasting (2012)	-	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Harkonen (2007)	-	**1.000**	**0.936**	0.345
				Hasting (2012)	-	***0.022***	***< 0.001***	***< 0.001***
	Z. californianus	Female	Life exp.	Hernandez (2008)	1	0.229	***< 0.001***	***< 0.001***
				Delong (2017)	0.205	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Hernandez (2008)	1	**0.997**	***< 0.001***	***< 0.001***
				Delong (2017)	1	0.631	***< 0.001***	***< 0.001***
		Male	Life exp.	Hernandez (2008)	1	***0.005***	***< 0.001***	***< 0.001***
				Delong (2017)	0.999	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Hernandez (2008)	1	0.156	***< 0.001***	***< 0.001***
				Delong (2017)	1	0.461	***< 0.001***	***< 0.001***
	U. maritimus	Female	Life exp.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
		Male	Life exp.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
	T. truncatus	Female	Life exp.	StolenBarlow (2003)	-	0.336	***< 0.001***	***< 0.001***
				Mattson (2006)	-	0.487	***< 0.001***	***< 0.001***
			Lifesp. eq.	StolenBarlow (2003)	-	0.889	***< 0.001***	***< 0.001***
				Mattson (2006)	-	**0.965**	***0.009***	***0.002***
		Male	Life exp.	StolenBarlow (2003)	-	0.469	***< 0.001***	***< 0.001***
				Mattson (2006)	-	0.512	***< 0.001***	***< 0.001***
			Lifesp. eq.	StolenBarlow (2003)	-	**0.971**	0.174	0.205
				Mattson (2006)	-	**0.984**	0.245	0.260
age at sexual maturity	*P. vitulina*	Female	Life exp.	Harkonen (2007)	-	***< 0.001***	***< 0.001***	***< 0.001***
				Hasting (2012)	-	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Harkonen (2007)	-	**0.970**	0.139	***0.002***
				Hasting (2012)	-	0.469	***< 0.001***	***< 0.001***
		Male	Life exp.	Harkonen (2007)	-	***< 0.001***	***< 0.001***	***< 0.001***
				Hasting (2012)	-	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Harkonen (2007)	-	**0.974**	0.510	***0.006***
				Hasting (2012)	-	0.455	***0.003***	***< 0.001***
	Z. californianus	Female	Life exp.	Hernandez (2008)	1	**0.968**	***< 0.001***	***< 0.001***
				Delong (2017)	0.002	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Hernandez (2008)	1	**1.000**	***0.022***	***< 0.001***
				Delong (2017)	1	**1.000**	***0.037***	***< 0.001***
		Male	Life exp.	Hernandez (2008)	1	***0.044***	***< 0.001***	***< 0.001***
				Delong (2017)	0.433	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Hernandez (2008)	1	0.474	***< 0.001***	***< 0.001***
				Delong (2017)	1	**1.000**	0.172	0.475
	U. maritimus	Female	Life exp.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
		Male	Life exp.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
			Lifesp. eq.	Lunn (2016)	< 0.001	***< 0.001***	***< 0.001***	***< 0.001***
	T. truncatus	Female	Life exp.	StolenBarlow (2003)	-	***0.003***	***< 0.001***	***< 0.001***

		Mattson (2006)	-	***< 0.001***	***< 0.001***	***< 0.001***
	Lifesp. eq.	StolenBarlow (2003)	-	0.594	0.145	0.107
		Mattson (2006)	-	0.122	***0.011***	***0.006***
Male	Life exp.	StolenBarlow (2003)	-	***0.039***	***< 0.001***	***< 0.001***
		Mattson (2006)	-	***0.010***	***< 0.001***	***< 0.001***
	Lifesp. eq.	StolenBarlow (2003)	-	**0.950**	0.394	0.471
		Mattson (2006)	-	0.747	0.106	0.223

Table S6. Summary of changes in zoological institutions management practices for the harbour seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), polar bear (*Ursus maritimus*), and common bottlenose dolphin (*Tursiops truncatus*), documented from the literature and workshop sessions gathering experts of the four studied species (on 2nd, 7th and 14th of December 2021).

Description of management change	Year	Species
Legislation and zoo & aquarium associations		
Creation of the Association of Zoos & Aquariums (AZA)	1924	All
Creation of the World Association of Zoos & Aquariums (WAZA)	1935	All
Creation of the Japanese Association of Zoos & Aquariums (JAZA)	1939	All
Passing of the Animal Welfare Act (USA)	1966	All
Creation of the British and Irish Association of Zoos and Aquariums (BIAZA)	1966	All
Passing of the Marine Mammal Protection Act (USA)	1972	All
Establishment of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)	1975	Polar bear, Appendix II (1996) Common bottlenose dolphin, Appendix II (2003)
Creation of the Southeast Asian Zoo Association (SEAZA)	1990	All
Creation of the Zoos & Aquariums Association (ZAA)	1990	All
Creation of the European Association of Zoos & Aquaria (EAZA)	1992	All
Passing of the Polar Bear Protection Act (Canada)	2002	Polar bear
Import ban for cetaceans (Switzerland)	2012	Common bottlenose dolphin
Ban on captive cetaceans (Canada)	2019	Common bottlenose dolphin
Ban on show cetaceans (France)	2021	Common bottlenose dolphin
Guidelines		
AZA accreditation starts	1974	All
AZA develop SSP	1983	All
Creation of the 19 first EEPs (Europe)	1985	All
	1994	Common bottlenose dolphin
	2006	Polar bear
EAZA first guidelines	1992	California sealion
	1994	Common bottlenose dolphin
	2006	Polar bear
Creation of the Alliance of Marine Mammal Parks & Aquariums (AMMPA)	1998	All
AMMPA accreditation starts	2000	All
AZA enrichment is mandatory	2000	All
Studbook	2006	Polar bear
EAZA Best Practices Guidelines 1st Edition	2018	
Veterinary medicine		
Creation of the International Association for Aquatic Animal Medicine (IAAAM)	1969	
Creation of the International Marine Animal Trainers' Association (IMATA)	1972	
Gradual improvements in marine mammal veterinary medicine[1,2]	1970s onwards	All
Improvement of anaesthetic protocols[1,3]	1970s onwards	Harbour seal California sealion Common bottlenose dolphin
Voluntary participation of animals in routine examinations	1990s onwards	All
First voluntary polar bear blood sample	2002	
Installation of lifting pool floors to restrain and treat bottlenose dolphins (especially in medical and nursery pools)	Mid-1990s	Common bottlenose dolphin
China increases the number of vets in zoos	2000s onwards	All
Nutrition		
Diets improved by accounting for the nutritional requirements for different species, sexes, and life stages[14,15,41]	1990s onwards	All

Improved defrosting protocols, food preparation methods, sourcing of human-grade food products, vitamin supplementation, and delivery of food through training and enrichment	1990s onwards	All
Habitat		
High point of view in the enclosure[4]	2010s	Polar bear
Not only concrete but also soil[4]	2010s	Polar bear
Colour of the pool, salinity, shield from sun[5]	2010s	Pinnipeds

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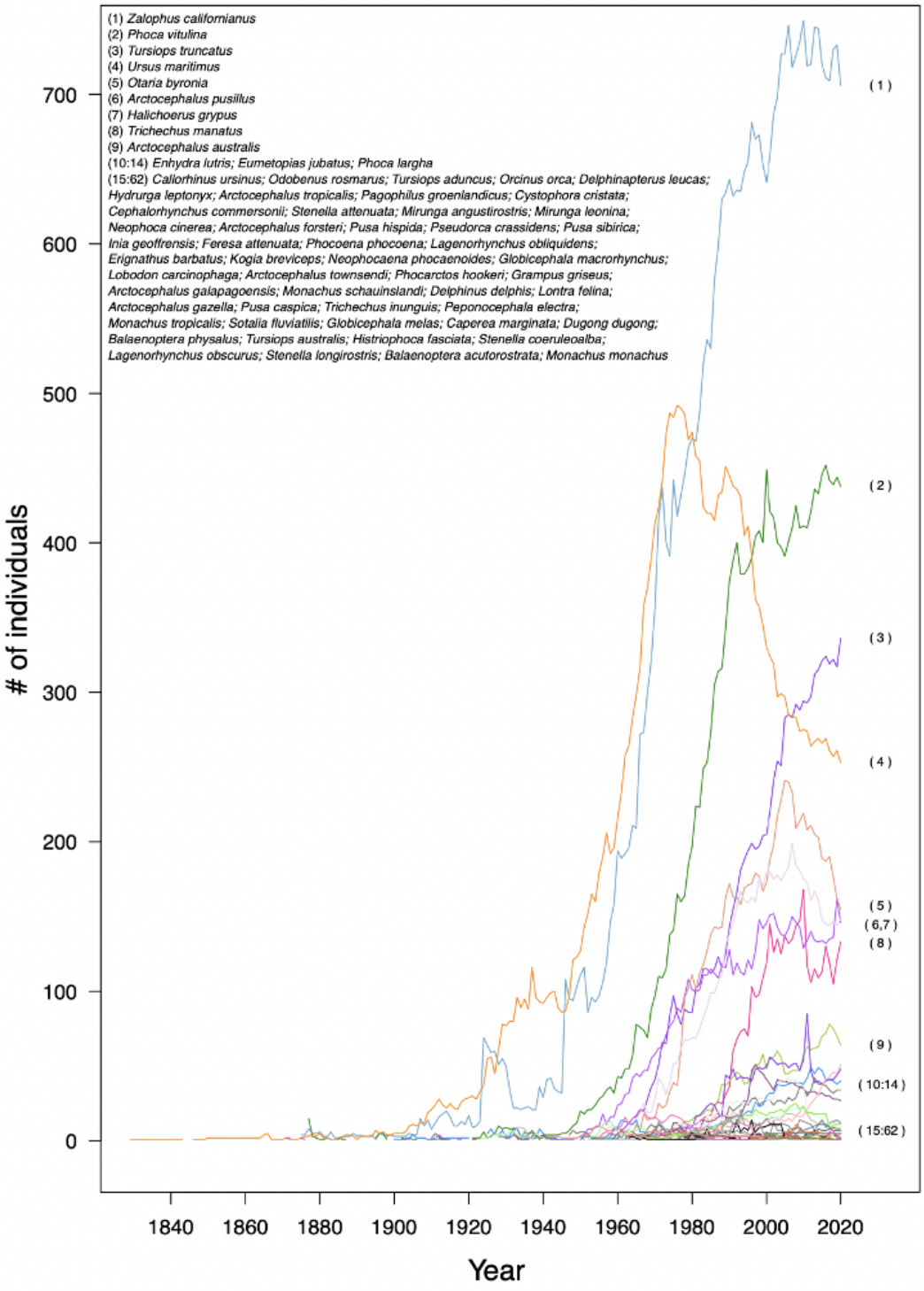

Figure S1. Records of the number of individuals for each marine mammal species present in the Species360 Zoological Information Management System. The California sea lion (*Zalophus californianus*, **1.00**), harbour seal (*Phoca vitulina*, **2**), common bottlenose dolphin (*Tursiops truncatus*, **3**), and polar bear (*Ursus maritimus*¸**4**) collectively represent 63.4% of all marine mammals recorded since the early 1800s.

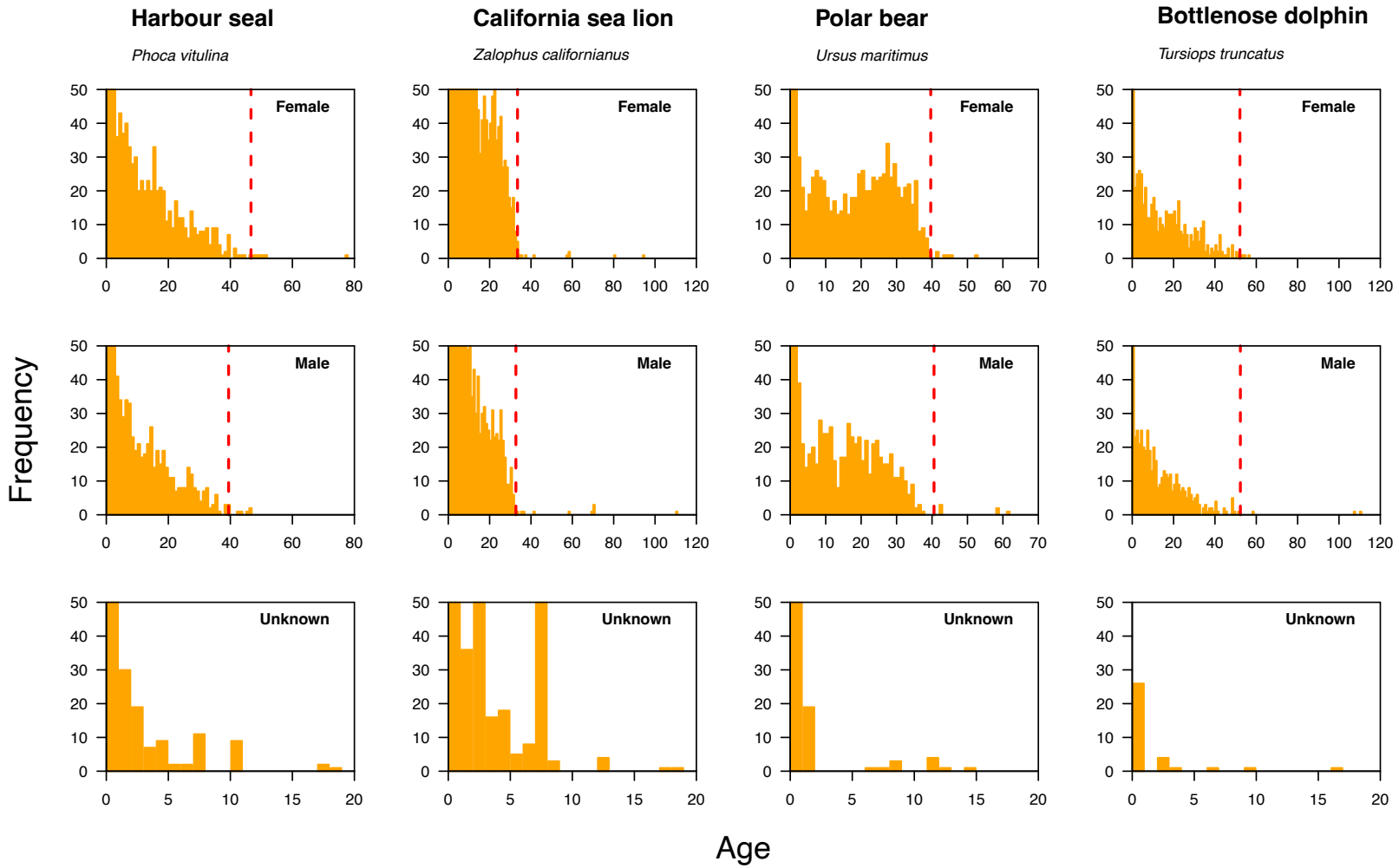

Figure S2. Distribution of the age at last observation (i.e., death or last detection) per species and sex, including unknown sexed individuals, for individuals recorded in the ZIMS database. The vertical red dashed line indicates the upper 99% cut-off, after which records were not included in the survival analyses. For display purposes, we limited the age range for the unknown sex individuals to 20 years since most records occurred within this window, while the y-axis in all plots was truncated at 50.

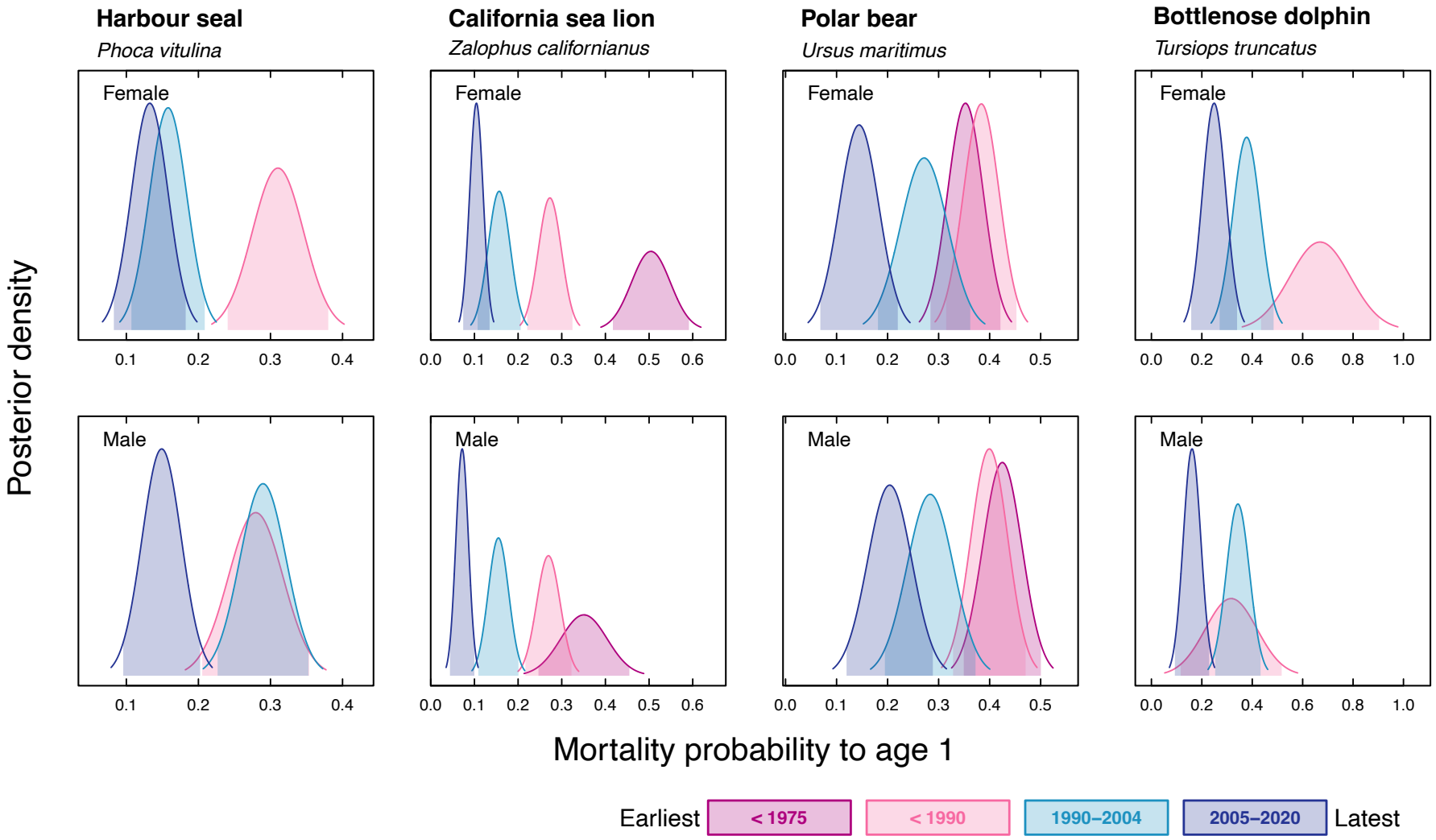

Figure S3. Posterior distribution of the mortality probability between birth and age one across time in zoological institutions for females and males of the four marine mammal species included in the study. The shaded polygons indicate the 95% credible intervals.

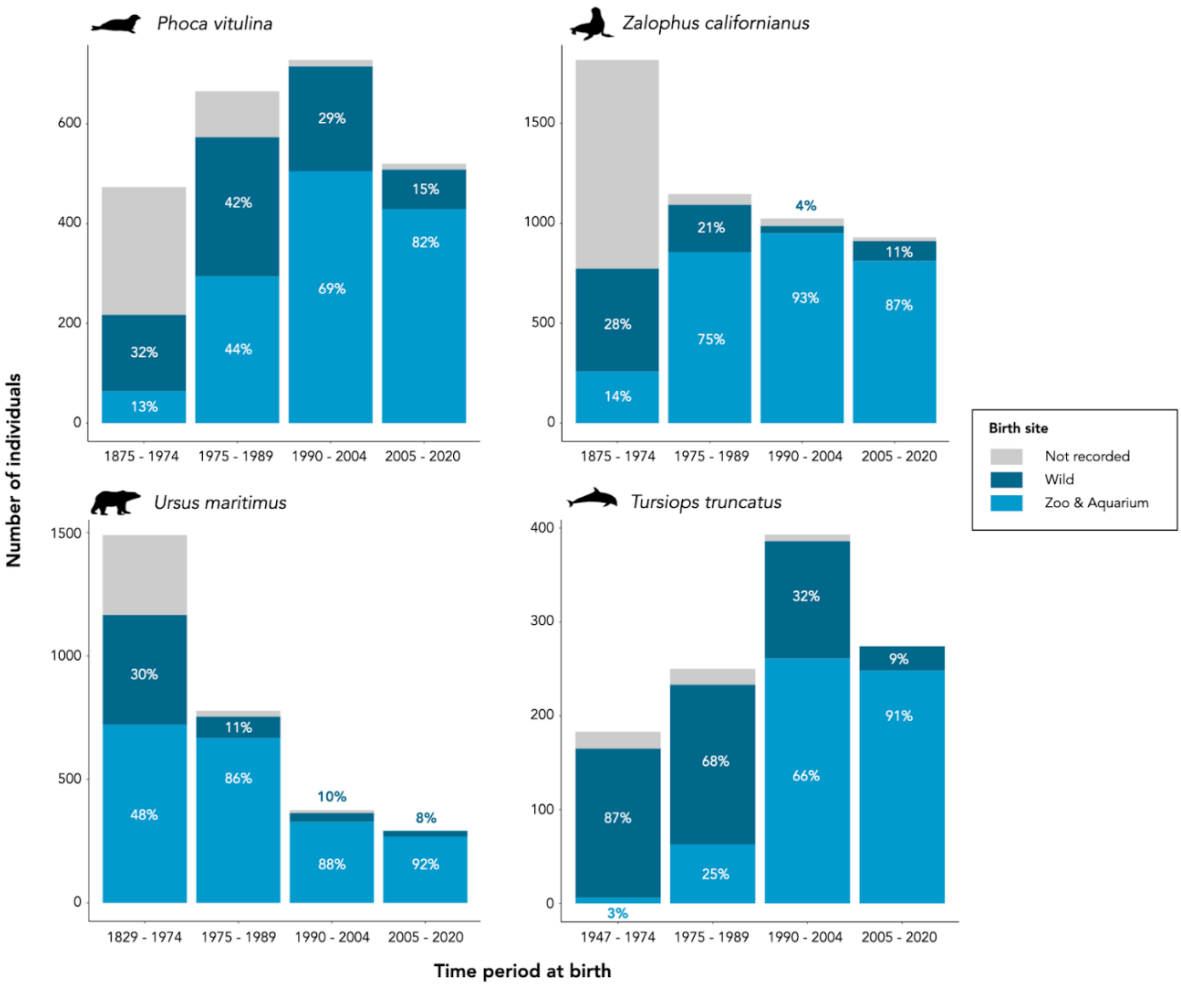

Figure S4. Number and percentage of individuals living in zoological institutions born in the wild (dark blue), in zoos (light blue), or with birth sites not recorded (light grey) per species and period.

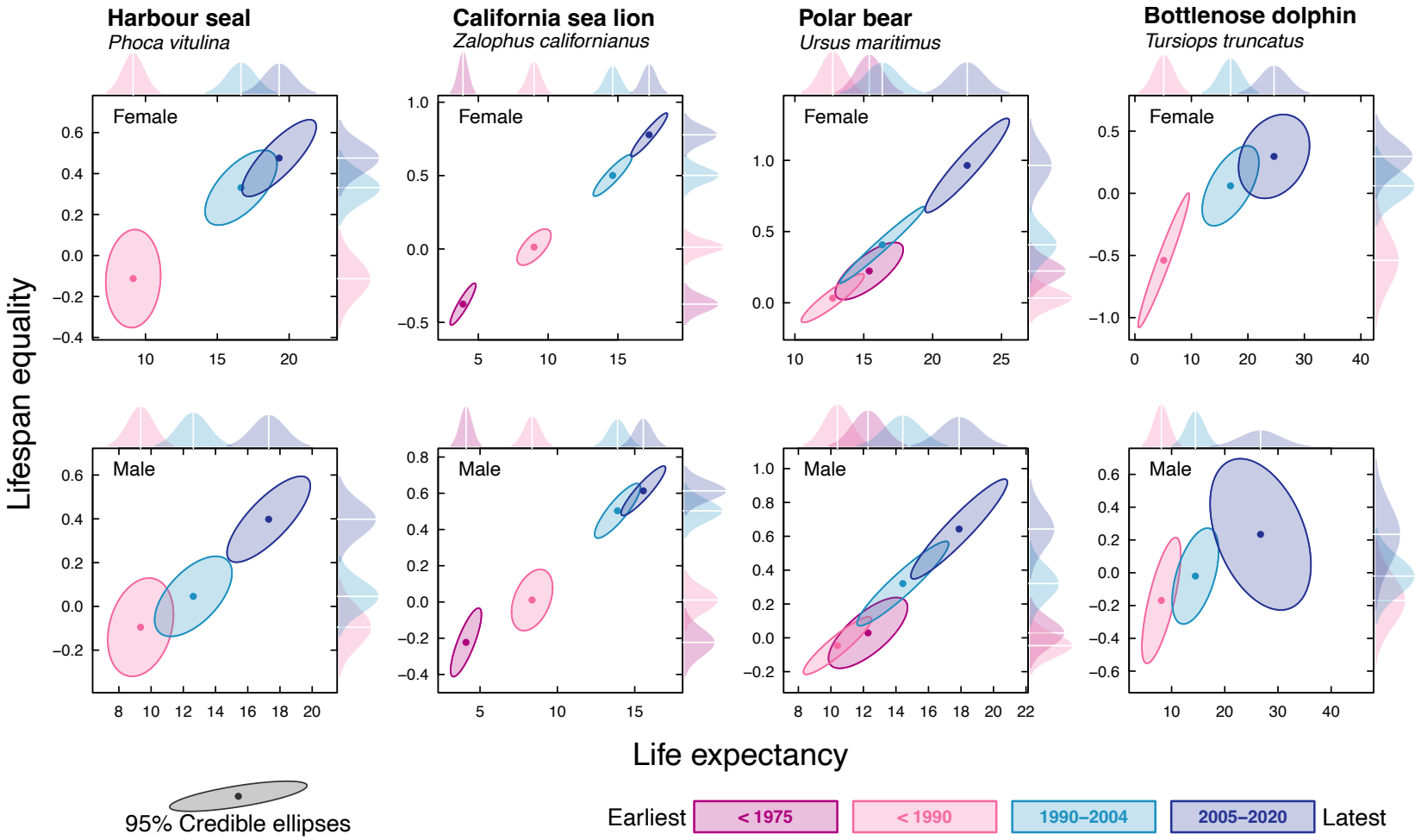

Figure S5. Life expectancy and lifespan equality from birth across time for both sexes of zoo-held populations of the four marine mammal species included in the study. The dots represent the mean values, while the size and shape of the ellipses represent the 95% confidence interval. Distributions on the top and left sides indicate the univariate posterior distributions of life expectancy and lifespan equality, respectively. Sample sizes are shown in Table S1. Kulback-Leibler values between periods using the recent period as a reference for each sex and species are shown in Table S3.

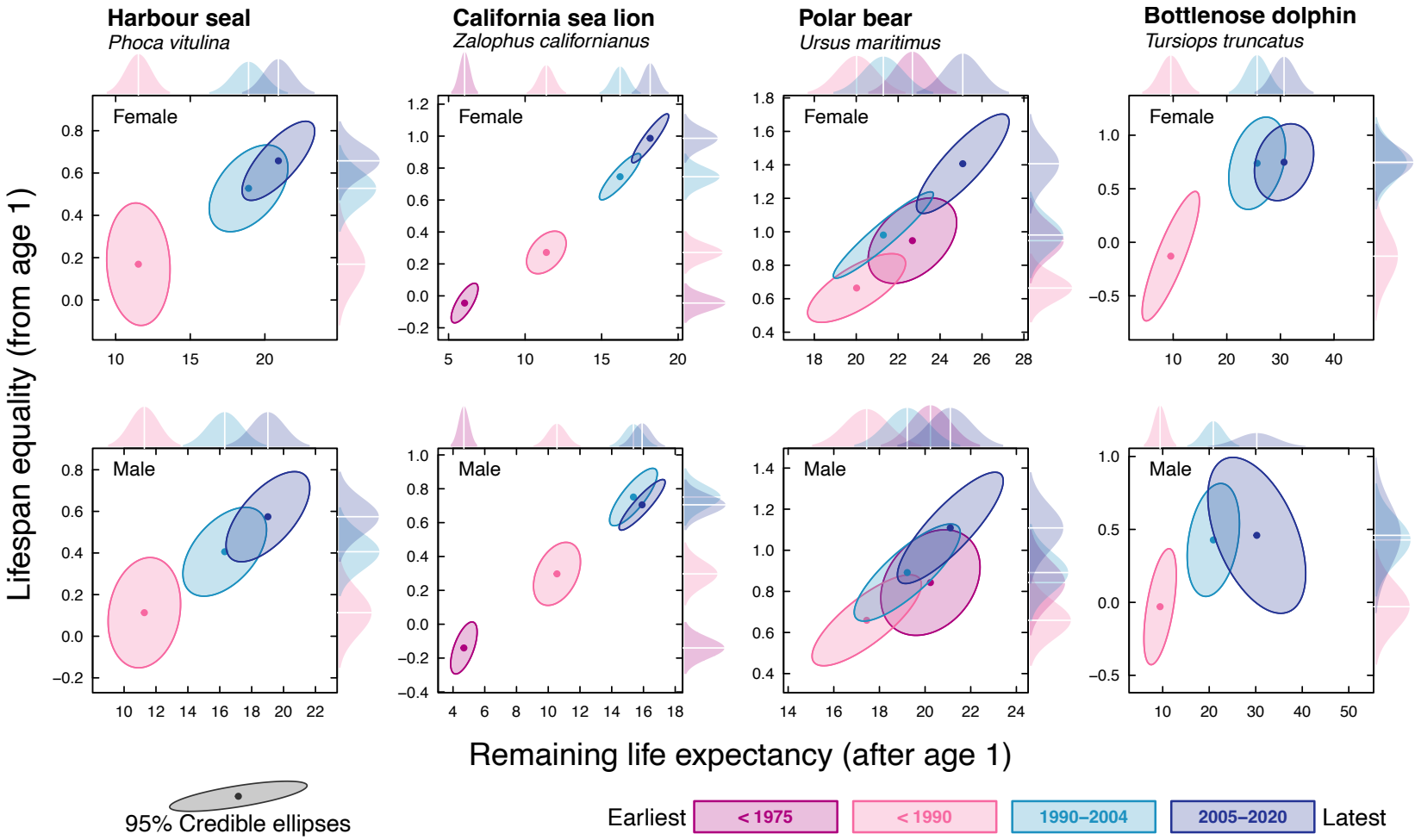

Figure S6. Life expectancy and lifespan equality from age one across time for both sexes of zoo-held populations of the four marine mammal species included in the study. The dots represent the mean values, while the size and shape of the ellipses represent the 95% confidence interval. Distributions on the top and left sides indicate the univariate posterior distributions of life expectancy and lifespan equality, respectively. Sample sizes are shown in Table S1. Kulback-Leibler values between periods using the recent period as a reference for each sex and species are shown in Table S3.

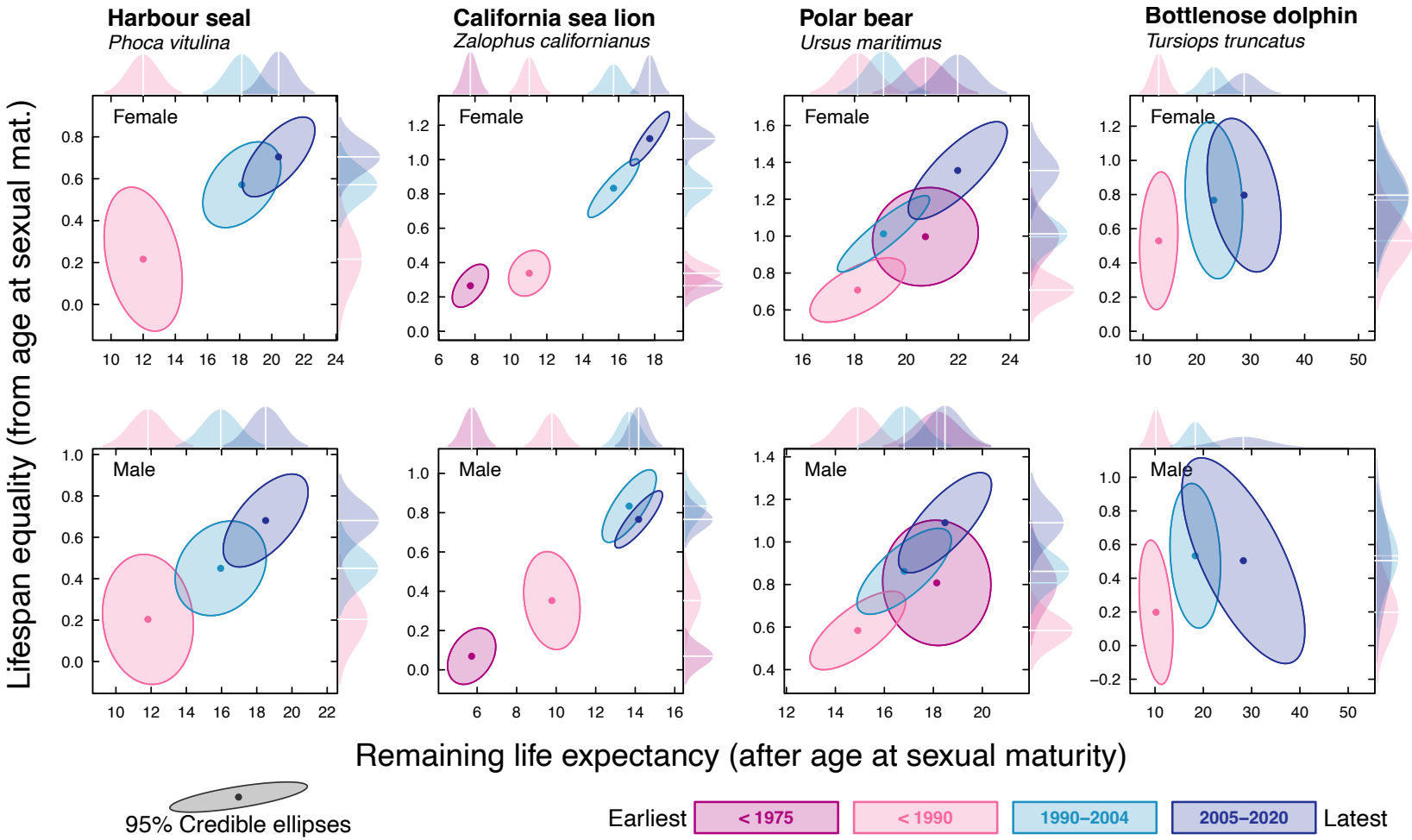

Figure S7. Remaining life expectancy and lifespan equality from age at sexual maturity across time for both sexes of zoo-held populations of the four marine mammal species included in the study. The dots represent the mean values, while the size and shape of the ellipses represent the 95% confidence interval. Distributions on the top and left sides indicate the univariate posterior distributions of life expectancy and lifespan equality, respectively. Sample sizes are shown in Table S1. Kulback-Leibler values between periods using the recent period as a reference for each sex and species are shown in Table S3.

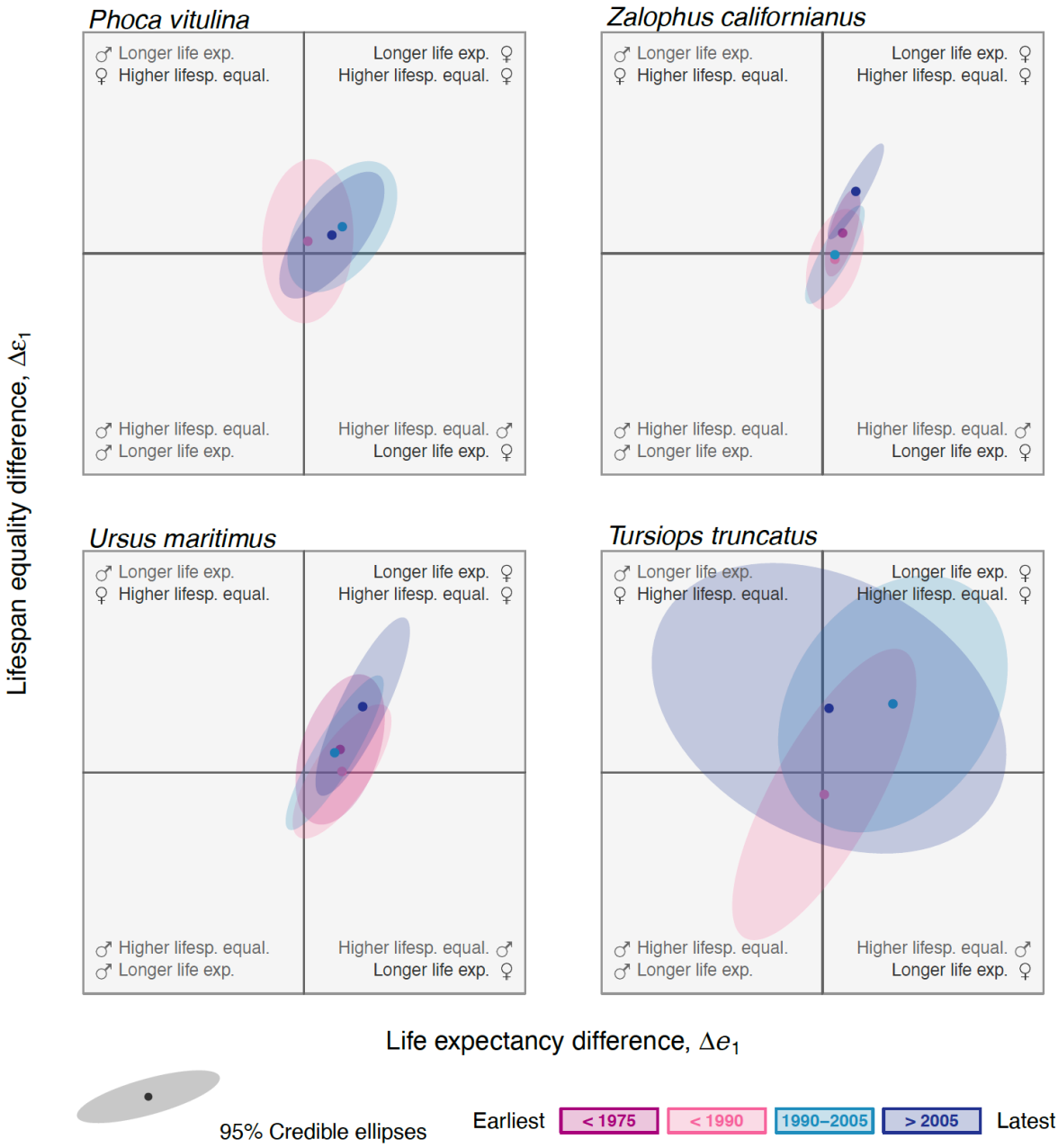

Figure S8. Changes in sex differences in remaining life expectancy and lifespan equality from one year of age across time for both sexes of zoo-held harbour seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), polar bear (*Ursus maritimus*), and common bottlenose dolphin (*Tursiops truncatus*). Sample sizes are shown in Table S1. Kulback-Leibler values between sexes for each period and species are shown in Table S4.