Proceedings of the Royal Society B. DOI: 10.1098/rspb.2018.1479

SUPPLEMENTARY INFORMATION

Maternal reproductive senescence shapes the fitness consequences of the parental age difference in ruffed lemurs

Morgane Tidière[1,*], Xavier Thevenot[1], Adamantia Deligiannopoulou[1], Guillaume Douay[2], Mylisa Whipple[3], Aurélie Siberchicot[1], Jean-Michel Gaillard[1] and Jean-François Lemaître[1]

[1] Université de Lyon, F-69000, Lyon; Université Lyon 1; CNRS, UMR5558, Laboratoire de Biométrie et Biologie Evolutive, F-69622, Villeurbanne, France

[2] Wildlife Reserve Singapore, 80 Mandai Lake Road, Singapore 729826, Singapore

[3] Saint Louis Zoo, MO-63110, St. Louis, Missouri, USA

[*] corresponding author, mtidiere@gmail.com

Table S1. Set of models fitted to assess the relationship between measures of litter size and offspring survival and the difference of age between parents (PAD) for captive ruffed lemurs. 'PADbt' and 'PADat' in a threshold model designate the slope before and after the threshold, respectively. Model selection was based on AIC (see methods section). k is the number of parameters, ΔAIC is the difference of AIC between the candidate model and the model having the lowest AIC, Dev. is the deviance and AICw is the AIC weight of each model. The final model retained (according to parsimony rules) occurs in bold, and the model with the lowest AIC occurs in italics. Analyses have been replicated with the location of the zoo of birth fitted as random effect but results were qualitatively unchanged.

	k	AIC	ΔAIC	Dev.	AICw	AIC	ΔAIC	Dev.	AICw
LITTER SIZE (N = 2279 litters)		**Random effects: mother and father identity number**				**Random effects: zoo at birth, mother and father identity number**			
Species + PADbt	**4**	***6774.20***	***0.00***	***-3382.10***	***0.31***	***6771.14***	***0.00***	***-3379.57***	***0.30***
Species + PADbt + Species : PADbt	5	6775.63	1.43	-3381.82	0.15	6772.70	1.56	-3379.35	0.14
Species + PADbt + PADat	5	6775.70	1.50	-3381.85	0.14	6772.66	1.52	-3379.33	0.14
Species + PADbt + PADat + Species : PADat	6	6777.10	2.89	-3381.55	0.07	6774.02	2.88	-3379.01	0.07
Species + PADbt + PADat + Species : PADbt	6	6777.12	2.92	-3381.56	0.07	6774.22	3.08	-3379.11	0.06
PADbt	3	6778.08	3.88	-3385.04	0.04	6773.19	2.05	-3381.59	0.11
Species	3	6778.36	4.15	-3385.18	0.04	6775.04	3.90	-3382.52	0.04
Species + PADbt + PADat + Species : PADbt + Species : PADat	7	6778.39	4.19	-3381.20	0.04	6775.47	4.33	-3378.73	0.03
Species + PAD + PAD^2	5	6779.17	4.97	-3383.59	0.03	6779.17	8.04	-3383.59	0.01
Species + PAD	4	6779.56	5.36	-3384.78	0.02	6779.56	8.42	-3384.78	0.00
PADbt + PADat	4	6779.62	5.41	-3384.81	0.02	6774.73	3.60	-3381.37	0.05
Species + PADat	4	6780.15	5.95	-3385.08	0.02	6776.83	5.69	-3382.41	0.02
Species + PAD + PAD^2 + Species : PAD^2	6	6780.31	6.11	-3383.15	0.01	6780.31	9.17	-3383.15	0.00
Species + PAD + PAD^2 + Species : PAD	6	6781.15	6.95	-3383.57	0.01	6781.15	10.01	-3383.57	0.00
Species + PAD + Species : PAD	5	6781.50	7.30	-3384.75	0.01	6781.50	10.36	-3384.75	0.00
Species + PADat + Species : PADat	5	6781.55	7.35	-3384.78	0.01	6778.18	7.04	-3382.09	0.01
Species + PAD + PAD^2 + Species : PAD + Species : PAD^2	7	6782.30	8.10	-3383.15	0.01	6782.30	11.16	-3383.15	0.00
PAD + PAD^2	4	6783.03	8.82	-3386.51	0.00	6783.03	11.89	-3386.51	0.00
PAD	3	6783.61	9.41	-3387.81	0.00	6783.61	12.47	-3387.81	0.00
PADat	3	6784.35	10.15	-3388.17	0.00	6779.14	8.01	-3384.57	0.01
OFFSPRING SURVIVAL (N = 4686 juveniles)		**Random effects: litter, mother and father identity number**				**Random effects: zoo at birth, litter, mother and father identity number**			
Litter size + PADbt + Species + Sex	*6*	*4847.90*	*0.00*	*-2417.95*	*0.09*	*4848.08*	*0.00*	*-2418.04*	*0.08*
Litter size + PADbt + PADat + Sex + Species + PADbt : Sex + PADat : Sex	9	4848.52	0.62	-2415.26	0.06	4848.90	0.82	-2415.45	0.05
Litter size + PADbt + Species + Sex + PADbt : Sex	7	4848.83	0.94	-2417.42	0.05	4849.13	1.04	-2417.56	0.04

Litter size + PADbt + Species	**5**	**4848.90**	**1.00**	**-2419.45**	**0.05**	**4848.59**	**0.50**	**-2419.29**	**0.06**
Litter size + PADbt + Species + Sex + PADbt : Species	7	4848.93	1.03	-2417.47	0.05	4849.20	1.12	-2417.60	0.04
Litter size + PAD + Species + Sex	5	4849.63	1.73	-2419.81	0.04	4849.30	1.22	-2419.65	0.04
Litter size + PADbt + PADat + Species + PADat : Species	7	4849.66	1.76	-2417.83	0.04	4849.64	1.55	-2417.82	0.03
Litter size + PADbt + PADat + Sex + Species	7	4849.73	1.83	-2417.86	0.03	4849.63	1.54	-2417.81	0.03
Litter size + PADbt + Species + Sex + PADbt : Species + PADbt : Sex	8	4849.84	1.94	-2416.92	0.03	4851.19	3.10	-2417.59	0.02
Litter size + PADbt + Species + PADbt : Species	6	4849.99	2.09	-2419.00	0.03	4849.76	1.68	-2418.88	0.03
Litter size + PAD + Species + PAD : Species	5	4850.36	2.46	-2420.18	0.03	4850.32	2.24	-2420.16	0.02
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADat : Species	9	4850.54	2.65	-2416.27	0.02	4850.88	2.79	-2416.44	0.02
Litter size + PAD + Species + Sex + PAD : Species + PAD : Sex	7	4850.59	2.70	-2418.30	0.02	4850.98	2.89	-2418.49	0.02
Litter size + PAD + Species	4	4850.61	2.71	-2421.30	0.02	4850.10	2.01	-2421.05	0.03
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species	7	4850.70	2.81	-2418.35	0.02	4850.68	2.59	-2418.34	0.02
Litter size + PADbt + PADat + Sex + Species + PADbt : Sex	8	4850.72	2.82	-2417.36	0.02	4851.72	3.64	-2417.86	0.01
Litter size + PADbt + PADat + Species	6	4850.81	2.91	-2419.40	0.02	4850.79	2.71	-2419.40	0.02
Litter size + PAD + Species + Sex + PAD : Species	6	4850.81	2.91	-2419.41	0.02	4849.22	1.14	-2418.61	0.04
Litter size + PADbt + PADat + Sex + Species + PADat : Species	8	4850.81	2.91	-2417.41	0.02	4850.86	2.78	-2417.43	0.02
Litter size + PAD + Species + Sex + PAD : Sex	6	4850.99	3.09	-2419.50	0.02	4850.59	2.51	-2419.30	0.02
Litter size + PADat + Species + Sex + PADat : Species	7	4851.05	3.15	-2418.52	0.02	4850.55	2.46	-2418.27	0.02
Litter size + PAD + PAD^2 + Sex + Species	6	4851.16	3.26	-2419.58	0.02	4851.08	2.99	-2419.54	0.02
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADat : Species	9	4851.20	3.30	-2416.60	0.02	4851.00	2.92	-2416.50	0.02
Litter size + Species	3	4851.32	3.42	-2422.66	0.02	4850.44	2.35	-2422.22	0.02
Litter size + PADbt + PADat + Species + PADbt : Species + PADat : Species	8	4851.57	3.67	-2417.78	0.01	4852.26	4.18	-2418.13	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADat : Species + PADbt : Sex	10	4851.60	3.70	-2415.80	0.01	4851.59	3.51	-2415.80	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADbt : Sex	9	4851.70	3.80	-2416.85	0.01	4851.95	3.86	-2416.97	0.01
Litter size + PAD + PAD^2 + Species + PAD : Species	6	4851.82	3.92	-2419.91	0.01	4851.65	3.56	-2419.82	0.01
Litter size + PADbt + PADat + Species + PADbt : Species	7	4851.94	4.04	-2418.97	0.01	4851.61	3.53	-2418.81	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Sex + PADat : Species	9	4851.97	4.07	-2416.99	0.01	4850.01	1.93	-2416.01	0.03
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD : Sex	8	4852.01	4.11	-2418.01	0.01	4852.03	3.95	-2418.02	0.01
Litter size + PADat + Species + PADat : Species	6	4852.03	4.13	-2420.01	0.01	4851.54	3.45	-2419.77	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Sex + PADat : Sex + PADat : Species	10	4852.11	4.21	-2416.05	0.01	4851.97	3.88	-2415.98	0.01
Litter size + PADat + Species + Sex	6	4852.17	4.27	-2420.08	0.01	4851.52	3.43	-2419.76	0.01
Litter size + PAD + PAD^2 + Species	5	4852.20	4.30	-2421.10	0.01	4851.85	3.77	-2420.93	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADat : Species + PADat : Sex	10	4852.64	4.74	-2416.32	0.01	4854.72	6.64	-2417.36	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Sex	7	4852.72	4.82	-2419.36	0.01	4852.31	4.23	-2419.15	0.01
Litter size + PADbt + PADat + Sex + Species + PADat : Sex	8	4852.96	5.06	-2418.48	0.01	4851.79	3.70	-2417.89	0.01
Litter size + PADat + Species + Sex + PADat : Species + PADat : Sex	8	4853.00	5.10	-2418.50	0.01	4852.50	4.41	-2418.25	0.01
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD^2 : Species	8	4853.00	5.10	-2418.50	0.01	4852.60	4.51	-2418.30	0.01
Litter size + PADat + Species	5	4853.11	5.21	-2421.56	0.01	4852.34	4.25	-2421.17	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADat : Sex	9	4853.15	5.25	-2417.58	0.01	4855.27	7.19	-2418.64	0.00
Litter size + PADbt + PADat + Sex + Species + PADbt : Species	8	4853.16	5.26	-2418.58	0.01	4852.94	4.85	-2418.47	0.01
Litter size + PAD + PAD^2 + Sex + Species + PAD^2 : Species	7	4853.16	5.26	-2419.58	0.01	4852.99	4.91	-2419.50	0.01

Litter size + PAD + PAD^2 + Sex + Species + PAD^2 : Sex	7	4853.17	5.27	-2419.59	0.01	4852.95	4.86	-2419.47	0.01
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD^2 : Sex	8	4853.19	5.29	-2418.59	0.01	4852.60	4.52	-2418.30	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Species + PADat : Species + PADbt : Sex + PADat : Sex	11	4853.44	5.54	-2415.72	0.01	4853.65	5.56	-2415.82	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD : Sex + PAD^2 : Species	9	4853.78	5.88	-2417.89	0.00	4854.54	6.45	-2418.27	0.00
Litter size + PADat + Species + Sex + PADat : Sex	7	4854.02	6.12	-2420.01	0.00	4853.44	5.35	-2419.72	0.01
Litter size + PADbt + PADat + Sex + Species + PADbt : Sex + PADbt : Species + PADat : Sex	10	4854.26	6.36	-2417.13	0.00	4854.50	6.42	-2417.25	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD : Sex + PAD^2 : Sex	9	4854.42	6.52	-2418.21	0.00	4853.98	5.90	-2417.99	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Sex + PAD^2 : Species	8	4854.49	6.59	-2419.25	0.00	4854.69	6.61	-2419.35	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD^2 : Species + PAD^2 : Sex	9	4854.54	6.64	-2418.27	0.00	4854.69	6.61	-2418.35	0.00
Litter size + PAD + PAD^2 + Species + PAD^2 : Species	6	4854.56	6.66	-2421.28	0.00	4853.98	5.90	-2420.99	0.00
Litter size + PAD + PAD^2 + Species + PAD : Species + PAD^2 : Species	7	4854.65	6.75	-2420.32	0.00	4853.58	5.50	-2419.79	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Sex + PAD^2 : Sex	8	4855.15	7.25	-2419.57	0.00	4854.29	6.20	-2419.14	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD^2 : Sex + PAD^2 : Species	8	4855.40	7.51	-2419.70	0.00	4854.82	6.74	-2419.41	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Sex + PAD^2 : Species + PAD^2 : Sex	9	4856.56	8.66	-2419.28	0.00	4856.41	8.33	-2419.21	0.00
Litter size + PAD + PAD^2 + Sex + Species + PAD : Species + PAD : Sex + PAD^2 : Species + PAD^2 : Sex	10	4856.63	8.73	-2418.32	0.00	4855.90	7.82	-2417.95	0.00

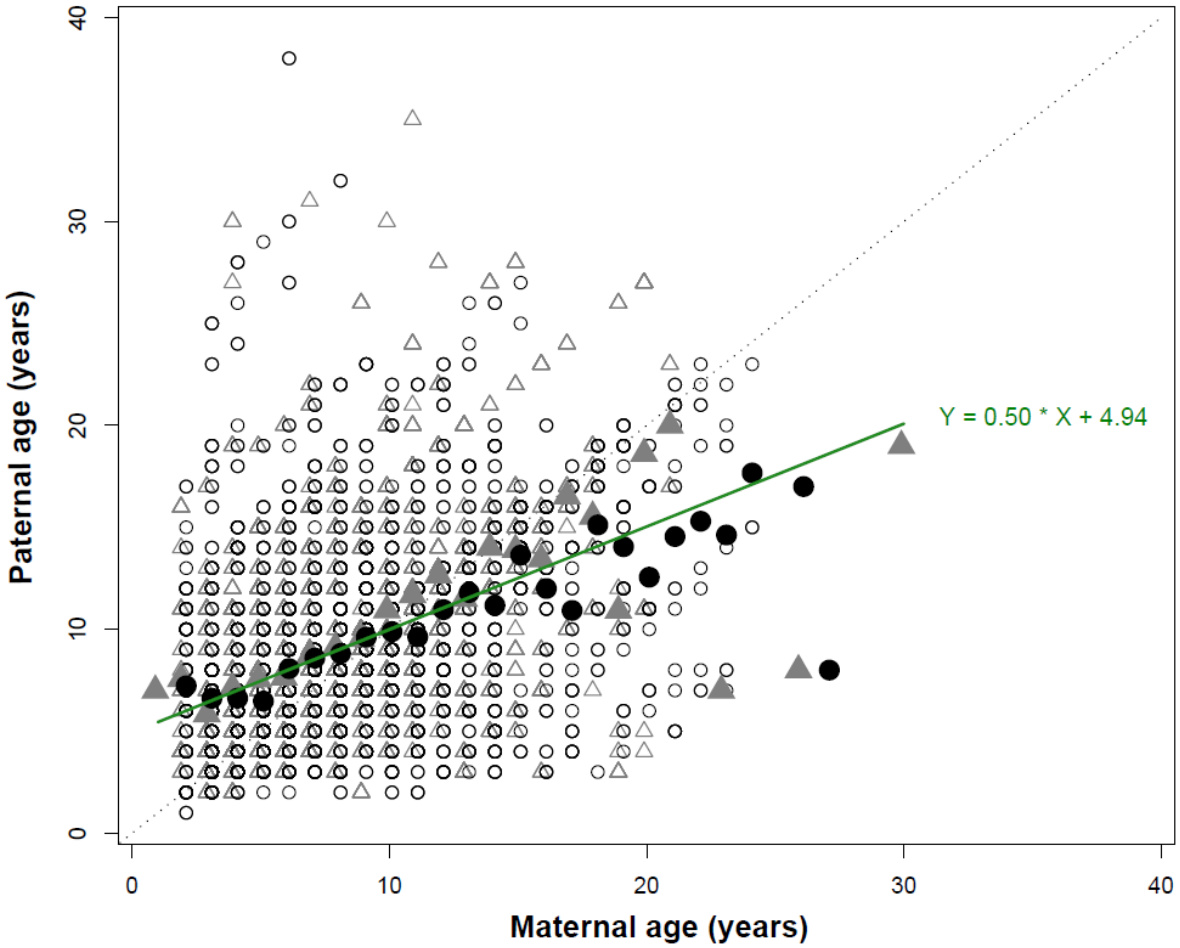
Table S2. Set of models fitted to assess the effect of parental age with or without the difference of age between parents (PAD) on litter size and offspring survival for captive ruffed lemurs. 'PADbt' in a threshold model designates the slope before the threshold. Model selection was based on AIC (see methods section). k is the number of parameters, ΔAIC is the difference of AIC between the candidate model and the model having the lowest AIC, Dev. is the deviance and AICw is the AIC weight of each model. The final model retained (according to parsimony rules) occurs in bold.

	k	AIC	ΔAIC	Dev.	AICw
LITTER SIZE (N = 2279 litters)		Random effects: mother and father identity number			
Species + Mother age (spline)	**5**	**6755.69**	**0.00**	**-3373.14**	**0.43**
Species + PADbt + Mother age (spline)	7	6757.25	1.56	-3371.63	0.19
Species + Mother age (spline) + Father age (spline)	6	6757.45	1.76	-3372.60	0.18
Species + Mother age + Mother age^2	4	6758.67	2.98	-3375.34	0.10
Species + PADbt + Mother age + Mother age^2	6	6760.39	4.70	-3374.19	0.04
Species + Mother age + Mother age^2 + Father age	5	6760.61	4.92	-3375.30	0.04
Species + Mother age + Mother age^2 + Father age + Father age^2	6	6761.01	5.32	-3374.50	0.03
Species + PADbt + Father age (spline)	5	6771.93	16.24	-3380.96	0.00
Species + PADbt	4	6774.20	18.51	-3383.10	0.00
Species + PADbt + Father age	5	6775.93	20.24	-3382.96	0.00
Species + PADbt + Mother age	5	6776.20	20.51	-3383.10	0.00
Species + Father age (spline)	3	6776.34	20.65	-3385.17	0.00
Species + PADbt + Father age + Father age^2	6	6777.54	21.85	-3382.77	0.00
Species + Mother age	4	6779.09	23.40	-3385.55	0.00
Species + Father age	4	6780.34	24.65	-3386.17	0.00
Species + Mother age + Father age	5	6780.94	25.25	-3385.47	0.00
Species + Father age + Father age^2	5	6782.14	26.45	-3386.07	0.00
Species + Father age + Father age^2 + Mother age	6	6782.86	27.17	-3385.43	0.00
Species + Mother age (categorical)	29	6790.06	34.38	-3366.03	0.00
Species + PADbt + Mother age (categorical)	31	6791.72	36.03	-3364.86	0.00
Species + PADbt + Father age (categorical)	37	6824.91	69.22	-3375.45	0.00
Species + Father age (categorical)	35	6829.51	73.82	-3379.75	0.00
OFFSPRING SURVIVAL (N = 4686 offspring)		Random effects: litter, mother and father identity number			
Litter size + Species + PADbt + Mother age + Mother age^2	7	4815.30	0.00	-2400.65	0.51
Litter size + Species + Mother age + Mother age^2	**5**	**4816.54**	**1.23**	**-2403.27**	**0.28**
Litter size + Species + Mother age + Mother age^2 + Father age	6	4817.69	2.39	-2402.85	0.16
Litter size + Species + Father age + Father age^2 + Mother age + Mother age^2	7	4819.82	4.52	-2402.91	0.05
Litter size + Species + PADbt + Mother age (categorical)	34	4830.60	15.30	-2381.30	0.00
Litter size + Species + Mother age (categorical)	32	4830.95	15.65	-2383.48	0.00
Litter size + Species + PADbt	5	4848.90	33.59	-2419.45	0.00
Litter size + Species + PADbt + Father age + Father age^2	7	4849.33	34.03	-2417.67	0.00
Litter size + Species + Mother age	4	4849.42	34.12	-2420.71	0.00
Litter size + Species + PADbt + Mother age	6	4849.91	34.61	-2418.95	0.00
Litter size + Species + PADbt + Father age	6	4849.92	34.62	-2418.96	0.00
Litter size + Species + Father age + Mother age	5	4850.71	35.41	-2420.35	0.00
Litter size + Species + Father age + Father age^2 + Mother age	6	4851.67	36.37	-2419.83	0.00
Litter size + Species + Father age	4	4853.26	37.96	-2422.63	0.00
Litter size + Species + Father age + Father age^2	5	4853.35	38.05	-2421.67	0.00
Litter size + Species + PADbt + Father age (categorical)	41	4866.59	51.29	-2392.30	0.00
Litter size + Species + Father age (categorical)	39	4872.50	57.20	-2397.25	0.00
Litter size + Species + PADbt + Mother age (spline)	11	5547.03	731.73	-2762.52	0.00
Litter size + Species + Mother age (spline)	9	5550.14	734.84	-2766.42	0.00
Litter size + Species + Mother age (spline) + Father age (spline)	10	5551.92	736.62	-2766.30	0.00
Litter size + Species + PADbt + Father age (spline)	12	5593.29	777.99	-2784.65	0.00
Litter size + Species + Father age (spline)	10	5607.97	792.67	-2794.20	0.00

Table S3. Parameter estimates from model selected to assess variation in offspring survival in relation to the mother and father age for ruffed lemur species in captivity. Parental age difference (PAD) in a threshold model corresponds to the slope before the threshold. For random effects, the variance (Var.) and standard deviation (s.d.) are given.

	Variables	**β**	**95%CI**	**z value**		**N**	**Var.**	**s.d.**
	Fixed effects				*Random effects*			
OFFSPRING	Intercept	1.367	0.588;2.147	3.44	Litter identity	2256	4.68	2.16
SURVIVAL	Litter size	-0.413	-0.577;0.248	-4.92	Mother identity	633	1.11	1.05
(N=4686 offspring)	Species (*V. variegata)*	-0.328	-0.784;0.128	-1.41	Father identity	552	1.54	1.24
	Mother age	0.409	0.276;0.542	6.03				
	Mother age^2	-0.018	-0.024;-0.012	-5.76				

Figure S1. Age-assortative mating for *V. rubra* (triangles) and *V. variegata* (circles) showing that females were paired preferentially with younger males (full line). Open triangles and circles indicated raw data while full triangles and circles indicated the mean paternal age for each maternal age. Black dotted line represents the regression line where paternal age is equal to maternal age.



Appendix S1. Detailed material and methods.

Data were obtained from the published International Studbook for ruffed lemurs [1,2], that compiled data for the majority of *V. rubra* and *V. variegata* living in captivity in the world (e.g. zoological gardens, primate centres) from 1959 to 31st December 2015. For each individual, the sex (male, female or unknown), date and location at birth, date and location of each transfer, and date and location at death if the individual died before 1st January 2016 were recorded. A total of 1,954 individuals of *V. rubra* and 4,169 individuals of *V. variegata* are registered in the studbook. We removed from this initial dataset all individuals for which the sex and/or the date of birth were unknown. We then obtained a final dataset of 1,721 (756 females and 965 males) and 3,637 (1,589 females and 2,048 males) individuals from *V. rubra* and *V. variegata*, respectively, representing 322 different zoos as location at birth (139 for *V. rubra* and 265 for *V. variegata*).

We only considered litters for which the identity and the age of both parents were known as well as their entire life history recorded. Indeed, some individuals have been given to institution and we have no information about them after the date of translocation. The dataset included then 2,279 litters (731 and 1,548 for *V. rubra* and *V. variegata* respectively) from 600 females and 525 males.

We estimated offspring survival as the probability to reach the weaning age (i.e. 146 days for the two ruffed lemur species [1,2]) to cover the period during which offspring mortality is mostly dependent of parents. When the identity of at least one of the two parents was unknown, we removed individuals from the analyses. However, individuals lost to follow up during their life were kept in analyses because this did not influence offspring survival. We finally obtained a dataset including 4,686 offspring (3122 and 1564 for *V. variegata* and *V. rubra* respectively) from 633 females and 552 males.

The number of males reproducing was lower than the number of females. Indeed, in our dataset, males had an average of 4.12 litters during their life (ranging from 1 to 24) while females had an average of 3.58 litters (ranging from 1 to 19). This difference is simply due to the fact that a male mated with different females more frequently than the other way around.

References for appendix S1

1. Whipple M. 2014 *International Studbook for Ruffed Lemurs*. Saint Louis, Missouri: Saint Louis Zoo.
2. Whipple M. 2016 *International and North American Regional Studbooks for Ruffed Lemurs*. Saint Louis, Missouri: Saint Louis Zoo.