

Supporting Information

Demographic consequences of changing environmental periodicity, *Ecology*

Eva Conquet, Arpat Ozgul, Daniel T. Blumstein, Kenneth B. Armitage, Madan K. Oli, Julien G. A. Martin, Tim H. Clutton-Brock, Maria Paniw

Appendix S3 - Vital-rate model selection results and coefficients estimates for all three species.

Best models for the population vital rates of all three study species

Tables S1–S4 summarize the best models for each vital rate, for all three study species. We first selected the best random effect structure by comparing the amount of variance explained by each random effect. For the marmots (Table S1) and the meerkats (Table S2), we compared a random effect of the year on the average vital rate and on both the average and the slope between seasons. For the vital rates occurring in a single season for the marmots and the vital rates of the stochastic post-fire state for the dewy pines (Table S4), we checked whether a random effect of the year on the average vital rate did explain part of the variance of the model. For all models, we selected the best fixed effect using the AICc.

For the dewy pines, we fitted GLMs to estimate the vital rates in the different sites in the deterministic post-fire habitat states TSF_0 to TSF_3 (see Table S3) and GLMMs with a year random effect for the two disturbance levels (high or low grazing) in the stochastic state $TSF_{>3}$ (see Table S4). We selected the best random and fixed effects following the same approach as described above for the marmot and meerkat vital rates.

Marmot vital rates

Table S1 - Best models (selected with the AICc) and model coefficients for the vital rates of the marmot population. This table presents the summaries of the best models for each vital rate. We estimated the survival (σ), recruitment (recruits), and transition rates (φ) for four life-history stages: juvenile (J), yearling (Y), and non-reproductive (N) and reproductive (R) adult. We first selected the best random effect structure by either comparing the amount of variance explained by a random effect of the year on the average vital rate only or on both the average and the slope between seasons, or by checking whether a random effect of the year on the average did explain part of the model variance. We then tested for the effect of the season and selected the best fixed effect using the AICc. Vital rates in bold were modeled with a quasi-Poisson distribution to correct for under- or overdispersion.

Vital rate	Covariates	Estimate	Standard error (SE)	P-value
J winter survival (σ_J)	Intercept	-0.097	0.11	0.35
	Random effect: (1 year)			
Y survival (σ_Y)	Intercept	1.1	0.095	<2e-16 ***
	Random effect: (1+season year)			
N survival (σ_N)	Intercept	1.5	0.12	<2e-16 ***
	Random effect: (1+season year)			

Demography under changing periodicity

R survival (σ_R)	Summer (intercept)	3.4	0.23	<2e-16 ***
	Winter	-2.1	0.23	<2e-16 ***
	Random effect: (1+season year)			
Recruitment (recruits)	Intercept	1.4	0.033	0
	Random effect: (1 year)			
Y transition to R (φ_Y)	Intercept	-0.023	0.21	0.91
	Random effect: (1 year)			
N transition to R (φ_N)	Intercept	0.90	0.29	0.0018 **
	Random effect: (1 year)			
R stasis (φ_R)	Intercept	1.8	0.28	5.8e-11 ***
	Random effect: (1 year)			

Meerkat vital rates

Table S2 - Best models (selected with the AICc) and model coefficients for the vital rates of the meerkat population. This table presents the summaries of the best models for each vital rate. We estimated the survival (σ), recruitment (recruits), emigration (ε), and transition rates (φ) for four life-history stages: juvenile (J), subadult (S), helper (H), and dominant (D). We first selected the best random effect structure by comparing the amount of variance explained by a random effect of the year on the average vital rate only or on both the average and the slope between seasons. We then tested for the effect of the season, population density and its quadratic term density², and interactions among these covariates, and selected the best fixed effect using the AICc. Vital rates in bold were modeled with a quasi-Poisson distribution to correct for under- or overdispersion.

Vital rate	Covariates	Estimate	Standard error (SE)	P-value
J survival (σ_J)	Dry season (intercept)	1.6	1.2	0.20
	Wet season	-6.7	2.1	0.0011 **
	Density	0.18	0.33	0.58
	Density ²	-0.019	0.021	0.37
	Wet season:density	2.1	0.61	0.00058 ***
	Wet season:density ²	-0.15	0.042	0.00031 ***
	Random effect: (1 year)			

Demography under changing periodicity

S survival (σ_S)	Intercept	0.98	0.56	0.082
	Density	0.18	0.076	0.017 *
	Random effect: (1+season year)			
H survival (σ_H)	Dry season (intercept)	2.2	0.13	<2e-16 ***
	Wet season	-0.71	0.18	0.00013 ***
	Random effect: (1+season year)			
D survival (σ_D)	Intercept	1.6	0.18	<2e-16 ***
	Random effect: (1+season year)			
Emigration (ε)	Intercept	-1.5	0.42	0.00047 ***
	Density	-0.094	0.056	0.091
	Random effect: (1+season year)			
H transition to D (φ)	Intercept	-0.53	0.31	0.084
	Density	-0.26	0.044	4.1e-09 ***
	Random effect: (1+season year)			

Demography under changing periodicity

H recruitment (recruits_H)	Intercept	-0.093	0.32	0.77
	Density	-0.24	0.046	0
	Random effect: (1+season year)			
D recruitment (recruits_D)	Dry season (intercept)	0.27	0.94	0.77
	Wet season	-1.8	1.3	0.16
	Density	0.029	0.28	0.92
	Density ²	-0.0071	0.019	0.71
	Wet season:density	0.52	0.38	0.18
	Wet season:density ²	-0.027	0.028	0.34
	Random effect: (1+season year)			

Dewy pine vital rates, deterministic and stochastic post-fire habitat states

Table S3 - Best models (selected with the AICc) and model coefficients for the vital rates of the dewy pine population in two naturally fire-disturbed and one human-disturbed site for the deterministic post-fire habitat states (TSF₁, TSF₂, and TSF₃). This table presents the summaries of the best models for each vital rate. We estimated the survival (σ), transition rates (φ), and reproductive parameters (p_{fl} , fls , and fps) for four life-history stages: seedling (SD), juvenile (J), and small (SR) and large reproductive individuals (LR). We tested for the effect of the time since fire (TSF), aboveground density and its quadratic term density², and interactions among these covariates, and selected the best fixed effect using the AICc. Vital rates in bold were modeled with a quasi-Poisson distribution to correct for under- or overdispersion.

Vital rate	Covariates	Estimate	Standard error (SE)	P-value
<i>Human-disturbed site</i>				
SD survival - TSF ₁ (σ_{SD})	Intercept	-1.8	1.2	0.13
	Density	0.15	0.076	0.045 *
J survival - TSF ₁ (σ_J)	Intercept	1.1	0.25	6.8e-06 ***
SR survival (σ_{SR})	TSF ₂ (intercept)	-2.0	0.56	0.00026 ***
	TSF ₃	1.6	0.55	0.0048 **
	Density	0.12	0.053	0.023 *
LR survival (σ_{LR})	Intercept	0.85	0.40	0.033 *

Demography under changing periodicity

J transition to LR -TSF ₁ (ϕ_J)	Intercept	-1.1	0.29	0.00010 ***
LR transition to SR - TSF ₃ (ϕ_{LR})	Intercept	-2.7	0.99	0.0067 **
	Density	0.41	0.20	0.038 *
SR flowering probability (p_{fl} SR)	TSF ₂ (intercept)	-3.9	1.0	0.00013 ***
	TSF ₃	3.2	1.1	0.0042 **
LR flowering probability - TSF ₃ ($p_{fl LR}$)	Intercept	0.53	0.40	0.18
LR number of flowering stalks - TSF₃ (fls_{LR})	Intercept	0.42	0.11	0.0018 **
<i>Naturally fire-disturbed site A</i>				
SD survival - TSF ₁ and TSF ₃ (σ_{SD})	TSF ₁ (intercept)	0.34	0.13	0.0074 **
	TSF ₃	-0.13	0.66	0.84
	density	0.0023	0.0012	0.043 *
	TSF ₃ :density	-0.16	0.079	0.042 *

Demography under changing periodicity

J survival (σ_J)	TSF ₁ (intercept)	4.9	1.1	1.52e-05 ***
	TSF ₂	-1.5	1.0	0.15
	TSF ₃	-4.6	1.1	3.5e-05 ***
	Density	-0.060	0.014	2.6e-05 ***
	Density ²	0.00031	8.2e-05	0.00019 ***
SR survival - TSF ₃ (σ_{SR})	Intercept	0.023	0.30	0.94
	Density	-0.06	0.012	2.0e-07 ***
LR survival - TSF ₃ (σ_{LR})	Intercept	0.81	0.17	3.7e-06 ***
	Density	-0.041	0.0093	1.2e-05 ***
J transition to LR (φ_J)	TSF ₁ (intercept)	2.5	0.55	8.5e-06 ***
	TSF ₂	-1.7	0.51	0.00072 ***
	TSF ₃	-1.8	0.64	0.0042 **
	Density	-0.053	0.011	4.3e-07 ***
	Density ²	0.00024	6.8e-05	0.00038 ***
SR transition to LR - TSF ₃ (φ_{SR})	Intercept	0.69	0.31	0.024 *

Demography under changing periodicity

LR transition to SR - TSF ₃ (φ_{LR})	Intercept	-3.0	0.56	6.7e-08 ***
	Density	0.19	0.068	0.026 *
	Density ²	-0.0027	0.0014	0.064
SR flowering probability - TSF ₃ ($p_{fl\ SR}$)	Intercept	-0.091	0.11	0.41
LR flowering probability - TSF ₃ ($p_{fl\ LR}$)	Intercept	1.0	0.14	1.7e-13 ***
SR number of flowering stalks - TSF₃ (fls_{SR})	Intercept	0.031	0.014	0.023 *
LR number of flowering stalks - TSF₃ (fls_{LR})	Intercept	0.79	0.047	<2e-16 ***
SR number of flowers per stalk - TSF₃ (fps_{SR})	Intercept	1.1	0.033	<2e-16 ***
LR number of flowers per stalk - TSF ₃ (fps _{LR})	Intercept	1.4	0.035	<2e-16 ***
<i>Naturally fire-disturbed site B</i>				
SD survival - TSF ₃ (σ_{SD})	Intercept	-0.83	0.66	0.21
	Density	-0.15	0.077	0.059
J survival - TSF ₁ and TSF ₃ (σ_J)	Intercept	0.42	0.22	0.054

Demography under changing periodicity

LR survival (σ_{LR})	TSF ₂ (intercept)	0.69	0.37	0.061
	TSF ₃	-1.3	0.47	0.0047 **
J transition to LR (ϕ_J) (TSF ₁)	Intercept	2.1	0.53	6.7e-05 ***
LR transition to SR (ϕ_{LR})	Intercept	-2.3	0.74	0.0019 **
LR flowering probability (ρ_{fl} LR)	Intercept	1.4	0.30	1.8e-06 ***
LR number of flowering stalks - TSF₃ (fls_{LR})	Intercept	0.32	0.34	0.35
	Density	0.26	0.10	0.019 *
	Density ²	-0.014	0.0062	0.037 *
LR number of flowers per stalk - TSF₃ (fps_{LR})	Intercept	1.7	0.059	<2e-16 ***

Table S4 - Best models (selected with the AICc) and model coefficients for the vital rates of the dewy pine population in little (LG) and highly-grazed sites (HG) for the stochastic post-fire habitat state (TSF_{>3}). This table presents the summaries of the best models for each vital rate. We estimated the survival (σ), transition rates (φ), and reproductive parameters (p_{fi} , fls , and fps) for four life-history stages: seedling (SD), juvenile (J), and small (SR) and large reproductive individual (LR). We first selected the best random effect structure by checking whether a random effect of the year on the average vital rate did explain part of the model variance. All models except LR-SR transition in highly-grazed sites (indicated with a *), had a random effect of the year on the average rate. We then tested for the effect of the aboveground density and its quadratic term $density^2$ and selected the best fixed effect using the AICc. Vital rates in bold were modeled with a quasi-Poisson distribution to correct for under- or overdispersion.

Vital rate	Covariates	Estimate	Standard error (SE)	P-value
<i>Low grazing</i>				
SD survival (σ_{SD})	Intercept	-1.0	0.31	0.00097 ***
	Density	-0.027	0.012	0.022 *
J survival (σ_J)	Intercept	-0.25	0.29	0.38
	Density	-0.046	0.016	0.0036 **
SR survival (σ_{SR})	Intercept	-1.0	0.42	0.017 *
LR survival (σ_{LR})	Intercept	-0.21	0.34	0.55
J transition to LR (φ_J)	Intercept	-0.96	0.42	0.020 *

Demography under changing periodicity

SR transition to LR (φ_{SR})	Intercept	-0.066	0.61	0.91
LR transition to SR (φ_{LR})	Intercept	-1.3	0.35	0.00018 ***
SR flowering probability ($p_{fl\ SR}$)	Intercept	-0.74	0.79	0.35
	Density	0.28	0.10	0.0047 **
	Density ²	-0.010	0.0046	0.022 *
LR flowering probability ($p_{fl\ LR}$)	Intercept	0.78	0.37	0.035 *
	Density	0.25	0.084	0.0034 **
LR number of flowering stalks (fl_{LR})	Intercept	1.0	0.14	0
LR number of flowers per stalk (fp_{SR})	Intercept	1.3	0.071	0
<i>High grazing</i>				
SD survival (σ_{SD})	Intercept	-2.1	0.40	1.8e-07 ***
	Density	0.11	0.031	0.00030 ***
	Density ²	-0.0024	0.00076	0.0014 **
J survival (σ_J)	Intercept	-0.55	0.28	0.050
SR survival (σ_{SR})	Intercept	-1.2	0.36	0.00076 ***
	Density	0.048	0.016	0.0026 **

Demography under changing periodicity

LR survival (σ_{LR})	Intercept	-0.17	0.44	0.71
J transition to LR (φ_J)	Intercept	-0.030	0.34	0.93
	Density	-0.042	0.017	0.010 *
SR transition to LR (φ_{SR})	Intercept	-0.22	0.49	0.65
LR transition to SR (φ_{LR}) *	Intercept	-1.9	0.42	8.9e-06 ***
	Density	0.088	0.031	0.0042 **
SR flowering probability ($p_{fl SR}$)	Intercept	-0.22	0.46	0.63
LR flowering probability ($p_{fl LR}$)	Intercept	0.69	0.32	0.031 *
	Density	-0.038	0.016	0.021 *
SR number of flowers per stalk (fps_{SR})	Intercept	1.4	0.13	0
	Density	-0.022	0.010	0.0415
LR number of flowers per stalk (fps_{LR})	Intercept	1.5	0.096	0

Selection of the most biologically relevant model for dominant recruitment in the meerkat population.

Model predictions for dominant recruitment showed an ever-increasing recruitment with density dependence (Fig. S1a and S1b). As dominant recruitment has been shown to decrease at high population densities (Paniw et al. 2019), we chose the model that included a squared density term for its biological relevance, although it was not the most parsimonious model according to AICc model selection. The discrepancy in our results and previous ones is likely due to the fact that we use a simplified measure of recruitment, where we model recruitment over a six-months instead of a monthly period as has been previously done, and integrate the probability of pregnancy and birth into our recruitment measure.

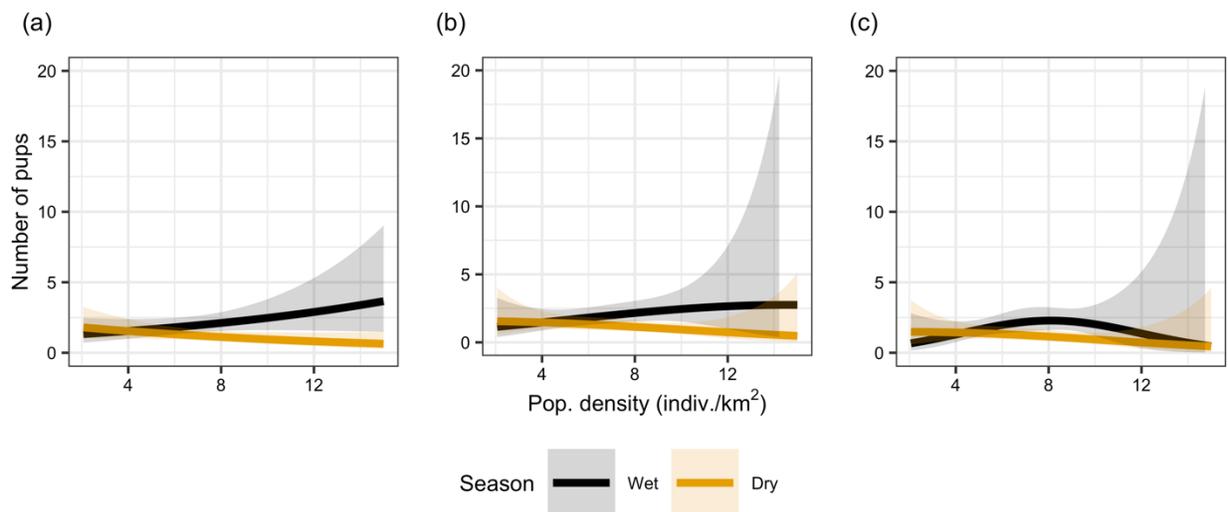


Figure S1 - Predictions of the models considered to estimate dominant recruitment. (a) and (b) The predictions of both first two best models according to the AICc (pups ~ season + density + season:density + (1+season|year) and pups ~ season + density + density² + season:density + (1+season|year); AICc 1636.9 and 1639.0, respectively) show that recruitment keeps increasing even at high values of population density during the wet season. However, at high population densities, recruitment should decrease (Paniw et al. 2019). (c) To model a biologically relevant relation between dominant recruitment and population density, we added an interaction between season and the quadratic term density² to the model, therefore choosing the third best

Demography under changing periodicity

model according to the AICc (recruitment \sim season + density + density² + season:density + season:density² + (1+season|year); AICc 1640.7). After model selection using the AICc, all three models were fitted again as quasi-Poisson models to account for overdispersion using the *glmmPQL* function from the *MASS* R package (Venables and Ripley 2002). Lines show the average estimates, shaded areas show the 95% confidence intervals and were obtained using the *easyPredCI* function proposed by Prof. Marc Girondot available at <https://biostatsr.blogspot.com/2016/02/predict-for-glm-and-glmm.html>.

Density dependence of vital rates in the meerkat and dewy pine populations

For the meerkats, in addition to season, population density affected most of the vital rates negatively (Fig. S2a and Table S2), but low population densities also had marked adverse effects on vital rates, especially in the wet season (Fig. S1 and Table S2; see also Paniw et al. 2019). As expected, emigration decreased with population density (Fig. S2a), due to the reduced non-occupied territories (Bateman et al. 2013) at high densities. Emigration was highest at low population densities as more territories became available, and benefits of living in a group decreased at low densities (Maag et al. 2018). Similarly, both helper recruitment and the probability for a helper to become dominant decreased significantly with density. On the other hand, subadult survival increased with population density. Finally, juvenile survival and dominant recruitment were highest at intermediate densities in the wet season (see Fig. S1c and Table S2). The effects of population density on vital rates are discussed in detail in Paniw et al. (2019) (see also Bateman et al. 2012; Bateman et al. 2013).

Demography under changing periodicity

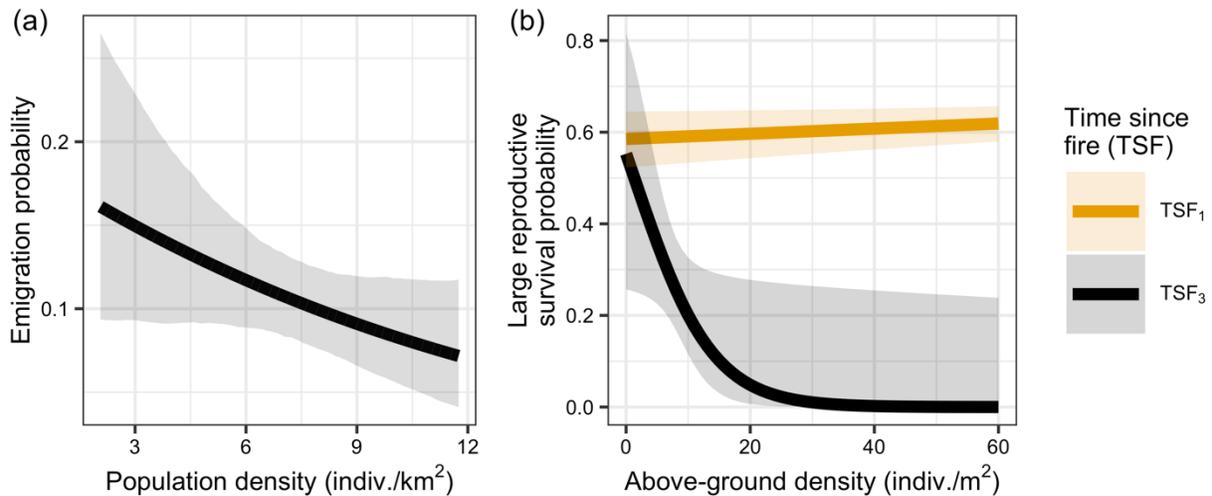


Figure S2 – Example of model predictions for density-dependent vital rates.

(a) For the meerkats, helper emigration probability; and (b) for the dewy pines, large reproductive individual (LR) survival probability in a natural population in TSF₂ and TSF₃ (time since fire). Lines show the average estimates, shaded areas show the 95% confidence intervals and were obtained using the *bootMer* function from the *lme4* R package (Bates et al. 2015).

In the dewy-pine population, various vital rates were affected by aboveground density (see Fig. S2b and Tables S3 and S4). In most cases and across TSF, this effect was negative, as intra-specific competition is likely to increase with habitat succession and thereby decrease survival in particular (Jennings and Rohr 2011; Paniw, Salguero-Gómez and Ojeda 2017). Other studies also showed the effect of aboveground individuals on the germination probability of seeds and the survival of seedlings due to competition for light (Correia and Freitas 2002; Gómez-González et al. 2018). Some models however showed that, in a perturbed population, reproductive parameters as well as survival of small individuals and seedlings can be increased with density, suggesting facilitation under environmental stress (Paniw, Salguero-Gómez and Ojeda 2017).

References – Appendix S3

- Bateman, A. W., A. Ozgul, T. Coulson, and T. H. Clutton-Brock. 2012. “Density dependence in group dynamics of a highly social mongoose, *Suricata suricatta*.” *Journal of Animal Ecology* 81 (3): 628–639. <https://doi.org/10.1111/j.1365-2656.2011.01934.x>.
- Bateman, A. W., A. Ozgul, J. F. Nielsen, T. Coulson, and T. H. Clutton-Brock. 2013. “Social structure mediates environmental effects on group size in an obligate cooperative breeder, *Suricata suricatta*.” *Ecology* 94: 587–597. <https://doi.org/10.1890/11-2122.1>.
- Bates, D., M. Mächler, B. Bolker, and S. Walker. 2015. “Fitting linear mixed-effects models using lme4.” *Journal of Statistical Software* 67 (1): 1–48. <https://doi.org/10.18637/jss.v067.i01>.
- Correia, E., and H. Freitas. 2002. “*Drosophyllum lusitanicum*, an endangered West Mediterranean endemic carnivorous plant: threats and its ability to control available resources.” *Botanical Journal of the Linnean Society* 140 (4): 383–390. <https://doi.org/10.1046/j.1095-8339.2002.00108.x>.
- Gómez-González, S., M. Paniw, K. Antunes, and F. Ojeda. 2018. “Heat shock and plant leachates regulate seed germination of the endangered carnivorous plant *Drosophyllum lusitanicum*.” *Web Ecology* 18 (1): 7–13. <https://doi.org/10.5194/we-18-7-2018>.
- Jennings, D. E., and J. R. Rohr. 2011. “A review of the conservation threats to carnivorous plants.” *Biological Conservation* 144 (5): 1356–1363. <https://doi.org/10.1016/j.biocon.2011.03.013>.
- Maag, N., G. Cozzi, T. H. Clutton-Brock, and A. Ozgul. 2018. “Density-dependent dispersal strategies in a cooperative breeder.” *Ecology* 99 (9): 1932–1941. <https://doi.org/10.1002/ecy.2433>.
- Paniw, M., N. Maag, G. Cozzi, T. H. Clutton-Brock, and A. Ozgul. 2019. “Life history responses of meerkats to seasonal changes in extreme environments.” *Science* 363 (6427): 631–635. <https://doi.org/10.1126/science.aau5905>.
- Paniw, M., R. Salguero-Gómez, and F. Ojeda. 2017. “Transient facilitation of

Demography under changing periodicity

resprouting shrubs in fire-prone habitats.” *Journal of Plant Ecology* 11 (3): 475–483.
<https://doi.org/10.1093/jpe/rtx019>.

Venables, W. N., and B. D. Ripley. 2002. *Modern Applied Statistics with S*. Fourth edition. Springer, New York, US.