Supporting Information for 'Climate warming: a loss of variation in populations can accompany reproductive shifts'

Figure S1. Location map of the study sites on Mont-Lozère (Cévennes National Park, Southern France). Site areas are approximately 0.5 ha. Altitude is 1410 m for CHA, 1430 m for EXP, 1420 m for PIM, ZDE and ZFD, 1465 m for ERM. The site EXP is the site where we experimentally tested for the effect of temperature on parturition date.

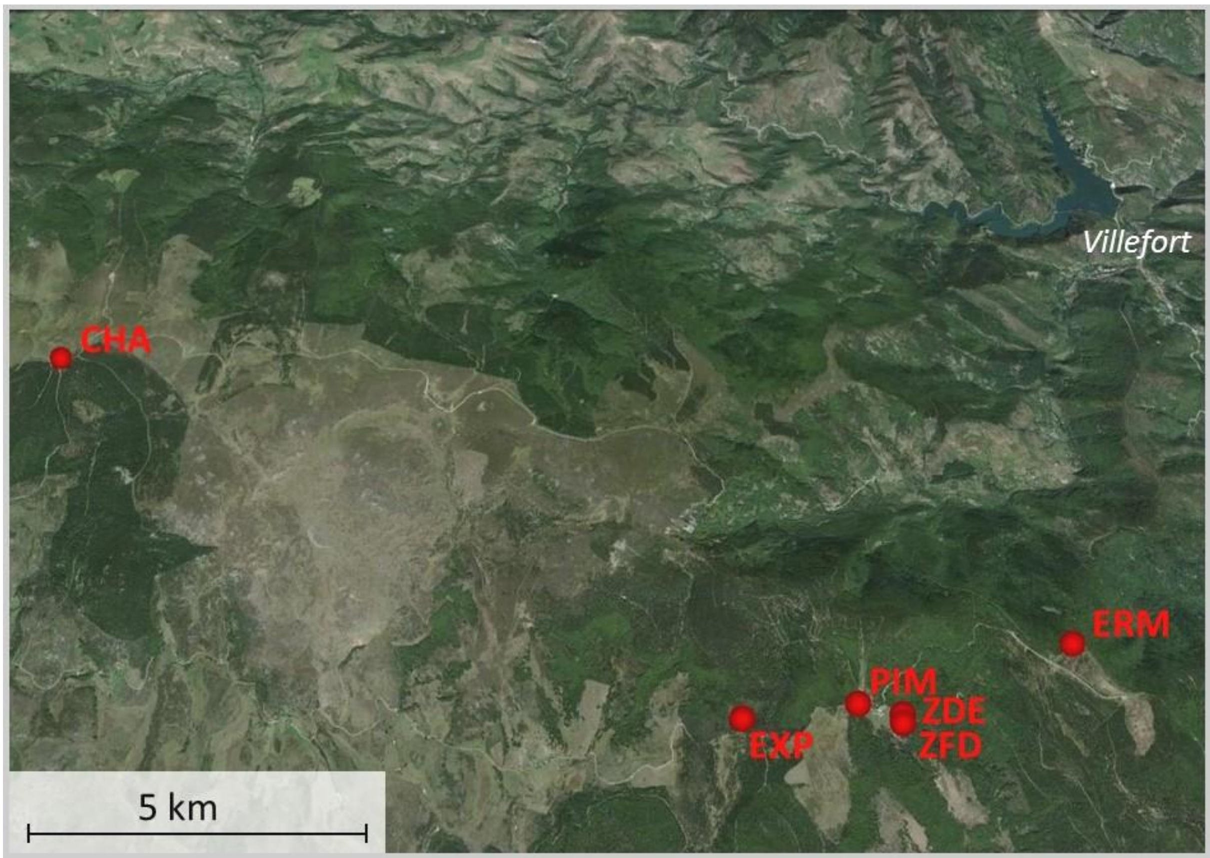

Figure S2. Frequency distributions of parturition dates in natural populations of the common lizard at Mont-Lozère (France). Frequency distributions are given for the five study sites from 1989 to 2001.

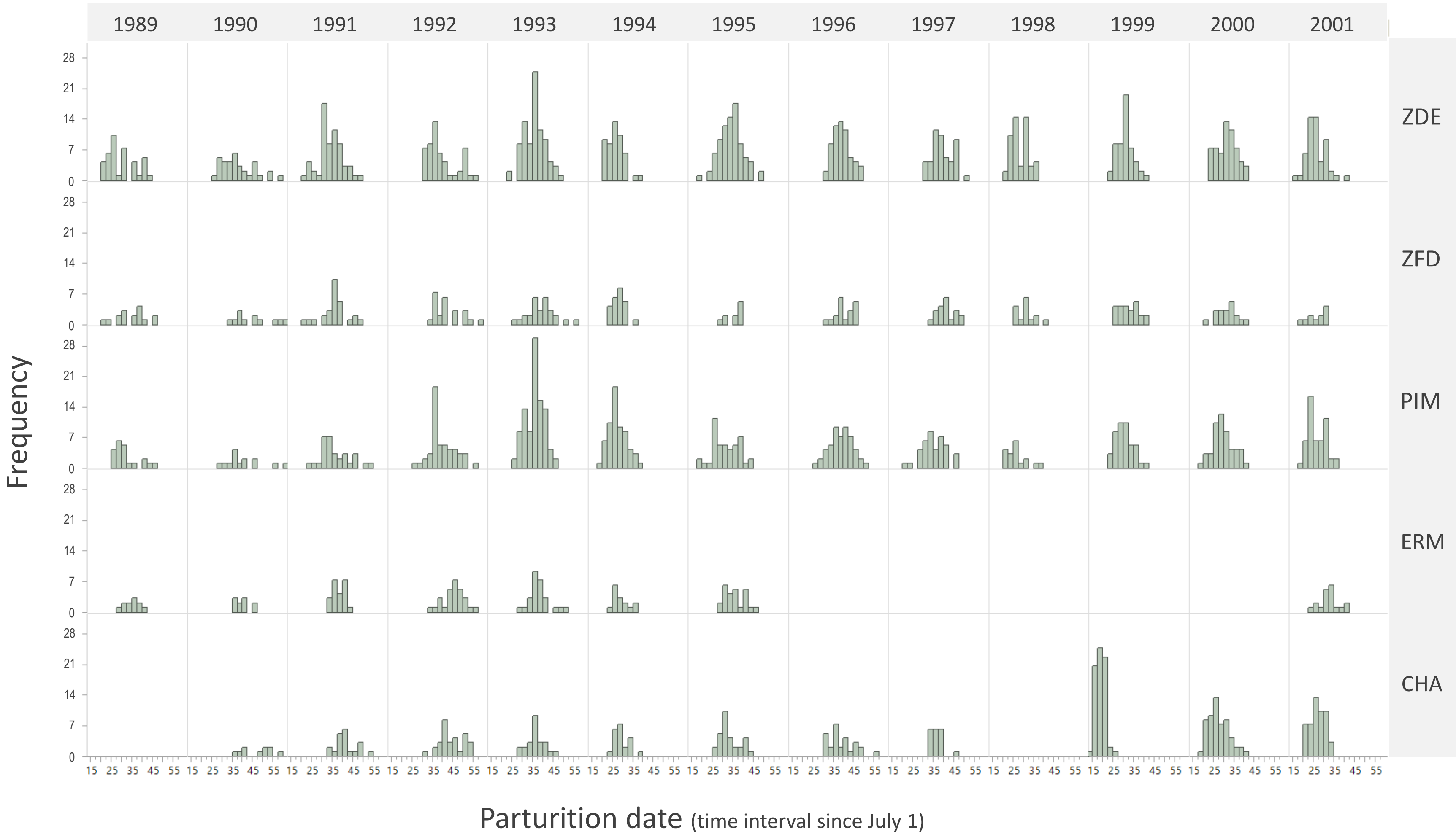

Figure S3. Relationship between the mean and the standard deviation of parturition dates. The relationship is reported for the estimates of the five natural population studied (r = 0.48). The three estimates of the 2005 experiment are also indicated by the red points.

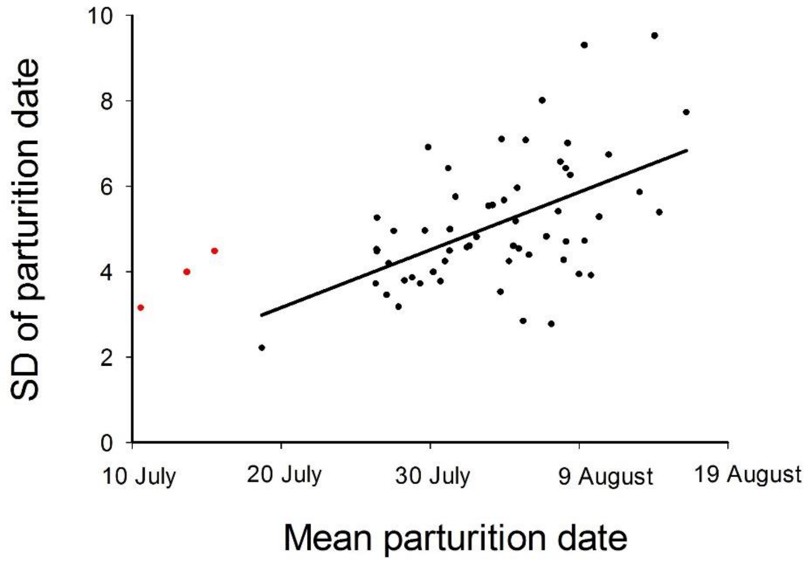

Figure S4. Phenological change related to dispersal in the common lizard. Relationships between the mean parturition date and the mean of daily maximum air temperature in June for dispersing juveniles (filled circles and solid line, $F_{1,18}$=11.2 P=0.004) and non-dispersing juveniles (open circles and dashed line, $F_{1,37}$=1.8 P=0.184). The interaction between dispersal status and temperature was significant ($F_{1,54}$=5.3 P=0.025).

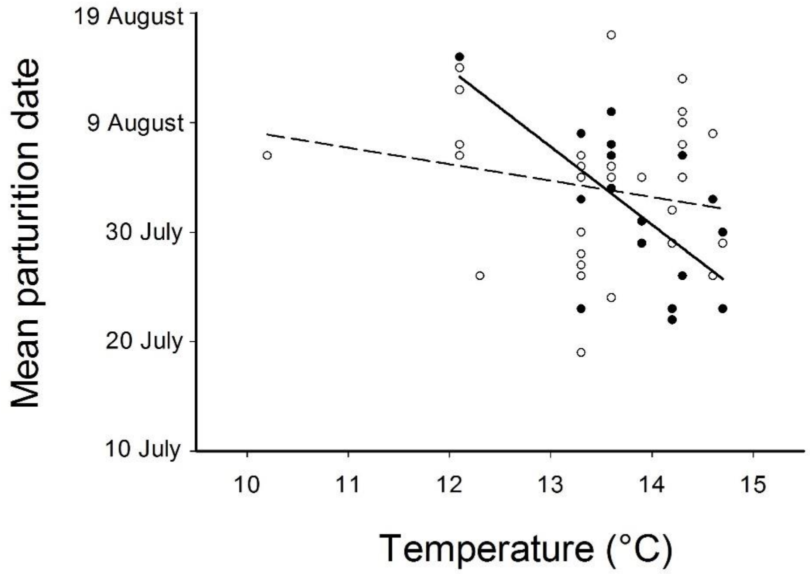

Table S1. Data collected on the phenology of the common lizard on five sites of the Mont-Lozère. Temperature is the mean of daily maximum air temperature in June (°C). Parturition dates are described by the mean of the time interval since July 1 (MEAN in days) and its standard deviation (SD). N is the sample size (number of litters per site and year).

SITE	YEAR	TEMPERATURE	MEAN	SD	N
ZFD	1989	14.0	34.81	7.10	16
ZFD	1990	12.4	45.08	9.52	12
ZFD	1991	12.3	35.85	5.96	27
ZFD	1992	10.2	42.00	6.74	24
ZFD	1993	13.6	38.75	6.57	28
ZFD	1994	14.2	27.88	3.17	24
ZFD	1995	13.3	35.30	4.24	10
ZFD	1996	14.3	40.37	4.72	19
ZFD	1997	12.1	40.80	3.91	20
ZFD	1998	14.3	31.00	4.24	15
ZFD	1999	13.9	32.63	4.60	24
ZFD	2000	14.6	31.32	4.49	19
ZFD	2001	14.7	26.45	4.50	11
ZDE	1989	14.0	29.87	6.91	39
ZDE	1990	12.4	37.53	8.01	34
ZDE	1991	12.3	34.20	5.56	60
ZDE	1992	10.2	39.24	7.01	51
ZDE	1993	13.6	35.75	5.18	83
ZDE	1994	14.2	26.35	3.72	48
ZDE	1995	13.3	33.94	5.54	80
ZDE	1996	14.3	38.97	4.27	58
ZDE	1997	12.1	39.13	4.70	48
ZDE	1998	14.3	28.28	3.79	50
ZDE	1999	13.9	30.71	3.77	51
ZDE	2000	14.6	31.34	4.99	58
ZDE	2001	14.7	26.40	4.52	53
PIM	1989	14.0	31.71	5.75	21
PIM	1990	12.4	40.36	9.30	14
PIM	1991	12.3	36.42	7.08	31
PIM	1992	10.2	39.42	6.26	50
PIM	1993	13.6	35.97	4.54	94
PIM	1994	14.2	27.22	4.19	60
PIM	1995	13.3	31.23	6.42	44
PIM	1996	14.3	38.61	5.41	51
PIM	1997	12.1	34.97	5.67	39

SITE	YEAR	TEMPERATURE	MEAN	SD	N
PIM	1998	14.3	26.44	5.26	18
PIM	1999	13.9	30.21	3.99	43
PIM	2000	14.6	29.64	4.96	50
PIM	2001	14.7	26.42	4.47	50
ERM	1989	14.0	34.73	3.52	11
ERM	1990	12.4	40.00	3.94	10
ERM	1991	12.3	38.14	2.77	22
ERM	1992	10.2	45.39	5.39	28
ERM	1993	13.6	37.81	4.82	27
ERM	1994	14.2	28.80	3.86	15
ERM	1995	13.3	35.60	4.60	25
ERM	2001	14.7	32.47	4.57	19
CHA	1990	12.4	47.20	7.73	10
CHA	1991	12.3	41.35	5.28	20
CHA	1992	10.2	44.07	5.86	30
CHA	1993	13.6	36.63	4.39	24
CHA	1994	14.2	29.33	3.72	21
CHA	1995	13.3	33.13	4.81	30
CHA	1996	14.3	39.11	6.42	27
CHA	1997	12.1	36.26	2.84	19
CHA	1999	13.9	18.70	2.21	70
CHA	2000	14.6	27.55	4.95	55
CHA	2001	14.7	27.08	3.45	50

Table S2. Statistics of relationships reported in the four panels of the figure 1. Correlation coefficients (*r*) and linear equations (*s* = slope, *i* = intercept) are provided for yearly and thermal trends of the mean parturition date (time interval since July 1), and of the standard deviation of parturition date. The number of study years per site was 11 for CHA, 8 for ERM, 13 for PIM, 13 for ZDE, 13 for ZFD.

Site	**Yearly trend**			**Thermal trend**		
	r	*s*	*i*	*r*	*s*	*i*
			Mean parturition date			
CHA	- 0.85	- 1.8599	3745.6435	- 0.66	- 4.1819	89.9360
ERM	- 0.48	- 0.5810	1194.6458	- 0.93	- 3.1625	78.0063
PIM	- 0.69	- 0.7677	1564.6265	- 0.70	- 2.6606	68.5612
ZDE	- 0.32	- 0.4353	901.6912	- 0.69	- 2.5298	67.0489
ZFD	- 0.56	- 0.8146	1660.6050	- 0.77	- 3.0402	76.2257
			SD of parturition date			
CHA	- 0.62	- 0.2757	554.8482	- 0.21	- 0.3657	9.5367
ERM	0.43	0.0870	- 169.3013	- 0.19	- 0.1479	6.1190
PIM	- 0.65	- 0.2267	457.9115	- 0.61	- 0.6129	13.8373
ZDE	- 0.69	- 0.2564	516.8035	- 0.58	- 0.6190	13.5082
ZFD	- 0.64	- 0.3157	635.2162	- 0.29	- 0.5861	13.2063

Appendix S1. Individual-based simulation of variance in reproductive dates.

Model description

The model is presented using the ODD protocol (Grimm *et al.* 2006, Grimm *et al*. 2010).

1. Purpose

The model explores the risk of extinction of a population, depending on the reproduction schedule represented by the time distribution of reproductive events: mean date of reproduction θ and standard deviation σ in days. The population, constituted of females, is regulated by resource abundance, either constant or cyclic with a one year period.

2. Entities and state variables

Every female individual is characterized by: age in days, date of annual reproduction in days, survival status (dead or alive), reproduction status (has reproduced or not), and a flag to indicate the beginning of the simulation (see *Initialization* below). Other parameters quantify the time distribution of reproduction (θ, σ), cyclic resource characteristics ($a, \theta_{res}, \sigma_{res}$) (Table 1), the strength of density dependence (α, α_{res}) (Tables 2 and 3). The main high level variable is population size along time.

3. Process overview and scheduling

The model runs in discrete time with a time step of one day. Daily survival rates are expressed from a female-based age-classified life cycle (Caswell 2001) where transitions last one year: the survival rate s_i from age i to age $i+1$ (in years) is converted into the daily survival rate

$$q_i = (s_i)^{\frac{1}{365}}. \qquad (1)$$

These survival rates are affected by population density, assuming a constant or cyclic resource.

The future date of reproduction of every individual is drawn at the beginning of every year (time $t \equiv 0$ modulo 365, corresponding to the 1st of January) using the normal distribution with mean θ and standard deviation σ.

At each time step t, alive individuals are tested for (1) survival drawn according to the Bernoulli distribution, then (2) reproduction: if the individual's reproduction date is the current day t, the number of offspring is drawn using the Poisson distribution with mean f_i, the age-specific yearly fecundity; the number of female offspring is then drawn using the binomial distribution with parameter the primary female sex ratio 0.5.

Table 1. Simulation parameters.

number of time steps		18 250 days (50 years)
number of trajectories (Monte Carlo)		10 000
life cycle		short-lived/long-lived
mean date of reproduction	θ	200 days (reference)
standard deviation in date of reproduction	σ	20 days (reference)
Cyclic resource function $R(t)$		
lowest abundance	a	0.01
peak	θ_{res}	240 days
standard deviation	σ_{res}	40 days

4. Design concepts

Basic principles. An age-classified demographic model with density dependent daily survival rates in a constant or cyclic environment.

Emergence. Monte Carlo simulation: the probability of extinction emerges from a set of replicate stochastic trajectories, some of which go extinct when population size is 0.

Interaction. Individuals compete for resource, either constant or cyclic. When resource abundance is cyclic, the *reference* scenario assumes that reproduction is tuned to the timing of the resource (with the values reported in Table 1): the mean date of reproduction θ is such that the peak of population size matches the date θ_{res} of the peak of the resource. The peak of population occurs close to the date $\theta + 2\sigma$, when most offspring is born (in fact, 95% of the offspring by the 2σ criterion). For the same reason, the half width of the population peak is 2σ. Accordingly, the Gaussian function modelling the resource in the reference scenario (see *Submodels* below) is chosen to have mean $\theta_{res} = \theta + 2\sigma$ and standard deviation $\sigma_{res} = 2\sigma$. The reference scenario is compared to scenarios where the mean date of reproduction occurs earlier or later in the year or the standard deviation is reduced (Table 4).

Stochasticity. Demographic stochasticity is accounted for by the design of an individual-based model. The only other source of stochasticity is in the individual date of reproduction.

Observation. A large number of trajectories (10 000) are cast over a time horizon of 50 years (18 250 days). The number of extinct trajectories divided by the total number of trajectories gives an estimate of the probability of extinction.

5. Initialization

At initialization, n_0 individuals aged a_0 years (a_0 depending on the life cycle) are introduced, and the future annual date of reproduction of each individual is drawn (time $t = 0$ corresponds to the 1st of January). Initial individuals do not suffer any mortality until their first reproduction. This feature has been chosen to ensure that a pool of exactly n_0 individuals reproduce at the beginning of the simulation independently of their date of reproduction, early or late in the year, and independently of their survival rate, low or high.

6. Input data

Two typical and contrasted life cycles are considered: a short-lived species (Table 2) and a long-lived species (Table 3) (Legendre *et al.* 1999). A small lizard like *Zootoca vivipara* considered in the main text has a life cycle similar to that of the short-lived species.

7. Submodels

In the constant environment, the population is regulated by density according to a Ricker function acting on survival:

$$q_d = q\exp(-\alpha n(t)).$$

Here, the index i of the age-class (Eq. 1) has been dropped for simplicity but the survival rates of all age classes are affected by density in this way, q is the density independent daily survival rate, α parameterizes the strength of density dependence (inversely related to constant resource abundance), and $n(t)$ is total population size at time t.

In the cyclic environment, the fluctuation of resource abundance is described by a Gaussian curve repeated over each one year period:

$$R(t) = a + (1-a)\exp\left(-\frac{(t \bmod 365 - \theta_{res})^2}{\sigma_{res^2}}\right).$$

The resource is maximal at date θ_{res} (in days), the lowest abundance is parameterized by a, and the width of the time window of the resource is parameterized by σ_{res}. Resource abundance affects survival according to

$$q_{res} = q\exp\left(-\frac{\alpha_{res}}{R(t)}n(t)\right)$$

with the parameter α_{res}. The more abundant the resource, the less stringent the reduction on survival.

Table 2. Yearly demographic parameters for short-lived species. Strength of density dependence is a daily parameter.

juvenile survival	s_0	0.2
subadult survival	s_1	0.35
adult survival	s_2	0.5
subadult fecundity	f_1	7
adult fecundity	f_2	7
growth rate	λ	1.1050
generation time	T	1.67
initial population size	n_0	30
age of initial individuals	a_0	1 year
strength of density dependence (constant environment)	α	0.00001
strength of density dependence (cyclic environment)	α_{res}	0.0000002

Table 3. Yearly demographic parameters for long-lived species. Strength of density dependence is a daily parameter.

juvenile survival	s_0	0.8
immature survival 1	s_1	0.8
immature survival 2	s_2	0.8
immature survival 3	s_3	0.84
adult survival	s_4	0.9
adult fecundity	f_4	0.8
growth rate	λ	1.0480
generation time	T	10.04
initial population size	n_0	30
age of initial individuals	a_0	4 years
strength of density dependence (constant environment)	α	0.000002
strength of density dependence (cyclic environment)	α_{res}	0.0000005

Results

The probability of extinction P_{ext} is determined for the short-lived and long-lived species under the constant and cyclic environments, and varying the mean θ and standard deviation σ of the reproduction date (Table 4). For the short-lived species, the probability of extinction increases when the width of the reproduction period is reduced, both in the constant and cyclic environments. We observe low variation of P_{ext} for the long-lived species, especially when varying the standard deviation σ. Note that the environments (constant or cyclic) and the life cycles are explored independently: no relation exists between the scenarios, the probabilities of extinction must be compared only within a given environment and for a given life cycle, not across.

In the cyclic environment, the probability of extinction increases when the peak of population is shifted with respect to the peak of the resource. This also holds for other life cycles we have explored whose results are not shown here. With the demographic parameters considered here, the effect of a shift in reproduction date is more pronounced when reproduction occurs after the peak of resource abundance.

Table 4. Probability of extinction P_{ext} for the short-lived and long-lived species, in the constant and cyclic environment, varying mean date of reproduction θ and standard deviation σ (in days).

Environment	θ	σ	P_{ext} short-lived	P_{ext} long-lived
Constant	200	20	0.3586	0.3706
	200	5	0.3971	0.3581
Cyclic	200	20	0.2851	0.3061
	200	5	0.3247	0.3092
	100	20	0.3495	0.3079
	100	5	0.3924	0.3077
	280	20	0.4556	0.3238
	280	5	0.4936	0.3219

The difference in the short-lived and long-lived species with respect to the incidence of reproduction on the growth rate, and consequently on the probability of extinction, is explained in terms of sensitivities (Caswell 2001): for short-lived species, the most sensitive parameters are juvenile survival and fecundity whereas for long-lived species the most sensitive parameter is adult survival (Legendre *et al.* 1999).

For short-lived species, the simulation shows two points:

(1) reducing the variance in reproductive dates increases the probability of extinction,

(2) shifting the peak of cyclic resource with respect to the average date of reproduction increases the probability of extinction.

Program download

The program source files and executable can be downloaded at

http://www.biologie.ens.fr/~legendre/day/day.html

References

Caswell, H. (2001). *Matrix Population Models: Construction, Analysis, and Interpretation* (2nd edition). Sinauer Associates, Sunderland, Massachusetts.

Grimm, V. *et al*. (2006). A standard protocol for describing individual-based and agent-based models. *Ecol. Mod.*, 198, 115–126.

Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J. & Railsback, S. F. (2010). The ODD protocol: a review and first update. *Ecol. Mod.*, 221, 2760–2768.

Legendre, S., Clobert, J., Møller, A.P. & Sorci, G. (1999). Demographic stochasticity and social mating system in the process of extinction of small populations: the case of passerines introduced to New Zealand. *Am. Nat.*, 153, 449–463.