Gienapp *et al.* (2013) Predicting demographically-sustainable rates of adaptation: can great tit breeding time keep pace with climate change? *Phil Trans Roy Soc B* **368** doi: 10.1098/rstb.2012.0289

S3 Dynamic state model - parameters

Parameter estimation temperature model

To simulate realistic temperature patterns (e.g. long-term average daily temperatures, and day-to-day variation (and how it varies over the season)), we calculate for each 30 year period from 1951-2100 (with a sliding window of 10 years) the characteristics of that specific temperature data series (i.e. 17 replicates of the IPCC SRES 1AB) that we obtained from the KNMI, and also for the corresponding 17 replicates of the medium and extreme derivation of this scenario. Day-to-day variation is calculated by first removing the annual periodicity from the daily temperatures by subtracting the long-term (30 years) climatologically mean. This provides temperature-anomaly data $a(d) = T(d) - T_{avg}(d)$. Next, we calculate the temperature-anomaly difference between two consecutive days $v(d) = a(d+1) - a(d)$. For each week, we calculated the mean ($\mu_q(w)$) and the standard deviation ($\sigma_q(w)$) of the temperature-anomaly differences of all days in that week and for the period of 30 year.

Parameter estimation caterpillar biomass model

We used data caterpillar biomass from the Hoge Veluwe, from 1993-2009 to estimate the average temperature sum at the peak date. We use a simple model for the temperature sum. We start at the 8 March (d = 67) and add all temperatures higher than 5.4°C. Furthermore, [1] found that the width of the caterpillar peak was 24.3 days. Therefore we also calculated the temperature sum 12 days before and 12 days after the caterpillar peak. The peak of caterpillar biomass starts at 249.4 GDD (SD= 21.5), peaks at 305.6 GDD (SD=18.3) and ends at 303.7GDD (SD=18.3). Therefore we take μ_F=306 and σ_F=70. We assume that the height of the food peak is the same each year and set A_F=1300. With these values the maximum difference between the estimated and the observed food peak for the period of 1993 to 2010 is 3.5 days, the average difference was 0.055 days and the total sum of squared differences was 53.5 days.

Conversion of food availability in available energy

We convert the estimated caterpillar biomass into available energy in the environment in one day. This enables us to make a direct link between food availability and daily energy expenditure (DEE) of the adult bird and age dependent energy requirements of the young. Naef-Daenzer et al. ([2] Fig. 8) found that the caterpillars delivered is dependent on the caterpillar biomass (mg m^{-1} of branch) with y=-208.76 + 195.93*log(biom). In the Hoge Veluwe caterpillar biomass is measured in g caterpillar per m^2 per day. Visser et al [1] found that both measures for caterpillar biomass are highly correlated. Based on their original data (R^2=0.6255), we found that: biom (g m^{-2}) = 61.205*biom (g m^{-1} of branch) + 0.2358. Naef-Daenzer et al. ([2] Fig. 8) give the caterpillars delivered as function of caterpillar biomass in mg caterpillar per nestling per hour. We assume that the working day of a Great tit is 16 hours. Furthermore, we assume that the maximum number of chicks that a Great tit can feed enough for their optimal growth is 12 chicks. Moreover, the adult is also able to find food for itself. We assume that also when there are no caterpillars available that there is always 90 kJ per day available from other food sources in the environment. Furthermore, we converted delivered caterpillars into delivered energy by taking into account that the energy content of a caterpillar is 21.4 kJ per g dry weight [3], and assuming that the water content of a caterpillar is 2/3 of its body weight. If we combine these assumptions and conversions we get eq. 5 (S2). On top of this base value of 90 kJ and the energy of the caterpillars biomass, there is also another food source that is seasonally varying given by

$$E(s) = E_{cat}(s) + 25\sin\left(log_{10}(0.75s + 1) - \frac{\pi}{2}\right)$$

Sensitivity analysis of input parameters for modelling the optimal egg-laying date

In the stochastic dynamic model to predict optimal egg-laying dates the optimal breeding time was not only determined by the timing of the food peak, which determines the optimal chick rearing time, but also by other parameters related to the reproductive physiology and ecology of great tits. We assumed that egg production is energetically costly and that this cost is affected by ambient temperatures with a higher cost under colder temperatures. Incubation is also energetically costly and this costs is affected by ambient temperature in the same way as egg production. The amount of offspring needs was affected by the age of the chicks and also ambient temperature.

Unfortunately, there are few exact estimates of these parameters from natural populations, so we tested how sensitive the predicted environmental change was to variation in these parameters. We ran the following scenarios: costs of egg production reduced by 50% (E50), costs of egg production increased by 50% (E150), costs of incubation reduced by 25% (I75), nestling energy needs reduced by 25% (N75) and nestling energy needs increased by 25% (N125). The recruitment probability of fledged chicks was modelled as a Gaussian function with the peak at the optimal breeding time. We modified how steeply recruitment probability declines with distance from the optimal breeding time by changing the standard deviation of this function to 25 (R25) and 400 (R400).

From the optimal egg-laying dates predicted by these scenarios and the egg-laying dates predicted from the proportional hazards model we calculated the mistiming as our measure of environmental change and calculated the rate of environmental change as the change in mistiming with year. As can be seen from Fig.A1 the rate of environmental change is mainly driven by the peak food abundance as the input parameters varied in our scenarios had little effect on it. Uncertainties in the costs of egg production, costs of incubation, nestling energy needs and the relationship between date and recruitment probability are hence not crucial for predicting the rate of environmental change.

References

1 Visser, M. E., L. J. M. Holleman, and P. Gienapp. (2006) Shifts in caterpillar biomass phenology due to climate change and its impact on the breeding biology of an insectivorous bird. Oecologia 147:164-172.

2 Naef-Daenzer, N., Naef-Daenzer, B. and Nager, R.G. (2000) Prey selection and foraging performance of breeding great tits *Parus major* in relation to food availability. Journal of Avian Biology, 31 (2): 206-214

3 Bell, G.P. (1990) Birds and mammals on an insect diet: a primer on diet composition analysis in relation to ecological energetic. Studies in Avian Biology 13: 416-422.

Table for S3 Description and values of the parameters. Units: GDD is growth degree days, *f* is working day, *c* is brood size.

Parameter	Description	Value	Units
c_{max}	Maximum brood size	12	#
a_{inc}	Number of days needed for incubation	12	d
a_{max}	Age at fledging	18	d
Δq_{max}	Maximum deviation from average temperature *q* (±)	10	°C
Δp_{max}	Maximum deviation from average temperature sum *p* (±)	300	GDD
T_{st}	Lower threshold temperature for temperature sum	5.4	°C
α	Parameter that controls the strength of autocorrelation in daily temperature	0.005	-
A_F	Adjusts the height of the caterpillar biomass	1300	g $m^{-2}d^{-1}$
μ_F	Temperature sum at peak of the caterpillar biomass	306	GDD
σ_F	Adjusts the width of the caterpillar biomass peak	70	GDD
A_E	Maximum energy at caterpillar peak	360	kJ
β_E	Affects the slope of the biomass dependent energy increase	0.6	$g^{-1} m^2 d$
γ_E	Biomass at which the increase starts to decelerate	1.8	g $m^{-2}d^{-1}$
E_g	Energy level in environment of other food sources	65	kJ
m_1	Resting metabolic rate in thermal neutral zone	29.98	kJ d^{-1}
m_2	Increase in RMR below temperature threshold neutral zone	0.899	kJ d^{-1} °C^{-1}
T_t	Lower temperature threshold thermal neutral zone	8	°C
f	Working day	8	h
h	Increased energy expenditure during foraging	71.021	kJ f^{-1}
i_1	Intercept energy expenditure during incubation at night	1.789	kJ h^{-1}
i_2	Temperature dependent decrease in energy expenditure	0.076	kJ h^{-1}°C^{-1}
i_3	Intercept energy expenditure during incubation during day	6.084	kJ h^{-1}
i_4	Temperature dependent decrease in energy expenditure	0.216	kJ h^{-1}°C^{-1}
i_5	Temperature dependent increase in time available for foraging during incubation	0.03	f°C^{-1}
A_y	Maximum daily energy intake per nestling	19.209	kJ c^{-1} d^{-1}
β_y	Affects the slope of the rapid increase	0.489	d^{-1}
γ_y	Age at which the rapid daily increase of energy demand starts to decelerate	4.569	d
y_1	Parameters that controls how the energy need of one nestling depends on temperature and clutch size	-0.398	°C^{-1}
y_2	Parameters that controls how the energy need of one nestling depends on temperature and clutch size	10.069	-
y_3	Parameters that controls how the energy need of one nestling depends on temperature and clutch size	0.029	°C^{-1}
y_4	Parameters that controls how the energy need of one nestling depends on temperature and clutch size	1.006	-
d	Mortality probability due to predation	0.0012	-
A_v	Adjusts the peak reproductive value for one fledged young	50	-
μ_v	Temperature sum at peak reproductive value for young	306	GDD
σ_v	Adjusts width of the normal distribution of the reproductive value measured in degree days.	100	GDD

Figure

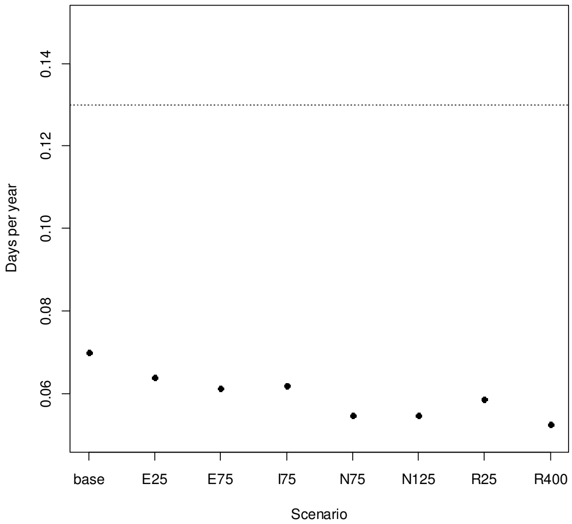

Fig.S3 Sensitivity of the predicted rate of environmental change (filled symbols) to variation in the input parameters of the model for optimal breeding time. 'Base' is the baseline scenario used in our analysis. The other scenarios (E25-R400) vary in egg production costs, incubation costs, nestling energy needs and recruitment probability (see text for details). The dotted line indicates the 'critical rate of environmental change' (k_c) as predicted from the Bürger & Lynch-model.