

APPENDIX S1

METHODS – LITERATURE REVIEW

We conducted a search of the literature using ISI Web of Science (www.isinet.com) and Google Scholar (www.scholar.google.com) to find and categorise hypothesised explanatory characteristics. The search terms included various combinations of: “climate, climate change, climate change impact, phenology, sex-skew, body size, body mass, migration, physiology, demography, survival, reproductive success, fecundity, population, population trend, elasticity, sensitivity, counteract, reinforce, multiple climate variables, multiple climate factors, multifactor climate experiment, multiple climate change drivers, life history, traits and characteristics”. Relevant articles were initially identified based on their titles and abstracts and relevant citations within papers were also checked.

METHODS – WORKED EXAMPLE

CLIMATE WINDOWS

The R package *climwin* (Bailey & van de Pol 2015) was used to find the time period during which mean temperature explained the most variation in mean lay dates (weighted by annual sample size) for each species. We looked at every possible combination of dates from a cut-off (37 days after the latest mean lay date across all years) back to 365 days ago.

The best window was selected (as judged by the lowest AICc value) and those temperature values were used in the subsequent analyses. There were, however, a couple of cases where the best model appeared to be a false positive resulting from the large number of windows being tested, because the next best models all suggested a very different time period. In this case, this model was disregarded and the best model from the different time period was selected. If there was no clear temperature window (following Bailey & van de Pol 2015, this was defined as (1) AICc values less than 10-15 better than the null model, (2) the better models suggest a large, seemingly random

range of periods, or (3) the best window spans less than 10 days) that species was removed from any further analyses as we were only interested in those species that showed a lay date response to temperature.

Only 8 out of 35 species were not found to have temperature affect the date of laying, and were therefore excluded (Table S1). These species were often opportunistic species (e.g. doves and pigeons), or had small sample sizes. For the majority of species, mean spring temperature (roughly March-May) was the important climate factor for changes in lay date. Previous studies have identified similar windows using the same data but with different techniques (Thackeray *et al.* submitted; Phillimore *et al.* submitted). Most temperature signals were as expected, with early breeders responding to earlier temperatures (e.g. robin) and long-distance migrants responding to later temperatures (e.g. redstart).

Table S1 The periods that mean temperature was calculated from for each species and whether they were included in any further analyses.

	Species	WindowOpen	WindowClose	Included
1	Blackbird	11-Mar	9-Apr	Yes
2	Blackcap	8-Mar	8-May	Yes
3	Blue tit	22-Mar	1-May	Yes
4	Chaffinch	7-Mar	10-May	Yes
5	chiffchaff	6-Mar	6-May	Yes
6	Coal tit	19-Mar	3-May	Yes
7	Dunnock	27-Mar	1-Apr	Yes
8	Garden Warbler	22-Mar	9-May	Yes
9	Great spotted woodpecker	14-Mar	29-Apr	Yes
10	Great tit	13-Mar	5-May	Yes
11	Jackdaw	17-Mar	25-Apr	Yes
12	Little owl	15-Feb	28-Apr	Yes
13	Magpie	5-Mar	31-Jul	Yes
14	Marsh tit	18-Mar	1-May	Yes
15	Mistle thrush	11-Mar	30-Mar	Yes
16	Nuthatch	11-Feb	1-May	Yes
17	Pied Wagtail	25-Mar	10-May	Yes
18	Redstart	9-Apr	2-Jun	Yes
19	Reed bunting	16-Jan	22-May	Yes
20	Reed Warbler	26-Jan	16-Jul	Yes
21	Robin	9-Feb	20-Apr	Yes
22	Sedge Warbler	8-Jan	10-May	Yes

23	Song thrush	18-Mar	31-Mar	Yes
24	Spotted flycatcher	27-Apr	3-Jun	Yes
25	Treecreeper	8-Mar	12-Jun	Yes
26	Whitethroat	14-Apr	2-Jun	Yes
27	Wren	14-Mar	28-May	Yes
28	Bullfinch	20-Feb	24-Feb	No
29	Collared dove	25-Mar	25-Mar	No
30	Corn bunting	7-Feb	28-Jul	No
31	Tawny Owl	24-Mar	24-Mar	No
32	Turtle dove	19-May	28-May	No
33	Woodpigeon	8-Sep previous year	15-Sep previous year	No
34	Yellow wagtail	15-Apr	9-May	No
35	Yellowhammer	30-Sep previous year	30 -ep previous year	No

EFFECT SIZE CALCULATIONS

We analysed annual estimates of mean egg laying dates, mean number of fledglings produced per breeding attempt (FPBA) and an index of population size on birds throughout the United Kingdom between 1966 and 2013 provided by the British Trust for Ornithology's Nest Record Scheme and the joint common bird census (CBC) and Breeding bird survey (BBS). The estimates of FPBA were not derived from direct observations, but rather as a function of maximum recorded brood size and egg and chick stage nest failure rates. As a consequence, these data do not take partial brood losses into account (Crick *et al.* 2003), so annual variation in breeding success may be under-estimated. However, FPBA is the standard productivity parameter used by BTO to identify temporal trends in breeding success (Baillie *et al.* 2014) and to explore the relationship between breeding success and population trajectory (e.g. Siriwardena *et al.* 2000; Finch *et al.* 2014; Morrison *et al.* 2015). The population values were an index (relative to an arbitrary value of 100 assigned for the population values in 2011) of population size, so they did not provide actual estimates of the numbers of animals, but rather the difference in population size compared to those in 2011. This rescaling has no effect on the estimates of population growth rate. We calculated the annual population growth rate as $r_t = \log\left(\frac{nt+1}{nt}\right)$, where n is the indexed annual population value. The corn bunting, great spotted woodpecker, marsh tit and little owl were all missing information for some of the 48 years.

We constructed structural equation models (SEMs) for each species individually. Each species had the same model (Fig. 3i presents the model used for this analysis) that partitioned the net effects of temperature on the three response variables into direct and indirect effects. The indirect pathway was the focal pathway by which temperature impacted population growth via laying date and reproduction. The direct and indirect path coefficients and bootstrapped standard errors from each species were used in subsequent comparative analyses. The temperature values for each window were mean centred for these analyses. Lay dates, FPBA and the population growth rate were approximately normally distributed within species. All SEMs fitted the data well (poor model fit was determined if the RMSEA value was greater than 0.06 and if CFI values were less than 0.95; Hu & Bentler 1999) with the exception of four species (the coal tit, dunnock, jackdaw and spotted flycatcher). We investigated these 4 species using linear regressions and in all cases there was at least one pathway that had a negative R^2 value because there was no clear trend (i.e. the fit was worse than fitting a horizontal line because the data were evenly spread). However, we decided to include these species in the comparative analysis because (1) their slope estimates could not be distinguished from zero, (2) their slope estimates were not very different to the estimates produced by the well fitted models, and (3) the comparative analysis results did not change when these four species were excluded.

To test the single pathway hypothesis, annual number of reproductive events, we used the information from Fergusson-Lees *et al.* (2011) on the number of broods of each species. Some single-brooded species are known to have replacement broods if their first attempt fails, but this was not taken into account in this analysis. To test the density-dependence multiple pathway hypothesis, we calculated the strength of density-dependence by linear regression of the population growth rate (r_t) over the population size in year t . In the analysis, continuous density dependent values were used, however, in order to visually represent their pattern in Figure 4d we designated each species to be either weakly density-dependent if their slope values were less than -0.0001, or strongly density-dependent if they were greater than -0.0001.

80 SPECIES COMPARISON

81 The path estimates from the SEMs were used to compare the sensitivities across all of the species at
82 each hierarchical level. Linear models weighted by the inverse of the estimated standard error of the
83 regression coefficient were used to investigate patterns in sensitivities and the two *a priori* selected
84 hypotheses, number of broods and density dependence (Table 1). We compared the linear models
85 by using the second order Akaike's Information Criteria (AICc) scores. Models within 2 AICc units of
86 each other were considered equally well supported (Burnham and Anderson 2002).

87 SUPPLEMENTARY REFERENCES

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RESULTS – WORKED EXAMPLE

Table S2 Models investigating the variables that best explain the total effect of temperature on reproductive success among species. $\frac{dRS}{dTemp}$ refers to the total effect of temperature on reproductive success (all pathways are included), $\frac{dLay}{dTemp}$ refers to the effect of temperature on of lay date and the factor broods refers to whether species are single- or multi-brooders. The variable $\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay}$ refers to the indirect pathway (i.e. the effect of temperature on reproductive success that is mediated by laying date) where $\frac{\partial RS}{\partial Lay}$ refers to the partial effect of lay date on reproductive success, holding temperature constant. The value 1 refers to an intercept only (null) model.

	Model	Log-likelihood	AICc	$\Delta AICc$	Weight	Estimate $\pm$ SE	R ²
2	$\frac{dRS}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} \right)$	24.1	-41.2	0.0	0.98	0.77 $\pm$ 0.18	0.41
1	$\frac{dRS}{dTemp} \sim \frac{dLay}{dTemp}$	20.1	-33.2	8.0	0.02	-0.03 $\pm$ 0.01	0.21
3	$\frac{dRS}{dTemp} \sim \frac{dLay}{dTemp} * \text{broods}$	21.1	-29.4	11.8	0.00	-0.03 $\pm$ 0.02	0.20
0	$\frac{dRS}{dTemp} \sim 1$	16.4	-28.4	12.8	0.00	0.06 $\pm$ 0.02	

Table S3 Models investigating the variables that best explain variation in the effect of temperature on population growth rates among species. $\frac{dPop}{dTemp}$ refers to the total effect of temperature on the population growth rate (all pathways are included), $\frac{dLay}{dTemp}$ refers to the effect of temperature on of lay date, the factor broods refers to whether species are single- or multi-brooders and the factor density refers to the strength of density-dependence. The variable $\left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right)$ refers to the indirect pathway (i.e. the effect of temperature on the population growth rate via laying date and reproductive success) where $\frac{\partial RS}{\partial Lay}$ refers to the partial effect of lay date on reproductive success, holding temperature constant and $\frac{\partial Pop}{\partial RS}$ refers to the partial effect of reproductive success on population growth, holding temperature constant. The value 1 refers to an intercept only (null) model.

	Model	Log-likelihood	AICc	$\Delta AICc$	Weight	Estimate $\pm$ SE	R ²
3	$\frac{dPop}{dTemp} \sim \text{broods}$	105.0	-202.9	0.0	0.88	-0.006 $\pm$ 0.002	0.22
0	$\frac{dPop}{dTemp} \sim 1$	101.0	-197.6	5.3	0.06	0.0005 $\pm$ 0.001	
1	$\frac{dPop}{dTemp} \sim \frac{dLay}{dTemp}$	101.8	-196.6	6.3	0.04	0.0007 $\pm$ 0.0005	0.02
2	$\frac{dPop}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right)$	101.4	-195.7	7.2	0.02	0.15 $\pm$ 0.18	0.00
4	$\frac{dPop}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right) * \text{Density}$	101.6	-190.3	12.6	0.00	-224.0 $\pm$ 521.1	0.00

Table S4 Models investigating the variables that best explain the total effect of temperature on reproductive success among species with the Magpie removed. See Table S2 for details.

	Model	Log-likelihood	AICc	Δ AICc	Weight	Estimate $\pm$ SE	R ²
2	$\frac{dRS}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} \right)$	25.8	-44.6	0.0	0.98	0.63 $\pm$ 0.17	0.33
0	$\frac{dRS}{dTemp} \sim 1$	20.0	-35.6	9.0	0.01	0.05 $\pm$ 0.02	
1	$\frac{dRS}{dTemp} \sim \frac{dLay}{dTemp}$	21.3	-35.5	9.1	0.01	-0.02 $\pm$ 0.01	0.05
3	$\frac{dRS}{dTemp} \sim \frac{dLay}{dTemp} * \text{broods}$	21.7	-30.4	14.1	0.00	0.006 $\pm$ 0.03	0.00

Table S5 Models investigating the variables that best explain variation in the effect of temperature on population growth rates among species with the Magpie removed. See Table S3 for details.

	Model	Log-likelihood	AICc	Δ AICc	Weight	Estimate $\pm$ SE	R ²
3	$\frac{dPop}{dTemp} \sim \text{broods}$	101.5	-195.9	0.0	0.80	-0.005 $\pm$ 0.002	0.18
0	$\frac{dPop}{dTemp} \sim 1$	98.3	-192.1	3.8	0.12	0.001 $\pm$ 0.001	
2	$\frac{dPop}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right)$	98.6	-190.1	5.8	0.04	0.13 $\pm$ 0.17	0.00
1	$\frac{dPop}{dTemp} \sim \frac{dLay}{dTemp}$	98.3	-189.5	6.4	0.03	0.00008 $\pm$ 0.0007	0.00
4	$\frac{dPop}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right) * \text{Density}$	99.1	-185.2	10.7	0.00	-349.9 $\pm$ 503.4	0.00

Table S6 Models investigating the variables that best explain variation in the effect of temperature on population growth rates among species with the Redstart removed. See Table S3 for details.

	Model	Log-likelihood	AICc	Δ AICc	Weight	Estimate $\pm$ SE	R ²
3	$\frac{dPop}{dTemp} \sim \text{broods}$	102.4	-197.8	0.0	0.96	-0.007 $\pm$ 0.002	0.30
0	$\frac{dPop}{dTemp} \sim 1$	97.3	-190.1	7.7	0.02	0.0003 $\pm$ 0.001	
1	$\frac{dPop}{dTemp} \sim \frac{dLay}{dTemp}$	98.3	-189.5	8.2	0.02	0.0007 $\pm$ 0.0005	0.03
2	$\frac{dPop}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right)$	97.4	-187.7	10.1	0.01	-0.21 $\pm$ 0.56	0.00
4	$\frac{dPop}{dTemp} \sim \left(\frac{dLay}{dTemp} * \frac{\partial RS}{\partial Lay} * \frac{\partial Pop}{\partial RS} \right) * \text{Density}$	98.1	-183.2	14.5	0.00	-71.9 $\pm$ 533.4	0.00