Supplemental materials: The illusion of declining temperature sensitivity with warming

the lab & friends

1 Models of leafout timing

Here we consider how a common process model of leafout day (n) varies as a function of average daily temperature (X_i). In this model leafout occurs after accumulated daily temperatures cross a critical threshold (β). Ideally, researchers would know the date that temperatures generally start to accumulate, and accumulate from that zero point to n. In practice researches often accumulate over a fixed window ($[a, b]$ such as March 1 to April 30) that they apply to all species or sites. Thus, let:

$$
\begin{aligned}
i &= \text{index the days, } i = 0, 1, ..., N \\
X_i &= \text{observed temperature on day } i\text{, assume } X_0 = 0 \\
\mu * i &= \text{average temperature on day } i = 1; X_i \sim \mathcal{N}(\mu * i, \sigma), i > 0 \\
[a, b] &= \text{temporal window over which temperature is measured, where } 0 <= a < n <= b <= N \\
S_a^b &= \sum_{i=a} bX_i \\
\beta &= \text{a threshold of interest, } \beta > 0, \text{ (for example, F* or required GDD)} \\
n &= \text{the first day such that } \beta < S_n, \text{ (for example, day of year (doy) of budburst)}
\end{aligned}
$$

Here, X_i is a gaussian random walk with drift and n is a hitting time. Thus, the continuous time generalization would be a Brownian motion with instantaneous variance σ and drift μ. The time, t, the process hits some threshold β is distributed Inverse Gaussian Distribution, having mean μ/β and variance $\mu * \sigma/\beta^3$. Assuming $a = 0$ and $n = b$, then regressing n (e.g., day of leafout) against average daily temperature until n (as much research does when calculating temperature sensitivities currently), then this is equivalent to: $S_a^n/n \approx \beta/n$. Thus, $log(n) \approx log(\beta) - log(S_a^n/n)$ and $log(n)$ is linear in log-average daily temperature with a slope -1 and intercept $log(\beta)$ (e.g., in simulations in Fig. 1 in main text slope is -1, and intercept is $log(200) = 5.3$).

2 Results using long-term empirical data from PEP725

To examine how estimated sensitivities shift over time, we selected sites of two common European tree species (*Betula pendula* (silver birch) and *Fagus sylvatica* (European beech)) that have long-term observational data of leafout, through the Pan European Phenology Project (PEP725, **?**).

We used a European-wide gridded climate dataset *(*E-OBS, **?***)* to extract daily minimum and maximum temperature for the grid cells where observations of leafout for these two species were available.

3 Tables

Table S1: Climate and phenology statistics for two species (*Betula pendula, Fagus sylvatica*, across 45 and 47 sites respectively) from the PEP725 data across all sites with continuous data from 1950-1960 and 2000-2010. ST is spring temperature from March 1 to April 30, ST.leafout is temperature 30 days before leafout, and GDD is growing degree days 30 days before leafout. We calculated all metrics for for each species x site x 10 year period before taking mean or variance estimates. See also Fig. S4.

		mean(ST)	mean(ST.leafout)	var(ST)	var(leafout)	mean(GDD)	slope	log-slope
1950-1960	Betula pendula	5.6	7.0	3.4	110.5	71.7	-4.3	-0.17
2000-2010	Betula pendula	6.6	6.8	1.2	47.0	64.6	-3.6	-0.22
1950-1960	Fagus sylvatica	5.6	7.5	3.3	71.9	83.8	-2.8	-0.11
2000-2010	Fagus sylvatica	6.7	7.7	1.2	38.3	86.7	-3.4	-0.20

Table S2: Climate and phenology statistics for two species (*Betula pendula, Fagus sylvatica*, across 17 and 24 sites respectively) from the PEP725 data across all sites with continuous data from 1950-2010. ST is spring temperature from March 1 to April 30, ST.leafout is temperature 30 days before leafout, and GDD is growing degree days 30 days before leafout. We calculated all metrics for for each species x site x 20 year period before taking mean or variance estimates. See also Fig. S5. **Side note: Need to work on hline.after and italics.**

		mean(ST)	mean(ST.leafout)	var(ST)	var(leafout)	mean(GDD)	slope	log-slope
1950-1970	Betula pendula	5.8	7.1	2.6	79.9	72.5	-4.3	-0.19
1970-1990	Betula pendula	5.9	7.2	1.3	104.8	72.2	-6.1	-0.33
1990-2010	Betula pendula	6.8	6.7	0.9	36.2	60.0	-3.3	-0.21
1950-1970	Fagus sylvatica	5.6	7.6	2.7	63.4	86.0	-3.1	-0.12
1970-1990	Fagus sylvatica	5.6	7.5	1.3	56.2	81.3	-2.5	-0.12
1990-2010	Fagus sylvatica	6.7	7.3	1.2	31.4	76.0	-3.4	-0.19

4 Figures

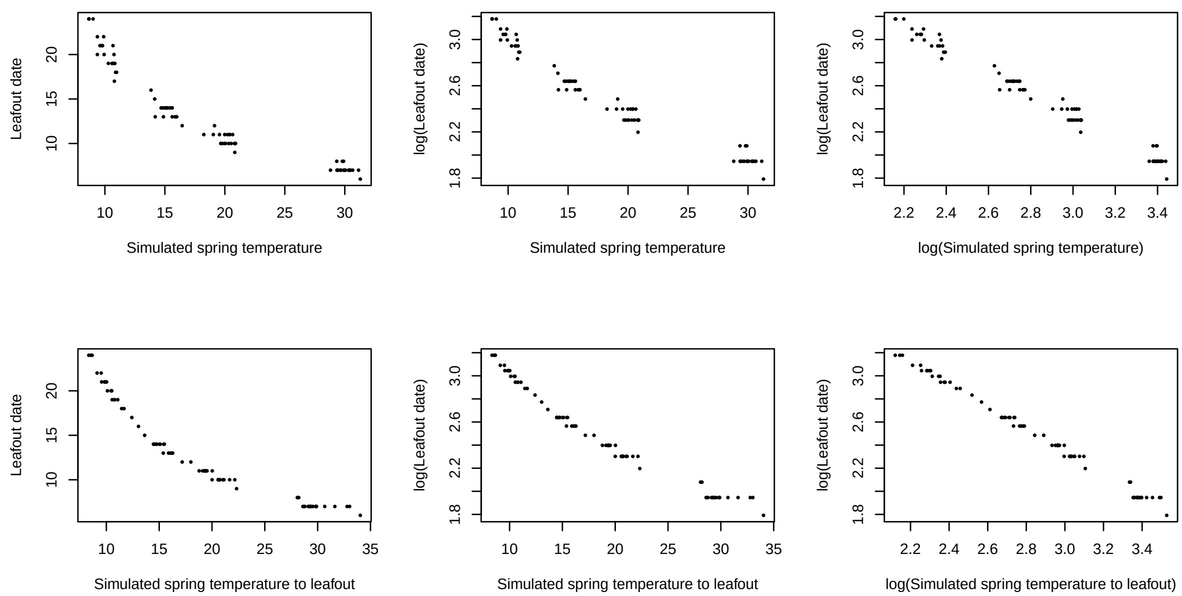

Figure S1: **Simulated leafout as a function of temperature across different temperatures highlights non-linearity of process.** Here we simulated sets of data where leafout constantly occurs at 200 growing degree days across mean temperatures of 0, 5, 10 and 20C (constant SD of 4), we calculated estimated mean temperature across a fixed window (top row, similar to estimates of 'spring temperature') or until leafout date (bottom row). While within any small temperature range the relationship may appear linear, is non-linear relationship becomes clear across the range shown here (left). Taking the log of leafout (middle) reduces this some, but taking the log of both leafout and temperature (right) linearized the relationship.

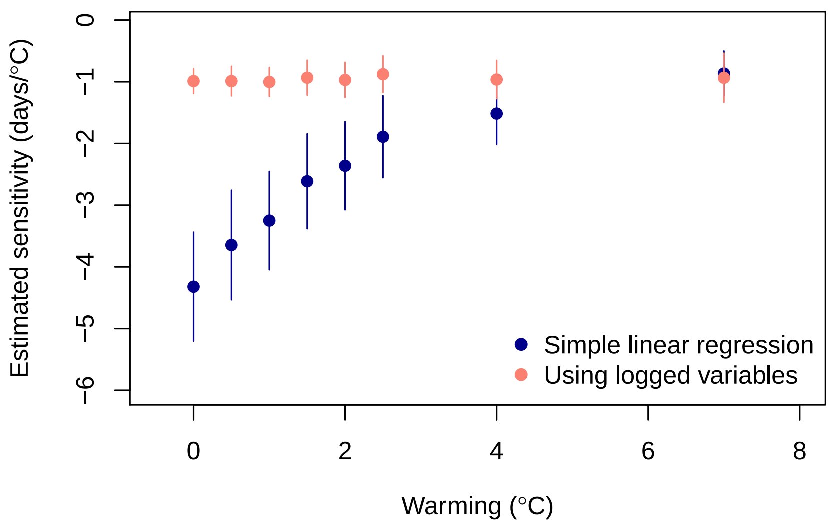

Figure S2: **A simple model generates declining sensitivities with warming.** We found declines in estimated sensitivities with warming from simulations with no underlying change in the biological process when sensitivities were estimated with simple linear regression ("Simple linear regressions"). This spurious decline disappears using regression on logged predictor and response variables ("Using logged variables").

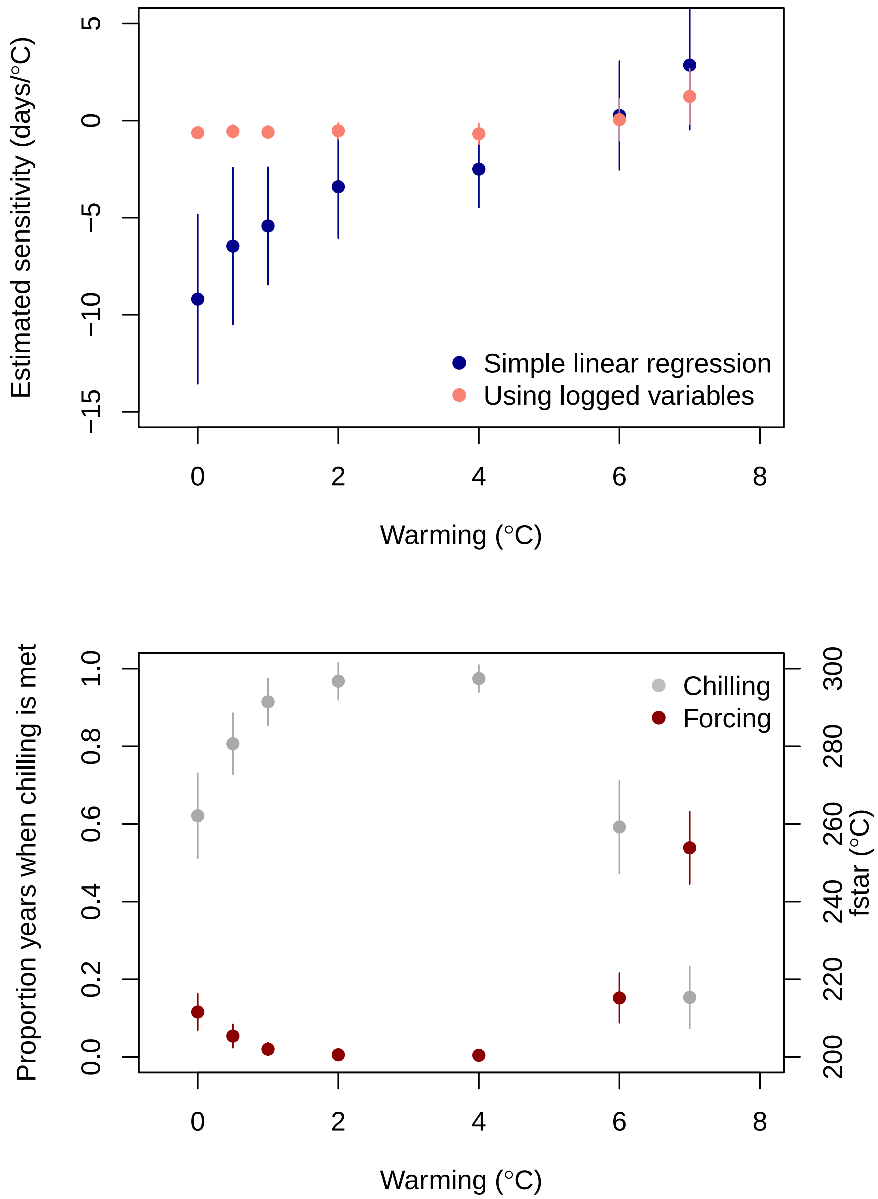

Figure S3: **Simulated leafout as a function of temperature across different temperatures with shifts in underlying cues.** Here we simulated sets of data where leafout occurs at 200 growing degree days ('fstar') when chilling is met, and requires additional growing degree days when chilling is not met. We show estimates sensitivities in the top panel, and the shifting cues on the bottom panel.

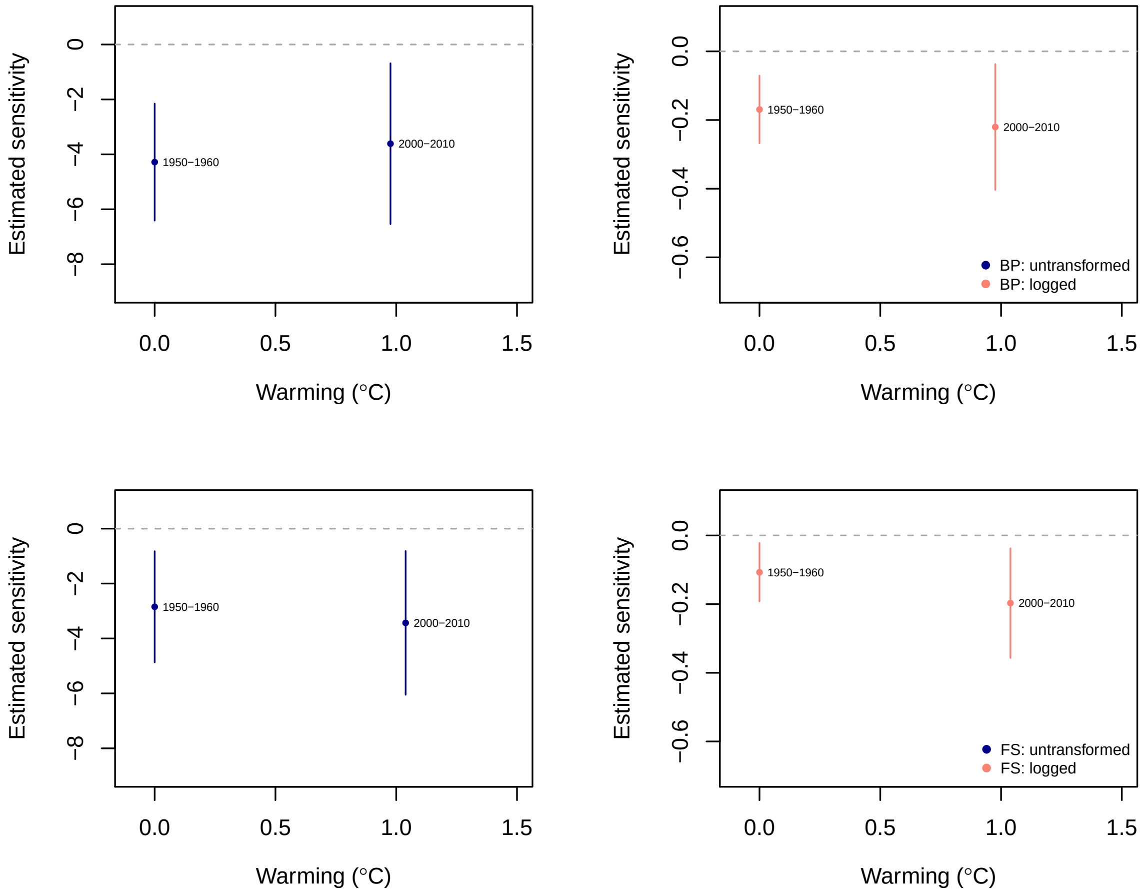

Figure S4: **Sensitivities from PEP725 data using 10 year windows of data** for two species (top – *Betula pendula*, bottom – *Fagus sylvatica*; all lines show 78% confidence intervals from linear regressions). Amounts of warming are calculated relative to 1950-1960 and we used only sites with leafout data in all years shown here. Both approaches show variation in sensitivity across time. See Table S1 for further details.

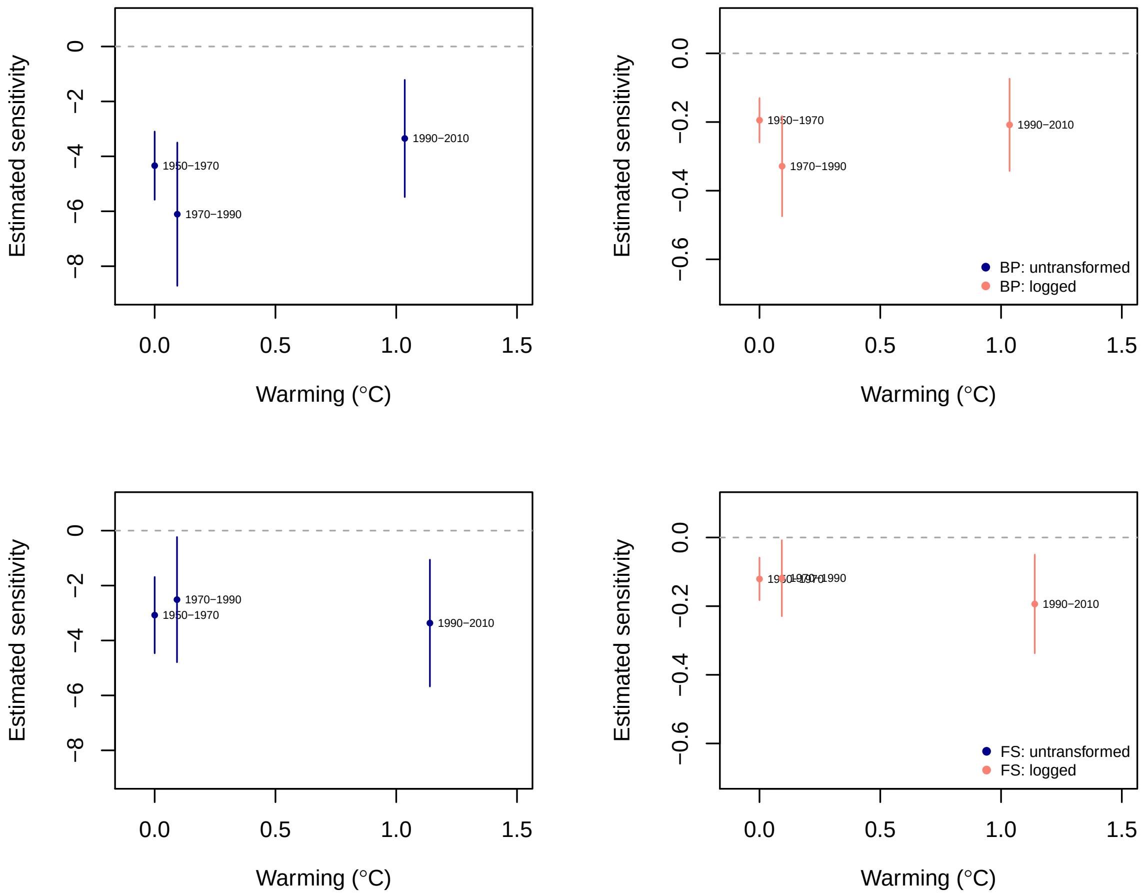

Figure S5: **Sensitivities from PEP725 data using 20 year windows of data** for two species (top – *Betula pendula*, bottom – *Fagus sylvatica*; all lines show 78% confidence intervals from linear regressions). Amounts of warming are calculated relative to 1950-1970 and we used only sites with leafout data in all years shown here. Both approaches show variation in sensitivity across time. See Table S2 for further details.