

1 Data

Phenological data

We developed two large-scale databases comprising 50 studies (Table S1, Figure S1) for our analyses. For observational records of plant phenology we built a new compilation of long-term observational plant phenology datasets, the *Network of Ecological and Climatological Timings Across Regions* (NECTAR) database. This database is unique in focusing on wild plant species, with special emphasis on observations of communities; it represents a mix of datasets spanning over 200 years reporting mainly flowering and leafing, including first event data (e.g., first flower, FFD or first leaf, FLD) and monitoring data (e.g., observations of phenological state every several days) at site and sub-site (plot) level. To make the data comparable we converted all events to first event per species x site x year: unpublished analyses suggest conversion to first-events at the level of site produce unbiased, highly similar sensitivities to those calculated at the plot level. For monitoring data (see Table S2), which recorded whether a species was flowering, or, for some sites, leafing, we took first date as the first observation when flowering or leafing was observed (Table S2). For Harvard Forest (USA) we considered FLD to be when the percentage of buds on the tree that have broken open, revealing leaves, was > 0 and FFD when the percentage of flower buds open on a tree was > 0 . For UW-Milwaukee (USA) we set FLD as the first date on which individuals of the species had recognizable leaves visible in 50% of their buds. We included only datasets for which we could robustly calculate sensitivities to mean annual temperatures (MAT). Thus we used only those sites that could be matched with mean annual climate data (i.e., we did not use data where a relatively local climate station was unavailable for the duration of the data), and were geographically-constrained (i.e., we did not use state or country-wide network datasets). Additionally, we used only observational studies that included a minimum of 5 years of phenology data. While many of the datasets in NECTAR have been analyzed previously (Table S1), this is the first publication using this database.

For our experimental data we developed a new database, *Synthesis of Timings Observed in iNcrease Experiments* (STONE) which includes data from 36 (37 with one outlier species, representing one study) warming experiments focused explicitly on assessing phenological change with temperature increases. To find these studies we searched the Web of Science (ISI) for Topic=(warm* OR temperature*) AND Topic=(plant* AND phenolog*) AND Topic=(experiment* OR manip*) in November 2009 and examined all 401 records, updating results through December 2010. To obtain the most accurate data we contacted authors, requesting access to their data (receiving 16.7% of data directly) then extracted phenological event dates and magnitude of warming data from the papers if authors could not share data. Studies conducted in distinctly different areas or habitats presented in one paper were each treated as individual sites. We compared all data once extracted and removed data that appeared to be duplicated (e.g., a publication would use data from 1994-1996 and another 1996-1999, if the data were identical we included the 1996 data only once), but we did not combine studies that appeared to be conducted at the same field site unless they specifically stated they were from the identical experiment. We generally extracted data for all treatments reported (e.g., several studies had additional snow or precipitation treatments) but found we had only sufficient data on temperature treatments for comparisons and analyses. We extracted all phenological data across all events (leafing, flowering and fruiting), but could only contrast leafing and flowering given the lack of fruiting records in NECTAR. When more than one phenological metric was reported per event (4 studies) we prioritized the earliest event to make the experiments most comparable to the observational data. For example, in one study first, mean and mode of flowering dates were reported, thus we used first flowering for our analyses. This resulted in almost all sensitivities from experimental studies being calculated from first flower (94.9% of flowering phenology data from experiments were first-flower data) or first leaf (98.4%), and thus comparable to observational data (100% first-flower or first-leaf).

Climate data

For our long-term observational sites we used climate data from the standardized Global Historical Climatology Network (GHCN) whenever possible (1). We give specific climate information for observational sites and additional information for all sites in Table S1 and S2. To examine the effect of interannual variability in temperature on all sites (observational and experimental) we calculated the standard deviation in temperature, using Version 2.1 of the climate grids from the Climate Research Unit (2), selecting the closest half degree gridcell to each site and using a standard period of years for all sites. Climate data for comparison against the Pan European Phenology (PEP725) database were taken from the European Climate Assessment (ECA) (3; 4; 5). In the ECA data, daily temperature and precipitation for 1950-2009 are interpolated from meteorological stations to a continuous quarter degree grid covering the European continent. We matched the PEP725 phenology records to daily ECA temperature and precipitation at the geographically closest grid cell.

Experiments reported mainly air or soil temperatures with most studies reporting only changes in air temperatures; for the 13 sites that reported both air and soil temperatures, we used air temperatures to make sensitivities calculated from experiments most comparable to the use of MAT in observational studies. Using soil instead of air temperatures when possible did not alter conclusions (Table S3). For the three experiments with multiple temperature treatments we calculated sensitivities for each species at each warming level. Because of varying experimental designs warming may have been more or less constant between days and seasons, however data on this were rarely reported (see main text for further discussion) thus we used the mean reported difference between control and experimentally-warmed plots.

2 Methods

Calculating sensitivities

To contrast experimental and observational findings we calculated temperature sensitivities for each species within a site i —a total of 2,298 sensitivities. We calculated all sensitivities ourselves from raw data for observations and experiments and from given phenological dates and temperature changes extracted from papers for experiments when raw data were not available.

For observational sites we calculated sensitivity in several different ways (see *MAT versus monthly temperatures* section) to prevent bias in our method yielding artificial differences between observational and experimental data. Our main method (presented in the main text), which is the most comparable to experiments, uses the β coefficient from a simple linear regression of

$$\text{phenological event date}_i = \beta_i(\text{MAT}) + \epsilon_i \quad (1)$$

where MAT is mean annual temperature for each site. MAT provides a coarse estimate of sensitivity, as it includes climate information outside the seasons of phenological response (primarily spring); this also yields more conservative estimates of sensitivity as focusing on mean temperatures experienced during shorter (and possibly more biologically relevant) periods generally increases sensitivities (6). However, given the limited reporting in the experimental studies on the timing and magnitude of the warming treatment, it provides the closest approximation to temperature data reported in experimental studies.

For each experiment we calculated sensitivity of each species, again, as the β coefficient from a simple linear regression using the data from control and warmed treatments. This simplifies to:

$$(\text{phenological event date}_{i,\text{warm}} - \text{phenological event date}_{i,\text{control}})/\Delta T \quad (2)$$

where ΔT was the change in temperature reported between warmed and control plots (whenever given we used data from control plots that included shams). Our regression-based estimates of temperature sensitivity were thus common across both experimental and observational data, and therefore directly comparable (7; 8). We did not use traditional meta-analytic statistics such as *hedge's g* (8) because our sensitivity calculations transformed all data into common, biologically-meaningful units that have been widely used in similar climate change studies (6; 9). Further, meta-analytic statistics can be vulnerable to systematic variation in sample sizes and variances (7), and fewer than half of the experiments assessed reported all metrics necessary for robust meta-analysis (8).

Statistics

We examined differences between observations and experiments using mixed-effects models implemented in R 2.12.0 (10), package nlme. Mixed-effects models include both fixed and random effects; this allows for non-independence among datapoints via the random effects part of a model and gives an overall unbiased estimate of the fixed effects (e.g., study type). Given the hierarchical nature of our data we chose mixed-effects models, even though such models often suffer from lower power than models without random effects. For our models we treated site and species, nested within site, as random effects: thus our models statistically incorporate varying trends across sites and species within sites to yield overall-estimates of plant responses. Because we had far more data for flowering than leafing (2,153 versus 123 unique species x site sensitivities), and thus substantial differences in variances between the two event types, we examined flowering and leafing via separate models and only examined trends with study type and other variables that required more complex models for flowering. Three of our 2,298 sensitivities were outliers, violating model assumptions of equal variance across groups: thus we report all estimates in the main text without these values and report model estimates with and without them here in the supplement—in all cases, the removal of these data does not change the results and most often produces more conservative estimates of the difference between experimental and observational studies.

For our observational and experimental sensitivities we did not exclude any values based on significance. The reason for this is two-fold. Most importantly, we were interested in the mean effect across species to climate change and a robust estimate must include those species significantly responding as well as those not responding (11), otherwise estimates will naturally bias towards higher rates of change per °C. Second, due to data limitations (> 51% of all studies failed to report sample size or a variance estimate) we had no way to integrate information related to significance for experimental studies.

We examined how the degree of temperature change affected sensitivities. We analyzed experiments and observations separately given the different variability (at the degree change x site x species level) in each dataset. For the observations we used a Monte-Carlo approach to compare all years to all others. We used only sites for which most monitored species experienced up to a 2 °C temperature range (9 of 14 sites); while some species at some sites experienced up to 5 °C difference, including these higher estimates would have violated model assumptions of equal variance and produced biased estimates. For each species within a site we compared all pairwise-years and calculated a sensitivity (thus, in a manner identical to the experimental warming sensitivities). We then binned changes from 0.5 to 2.5 °C temperature differences (0.5 °C intervals). We then restricted analyses to those species x site x degree change based on a median of sensitivities calculated on $n > 3$ year pairs (results are similar using a cut-off of 5). We used mixed-effects models where temperature change was the only fixed effect and species nested within site was random.

To test for evidence that temporal differences between experimental and observational studies could explain the smaller sensitivities observed in experimental studies we used several methods based on our observational data. Because we wished to look at differences in sensitivities collected over longer-periods and also before versus after the 1970s, when significant anthropogenic warming began (12; 13), we used only the datasets that were long-term (> 30 yrs), and included at least 10 years before and after 1970 and for which we had local climate data—which yielded two sites: Mohonk, NY, USA and Chinnor, UK. To determine whether sensitivities varied when calculated over short versus long-periods we used a Monte-Carlo approach: comparing each year to every other year to calculate sensitivities based on binomial years then taking the median sensitivity for each species. We then compared sensitivities calculated on data taken 31-35 years

apart versus 5 or fewer years apart for each species using a sign test (exact binomial test). To test whether sensitivities varied before and after 1970 and 1985 we used our linear regression approach, estimating the sensitivity via the β coefficient after dividing the data for both sites at 1970 and at 1985. We then again compared differences between the two sensitivities using sign tests.

3 Results

Observational sensitivities: MAT versus monthly-temperatures

For comparison to MAT, we also used a model based on monthly temperatures, similar to several studies of individual datasets (14; 15). For each species at each site we calculated its mean first month of flowering, we then took the mean of the preceding three months' mean temperatures and repeated our regression approach, using this annual 3-month mean temperature in place of MAT. Results were highly similar (Figure S2) to those using MAT. Finally, we also used a growing-degree day (GDD) model (using 0°C as the threshold) for the sites with comparable climate data (those with GHCN data, see Table S1). We summed GDD over overlapping 3-month periods (e.g., January-March, February-April, etc.), standardized to zero mean and unit standard deviation and selected the best-fitting model based on R^2 . This yielded far more species that were significant temperature responders (see main text), and though we cannot fit such a model for experiments given data limitations (experiments do not give standardized daily climate data), it suggests that any more refined models of temperature sensitivity for observational datasets would only exaggerate differences between experiments and observations.

NECTAR observational sensitivities: Comparisons with PEP725

Because our NECTAR database is unique from other phenological databases in focusing on wild-species and in containing many community-level datasets we compared results from it to a major phenological database, the PEP725 Pan European Phenology Data. This database contains far more sites than NECTAR (1,777 for FFD data, and 1,486 for FLD data) but fewer species (39 for FFD, 14 for FLD). We found that PEP725 sensitivities calculated using MAT (from the the European Climate Assessment) and a similar mixed-effects model approach fell within the range of our NECTAR sensitivities (Figure S2c), suggesting observational sensitivities are robust to the datasets used to calculate them. We provide our estimated PEP725 sensitivities as additional Supplementary Information (csv files).

Observational sensitivities: Comparisons with long-term trends & 1971-2000 standard

Our method of calculating observational sensitivities exploits interannual fluctuations in temperature to estimate how plants respond to temperature variability and change; this is comparable to experiments but does not rely on long-term temperature trends. To test that sensitivities to interannual fluctuations in temperature are similar to long-term responses we calculated observational sensitivities using a similar linear regression approach as explained above (equation 1) but using long-term trends:

$$\text{long-term trend in phenological event date/long-term trend in MAT} \quad (3)$$

Long-term trends analysis is, however, highly dependent on the timeframe and serial completeness of the data. Thus we subsetting our NECTAR data to observations that were on average at least 80% serially complete between the often-used standard time frame of 1971-2000 (9; 16). We found sensitivities calculated from long-term trends were quite similar to those calculated from interannual variation (Figure 3, main text). Additionally, the sensitivities estimated from this method (-6.8 ± 3.3 , mean \pm SE) were similar to those calculated using the full NECTAR database and interannual variations.

We also tested results using the long-term trend method directly against experiments. For this, we used PEP725 data—again, subsetting to sites with observations from 1971–2000 that were at least 80% serially complete, which yielded 236 stations and 35 species for FFD and 216 stations and 13 species for FLD. Using the same mixed-effects model explained previously in the methods we compared sensitivities calculated from experiments with those calculated from observational PEP725 data. As in the main text we found experimental sensitivities were significantly smaller than observational ones (Figure S3).

We found evidence that sensitivities calculated over longer periods and including data recorded before 1970—as in some of the observational studies—should not bias their sensitivity estimates to be higher than those calculated from short-term, relatively recent experiments. Sensitivities calculated over periods separated by 31–35 years tended to be smaller than those separated by 5 years or less (for Chinnor, UK, $p = 0.022$, $n = 384$, for Mohonk, USA, $p = 0.0076$, $n = 18$).

We found no significant difference in sensitivities calculated before and after known climate shifts. There was no significant difference in sensitivities using data before versus after 1970 (Figure S4a, for Chinnor, UK, $p = 0.11$, $n = 384$, for Mohonk, USA, $p = 0.48$, $n = 18$), when warming trends began to accelerate (12; 13), though in both cases sensitivities tended to be smaller after 1970. Nor was there any significant difference before versus after 1985 (Figure S4b, for Chinnor, UK, $p = 0.72$, $n = 384$, for Mohonk, USA, $p = 0.10$, $n = 18$), an important changepoint found in other studies (17), however, sensitivities calculated after 1985 tended to be greater (e.g., species advance more with warming).

Influence of species sampling & characteristics

Considering all species, experiments underpredicted the magnitude of phenological advance in response to temperature increase (Figure S5, Table S3). We additionally used a Monte-Carlo version of the basic mixed-effects model where we randomly sampled in only 3 species per observational dataset for each model run (999 total iterations), which helped to equalize species numbers per site for observations and experiments: estimates and significance were highly similar to the main method presented (for flowering compare main-text estimates in Table S3 with: experiments: -0.56, observations: -3.96).

We also looked at whether differences in species composition could have influenced results. Experiments and observations sampled mainly perennial and herb/forb species: thus we do not expect differences between sensitivities calculated from experiments and observations due to composition. Further, sensitivities did not differ among plant lifeforms ($F_{1,1891} = 0.17$, $p = 0.68$, Figure S6), but did vary with lifespan: sensitivities for annual species tended to advance 1.82 days/°C more than perennial species ($F_{1,1891} = 6.28$, $p = 0.012$)—however, this was consistent in both experiments and observations ($F_{1,1891} = 0.19$, $p = 0.66$, Figure S6).

Importance of other environmental variables to spring phenology

Numerous abiotic cues may control phenology depending on the species and location, including temperature, photoperiod, irradiance and soil moisture (18; 19; 20; 21). We focus here on temperature, however, for several reasons: First, temperature is the most consistent and dominant controller on spring phenology (22). In contrast, the exact role and impact of many other cues such as photoperiod, irradiance, CO_2 and precipitation, is unclear and varies strongly by site (23; 24; 25). Second, temperature was the dominant focus of most experiments and the only environmental variable with sufficient data to examine. Of our 36 experimental studies, 14 mentioned that precipitation may be important but for the seven that tested it results were equivocal, with five finding no effect (26; 27; 28; 24; 29) and two finding the effect varied by species (30; 31). Three studies manipulated CO_2 , two found no effect (32; 33) while one found it delayed flowering of some species (27).

One study mentioned that photoperiod may have affected results of a high temperature warming treatment (29). Photoperiod is expected to be critical to warming responses because it may limit a species ability to respond to temperature increases (19). However, recent studies suggest it may not be as dominant as expected: For tree species suspected to have strong photoperiod controls temperature can override physiological pathways of photoperiod control on phenology (34; 35). Thus, while photoperiod may be important at large scales (36), for some species and sites and clearly warrants further research we do not consider it here beyond testing for any change in sensitivities with the degree of warming.

Four studies (37; 38; 39; 40) also mentioned that snowmelt may be critical to predicting spring phenology at their sites. Snowmelt is expected to be an important controller in sites where snowpack is present throughout the winter season (41) and models that include snowmelt and temperature predict phenology better than only temperature for several species in one alpine habitat (37), however given the limited data available on it for both experiments and observations we were unable to examine its role here. Future work using both experimental and observational approaches would benefit from considering multiple environmental drivers, including—depending on site and species—precipitation and snowmelt, CO_2 and photoperiod as well as the differential roles of spring warming and winter chilling (42). Developing robust models about how to incorporate such variables, however, will most probably require novel modeling techniques and increased physiological data for a diversity of species (34; 43; 20; 44; 35).

Differences between experiments and observations may be produced if changes in MAT are correlated with unexamined variables that influence phenological events, a possibility given the many factors that have shifted or may shift with anthropogenic climate change (e.g., absolute humidity, cloud cover, 45; 40). Unfortunately we do not have data on many important metrics at the site \times year level necessary for analyses. However, we found no correlation between MAT and total precipitation (mixed effects model with site as random: $F_{1,297} = 0.07$, $p = 0.79$). Further, MAT has been far more variable over time than the relatively linear increase in CO_2 , and because nitrogen deposition is usually tied strongly with local sources (e.g., industry and urbanization-related sources, 46) there is little reason to believe it would correlate tightly with MAT.

Additionally, temperature ranges covered by experiments and observations were similar (Figure S7). Together this suggests that, given available data, MAT is a robust metric of changes in temperature for this study. However, given the complex changes in climate expected with global warming, the discrepancy in observational versus experimental results could be, in part, due to yet-unknown correlations among global change variables or nuanced shifts in global climate that experiments do not replicate. For example, if temperature co-varies strongly with other factors for which we did not have data (e.g., irradiance, nitrogen deposition or soil moisture) and these factors also strongly advance phenology, then observational data may overestimate temperature-specific sensitivities. The few experimental studies that manipulate multiple factors have found generally inconsistent effects of other factors (see above and 47; 23), so it remains unclear what factor(s) could co-vary strongly and consistently enough with temperature to amplify plant sensitivities.

Experimental design

We also tested for a variety of factors that could affect the sensitivities of experiments (Table S5). Sensitivities calculated from experiments did not vary between passive versus active warming designs ('active' includes all studies using soil cables and above-canopy heating while 'passive' is opentop chambers and other methods that did not actively introduce heat). However, for flowering, sensitivities varied with the exact design of warming ($F_{2,22} = 7.21$, $p = 0.004$, categories were: above-canopy heating, opentop or other, see Table S2 for variation in designs), with above-canopy designs showing the greatest advance with warming (Figure S8). There was no variation in sensitivities between the three study designs for leafing ($F_{2,12} = 0.19$, $p = 0.83$). We also examined the warming designs of studies with mean sensitivities in the lowest quartile (e.g., greatest advance with warming). The seven studies with lowest flowering sensitivities (sites 0, 1, 5, 6, 16, 29, 32, see Table S2), and the four studies with lowest leafing sensitivities (8, 11, 21, 22 in Table S2) were not significantly different from a random sample of warming designs (flowering: $\chi^2 = 1.62$, $df = 2$, $p = 0.45$, leafing: $\chi^2 = 0.33$, $df = 3$, $p = 0.95$). Taken together these results suggest that above-canopy heating methods may warm plots more realistically (48; 49; 50; 51), but that far more experimental studies are needed—including those that directly compare methods—to make strong inferences about the best overall design. Additionally, in contrast to the majority of studies in the meta-analysis, future experiments should quantify and report artifacts or use sham-controls.

The only current published comparison of phenological responses from experiments and observations (37), of which we are aware, comes from Gothic, Colorado (site 29). We thus examined our data from this study in detail. Our data differ in comparison to those used in (37) in several key ways: namely we used FFD, as opposed to a modeled estimate of phenology, to maintain consistency with other studies, and we used 10 additional years of observational long-term data. For this site we additionally calculated sensitivities

based on snowmelt for comparison to previous studies (long-term snowmelt data are uniquely available at this site, *B. Barr, unpublished data*). We calculated snowmelt sensitivities for long-term observations and experiments using the same methods as for temperatures (equation 1) but substituting snowmelt date for temperature. We found that sensitivities at site 29 (to temperature or snowmelt) from experiments and observations were very similar, though sensitivities were slightly smaller—on average—for the experimental warming study (mean temperature sensitivity for experiments: -4.7 , for long-term observational data -6.8 ; mean snowmelt sensitivity for experiments: 0.31 days advance of flowering/days advance of snowmelt, for long-term observational data: 0.45).

Sensitivities estimated from experiments did not vary with habitat type or study length, nor was there any relationship between sensitivities and whether we used raw or derived data (i.e., we extracted it from papers) or publication year. We also examined whether the design of phenological data collection affected sensitivities: some experiments tag individuals and monitor them throughout the study period, while others tagged a number of individuals per plot to develop a plot average and others simply took the first event (leafing or flowering) per species per plot. We found no relationship between the method of phenological data collection and the resulting sensitivity (Table S5).

Finally many open-top chamber experiments remove warming structures during the winter for logistical reasons and to prevent excess snowpack build-up around structures. Such non-year-round manipulations may fail to advance snowmelt, an important trigger for plant phenology in many snowpack-dominated systems (see above). However, we found no relationship in sensitivities with whether experimental warming was applied year-round or only during the growing season (Table S5).

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5 Data release

Sensitivities used from this paper, the complete STONE database and all related R code will be posted to Knowledge Network for Biodiversity (KNB, <http://knb.ecoinformatics.org/>) within 6 months of publication.

Table S1: Sites included in the meta-analysis. Experimental sites correspond to map (Figure S1) numbers 0-36, observational sites are 37-50. We give the source, the number of species, the maximum number of and exact years of data, and climate data used for the observational sites. Note that some sites may have multiple sources, we give only one, for experiments we give the one from which we extracted data, when applicable. For experiments we give the first year of the experiment parenthetically when it is not the first year of data.

map	site name	source	spp.	n (yrs)	data yrs	climate data
(0)	Bogong High Plains, Australia	(52)	14	4	2003-2006	
1	Abisko, Sweden (2004)	(53)	2	3	2001-2002 (2000)	
2	Abisko, Sweden (2008)	(39)	3	1	2007	
3	Aelmoeseneic, Belgium	(54)	1	2	2008-2009	
4	Atqasuk, AK, USA	(55)	2	3	1996-1999	
5	Barrow, AK, USA - wet	(55)	2	5	1994-1999	
6	Barrow, AK, USA - dry	(55)	2	5	1995-1999	
7	Clocaenog, UK	(56)	6	3	2000-2004 (1999)	
8	Corvallis, OR, USA	(57)	4	1	1996 (1993)	
9	Fargo, ND, USA	(58)	13	1	2009	
10	Finse, Norway	(59)	3	1	1995-1997	
11	Garraf, Spain (2009)	(56)	2	7	2001-2004 (1999)	
12	Garraf, Spain (2008)	(31)	2	6	1999-2001	
13	Garraf, Spain (2005)	(60)	3	2	2003-2005 (1999)	
14	Harvard Forest, MA, USA	(61)	3	7	1993 (1991)	
15	Hungary	(56)	1	2	2003-2004	
16	Jasper Ridge, CA, USA	(23)	9	5	2000-2002 (1998)	
17	Kangerlussuaq, Greenland	(62)	7	3	2003-2004 (2002)	
18	Latnajaure, Sweden	(30)	2	3	1996-1998 (1993)	
19	Latnajaure, Sweden	(63)	1	2	1993-1995	
20	Latnajaure, Sweden (2005)	(38)	1	6	1994 (1993)	
21	Mols, Denmark	(56)	2	5	2003 (1999)	
22	Montpellier, France	(29)	3	3	2003-2005	
23	Mt. Sandalsnuten, Norway	(64)	1	4	1994-1997	
24	Ny-Alesund, Norway	(26)	1	1	1991	
25	Oklahoma USA	(28)	12	2	2003-2004	
26	Oldebroek, Netherlands	(56)	1	5	2003 (1999)	
27	Plum Island, MA, USA	(24)	3	1	2006	
28	Roane County, TN, USA	(32)	3	4	1995-1997 (1994)	
29	RMBL, Gothic, CO, USA	(37)	10	8	1995-1998 (1991)	
30	Sardinia, Italy	(56)	1	2	2002-2003	
31	Sheffield, UK	(65)	1	2	1993-1994	
32	Taisetsu Mountains, Japan	(66)	3	2	1995 (1994)	
33	Theix, France	(33)	6	3	2006-2007 (2005)	
34	Thompson, MB, Canada	(67)	1	3	2004-2006	
35	Toolik Lake, AK, USA	(41)	4	9	1983-1989 (1981)	
36	Zackenbergl, Greenland	(40)	1	9	2004-2007	
37	Chinnor, UK	(68)	384	47	1954-2000	GHCN UK000056225
38	Concord, MA, USA	(15)	486	26	1851-1858, 1878-1903, 2003-2006	Blue Hill Met.
39	Fargo, ND, USA	(69)	320	53	1910-1961, 2007-2010	GHCN USC00212142
40	Gullsmåra, Sweden	Bolmgren <i>in prep</i>	25	58	1934-2006	WMO 2464
41	Harvard Forest LTER, USA	LTER data	58	20	1990-2009	GHCN USC00199923
42	Hubbard Brook LTER, USA	LTER data	3	20	1989-2008	GHCN USC00275995
43	Konza Prairie LTER, USA	LTER data	204	9	2001-2009	GHCN USC00144972
44	Mohonk, NY, USA	(70)	18	59	1928, 1930-1933, 1938-2002	GHCN USC00305426
45	Niwot Ridge LTER, USA	LTER data	6	7	1984-1989, 1992	LTER daily temp from 3018m
46	RMBL, Gothic, CO, USA	(71)	90	35	1973-1977, 1979-1989, 1991-2009	GHCN USC00051959
47	Marsham, UK	(6)	17	184	1739-1810, 1834, 1836-1958	Central England (72; 73)
48	Washington, DC, USA	(74)	477	23	1985-2007	GHCN USW00013721
49	Wauseon, OH, USA	(75)	25	15	1883-1912	GHCN USC00338822
50	UW-Milwaukee, WI, USA	(76)	26	10	2000-2009	GHCN USC00473058

Table S2: **Additional information on sites** included in the meta-analysis (see also Table S1). Derived data indicates phenological data were extracted from papers, versus received from dataholders. Minimum temperature (min T) and mean precipitation (mean P) are taken from CRU (2). Event types for each site were F, corresponds to flowering, L, to leafing. For observational data, monitoring data (*) and canopy leafing data (**) were converted to FFD and FLD. See *Data* section for details.

map	WarmingDesign	Data Rec'd	Warming type	Long	Lat	min T	mean P	Event types	Event details
(0)	opentop	derived	passive	147.28	-36.90	3.70	1094.81	F	FFD
1	opentop	derived	passive	18.82	68.35	-8.11	754.77	F	medianFD
2	heating lamps & soil heating cables	derived	active	18.82	68.35	-8.11	754.77	F, L	FFD, FLD
3	opentop	derived	passive	3.82	50.97	5.74	851.99	F	FFD
4	opentop	derived	passive	-157.42	70.48	-14.29	139.28	F	FFD
5	opentop	derived	passive	-156.67	71.30	-15.21	105.79	F	FFD
6	opentop	derived	passive	-156.67	71.30	-15.21	105.79	F	FFD
7	nightcover	derived	passive	-3.47	53.05	5.11	983.95	L	FLD
8	chamber & electric heater	derived	active	-123.26	44.56	5.05	1166.85	L	FLD
9	opentop	raw	passive	-96.47	46.86	-1.65	570.04	F	FFD
10	opentop	derived	passive	7.53	60.12	0.21	751.42	F	FFD
11	nightcover	derived	passive	1.82	41.30	9.99	552.88	F	FLD
12	nightcover	derived	passive	1.80	41.30	10.62	598.56	F	FFD
13	nightcover	derived	passive	1.82	41.30	10.62	598.56	F	FFD
14	soil heating cables	raw	active	-72.18	42.54	1.48	1050.48	F	FFD
15	nightcover	derived	passive	19.38	46.88	5.25	541.59	L	FLD
16	above-canopy heating	raw	active	-122.14	37.24	9.21	650.36	F	FFD
17	opentop	derived	passive	-50.33	67.12	-9.73	225.00	F, L	FFD, FLD
18	opentop	derived	passive	18.31	68.22	-8.25	911.73	F	FFD
19	opentop	derived	passive	18.48	68.37	-8.25	911.73	F	FFD
20	opentop	derived	passive	18.48	68.37	-8.25	911.73	F	FFD
21	nightcover	derived	passive	10.95	56.38	4.36	556.98	L	FLD
22	above-canopy heating	derived	active	3.86	43.64	8.09	787.21	L	FLD
23	opentop	derived	passive	7.53	60.12	0.21	751.42	F	FFD
24	opentop	derived	passive	11.83	78.94	-10.14	599.88	F	FFD
25	above-canopy heating	raw	active	-97.31	34.58	9.99	863.25	F	FFD
26	nightcover	derived	passive	5.92	52.40	5.25	758.63	L	FLD
27	opentop	derived	passive	-70.85	42.72	3.37	1052.59	F	FFD
28	opentop with coolers & heaters	derived	active	-84.6	35.90	8.07	1302.81	L	FLD
29	above-canopy heating	raw	active	-107.03	38.53	-9.28	586.83	F	FFD
30	nightcover	derived	passive	8.15	40.60	11.94	734.77	L	FLD
31	soil warming by cables	derived	active	-1.49	53.38	5.23	770.32	L	ShootEmerge
32	opentop	derived	passive	142.88	43.55	-1.81	1125.49	L	modeFLD
33	move inelevation	raw	passive	3.01	45.43	4.39	952.25	F	FFD
34	greenhouse chamber & soil heating cables	derived	active	98.33	55.88	-8.00	405.64	L	FLD
35	opentop	derived	passive	-149.57	68.63	-14.19	153.95	L	FLD
36	above-canopy heating	raw	active	21.00	74.30	-5.42	507.82	L	meanFFD
37		raw		-0.54	51.42	5.43	766.52	F	FFD
38		raw		-71.21	42.27	4.01	1154.51	F	FFD
39		raw		-96.28	46.51	-1.65	570.04	F	FFD
40		raw		16.95	60.13	0.61	611.65	F	FFD
41		raw		-72.19	42.53	1.48	1050.48	F, L	FFD**, FLD**
42		raw		-71.75	43.94	-1.31	1072.63	L	FLD*
43		raw		-96.43	39.13	5.93	935.49	F	FFD
44		raw		-74.16	41.77	3.15	1140.29	F	FFD
45		raw		-105.36	40.30	-0.76	424.58	F, L	FFD*, FLD*
46		raw		-106.59	38.57	-9.55	539.13	F	FFD*
47		raw		1.18	52.37	5.96	615.34	F, L	FFD
48		raw		-76.70	38.40	8.04	1083.83	F	FFD
49		raw		-84.09	41.33	3.70	864.10	L	FLD
50		raw		-88.22	43.23	2.42	789.93	L	FLD**

Table S3: **Mixed-effects model estimates including all species for flowering and leafing separately.** We present model estimates with 3 outliers removed (presented in the main text), estimates including 3 outlier values and estimates using soil instead of air temperatures when both were given (13 sites).

	numDF	denDF	F	p	exp estimate	obs estimate
flowering: main text	1	34	9.70	0.004	-0.534	-4.524
flowering: w/outliers	1	34	9.89	0.003	-0.563	-4.517
flowering: soil temperatures	1	32	9.47	0.004	-1.246	-4.511
leafing: main text	1	18	2.81	0.111	-1.625	-6.412
leafing: w/outliers	1	19	1.63	0.217	2.213	-6.421
leafing: soil temperatures	1	20	3.33	0.083	-1.497	-6.405

Table S4: **Effects on sensitivities of mean event date per species x site (e.g., timing within a growing season), site latitude and site temperature variability.** Estimates of 0 for a p-value are less than 0.0001. As reported here in the SI we performed more complex models on flowering only, given the highly limited leafing data.

	numDF	denDF	F	p	exp estimate	obs estimate
Mean event: main text	1	2114	93.22	0.000	0.007	0.034
Mean event: w/outliers	1	2116	91.75	0.000	0.007	0.035
Temp variability: main text	1	31	0.14	0.711	-0.368	10.007
Temp variability: w/outliers	1	31	0.15	0.698	-0.314	10.261
Latitude: main text	1	31	0.02	0.877	0.010	-0.162
Latitude: w/outliers	1	31	0.01	0.910	0.010	-0.159

Table S5: **Effects on sensitivities of various aspects of study attributes:** habitat type (grassland, forest, alpine, tundra, shrubland or saltmarsh), warming type (active or passive), whether warming was year-round or for only the growing season (for those studies for which we could determine period of warming), whether phenological data was collected by: monitoring single marked individuals per species per plot, averaged over measurement of individuals per plot, taken as first-events per plot or could not be determined, datatype (derived or raw data received), publication year and study-length.

	numDF	denDF	F	p
Habitat: flowering	5	19	1.25	0.324
Habitat: leafing	3	10	0.05	0.986
Habitat: leafing: w/outliers	3	11	0.36	0.784
Warming: flowering	1	23	0.05	0.831
Warming: leafing	1	12	1.12	0.312
Warming: leafing: w/outliers	1	13	0.12	0.737
Year-round warming: flowering	1	18	0.52	0.479
Year-round warming: leafing	1	11	0.02	0.889
Year-round warming: leafing: w/outliers	1	12	0.37	0.552
Data collection method: flowering	3	20	1.31	0.299
Data collection method: leafing	3	10	0.86	0.492
Data collection method: leafing: w/outliers	3	11	0.10	0.957
Datatype: flowering	1	23	0.82	0.375
Datatype: leafing	1	12	0.06	0.817
Datatype: leafing: w/outliers	1	13	0.02	0.889
PubYr: flowering	1	21	0.50	0.485
PubYr: leafing	1	12	0.00	0.999
PubYr: leafing: w/outliers	1	13	0.42	0.530
Studylength: flowering	1	19	0.36	0.553
Studylength: leafing	1	12	3.61	0.082

Table S6: **Mixed-effects model estimates including only those species for which we had both experimental and observational data.**

	numDF	denDF	F	p	exp estimate	obs estimate
flowering: main text	1	16	3.97	0.064	1.646	-4.641
leafing: main text	1	4	33.19	0.005	-0.228	-5.474

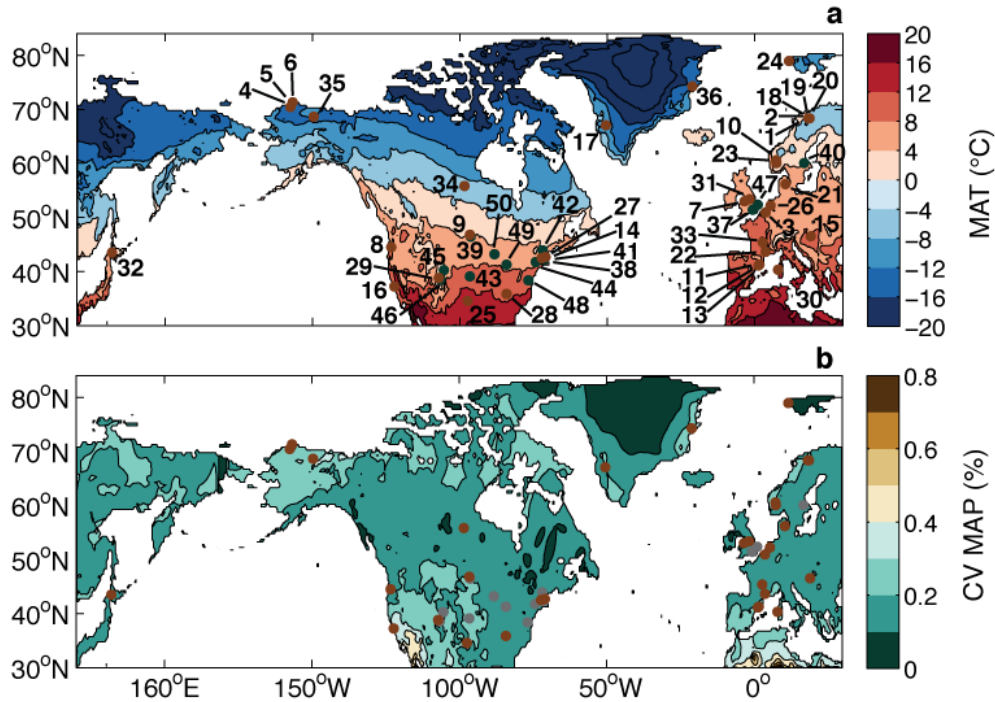


Figure S1: Sites used in the meta-analysis came from predominantly temperate regions with varying temperature regimes (a) and similar interannual variation in precipitation (b). Experiment sites are represented in dark red, while observation sites are in green (a) or gray (b). Data for mean annual temperature (MAT) and the coefficient of variation in mean annual precipitation (CV MAP) come from CRU 2.1 climate grids (2).

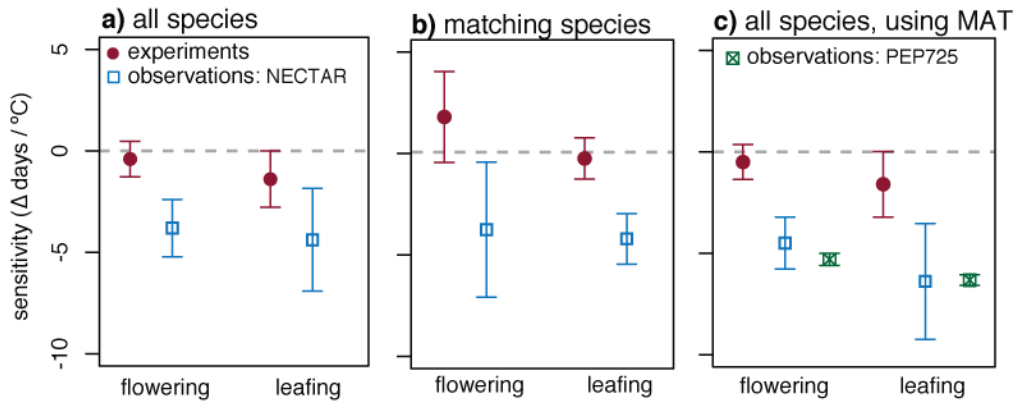


Figure S2: MAT vs. monthly temperatures & NECTAR vs. PEP725: Results of comparison of temperature sensitivities based on experiments and observations using a more granular metric than MAT for observational data. Here we show the results using the mean temperature of the 3 months prior to mean flowering date for all species (a) and those we had matching species data (b). Note that results are highly similar to those which used MAT (c). Further, estimates based on MAT using NECTAR were similar to calculations using PEP725 (c).

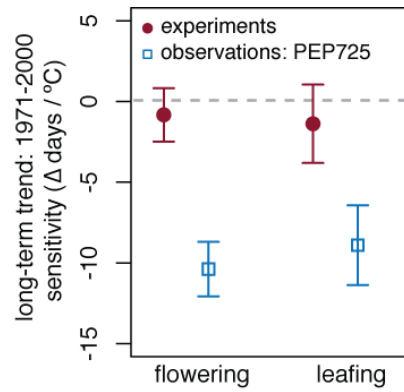


Figure S3: **Sensitivities calculated from long-term trends using PEP725** data showed greater advances with warming than those calculated from experiments. Mixed-effects models: FFD: $F_{1,257} = 32.09$, $p < 0.0001$; for FLD, $F_{1,226} = 9.25$, $p = 0.0003$.

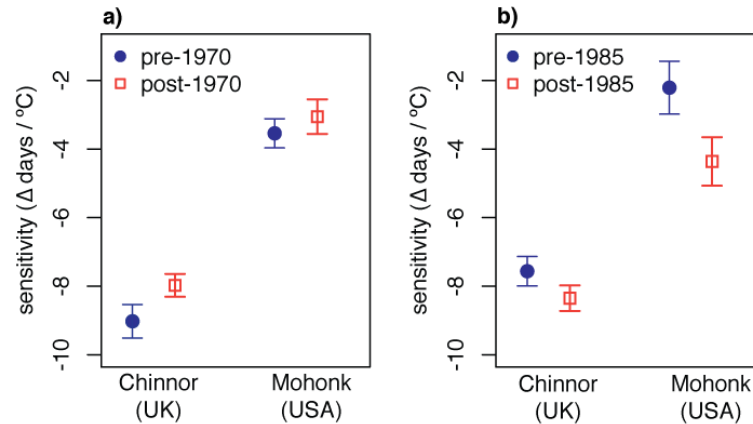


Figure S4: **Sensitivities calculated before and after (a) 1970 and (b) 1985** for two datasets from NECTAR: Chinnor, UK and Mohonk, NY, USA.

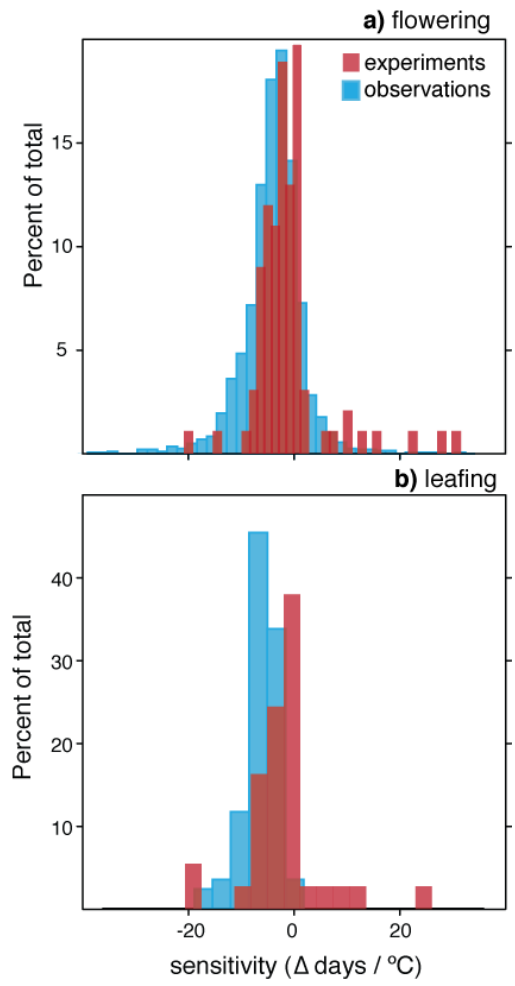


Figure S5: **Histograms of all calculated sensitivities** for experiments and observations for flowering (a) and leafing (b).

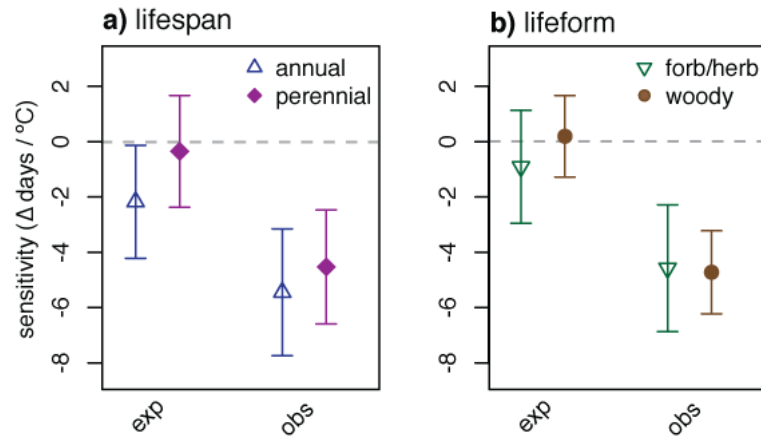


Figure S6: Mixed-effects estimates of **effects of lifespan (a) and lifeform (b) on flowering sensitivity**. Annuals had significantly greater negative sensitivities than perennials in both experiments and observations (main effect of lifespan: $F_{1,1891} = 6.28, p = 0.012$, main effect of study type: $F_{1,34} = 9.76, p = 0.004$, intxn: $F_{1,1891} = 0.19, p = 0.66$). The sensitivities of herbs and forbs, however, did not differ from woody species (main effect of lifeform: $F_{1,1891} = 0.17, p = 0.68$, main effect of study type: $F_{1,34} = 10.09, p = 0.003$, intxn: $F_{1,1891} = 0.69, p = 0.41$).

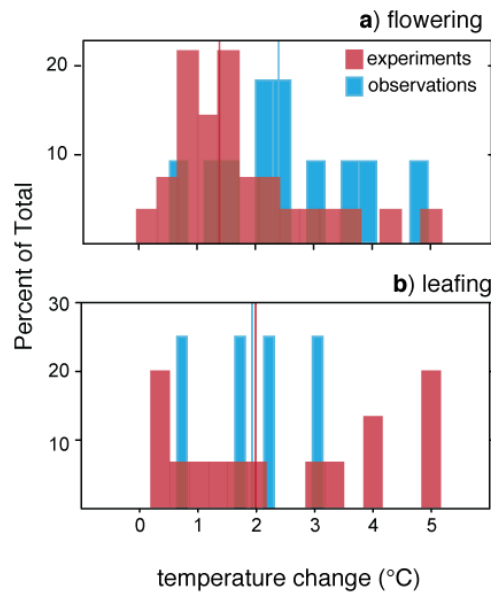


Figure S7: **Temperature ranges experienced by species in the experimental and observational studies** for flowering (a) and leafing (b). For experiments we give each unique temperature increase per site while for observations we give the greatest temperature range between any two years for each site. Lines represent median values.

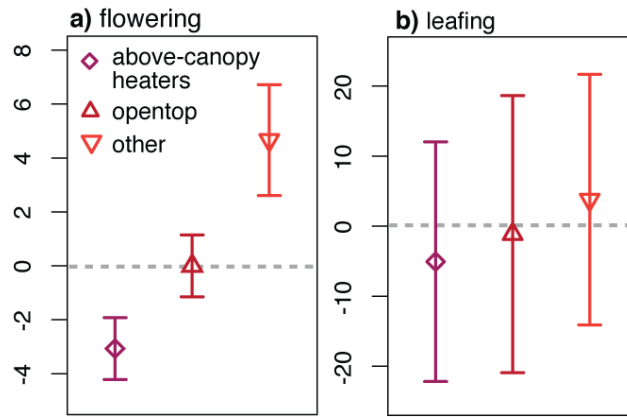


Figure S8: **Effect of different warming designs on sensitivities** for (a) flowering and (b) leafing. The dashed gray line represents 0 sensitivity to temperature. See Table S2 for warming designs that were not well-enough represented (by leafing and flowering data) to categorize alone and thus were included as ‘other.’

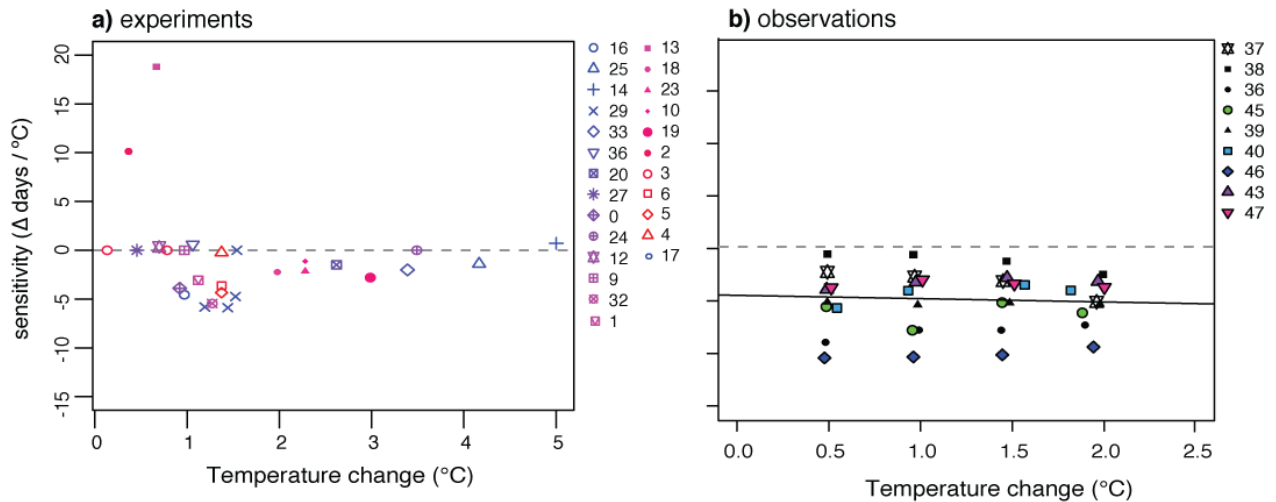


Figure S9: **Effect of magnitude of temperature change on sensitivity:** experiments (a) and observations (b). Species sensitivities calculated from experiments did not vary with temperature change (mixed-effects model: $F_{1,76} = 1.13, p = 0.30$), observations did however show a slight increase in sensitivities with greater temperature differences (mixed-effects model: $F_{1,4856} = 12.27, p = 0.0005$). We show data aggregated to the site x temperature change level here. The dashed gray line represents 0 sensitivity to temperature.

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