Supplemental materials for Spatial and temporal shifts in photoperiod with climate change

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Supplemental Methods

Quantifying and mapping differences in green-up across the United States and Europe (Figure 2)

Satellite images can be combined with algorithms—e.g. MODIS Land Cover Dynamics— to identify the dates on which phenophases transition from one to the next. Using data from the MODIS sensor (available at: https://lpdaacsvc.cr.usgs.gov/appeears/), we extracted spatial data for North American and Western European green-up—the beginning of seasonal greening—for the years 2009 and 2012. Green-up dates are calculated on the basis of the onset of the Enhanced Vegetation Index (Huete et al., 2002). From green-up maps for each year, we derived the photoperiod corresponding to each pixel (according to its geographic coordinates and day of the year), using R function "daylength" in package geopshere (see Fig. 2a,b in main text). Finally, we mapped spatial patterns of temporal shifts in green-up by comparing an early and late spring years. To do so, we substracted the 2013 green-up map from the 2009 one. The spatial resolution corresponding to the maps is of 0.1 x 0.1 degrees.

Nonlinearities in phenological responses to daylength (Figure 3)

We selected OSPREE publications that had three or more photoperiod treatments, and, after reading the methods of these papers in detail, identified three that used three or more photoperiod treatments in the same experiment: Ashby et al. (1962); Heide (1993) and Caffarra et al. (2011). These experiments used forcing temperatures of 21 or 22°C. Chilling varied considerably across experiments, and chilling level was categorized as follows:

- <1 Chill Portions = None
- 1-44 Chill Portions = Low
- 45-69 Chill Portions = Medium
- 70-106 Chill Portions = High
- >106 Chill Portions = Very High

Mapping temporal and spacial shifts in space and time (Figure 4)

To examine the range of photoperiod treatments imposed in growth chamber experiments of woody plants, and compare these treatments to shifts in photoperiod that may be expected due to climate change induced spatial

and temporal shifts, we identified all experiments in the OSPREE database with at least two photoperiod treatments; this resulted in 30 experiments (Table 1).

We wanted to compare experimental photoperiod treatment levels in these 30 experiments to temporal shifts that would be required for species to experience equivalent photoperiod shifts with climate change. To do this, we identified the dates between the winter and summer solstices on which daylengths at the latitude of the experiments matched treatment levels. When no date matched the experimental treatment level exactly, we chose the date with the most similar daylength, as long as it was within 0.5 hours of the photoperiod treatment level. For studies with only two photoperiod treatment levels, we identified matching dates for both levels. For studies with more than two daylength treatments, we identified matching dates for the lowest treatment level and the second lowest treatment level (e.g., if treatment levels were 10,12,14, and 16 hours of daylight, we identified dates with 10 and 12 hours of daylength only). This provided an estimate for the minimum temporal shift required during the spring that would equal the difference between the two treatments; that is, the minimum difference, in days, between dates with the lower daylength treatment and dates with higher daylength treatment. In 11 out of 30 cases, the experimental treatment differences exceeded what the difference in photoperiod experienced across the entire year at a given latitude (Xs in Figure 4).

To compare differences between experimental photoperiod treatment levels to differences in photoperiod species would experience with spatial shifts, we identified the daylength on the summer solstice for the latitudes of all 30 experiments in Table 1. To get potential changes in daylength experienced, we compared the summer solstice daylength at each latitude to the daylength on latitudes up to 40 degrees poleward (in continuous increments of 0.1°). Because latitudinal variation in daylength is greatest during the solcstices, this provides a maximum possible shift in daylength, at a constant day of year. We then matched the experimental change in photoperiod between two treatments levels to the latitudinal shift that provided an equivalent change in photoperiod. In 13 out of 30 cases, the experimental treatment differences exceeded the photoperiod change that would be experienced with a latitudinal shift of up to 40 °(red lines in Figure 4).

PhenoFit Methods (Figure 5)

We took current budburst data (1981-2000) and model projection budburst (2081-2100) using the A1Fi Phenofit scenario for two species – *Fagus sylvatica* and *Quercus robur* – and compared these points to data obtained from the OSPREE dataset. The OSPREE data points were collected from experiments and days of budburst were calculated from the start of the experiment, rather than from the start of the year. In order to render these points comparable to the current observations and the model projections, we scaled the days to budburst by adding the day of budburst from the first Phenofit observation to all of the OSPREE data points. We only used Phenofit estimates that had both current and projection data. In the right panel for *Quercus robur*, we explored the 3 OSPREE data points that have later day to budburst times than the current or projected days to budburst, which all had much lower forcing temperatures (**?**, 3.8-5.7°).

Supplemental Box S1. Dominant models of how photoperiod affects spring woody plant phenology

The molecular mechanisms and pathways underlying photoperiod sensitivity are poorly understood for most organisms, even in relatively well-studied phenophases such as spring budburst in woody plants (Ding and Nilsson, 2016). Spring budburst in woody plants is thought to be controlled by three main cues: chilling, forcing, and photoperiod, as well as interactions between them (Flynn and Wolkovich, 2018; Heide, 2008; Zohner et al., 2016). Our understanding of how plants interpret photoperiod comes largely from studies of flowering in the model plant *Arabidopsis thaliana* (e.g., Suárez-López et al., 2001) and fall budset in woody plant species (e.g., Howe et al., 1996).

Plants sense light inputs by blue light receptors and phytochromes, which have been found in nearly all

organs throughout the plant. Plants are thought to interpret photoperiod through a coordinated response to light in relation to the time of day. When the internal circadian rhythm coincides with an external signal (light) under certain conditions (e.g., warm days), a response is induced (Lagercrantz, 2009). This "external coincidence model" has been most widely studied in *Arabidopsis*, and is thought to be a relevant mechanism for photoperiod responses in diverse perennial and woody plant species (Bünning, 1936; Davis, 2002; Bastow and Dean, 2002; Kobayashi and Weigel, 2007; Andrés and Coupland, 2012; Petterle et al., 2013; Singh et al., 2017). The model proposes the existence of a circadian rhythm of light sensitivity, in which the night-phase is sensitive to light and the day-phase is insensitive to light. As days get longer in the spring, daylight illuminates the light sensitive phase, triggering a response.

Little is known about the genetic pathways responsible for the light-sensing apparatuses involved in spring budburst, and how they may vary across species or populations. Some genes have been identified that play a role in coordinating budburst in poplar (*Populus* spp.), and may occur in other woody species as well. Many similarities exist between the proposed regulatory networks of vegetative growth in *Populus* and those controlling floral initiation in *Arabidopsis*, Ding and Nilsson (2016). For example, vegetative growth and inhibition of budset are promoted by the FLOWERING LOCUS T2 (FT2) gene, a homolog of *Arabidopsis thaliana* gene FLOWERING LOCUS (FT). FT2 expression appears to be controlled by a pathway that is effective in long days and warm temperatures, marking the onset of the growing season (**?**). Its loss of expression in autumn, when the days are getting shorter, is associated with the onset of dormancy (Glover, 2014).

There are large gaps in our understanding of how photoperiod sensing pathways affect budburst, the genetics behind these pathways, and the extent of species- and population-level genetic variation. Questions also remain about how photoperiod sensing interacts with temperature sensing to affect responses. For example, Figure 3 shows the most detailed data we were able to find of budburst responses across different photoperiod and chilling treatments. These data underscore how variable responses to photoperiod are, across species and populations, and with different chilling treatments.

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Supplemental Tables

Table 1: **Locations, photoperiod treatments, and whether or not photoperiod had an effect on budburst**, in studies in the OSPREE database with at least two photoperiod treatments. These studies span 176 different woody species and are mapped in Figure 4.

reference	study	continent	latitude (°)	longitude (°)	daylength range (hrs)	photoperiod effect
Ashby et al. (1962)	exp1	North America	42.99	-89.41	8-16	Y
Basler and Körner (2014)	exp1	Europe	46.31	8.27	9.2-16	Y
Caffarra et al. (2011)	exp2	Europe	52.32	-6.93	10-16	Y
Falusi and Calamassi (1990)	exp1	Europe	46.03	10.75	9-13	N
Falusi and Calamassi (1996)	exp3	Europe	38.27	15.99	9-13	Y
Ghelardini et al. (2010)	exp1	Europe	43.72	11.37	8-16	N
Heide and Prestrud (2005)	exp1	Europe	56.18	-4.32	10-24	Y/N
Heide (2008)	exp1	Europe	48.40	11.72	10-24	Y
Heide (2011)	exp1	Europe	59.67	10.67	10-20	N
Heide and Sønsteby (2012)	exp1	Europe	56.50	-3.06	10-24	Y
Heide and Sonsteby (2015)	exp2	Europe	56.50	-3.06	10-15	Y
Heide (1993)	exp1	Europe	59.50	10.77	8-24	Y
Heide (1993)	exp1	Europe	59.67	10.83	8-24	Y
Heide (1993)	exp3	Europe	47.50	7.60	13-16	Y
Howe et al. (1995)	exp1	North America	40.55	-124.10	9-24	Y
Laube et al. (2014)	exp1	Europe	48.40	11.71	8-16	N
Myking and Heide (1995)	exp1	Europe	56.10	9.15	8-24	Y
Nienstaedt (1966)	exp1	North America	44.17	-103.92	8-20	Y
Okie and Blackburn (2011)	exp1	North America	32.12	-83.12	0-12	Y
Partanen et al. (2001)	exp1	Europe	61.93	26.68	6-16	Y
Partanen et al. (2005)	exp1	Europe	61.82	29.32	5-20	Y
Partanen et al. (1998)	exp1	Europe	60.03	23.05	8.66-12	Y
Pettersen (1972)	exp1	Europe	59.66	10.77	10-24	N
Sanz-Perez et al. (2009)	exp1	Europe	40.40	-3.48	10-16	Y
Viherä-Aarnio et al. (2006)	exp1	Europe	60.45	24.93	16-17	Y
Viherä-Aarnio et al. (2006)	exp1	Europe	67.73	24.93	20-21	Y
Viherä-Aarnio et al. (2006)	exp2	Europe	60.45	24.93	15-19	Y
Viherä-Aarnio et al. (2006)	exp2	Europe	67.73	24.93	22-23	Y
Worrall and Mergen (1967)	exp3	North America	41.31	-72.93	8-16	Y
Zohner et al. (2016)	exp1	Europe	48.16	11.50	8-16	Y