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

A.K. Ettinger, D. Buonaiuto, C. Chamberlain, I. Morales-Castilla, E. Wolkovich

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Methods

Greenup differences (Figure 2)

Satellite images are 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: http... DAN, could you please provide the website from where the maps were extracted), 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 (**?**). 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 XXX in package XXX (please Dan, fill these gaps) (see Fig. 2a,b in main text). Finally, we mapped spatial patterns of temporal shifts in green-up comparing an early and late spring years. To do so, we simply substracted the 2013 green-up map to the 2009 one. The spatial resolution corresponding to the maps is of 0.1 x 0.1 degrees.

Dan's methods for making the photo period curves (June 27 2018)

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 (**??**).These experiments used forcing temperatures of 21 or 22 °C, Chilling varied considerably across experiments, and chilling level was categorized as follows:

- <31 Chill Portions = None
- 31-80= Low
- 81-130<-Medium
- >130= High

PhenoFit Methods (Figure 3)

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 data that had both current and projected data for *Fagus sylvatica* and

Quercus robur. Several responses for *Quercus robur* in OSPREE consisted of days to budburst that are much longer than current or projected days. These responses are associated with photoperiods that are 5-8 hours shorter than is biologically possible in their range (Cat: add the study) or were combined with treatments involving little or no experimental chilling (Cat: add the study).

Supplement: 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 (**?**). Spring budburst in woody plants is thought to be controlled by three main cues: chilling, forcing, and photoperiod, as well as interactions between them (**???**). Our understanding of how plants interpret photoperiod comes largely from studies of flowering in the model plant *Arabidopsis thaliana* (e.g., **?**) and fall budset in woody plant species (e.g., **?**).

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 (**?**). 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 (**??????**). 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*, **?**. 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 (**?**).

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 **??** 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.