Supplementary Material

Phylogenetic estimates of species-level phenology improve ecological forecasting

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Extended Methods

Details on data: sources and structure.

In this section we provide additional details on how our dataset is structured, including the data sources and the geographical bias of the data. First, in Fig. S2 we show the distribution of the response and predictor variables. Second, we show a map (Fig. S1) of the locations where woody plant samples were collected. As our data are geographically limited to mainly temperate Europe and North America, further experimental research on the phenology of extra-temperate woody species will be important for determining the extent to which the results in this work hold in other biomes and climates. Such data would also provide a more representative picture of how cues affect phenology in different parts of the world and would allow addressing questions such as, is variability in cue sensitivity across species larger in temperate than tropical latitudes? Third, we provide a table (S1) identifying the original sources from which the data were compiled.

Interpretation of λ_j and σ_j^2 on slopes and intercepts

Most current phylogenetic regression approaches aimed at controlling for phylogenetic non-independence of analysis units (i.e. usually species, see Revell, 2010) assume the λ scaling parameter is constant across the full set of predictors in the model. Thus, λ is estimated as a single parameter based on one single residual term VCV matrix. While useful for correcting for phylogenetic non-independence, this approach does not allow for different tempos and modes of evolution across different predictors.

In models with multiple cues, species responses to all cues are estimated as similarly phylogenetically structured, but this may not be the case. For example, in a PGLS model with three cues, it would be possible to have a high (close to 1) value of λ, due to either a strong phylogenetic signal in the response, but no phylogenetic structuring in the cues, or one or more predictors being strongly phylogenetically structured. In the latter case, phylogenetic structuring of responses to cues could be correlated (i.e., responses to cues evolving in a correlated fashion) or uncorrelated (i.e., independent evolution of responses to cues). Distinguishing among these different situations is challenging, in part because the phylogeny is constant across all data, and also because in practice multiple process affect the evolution of traits that each leave a signature of some kind in the data. Perhaps, in part, due to the complexity of the problem, most modern approaches take the conservative approach of focusing on whether model residuals are phylogenetically structured (i.e. in PGLS) or the amount of model variance attributable to the phylogeny and independent from other sources of variation (i.e., in PMM, see Housworth et al., 2004).

Because we are specifically interested in estimating the phylogenetic structure of each cue, our approach explicitly partitions variance into specific components relative to the model intercept and predictor (cue) slopes (see equation 5). The multivariate normal distributions of the intercept and slope terms each include a variance term (see equation 3), modelled with a λ scaling parameter. The interpretation of λs in our models are analogous to Pagel's λ (Pagel, 1999) parameter (Housworth et al., 2004), constrained to range from 0 to 1, with values of 0 indicating no phylogenetic signal, and values of 1 phylogenetic signal consistent with Brownian motion evolution (BM).

While the lambdas estimated through our fitting process will resemble those of lambdas estimated from non-phylogenetically informed models, our approach gives a number of benefits. First, the uncertainty associated with estimating parameters across shared data (the phylogeny) is directly incorporated into the fitting process itself: our posterior estimates are joint across that shared data and the uncertainty it introduces to our fitting process. Second, we expect our cues and their evolution to both be correlated, and assessing both simultaneously allows uncertainty in our ability to unpick precise evolutionary process is, again, incorporated into our uncertainty estimates. Third, this approach adjusts our partial pooling ('random effect' of species) based on evolutionary distance, more strongly pooling closely related species, and only weakly pooling distantly related species (see Gaussian process models in Gelman et al., 2014). This is particularly important for the practising ecologist who, unlike an evolutionary biologist, is not interested in controlling for past evolution *per se*, but is interested in using that past information to predict slopes for (un)measured species on the basis of their evolutionary history.

A traditional interpretation of σ^2 values under Brownian Motion evolution, is an 'evolutionary rate' or phenotypic accumulation over time (Revell et al., 2008). In PGLS, σ^2_ϵ is estimated for the model error term, which parameterises a multivariate normal with a VCV matrix given by $\sigma^2_\epsilon \boldsymbol{\Sigma_i}$. Here, similar to our approach to λ, we estimate four σ^2 values, corresponding to each model parameter. In our particular case (i.e., modelling a phenological response to three environmental cues), σ^2_α for the intercept could be interpreted as the phenological variation across species accummulated along evolution independently from the cues, and is perhaps most comparable to the interpretation of lambda in a PGLS as measuring phylogenetic signal in the residuals. The $\sigma^2_{\beta_{chill}}$, $\sigma^2_{\beta_{force}}$, and $\sigma^2_{\beta_{photo}}$, corresponding to model slopes, would represent the phylogenetic variance linked to species responses to each of the modelled cues. This is, the variability in how species shift their phenology responding to temperature and light, accumulated along the evolutionary process and considered in concert.

Does accounting for phylogenetic relationships affect forecasts?

We forecasted estimated shifts in species phenologies from our phylogenetic and non-phylogenetic models for two species with overlapping European ranges to show the impact of differences across models in a well (*Betula pendula*, $n = 311$) versus poorly sampled (*Acer campestre*, $n = 6$) species. For this, we first fit our phylogenetic and non-phylogenetic models using natural (i.e., not z-scored) units. Second, we projected fitted models to the European geographic range of each species using two climate scenarios within species distributions: a scenario of historical climate (1980-2016) and a scenario of 2°C of warming. These projections yield four predictions for each species: phylogenetic-historical, phylogenetic-warmer, non-phylogenetic-historical and non-phylogenetic-warmer. Third, for each species we compared phylogenetic vs. non-phylogenetic models (see Fig. S8). Finally, for each species we quantified how phenological shifts expected due to warming differ as a result of using a phylogenetic model instead of a non-phylogenetic model.

Species distributional data were extracted from published distributional maps (Caudullo et al., 2017). We extracted climate data corresponding to all grid cells contained within each species' range from daily gridded meteorological datasets. Specifically, we extracted minimum and maximum daily temperatures from the E-OBS dataset v.25 at 0.25 latitudinal degrees (https://cds.climate.copernicus.eu/cdsapp#!/dataset/insitu-gridded-observations-europe?tab=overview; last accessed in May 2023). Daily temperatures were used to compute both forcing (mean daily temperature from March 1st through April 30th) and chilling (Utah units from from 1 September through 30 April). Utah units were calculated using the chillR package in R. We used yearly values of forcing and chilling computed for each location (i.e., grid cell) as inputs in the models to predict date of budburst under each scenario for each 12637 locations for *Betula pendula* and 7537 locations for *Acer campestre*. Lastly, we compared model forecasts from phylogenetic and non-phylogenetic models (i.e., by calculating the difference PMM-HMM) and quantified the change in forecasted phenological shifts due to warming resulting from using non-phylogenetic models instead of phylogenetic ones (i.e., calculating the difference $[PMM_{historical} - PMM_{warming}] - [HMM_{historical} - HMM_{warming}]$).

Our forecasted bias from HMM compared to PMM (Fig. 4) would likely extend to many other species, based on shifts in estimated responses to temperature and daylength (model coefficients) across our studied species. Across all 191 species, accounting for phylogenetic structuring shifted many species estimates (Fig. 3). Not accounting for phylogeny (i.e., assuming $\lambda = 0$ as done in HMM) biased model coefficients on average, particularly so for forcing and somewhat less for chilling (Fig. 3). Specifically, species sensitivities to forcing and chilling were underestimated on average (model slopes shifted by 7.2% and 3.7%, respectively). Sensitivities to photoperiod, which showed weak phylogenetic signal were not biased in non-phylogenetic models (Fig. 3), likely associated to their low estimated λ values.

However, as explained in the main text, these biases do not apply homogeneously to all species. Over represented species (i.e., high number of observations) suffer little to no bias if a non-phylogenetic model is used and underrepresented species can experience large shifts when phylogenetic relationships are ignored (see Fig. S8). Interestingly the bias in forecasts for underrepresented species does not distribute homogeneously across the geography, indicating that ignoring phylogeny can lead to biased forecasts for these species, more so in particular regions (coinciding with coldest locations in our example; Fig. S8b).

Leave-One-Clade-Out model cross validation.

Forecasts derived from our models showed virtually identical results for overrepresented species and markedly different predictions for species with few observations in the dataset (see Fig. S8). Our data does not allow testing which divergent forecasted values would be more accurate (either those from PMM or from HMM) because we do not have future neither past observational data against which testing model predictions. This issue is well known in the ecological forecasting literature (REF!!), and is often dealt with using different cross-validation schemes. Here, we conduct a cross-validation analysis to test for the ability of each PMM and HMM model to accurately predict observed response values for species left out from the analysis and, to test for stability in modelled estimates of species sensitivities to a given cue. Specifically, our Leave-One-Clade-Out approach to cross validation followed the next steps:

1. Identify the top 25 genera with more observations in the dataset and at least two species.
2. Iteratively subset the dataset leaving out one of these genera at a time.
3. Run both PMM and HMM for each subset of data recording the posterior distribution of predicted values.
4. Compare the observed response of left out species against the predicted response for those species inferred by the subset version of the models that excluded those species.
5. Compare model coefficients (i.e., slopes) estimated by the subset version of the models and the full models, only for species left in.

Due to time constraints, we ran this analyses for a simplified version of the PMM and HMM models that only included forcing. Results showed that predicted response values by the PMM model were more correlated with the observed responses of left out species than predictions by the HMM model (Fig. S9). Results also supported a higher stability of model coefficients as estimated by PMM than by HMM (Fig. S10). The algorithms and code to develop these analyses are available in GitHub https://github.com/MoralesCastilla/PhenoPhyloMM/.

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Supporting Figures and Tables

Table S1: Species and references for included in the phylogenetic model.

Species	*Num.Studies*	*Reference*
Acer barbinerve	1	*(Zohner et al., 2016)*
Acer campestre	1	*(Zohner et al., 2016)*
Acer ginnala	1	*(Zohner et al., 2016)*
Acer negundo	1	*(Laube et al., 2014*a*)*
Acer pensylvanicum	1	*(Flynn and Wolkovich, 2018)*
Acer platanoides	1	*(Zohner et al., 2016)*
Acer pseudoplatanus	4	*(Basler and Körner, 2012, 2014; Laube et al., 2014*a*; Malyshev et al., 2018)*
Acer rubrum	2	*(Flynn and Wolkovich, 2018; Nanninga et al., 2017)*
Acer saccharinum	1	*(Webb, 1977)*
Acer tataricum	1	*(Laube et al., 2014*a*)*
Aesculus flava	1	*(Zohner et al., 2016)*
Aesculus hippocastanum	3	*(Basler and Körner, 2012; Laube et al., 2014*a*; Zohner et al., 2016)*
Aesculus parviflora	1	*(Zohner et al., 2016)*
Alnus glutinosa	2	*(Heide, 1993*a*; Myking, 1998)*
Alnus incana	3	*(Flynn and Wolkovich, 2018; Heide, 1993*a*; Zohner et al., 2016)*
Alnus maximowiczii	1	*(Zohner et al., 2016)*
Amelanchier florida	1	*(Zohner et al., 2016)*
Amelanchier laevis	1	*(Zohner et al., 2016)*
Amorpha fruticosa	1	*(Laube et al., 2014*a*)*
Aronia melanocarpa	2	*(Flynn and Wolkovich, 2018; Zohner et al., 2016)*
Berberis dielsiana	1	*(Zohner et al., 2016)*
Betula alleghaniensis	2	*(Calmé et al., 1994; Flynn and Wolkovich, 2018)*
Betula lenta	2	*(Flynn and Wolkovich, 2018; Zohner et al., 2016)*
Betula nana	1	*(Zohner et al., 2016)*
Betula papyrifera	3	*(Flynn and Wolkovich, 2018; Man et al., 2017; Nanninga et al., 2017)*
Betula pendula	10	*(Basler and Körner, 2012; Heide, 1993*a*; Laube et al., 2014*a,b*; Li et al., 2005; Linkosalo and Lechowicz, 2006; Myking and Heide, 1995; Myking, 1998; Rinne et al., 1997; Skuterud and Dietrichson, 1994)*
Betula populifolia	1	*(Zohner et al., 2016)*
Betula pubescens	6	*(Caffarra and Donnelly, 2011; Caffarra et al., 2011; Heide, 1993*a*; Myking and Heide, 1995; Myking, 1997; Rinne et al., 1994)*
Buddleja albiflora	1	*(Zohner et al., 2016)*

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Species	*Num.Studies*	*Reference*
Buddleja alternifolia	1	*(Zohner et al., 2016)*
Buddleja davidii	1	*(Zohner et al., 2016)*
Caragana pygmaea	1	*(Zohner et al., 2016)*
Carpinus betulus	4	*(Heide, 1993*b*; Laube et al., 2014*a*; Vitra et al., 2017; Zohner et al., 2016)*
Carpinus laxiflora	1	*(Zohner et al., 2016)*
Carpinus monbeigiana	1	*(Zohner et al., 2016)*
Carya cordiformis	1	*(Zohner et al., 2016)*
Carya laciniosa	1	*(Zohner et al., 2016)*
Celtis caucasica	1	*(Zohner et al., 2016)*
Celtis laevigata	1	*(Zohner et al., 2016)*
Celtis occidentalis	1	*(Zohner et al., 2016)*
Cephalanthus occidentalis	1	*(Zohner et al., 2016)*
Cercidiphyllum japonicum	1	*(Zohner et al., 2016)*
Cercidiphyllum magnificum	1	*(Zohner et al., 2016)*
Cercis canadensis	1	*(Zohner et al., 2016)*
Cercis chinensis	1	*(Zohner et al., 2016)*
Cladrastis lutea	1	*(Zohner et al., 2016)*
Cornus alba	2	*(Laube et al., 2014*a*; Zohner et al., 2016)*
Cornus kousa	1	*(Zohner et al., 2016)*
Cornus mas	2	*(Laube et al., 2014*a,b*)*
Corylopsis sinensis	1	*(Zohner et al., 2016)*
Corylopsis spicata	1	*(Zohner et al., 2016)*
Corylus cornuta	1	*(Flynn and Wolkovich, 2018)*
Decaisnea fargesii	1	*(Zohner et al., 2016)*
Deutzia gracilis	1	*(Zohner et al., 2016)*
Deutzia scabra	1	*(Zohner et al., 2016)*
Elaeagnus ebbingei	1	*(Zohner et al., 2016)*
Eleutherococcus senticosus	1	*(Zohner et al., 2016)*
Eleutherococcus setchuenensis	1	*(Zohner et al., 2016)*
Eleutherococcus sieboldianus	1	*(Zohner et al., 2016)*
Euonymus europaeus	1	*(Zohner et al., 2016)*
Euonymus latifolius	1	*(Zohner et al., 2016)*
Fagus crenata	1	*(Zohner et al., 2016)*
Fagus engleriana	1	*(Zohner et al., 2016)*
Fagus grandifolia	1	*(Flynn and Wolkovich, 2018)*
Fagus orientalis	1	*(Zohner et al., 2016)*
Fagus sylvatica	12	*(Basler and Körner, 2012, 2014; Caffarra and Donnelly, 2011; Falusi and Calamassi, 1990, 1996, 1997, 2003; Heide, 1993*b*; Laube et al., 2014*a*; Malyshev et al., 2018; Vitra et al., 2017; Zohner et al., 2016)*
Forsythia ovata	1	*(Zohner et al., 2016)*
Forsythia suspensa	1	*(Zohner et al., 2016)*
Fraxinus americana	1	*(Webb, 1977)*
Fraxinus chinensis	1	*(Laube et al., 2014*a*)*

Table S1: Species and references for included in the phylogenetic model.

Species	*Num.Studies*	*Reference*
Fraxinus excelsior	2	*(Basler and Körner, 2012; Laube et al., 2014*a*)*
Fraxinus latifolia	1	*(Zohner et al., 2016)*
Fraxinus nigra	1	*(Flynn and Wolkovich, 2018)*
Fraxinus ornus	1	*(Zohner et al., 2016)*
Fraxinus pennsylvanica	1	*(Laube et al., 2014*a*)*
Hamamelis japonica	1	*(Zohner et al., 2016)*
Hamamelis vernalis	1	*(Zohner et al., 2016)*
Hamamelis virginiana	1	*(Flynn and Wolkovich, 2018)*
Heptacodium miconioides	1	*(Zohner et al., 2016)*
Hibiscus syriacus	1	*(Zohner et al., 2016)*
Hydrangea arborescens	1	*(Zohner et al., 2016)*
Hydrangea involucrata	1	*(Zohner et al., 2016)*
Hydrangea serrata	1	*(Zohner et al., 2016)*
Ilex mucronata	1	*(Flynn and Wolkovich, 2018)*
Juglans ailantifolia	1	*(Laube et al., 2014*a*)*
Juglans cinerea	1	*(Laube et al., 2014*a*)*
Kalmia angustifolia	1	*(Flynn and Wolkovich, 2018)*
Ligustrum tschonoskii	1	*(Zohner et al., 2016)*
Liquidambar orientalis	1	*(Zohner et al., 2016)*
Liquidambar styraciflua	1	*(Zohner et al., 2016)*
Liriodendron tulipifera	1	*(Zohner et al., 2016)*
Lonicera alpigena	1	*(Zohner et al., 2016)*
Lonicera caerulea	1	*(Zohner et al., 2016)*
Lonicera canadensis	1	*(Flynn and Wolkovich, 2018)*
Lonicera maximowiczii	1	*(Zohner et al., 2016)*
Lyonia ligustrina	1	*(Flynn and Wolkovich, 2018)*
Nothofagus antarctica	1	*(Zohner et al., 2016)*
Nyssa sylvatica	1	*(Flynn and Wolkovich, 2018)*
Oemleria cerasiformis	1	*(Zohner et al., 2016)*
Orixa japonica	1	*(Zohner et al., 2016)*
Ostrya carpinifolia	1	*(Zohner et al., 2016)*
Ostrya virginiana	1	*(Zohner et al., 2016)*
Paeonia rockii	1	*(Zohner et al., 2016)*
Parrotia persica	1	*(Zohner et al., 2016)*
Parrotiopsis jaquemontiana	1	*(Zohner et al., 2016)*
Photinia villosa	1	*(Zohner et al., 2016)*
Populus deltoides	1	*(Thielges and Beck, 1976)*
Populus grandidentata	1	*(Flynn and Wolkovich, 2018)*
Populus koreana	1	*(Zohner et al., 2016)*
Populus tremula	3	*(Heide, 1993*a*; Laube et al., 2014*a,b*)*
Prinsepia sinensis	1	*(Zohner et al., 2016)*
Prinsepia uniflora	1	*(Zohner et al., 2016)*
Prunus padus	3	*(Heide, 1993*a*; Myking, 1998; Zohner et al., 2016)*
Prunus pensylvanica	1	*(Flynn and Wolkovich, 2018)*

Table S1: Species and references for included in the phylogenetic model.

Species	*Num.Studies*	*Reference*
Prunus serotina	1	*(Laube et al., 2014*a*)*
Prunus serrulata	1	*(Zohner et al., 2016)*
Prunus tenella	1	*(Zohner et al., 2016)*
Ptelea trifoliata	1	*(Zohner et al., 2016)*
Pyrus elaeagnifolia	1	*(Zohner et al., 2016)*
Pyrus ussuriensis	1	*(Zohner et al., 2016)*
Quercus alba	1	*(Flynn and Wolkovich, 2018)*
Quercus bicolor	1	*(Laube et al., 2014*a*)*
Quercus coccifera	1	*(Sanz-Pérez and Castro-Díez, 2010)*
Quercus ellipsoidalis	1	*(Nanninga et al., 2017)*
Quercus faginea	2	*(Sanz-Perez et al., 2009; Sanz-Pérez and Castro-Díez, 2010)*
Quercus ilex	3	*(Morin et al., 2010; Sanz-Perez et al., 2009; Sanz-Pérez and Castro-Díez, 2010)*
Quercus petraea	3	*(Basler and Körner, 2012, 2014; Vitra et al., 2017)*
Quercus pubescens	1	*(Morin et al., 2010)*
Quercus robur	5	*(Laube et al., 2014*a,b*; Malyshev et al., 2018; Morin et al., 2010; Zohner et al., 2016)*
Quercus rubra	3	*(Calmé et al., 1994; Flynn and Wolkovich, 2018; Laube et al., 2014*a*)*
Quercus shumardii	1	*(Zohner et al., 2016)*
Quercus velutina	1	*(Flynn and Wolkovich, 2018)*
Rhamnus alpina	1	*(Zohner et al., 2016)*
Rhamnus cathartica	2	*(Nanninga et al., 2017; Zohner et al., 2016)*
Rhamnus frangula	1	*(Flynn and Wolkovich, 2018)*
Rhododendron canadense	1	*(Zohner et al., 2016)*
Rhododendron dauricum	1	*(Zohner et al., 2016)*
Rhododendron mucronulatum	1	*(Zohner et al., 2016)*
Rhododendron prinophyllum	1	*(Flynn and Wolkovich, 2018)*
Ribes alpinum	1	*(Zohner et al., 2016)*
Ribes divaricatum	1	*(Zohner et al., 2016)*
Ribes glaciale	1	*(Zohner et al., 2016)*
Robinia pseudoacacia	2	*(Laube et al., 2014*a,b*)*
Rosa hugonis	1	*(Zohner et al., 2016)*
Rosa majalis	1	*(Zohner et al., 2016)*
Salix gracilistyla	1	*(Zohner et al., 2016)*
Salix repens	1	*(Zohner et al., 2016)*
Salix smithiana	1	*(Caffarra and Donnelly, 2011)*
Sambucus pubens	1	*(Zohner et al., 2016)*
Sambucus tigranii	1	*(Zohner et al., 2016)*
Sinowilsonia henryi	1	*(Zohner et al., 2016)*
Sorbus aria	1	*(Zohner et al., 2016)*
Sorbus aucuparia	2	*(Basler and Körner, 2012; Heide, 1993*a*)*
Sorbus commixta	1	*(Zohner et al., 2016)*
Sorbus decora	1	*(Zohner et al., 2016)*

Table S1: Species and references for included in the phylogenetic model.

Species	*Num.Studies*	*Reference*
Sorbus torminalis	1	*(Malyshev et al., 2018)*
Spiraea canescens	1	*(Zohner et al., 2016)*
Spiraea chamaedryfolia	1	*(Zohner et al., 2016)*
Spiraea japonica	1	*(Zohner et al., 2016)*
Spirea alba	1	*(Flynn and Wolkovich, 2018)*
Stachyurus praecox	1	*(Zohner et al., 2016)*
Stachyurus sinensis	1	*(Zohner et al., 2016)*
Symphoricarpos albus	2	*(Laube et al., 2014*a,b*)*
Syringa josikaea	1	*(Zohner et al., 2016)*
Syringa reticulata	1	*(Zohner et al., 2016)*
Syringa villosa	1	*(Zohner et al., 2016)*
Syringa vulgaris	3	*(Basler and Körner, 2012; Laube et al., 2014*a,b*)*
Tilia cordata	3	*(Basler and Körner, 2012; Caffarra and Donnelly, 2011; Malyshev et al., 2018)*
Tilia dasystyla	1	*(Zohner et al., 2016)*
Tilia japonica	1	*(Zohner et al., 2016)*
Tilia platyphyllos	1	*(Zohner et al., 2016)*
Toona sinensis	1	*(Zohner et al., 2016)*
Ulmus americana	1	*(Zohner et al., 2016)*
Ulmus glabra	1	*(Ghelardini et al., 2010)*
Ulmus laevis	1	*(Zohner et al., 2016)*
Ulmus macrocarpa	1	*(Ghelardini et al., 2010)*
Ulmus minor	1	*(Ghelardini et al., 2010)*
Ulmus parvifolia	1	*(Ghelardini et al., 2010)*
Ulmus pumila	1	*(Ghelardini et al., 2010)*
Ulmus villosa	1	*(Ghelardini et al., 2010)*
Vaccinium myrtilloides	1	*(Flynn and Wolkovich, 2018)*
Viburnum betulifolium	1	*(Zohner et al., 2016)*
Viburnum buddleifolium	1	*(Zohner et al., 2016)*
Viburnum carlesii	1	*(Zohner et al., 2016)*
Viburnum cassinoides	1	*(Flynn and Wolkovich, 2018)*
Viburnum lantanoides	1	*(Flynn and Wolkovich, 2018)*
Viburnum opulus	1	*(Zohner et al., 2016)*
Viburnum plicatum	1	*(Zohner et al., 2016)*
Weigela coraeensis	1	*(Zohner et al., 2016)*
Weigela florida	1	*(Zohner et al., 2016)*
Weigela maximowiczii	1	*(Zohner et al., 2016)*

Table S2: Model parameters estimated for 191 tree species including mean, standard deviation (sd), 2.5%, 50%, and 97.5% uncertainty intervals (z-scored model, thus predictors are directly comparable to one another), alongside model diagnostics.

Parameter	mean	sd	2.5%	50%	97.5%	n_{eff}	Rhat
μ_{α}	30.63	3.41	23.94	30.66	37.26	12315.84	1.00
$\mu_{\beta_{force}}$	-6.12	2.11	-10.24	-6.15	-1.85	3989.87	1.00
$\mu_{\beta_{chill}}$	-6.86	2.18	-10.98	-6.91	-2.39	7444.80	1.00
$\mu_{\beta_{photo}}$	-1.22	0.77	-2.73	-1.22	0.36	2482.96	1.00
λ_{α}	0.34	0.10	0.16	0.34	0.55	7668.82	1.00
$\lambda_{\beta_{force}}$	0.65	0.20	0.22	0.67	0.97	630.96	1.01
$\lambda_{\beta_{chill}}$	0.54	0.15	0.25	0.55	0.82	1834.14	1.00
$\lambda_{\beta_{photo}}$	0.40	0.24	0.03	0.38	0.88	672.39	1.00
σ_{α}	15.99	1.15	13.98	15.91	18.47	6970.37	1.00
$\sigma_{\beta_{force}}$	5.80	1.01	4.06	5.70	8.01	1043.34	1.00
$\sigma_{\beta_{chill}}$	7.10	0.88	5.53	7.04	8.99	1767.13	1.00
$\sigma_{\beta_{photo}}$	2.36	0.41	1.61	2.34	3.23	636.82	1.01
σ_{y}	12.58	0.18	12.24	12.58	12.93	10904.90	1.00

Table S3: Model parameters for non-phylogenetic model ($\lambda = 0$) estimated for 191 tree species including mean, standard deviation (sd), 2.5%, 50%, and 97.5% uncertainty intervals (z-scored model, thus predictors are directly comparable to one another), alongside model diagnostics.

Parameter	mean	sd	2.5%	50%	97.5%	n_{eff}	Rhat
μ_{α}	31.79	1.28	29.29	31.77	34.35	13779.62	1.00
$\mu_{\beta_{force}}$	-7.46	0.89	-9.19	-7.46	-5.71	2960.28	1.00
$\mu_{\beta_{chill}}$	-8.75	0.81	-10.29	-8.76	-7.11	6051.59	1.00
$\mu_{\beta_{photo}}$	-1.21	0.46	-2.10	-1.20	-0.29	2175.88	1.00
σ_{α}	16.35	1.00	14.46	16.31	18.41	10178.43	1.00
$\sigma_{\beta_{force}}$	5.20	0.82	3.76	5.15	6.93	677.74	1.00
$\sigma_{\beta_{chill}}$	6.84	0.78	5.40	6.80	8.46	1815.10	1.00
$\sigma_{\beta_{photo}}$	2.27	0.35	1.61	2.25	2.99	649.15	1.00
σ_{y}	12.57	0.18	12.23	12.57	12.94	12887.31	1.00

Table S4: Model parameters estimated for 191 tree species including mean, standard deviation (sd), 2.5%, 50%, and 97.5% uncertainty intervals (z-scored model, thus predictors are directly comparable to one another), alongside model diagnostics. This model uses Chill Portions instead of chilling Utah units.

Parameter	mean	sd	2.5%	50%	97.5%	n_{eff}	Rhat
μ_{α}	30.07	3.46	23.26	30.09	37.05	13454.54	1.00
$\mu_{\beta_{force}}$	-6.21	2.03	-10.14	-6.25	-2.07	3322.83	1.00
$\mu_{\beta_{chill}}$	-5.81	1.98	-9.58	-5.86	-1.77	8346.15	1.00
$\mu_{\beta_{photo}}$	-1.33	0.77	-2.81	-1.36	0.24	2598.50	1.00
λ_{α}	0.35	0.10	0.17	0.35	0.56	7138.11	1.00
$\lambda_{\beta_{force}}$	0.66	0.21	0.20	0.68	0.97	428.34	1.00
$\lambda_{\beta_{chill}}$	0.52	0.13	0.26	0.52	0.77	2850.91	1.00
$\lambda_{\beta_{photo}}$	0.46	0.25	0.04	0.45	0.93	335.00	1.03
σ_{α}	16.00	1.14	13.96	15.93	18.43	6926.49	1.00
$\sigma_{\beta_{force}}$	5.44	0.98	3.78	5.35	7.57	919.27	1.00
$\sigma_{\beta_{chill}}$	6.89	0.75	5.56	6.85	8.47	2579.79	1.00
$\sigma_{\beta_{photo}}$	2.36	0.40	1.64	2.33	3.21	754.25	1.01
σ_{y}	12.08	0.17	11.76	12.08	12.42	9826.08	1.00

Table S5: Model parameters for non-phylogenetic model ($\lambda = 0$) estimated for 191 tree species including mean, standard deviation (sd), 2.5%, 50%, and 97.5% uncertainty intervals (z-scored model, thus predictors are directly comparable to one another), alongside model diagnostics. This model uses Chill Portions instead of chilling Utah units.

Parameter	mean	sd	2.5%	50%	97.5%	n_{eff}	Rhat
μ_{α}	31.32	1.25	28.82	31.32	33.77	13796.71	1.00
$\mu_{\beta_{force}}$	-7.39	0.83	-8.99	-7.38	-5.75	3253.91	1.00
$\mu_{\beta_{chill}}$	-7.35	0.69	-8.71	-7.36	-5.99	7607.11	1.00
$\mu_{\beta_{photo}}$	-1.36	0.45	-2.23	-1.36	-0.47	2528.36	1.00
σ_{α}	16.50	1.00	14.66	16.45	18.58	11407.70	1.00
$\sigma_{\beta_{force}}$	4.91	0.76	3.57	4.85	6.56	706.89	1.00
$\sigma_{\beta_{chill}}$	6.51	0.65	5.33	6.49	7.87	2590.38	1.00
$\sigma_{\beta_{photo}}$	2.20	0.34	1.56	2.20	2.90	540.06	1.01
σ_{y}	12.08	0.17	11.76	12.08	12.42	14353.28	1.00

Table S6: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the full model accounting for phylogenetic relationships.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Populus deltoides	-15.16	-25.05	-5.82	-6.43	-13.73	1.82	-0.97	-5.39	3.23
Populus koreana	-8.65	-18.98	1.84	-7.47	-15.61	1.11	-0.87	-5.03	3.22
Populus tremula	-1.94	-7.35	3.60	-7.41	-10.54	-4.23	0.05	-2.11	2.28
Populus grandidentata	-14.08	-21.56	-6.90	-9.98	-15.90	-4.64	-1.18	-5.12	2.65
Euonymus europaeus	-3.61	-15.78	8.88	-6.23	-17.68	5.35	-1.15	-5.80	3.39
Euonymus latifolius	1.12	-9.12	11.97	-6.32	-17.69	5.22	-1.01	-5.32	3.41
Nothofagus antarctica	-10.16	-22.40	1.95	-6.62	-17.37	4.52	-1.63	-6.10	2.79
Carya cordiformis	-15.52	-25.34	-6.01	-4.51	-14.91	6.16	-2.65	-7.00	1.57
Carya laciniosa	-17.48	-27.47	-7.95	-4.03	-14.28	6.79	-1.72	-6.04	2.60
Alnus incana	-1.73	-5.59	2.12	-10.18	-14.56	-5.96	-0.52	-2.82	1.82
Alnus glutinosa	-5.85	-12.14	0.49	-10.25	-15.37	-5.24	-0.60	-3.06	1.93
Alnus maximowiczii	-5.35	-14.90	4.33	-7.32	-16.89	2.55	-1.05	-5.26	3.15
Betula nana	-5.76	-14.88	3.60	-5.15	-13.97	3.61	-0.92	-4.90	3.08
Betula pendula	-4.33	-5.44	-3.23	-1.38	-3.58	0.76	-0.42	-1.41	0.59
Betula pubescens	-2.13	-3.47	-0.83	-6.64	-9.29	-4.11	-0.75	-1.85	0.33
Betula populifolia	-5.30	-14.54	4.00	-5.48	-14.46	3.60	-0.86	-4.88	3.16
Betula papyrifera	-27.28	-33.48	-21.06	-5.69	-10.02	-1.32	1.25	-2.24	5.13
Betula alleghaniensis	-11.23	-18.21	-4.10	-6.99	-10.69	-3.42	-1.47	-5.48	2.47
Betula lenta	-3.33	-10.33	3.85	-4.84	-12.37	2.89	-0.98	-5.16	2.98
Corylus cornuta	-6.20	-17.60	5.56	-7.24	-15.02	0.13	-1.35	-5.69	2.86
Ostrya carpinifolia	-5.52	-14.52	3.75	-4.92	-14.08	3.93	-0.92	-4.91	3.01
Ostrya virginiana	-11.38	-20.74	-2.10	-4.75	-14.01	4.43	-0.75	-4.80	3.43
Carpinus laxiflora	-8.99	-19.72	1.53	-4.74	-13.68	3.95	-0.91	-5.22	3.32
Carpinus betulus	-12.30	-18.99	-5.82	-2.59	-7.41	2.38	-0.59	-4.06	3.02
Carpinus monbeigiana	-5.66	-14.75	3.82	-4.73	-13.83	4.11	-0.89	-4.97	3.20
Rosa majalis	-4.26	-14.32	5.85	-7.15	-17.85	3.38	-0.94	-5.20	3.37
Rosa hugonis	-6.88	-18.69	5.08	-7.23	-17.86	3.75	-1.03	-5.49	3.50
Aronia melanocarpa	-2.38	-10.96	6.08	-5.07	-12.57	2.62	-0.74	-4.72	3.33
Photinia villosa	-2.92	-11.68	5.92	-5.86	-14.58	2.79	-0.76	-4.64	3.30
Spiraea japonica	-3.74	-12.85	5.42	-6.66	-16.49	3.07	-0.71	-4.74	3.41
Spiraea chamaedryfolia	-4.02	-13.48	5.21	-6.72	-16.37	3.13	-0.73	-4.89	3.58
Spiraea canescens	-5.16	-16.13	5.65	-6.78	-16.48	2.85	-0.79	-5.14	3.64
Prunus tenella	-3.89	-15.10	7.59	-7.19	-16.37	2.29	-0.93	-5.27	3.29
Prunus serrulata	-4.63	-15.76	6.60	-7.08	-15.83	2.23	-0.78	-4.88	3.43
Prunus pensylvanica	-3.85	-14.58	7.26	-7.01	-14.53	0.66	-0.91	-5.02	3.29
Prunus serotina	-7.40	-16.97	2.22	-6.26	-14.41	2.36	-0.83	-4.90	3.31
Prunus padus	-1.76	-7.09	3.46	-10.44	-14.27	-6.74	-0.96	-2.96	1.03
Prinsepia uniflora	-5.04	-16.35	6.67	-6.97	-16.85	3.27	-0.72	-4.89	3.49
Prinsepia sinensis	-5.07	-17.10	6.91	-7.03	-16.88	3.01	-0.80	-5.04	3.55
Oemleria cerasiformis	-4.93	-15.87	6.42	-6.84	-16.51	3.03	-0.75	-4.99	3.60
Ulmus minor	-16.20	-20.78	-11.59	-10.39	-14.29	-6.49	-2.57	-6.32	0.98

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Table S6: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the full model accounting for phylogenetic relationships.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Ulmus glabra	-18.61	-25.10	-12.12	-10.25	-17.35	-2.78	-1.49	-5.16	2.38
Ulmus macrocarpa	-17.08	-23.91	-10.39	-10.51	-18.27	-2.82	-1.49	-5.27	2.54
Ulmus pumila	-12.48	-17.10	-7.94	-10.68	-14.62	-6.65	-1.81	-5.35	1.76
Ulmus parvifolia	-15.59	-20.21	-10.92	-9.42	-13.49	-5.28	-2.39	-6.08	1.18
Ulmus laevis	-16.26	-25.01	-7.62	-9.63	-17.46	-1.30	-1.64	-5.64	2.43
Ulmus americana	-13.53	-22.09	-4.68	-9.81	-17.57	-1.43	-1.59	-5.51	2.44
Ulmus villosa	-15.74	-20.40	-11.06	-11.92	-15.90	-8.04	-1.94	-5.59	1.65
Caragana pygmaea	-5.09	-16.95	6.79	-4.36	-14.86	6.22	-1.14	-5.42	3.32
Robinia pseudoacacia	-5.49	-15.64	4.60	-0.16	-5.50	5.18	-0.98	-5.30	3.51
Amorpha fruticosa	-1.98	-12.24	8.75	-3.88	-13.42	5.70	-1.04	-5.35	3.42
Cercis chinensis	-0.91	-10.52	9.36	-5.45	-16.53	5.76	-1.86	-6.37	2.54
Cercis canadensis	-4.02	-13.75	5.85	-5.15	-15.95	6.47	-1.45	-6.00	3.10
Tilia japonica	-2.93	-11.73	6.09	-8.03	-16.42	0.99	-1.26	-5.59	3.04
Tilia cordata	-3.70	-8.16	0.93	-9.91	-14.05	-5.82	-2.55	-6.15	0.92
Tilia dasystyla	-7.53	-17.00	1.52	-7.95	-16.41	1.18	-1.28	-5.47	2.95
Tilia platyphyllos	-4.30	-13.23	4.64	-7.95	-16.40	1.33	-1.27	-5.57	3.13
Hibiscus syriacus	0.01	-9.30	10.00	-7.50	-17.14	2.41	-1.26	-5.54	3.08
Aesculus flava	-14.90	-24.42	-5.70	-1.49	-10.89	7.74	-1.45	-5.58	2.77
Aesculus parviflora	-12.63	-21.95	-3.69	-2.00	-11.47	7.49	-2.00	-6.23	2.02
Aesculus hippocastanum	-8.33	-16.34	-0.34	1.57	-4.06	7.72	-1.33	-5.34	2.74
Toona sinensis	-3.77	-13.34	6.19	-4.78	-15.53	6.37	-1.31	-5.70	2.94
Orixa japonica	-5.76	-15.83	4.15	-4.75	-15.49	6.38	-1.21	-5.45	3.25
Ptelea trifoliata	-4.44	-14.20	5.45	-4.60	-15.22	6.67	-1.23	-5.57	3.14
Ribes divaricatum	-11.44	-23.49	0.20	-6.57	-18.06	4.68	-1.25	-5.82	3.30
Ribes glaciale	-7.39	-17.37	2.48	-6.69	-18.49	4.88	-0.96	-5.39	3.52
Ribes alpinum	-9.60	-21.69	2.07	-6.65	-18.27	4.94	-1.07	-5.56	3.50
Hamamelis virginiana	-8.19	-20.19	3.97	-9.99	-19.60	-0.73	-1.60	-6.28	3.08
Hamamelis vernalis	-12.75	-22.86	-2.86	-7.46	-18.49	3.77	-1.08	-5.47	3.33
Hamamelis japonica	-8.81	-18.66	1.17	-7.47	-18.61	3.42	-1.11	-5.53	3.31
Sinowilsonia henryi	-4.90	-15.08	5.12	-7.03	-18.68	4.55	-1.22	-5.58	3.34
Corylopsis sinensis	-7.56	-19.20	4.40	-7.10	-18.43	3.99	-1.33	-5.75	3.21
Corylopsis spicata	-7.91	-20.00	4.03	-7.06	-18.29	4.06	-1.42	-5.81	3.03
Liquidambar styraciflua	-7.91	-17.96	1.79	-6.68	-17.99	4.77	-1.51	-5.92	2.83
Liquidambar orientalis	-2.27	-12.08	7.89	-6.81	-18.31	4.47	-1.21	-5.61	3.23
Cercidiphyllum japonicum	-9.19	-20.49	2.23	-6.65	-17.89	4.96	-1.24	-5.71	3.26
Cercidiphyllum magnificum	-9.91	-19.98	-0.03	-6.58	-17.94	4.98	-1.30	-5.65	3.18
Parrotia persica	-8.06	-20.72	4.46	-6.62	-17.88	4.72	-1.01	-5.32	3.49
Paeonia rockii	-6.41	-18.74	6.05	-6.63	-18.19	5.11	-1.17	-5.66	3.44
Syringa villosa	-5.04	-15.49	5.54	-4.17	-12.82	4.14	-0.89	-5.19	3.46
Syringa vulgaris	-4.55	-13.61	4.73	-1.79	-6.08	2.68	-0.93	-5.22	3.18
Syringa josikaea	-4.34	-14.73	6.34	-4.07	-12.75	4.47	-0.96	-5.36	3.41
Syringa reticulata	-4.51	-15.06	5.98	-4.12	-12.75	4.24	-0.88	-5.17	3.50

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Table S6: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the full model accounting for phylogenetic relationships.

Species	$\beta_{chill,j}$	$lowUI$	$upUI$	$\beta_{force,j}$	$lowUI$	$upUI$	$\beta_{photo,j}$	$lowUI$	$upUI$
Ligustrum tschonoskii	-4.45	-14.78	5.75	-4.13	-12.79	4.31	-0.88	-5.20	3.49
Forsythia ovata	-4.34	-14.99	6.24	-4.68	-14.36	4.83	-0.88	-5.23	3.38
Forsythia suspensa	-4.40	-13.57	5.01	-4.73	-14.22	4.57	-0.83	-5.14	3.55
Cephalanthus occidentalis	-2.38	-12.22	7.91	-5.37	-16.10	5.42	-1.11	-5.46	3.35
Viburnum buddleifolium	-10.26	-21.58	0.26	-4.75	-13.53	4.42	-0.23	-4.45	4.30
Viburnum carlesii	-7.53	-18.46	2.95	-5.33	-14.31	3.30	-0.86	-5.13	3.60
Viburnum cassinoides	-4.06	-11.31	3.10	-4.63	-10.55	1.19	-1.07	-4.93	2.89
Viburnum lantanoides	-8.43	-15.76	-1.23	-7.04	-12.94	-1.20	-1.27	-5.27	2.77
Viburnum plicatum	-9.13	-20.55	1.66	-5.00	-13.89	4.25	-0.49	-4.90	4.04
Viburnum opulus	-6.20	-15.54	3.42	-5.27	-14.19	3.75	-0.80	-5.10	3.44
Viburnum betulifolium	-7.78	-18.78	3.06	-5.35	-14.50	3.79	-0.99	-5.29	3.27
Weigela coraeensis	-4.55	-14.12	4.95	-4.97	-15.03	5.46	-0.70	-4.94	3.65
Weigela florida	-5.05	-16.05	6.17	-5.02	-15.07	5.15	-0.72	-5.01	3.64
Weigela maximowiczii	-5.99	-15.36	3.50	-4.92	-15.24	5.49	-0.67	-4.88	3.66
Heptacodium miconioides	-4.27	-15.74	7.38	-5.05	-14.97	4.95	-0.78	-5.20	3.75
Symphoricarpos albus	-6.84	-16.49	2.74	-3.29	-8.35	1.96	-0.74	-5.02	3.60
Lonicera maximowiczii	-4.60	-16.20	6.94	-5.01	-14.15	4.06	-0.71	-4.96	3.80
Lonicera alpigena	-4.83	-16.11	6.80	-4.91	-14.25	4.31	-0.61	-4.86	3.79
Lonicera canadensis	-4.56	-16.34	7.44	-5.48	-13.30	1.79	-0.87	-5.28	3.53
Lonicera caerulea	-4.96	-17.41	7.31	-5.19	-14.44	3.80	-0.77	-5.21	3.86
Eleutherococcus sieboldianus	-3.08	-12.87	6.67	-5.51	-16.16	5.23	-0.75	-5.07	3.58
Eleutherococcus setchuenensis	-3.74	-15.08	7.72	-5.47	-16.29	5.56	-0.86	-5.32	3.72
Eleutherococcus senticosus	-3.20	-12.73	6.71	-5.45	-16.37	5.49	-0.72	-4.90	3.73
Ilex mucronata	-2.88	-10.53	4.87	-6.00	-12.28	0.16	-1.91	-6.17	2.25
Rhododendron prinophyllum	-3.02	-14.99	9.25	-11.17	-20.26	-2.67	-0.97	-5.49	3.70
Rhododendron canadense	0.00	-9.69	9.99	-10.20	-19.93	-0.41	-0.78	-4.94	3.73
Rhododendron dauricum	-1.90	-13.20	9.95	-10.15	-20.05	0.24	-0.66	-5.05	3.89
Rhododendron mucronulatum	-2.54	-14.20	9.05	-10.38	-20.08	-0.54	-0.78	-5.24	3.88
Kalmia angustifolia	-2.93	-14.96	9.56	-12.80	-21.36	-4.83	-1.53	-6.00	2.93
Vaccinium myrtilloides	-1.69	-13.89	10.77	-9.51	-17.61	-1.70	-0.80	-5.17	3.86
Lyonia ligustrina	-3.56	-15.92	9.13	-11.82	-20.72	-3.04	-0.99	-5.57	3.76
Nyssa sylvatica	-6.22	-19.01	6.72	-8.05	-17.75	1.31	-1.44	-6.02	3.16
Cornus alba	-4.43	-14.38	5.63	2.72	-4.19	9.86	-1.48	-5.75	2.74
Cornus kousa	-2.92	-12.91	6.78	-2.84	-12.93	7.21	-1.30	-5.77	3.02
Cornus mas	-4.83	-14.88	5.25	-2.17	-8.45	4.40	-1.15	-5.51	3.30
Hydrangea arborescens	-8.72	-18.61	0.95	-5.11	-16.13	6.25	-0.91	-5.30	3.50
Hydrangea involucrata	-8.38	-17.92	1.10	-5.18	-16.24	6.18	-0.96	-5.14	3.46
Hydrangea serrata	-7.90	-19.38	3.71	-5.24	-16.55	6.05	-0.95	-5.30	3.43
Deutzia gracilis	-5.33	-16.70	6.09	-5.43	-16.20	5.60	-0.87	-5.24	3.65
Deutzia scabra	-3.84	-13.80	6.13	-5.30	-16.00	5.63	-0.87	-5.16	3.50
Decaisnea fargesii	-8.07	-21.12	4.95	-6.02	-18.26	5.96	-1.05	-5.68	3.54
Berberis dielsiana	-5.03	-18.26	8.40	-6.23	-18.11	6.06	-0.98	-5.72	3.80

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Table S6: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the full model accounting for phylogenetic relationships.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Liriodendron tulipifera	-12.23	-26.09	1.05	-6.28	-18.58	5.93	-1.57	-6.32	3.20
Acer pseudoplatanus	-10.59	-16.87	-4.06	-9.06	-12.19	-5.96	-1.30	-4.58	2.05
Acer saccharinum	-7.95	-12.05	-3.92	-3.33	-10.91	4.47	-1.20	-5.57	3.07
Acer rubrum	-15.89	-22.63	-9.17	-0.34	-5.01	4.46	-0.42	-4.11	3.53
Acer barbinerve	-9.88	-20.06	0.71	-4.03	-12.65	4.64	-1.19	-5.29	2.92
Acer negundo	-11.88	-21.14	-2.52	-2.89	-10.66	5.24	-1.30	-5.54	2.85
Acer pensylvanicum	-9.42	-16.45	-2.35	-5.80	-11.67	-0.04	-1.97	-5.94	1.83
Acer platanoides	-10.35	-19.35	-1.41	-3.77	-12.18	4.69	-1.21	-5.25	2.80
Acer campestre	-11.25	-20.38	-2.26	-3.71	-12.17	5.09	-1.10	-5.10	3.04
Acer tataricum	-9.05	-18.10	0.14	-2.60	-10.40	5.71	-1.18	-5.31	3.01
Acer ginnala	-9.18	-19.83	1.23	-3.93	-12.38	4.92	-1.22	-5.43	3.05
Amelanchier laevis	-5.13	-15.80	6.01	-5.88	-14.63	2.85	-0.91	-5.08	3.31
Amelanchier florida	-6.02	-15.05	2.89	-5.86	-14.55	3.07	-0.72	-4.73	3.36
Buddleja davidii	-3.03	-15.36	9.46	-5.45	-15.85	5.04	-0.75	-5.13	3.84
Buddleja alternifolia	-2.79	-14.91	9.62	-5.45	-15.69	5.26	-0.83	-5.19	3.75
Buddleja albiflora	-3.35	-15.38	8.66	-5.48	-16.42	4.90	-0.79	-5.21	3.92
Celtis laevigata	-12.47	-22.42	-2.60	-7.60	-18.51	3.47	-1.60	-5.81	2.64
Celtis occidentalis	-7.70	-19.65	3.89	-7.48	-18.18	3.43	-1.40	-5.77	3.03
Celtis caucasica	-10.86	-20.81	-1.13	-7.54	-18.07	2.98	-1.29	-5.60	3.02
Cladrastis lutea	-9.69	-19.88	0.48	-4.68	-15.83	6.43	-1.93	-6.40	2.32
Elaeagnus ebbingei	-7.93	-20.04	4.44	-8.29	-19.52	2.52	-1.09	-5.42	3.40
Fagus crenata	-13.85	-22.96	-4.61	-7.94	-16.59	0.62	-3.49	-8.02	1.21
Fagus engleriana	-13.94	-22.98	-5.04	-7.93	-16.88	0.24	-3.39	-7.90	1.36
Fagus grandifolia	-13.77	-21.02	-6.50	-8.83	-14.77	-2.89	-4.52	-8.88	-0.31
Fagus orientalis	-16.38	-25.68	-7.38	-8.06	-16.89	0.26	-4.00	-8.52	0.42
Fagus sylvatica	-14.31	-15.89	-12.74	-2.91	-4.92	-0.92	-9.37	-11.91	-6.71
Fraxinus excelsior	-6.70	-15.49	1.96	-5.66	-13.56	1.70	-1.34	-5.59	2.76
Fraxinus ornus	-11.44	-20.97	-2.69	-4.07	-12.57	4.71	-0.88	-4.99	3.28
Fraxinus nigra	-6.30	-16.53	4.27	-7.89	-15.98	-0.64	-1.49	-5.81	2.64
Fraxinus pennsylvanica	-4.76	-13.81	4.38	-4.04	-11.90	4.08	-1.06	-5.25	3.18
Fraxinus americana	-7.23	-11.63	-2.76	-3.87	-11.48	4.02	-0.98	-5.27	3.39
Fraxinus latifolia	-7.66	-16.43	1.07	-4.63	-13.19	3.81	-1.45	-5.61	2.74
Fraxinus chinensis	-5.94	-14.92	2.99	-4.40	-12.35	3.60	-0.95	-5.04	3.16
Juglans cinerea	-11.11	-20.91	-1.25	-2.91	-12.33	7.19	-1.45	-5.75	2.70
Juglans ailantifolia	-11.61	-21.18	-2.29	-2.85	-12.14	7.07	-1.51	-5.90	2.77
Parrotiopsis jaquemontiana	-5.83	-15.63	3.89	-7.40	-18.44	3.63	-1.11	-5.55	3.32
Pyrus ussuriensis	-6.05	-16.71	4.34	-5.98	-14.58	2.52	-0.73	-4.74	3.31
Pyrus elaeagnifolia	-6.92	-15.89	1.86	-5.85	-14.48	3.13	-0.80	-4.83	3.31
Quercus faginea	-20.99	-32.47	-10.85	-12.86	-18.58	-7.15	-3.69	-8.03	0.37
Quercus bicolor	-15.08	-23.84	-6.01	-9.69	-16.58	-1.46	-2.31	-6.48	1.89
Quercus alba	-14.33	-24.51	-3.88	-12.84	-19.68	-5.59	-2.69	-6.74	1.39
Quercus coccifera	-21.14	-32.27	-10.79	-12.91	-20.09	-5.50	-2.50	-6.73	1.85

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Table S6: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the full model accounting for phylogenetic relationships.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Quercus rubra	-18.25	-24.21	-12.29	-11.54	-15.11	-7.89	-2.56	-6.10	1.07
Quercus ellipsoidalis	-17.47	-27.04	-7.96	-13.15	-20.62	-5.69	-2.63	-6.89	1.63
Quercus velutina	-14.69	-25.24	-3.81	-13.13	-20.18	-6.08	-2.47	-6.65	1.80
Quercus shumardii	-17.04	-25.91	-8.41	-12.12	-19.62	-4.18	-2.40	-6.36	1.79
Quercus ilex	-23.29	-34.81	-13.14	-17.73	-24.27	-11.90	-2.57	-6.69	1.78
Quercus petraea	-16.47	-22.58	-10.32	-12.45	-15.88	-9.04	-2.64	-6.62	1.38
Quercus pubescens	-14.74	-25.34	-3.62	-16.42	-24.65	-9.56	-2.33	-6.61	2.28
Quercus robur	-13.18	-19.40	-6.83	-11.66	-15.22	-8.02	0.28	-3.49	4.35
Rhamnus cathartica	-4.58	-12.27	3.22	-11.90	-22.38	-2.51	-1.93	-6.12	2.18
Rhamnus alpina	-11.53	-21.67	-2.00	-8.90	-19.55	1.61	-1.14	-5.42	3.13
Rhamnus frangula	-6.98	-18.76	4.88	-10.67	-19.83	-1.62	-1.29	-5.82	3.19
Salix gracilistyla	-7.38	-18.54	3.62	-6.15	-15.42	3.21	-1.03	-5.34	3.26
Salix smithiana	-5.00	-11.20	1.20	-4.71	-10.10	0.96	-1.98	-6.28	2.08
Salix repens	-9.73	-19.17	-0.53	-6.02	-14.86	3.35	-1.16	-5.36	3.15
Sambucus tigranii	-8.12	-20.14	3.49	-5.33	-15.53	5.07	-0.83	-5.23	3.56
Sambucus pubens	-8.30	-20.17	3.35	-5.33	-15.75	5.11	-0.79	-5.26	3.70
Sorbus aucuparia	-5.67	-15.28	4.26	-5.60	-10.21	-0.98	-0.80	-4.24	2.58
Sorbus torminalis	-8.15	-17.44	0.37	-6.21	-14.71	2.47	-0.83	-4.46	2.95
Sorbus aria	-8.86	-18.00	0.08	-5.67	-14.08	2.86	-0.86	-4.74	3.09
Sorbus decora	-6.40	-15.18	2.22	-5.78	-14.19	2.78	-0.85	-4.88	3.17
Sorbus commixta	-5.84	-14.68	3.21	-5.88	-14.37	2.63	-0.77	-4.82	3.39
Spirea alba	-2.58	-14.70	10.38	-5.51	-13.84	2.80	-0.99	-5.28	3.46
Stachyurus praecox	-6.22	-18.40	6.27	-6.02	-16.95	5.21	-1.08	-5.46	3.37
Stachyurus sinensis	-6.14	-16.90	4.62	-5.65	-17.01	5.99	-0.97	-5.47	3.62

Table S7: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the non phylogenetic model.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Populus deltoides	-18.11	-28.51	-7.77	-6.23	-15.95	4.03	-1.26	-5.84	3.32
Populus koreana	-7.92	-20.17	4.43	-7.42	-18.36	3.81	-1.10	-5.60	3.35
Populus tremula	-0.58	-6.21	5.09	-7.44	-10.70	-4.20	0.08	-2.10	2.32
Populus grandidentata	-15.62	-23.79	-7.77	-11.33	-17.49	-5.03	-1.32	-5.36	2.76
Euonymus europaeus	-8.27	-20.53	4.41	-7.49	-17.98	2.90	-1.18	-5.65	3.40
Euonymus latifolius	0.39	-10.11	10.84	-7.43	-18.03	3.43	-0.92	-5.14	3.40
Nothofagus antarctica	-10.50	-23.34	2.22	-7.46	-17.74	3.05	-1.38	-5.87	3.14
Carya cordiformis	-14.04	-24.40	-3.93	-7.85	-18.59	2.95	-2.62	-7.25	1.74
Carya laciniosa	-17.27	-27.99	-6.99	-6.61	-17.22	4.39	-1.16	-5.49	3.25
Alnus incana	-1.59	-5.55	2.37	-10.38	-14.59	-6.15	-0.55	-2.95	1.88
Alnus glutinosa	-6.51	-13.31	0.43	-10.42	-15.83	-5.14	-0.61	-3.13	1.88
Alnus maximowiczii	-6.18	-16.56	4.39	-7.15	-17.62	3.58	-1.21	-5.73	3.36
Betula nana	-6.39	-16.31	3.94	-7.15	-17.95	3.49	-1.13	-5.50	3.18
Betula pendula	-4.32	-5.43	-3.24	-1.34	-3.51	0.83	-0.43	-1.41	0.55
Betula pubescens	-2.11	-3.42	-0.79	-6.88	-9.54	-4.20	-0.78	-1.88	0.31
Betula populifolia	-5.25	-15.53	5.25	-7.38	-18.12	3.16	-1.08	-5.38	3.30
Betula papyrifera	-29.62	-35.81	-23.48	-5.80	-10.59	-0.96	1.37	-2.37	5.36
Betula alleghaniensis	-9.92	-17.11	-2.60	-6.93	-10.75	-3.03	-2.03	-6.13	1.95
Betula lenta	-2.29	-9.47	5.25	-5.99	-14.69	2.79	-1.23	-5.54	3.13
Corylus cornuta	-6.37	-19.26	7.06	-9.25	-17.67	-1.12	-1.62	-5.98	2.70
Ostrya carpinifolia	-4.10	-14.33	6.22	-7.40	-18.07	3.12	-1.08	-5.33	3.33
Ostrya virginiana	-13.26	-23.48	-3.08	-6.97	-17.59	3.71	-0.85	-5.04	3.54
Carpinus laxiflora	-9.40	-22.06	3.28	-7.33	-18.04	3.19	-1.13	-5.57	3.27
Carpinus betulus	-13.38	-20.38	-6.35	-2.12	-7.22	3.01	-0.62	-4.38	3.08
Carpinus monbeigiana	-4.43	-14.44	6.14	-7.23	-17.98	3.60	-1.05	-5.41	3.16
Rosa majalis	-4.90	-14.82	5.20	-7.49	-18.17	2.80	-0.91	-5.30	3.54
Rosa hugonis	-8.24	-20.58	4.29	-7.48	-17.98	2.93	-1.01	-5.44	3.50
Aronia melanocarpa	-2.26	-12.02	8.08	-5.30	-13.53	3.41	-1.01	-5.18	3.30
Photinia villosa	-3.69	-13.75	6.68	-7.29	-17.69	3.12	-0.99	-5.24	3.28
Spiraea japonica	-5.62	-15.79	4.68	-7.23	-17.59	3.41	-0.90	-5.24	3.44
Spiraea chamaedryfolia	-6.08	-16.17	4.00	-7.35	-17.96	3.50	-0.90	-5.25	3.53
Spiraea canescens	-8.77	-21.15	3.53	-7.52	-17.64	3.02	-1.05	-5.46	3.37
Prunus tenella	-6.68	-18.91	6.02	-7.50	-18.67	3.50	-1.11	-5.55	3.30
Prunus serrulata	-8.11	-20.34	4.47	-7.26	-17.51	2.93	-0.94	-5.47	3.52
Prunus pensylvanica	-6.31	-18.71	6.34	-6.83	-14.73	1.34	-1.14	-5.66	3.25
Prunus serotina	-10.58	-21.02	-0.14	-5.49	-14.91	4.23	-1.09	-5.41	3.21
Prunus padus	-2.17	-7.46	3.09	-10.81	-14.58	-6.99	-1.02	-3.02	0.93
Prinsepia uniflora	-7.80	-20.33	4.82	-7.62	-18.52	3.05	-0.96	-5.31	3.54
Prinsepia sinensis	-8.08	-21.71	5.47	-7.73	-18.30	2.92	-1.03	-5.45	3.47
Oemleria cerasiformis	-7.71	-19.80	4.48	-7.38	-17.76	2.99	-0.89	-5.29	3.44
Ulmus minor	-15.63	-20.50	-10.78	-9.99	-14.32	-5.72	-2.53	-6.44	1.32
Ulmus glabra	-17.95	-25.56	-10.49	-8.23	-17.95	1.42	-0.95	-5.10	3.26
Ulmus macrocarpa	-16.04	-23.67	-8.80	-8.41	-18.61	1.26	-0.98	-5.12	3.21

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Table S7: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the non phylogenetic model.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Ulmus pumila	-11.49	-16.11	-6.71	-10.23	-14.42	-6.11	-1.42	-5.28	2.43
Ulmus parvifolia	-15.06	-19.83	-10.22	-8.70	-12.86	-4.46	-2.26	-6.03	1.52
Ulmus laevis	-14.85	-25.33	-4.77	-7.03	-17.89	3.92	-1.09	-5.44	3.11
Ulmus americana	-10.02	-20.18	0.50	-7.25	-17.66	3.23	-1.08	-5.43	3.28
Ulmus villosa	-15.17	-19.92	-10.37	-11.93	-16.26	-7.68	-1.64	-5.41	2.16
Caragana pygmaea	-6.71	-18.99	6.14	-7.62	-17.95	2.61	-1.00	-5.50	3.49
Robinia pseudoacacia	-6.86	-17.21	3.40	-0.60	-5.78	4.61	-0.75	-5.06	3.72
Amorpha fruticosa	-2.88	-13.18	7.81	-6.49	-15.80	3.00	-0.89	-5.06	3.46
Cercis chinensis	-1.56	-11.77	9.06	-7.60	-17.89	2.95	-1.74	-6.21	2.63
Cercis canadensis	-6.58	-16.76	3.84	-7.05	-17.67	3.67	-1.16	-5.52	3.17
Tilia japonica	-4.13	-14.09	6.20	-7.27	-17.82	3.35	-0.92	-5.13	3.38
Tilia cordata	-4.07	-8.65	0.70	-10.14	-14.18	-6.13	-2.80	-6.50	0.72
Tilia dasystyla	-11.94	-21.87	-2.13	-7.08	-17.24	3.43	-0.97	-5.30	3.48
Tilia platyphyllos	-6.54	-16.83	3.82	-7.15	-17.61	3.34	-0.95	-5.30	3.35
Hibiscus syriacus	-0.59	-11.02	10.10	-7.26	-17.56	3.34	-1.01	-5.34	3.55
Aesculus flava	-16.49	-27.49	-6.45	-6.64	-16.97	4.11	-1.19	-5.56	3.16
Aesculus parviflora	-12.49	-22.79	-2.37	-7.72	-18.11	3.24	-2.03	-6.34	2.29
Aesculus hippocastanum	-6.13	-14.54	2.27	0.38	-5.66	6.53	-1.15	-5.18	2.96
Toona sinensis	-4.10	-14.20	6.30	-7.25	-17.75	3.20	-1.17	-5.46	3.17
Orixa japonica	-6.50	-16.39	3.67	-7.19	-18.04	3.52	-1.13	-5.59	3.42
Ptelea trifoliata	-5.10	-15.40	5.25	-7.18	-17.65	3.19	-1.13	-5.31	3.00
Ribes divaricatum	-13.67	-26.45	-1.51	-7.57	-17.79	2.87	-1.34	-5.84	3.10
Ribes glaciale	-6.68	-16.53	3.71	-7.52	-18.12	3.24	-0.93	-5.24	3.38
Ribes alpinum	-10.17	-22.66	2.37	-7.55	-18.28	2.77	-1.09	-5.59	3.36
Hamamelis virginiana	-8.61	-21.51	4.26	-10.91	-20.31	-2.12	-1.71	-6.07	2.63
Hamamelis vernalis	-14.59	-24.87	-4.51	-6.98	-17.43	3.98	-0.99	-5.36	3.38
Hamamelis japonica	-9.15	-19.59	1.08	-7.27	-17.57	2.99	-1.06	-5.29	3.44
Sinowilsonia henryi	-5.24	-15.18	4.75	-7.49	-18.03	2.98	-1.18	-5.49	3.06
Corylopsis sinensis	-8.51	-21.07	3.86	-7.55	-18.23	3.10	-1.28	-5.87	3.26
Corylopsis spicata	-9.18	-22.03	3.41	-7.43	-17.82	3.06	-1.39	-5.73	2.99
Liquidambar styraciflua	-11.04	-21.08	-0.87	-7.33	-17.56	2.99	-1.53	-5.94	2.77
Liquidambar orientalis	-1.35	-11.39	9.46	-7.50	-17.89	2.68	-1.10	-5.42	3.36
Cercidiphyllum japonicum	-9.68	-22.12	2.60	-7.37	-17.85	2.64	-1.21	-5.57	3.14
Cercidiphyllum magnificum	-10.65	-20.75	-0.52	-7.40	-18.14	3.44	-1.26	-5.51	3.06
Parrotia persica	-9.39	-21.92	2.89	-7.29	-17.70	3.04	-0.96	-5.35	3.61
Paeonia rockii	-7.59	-19.89	4.62	-7.50	-17.90	2.67	-1.11	-5.54	3.45
Syringa villosa	-7.83	-20.07	4.59	-7.56	-17.94	3.00	-0.96	-5.47	3.67
Syringa vulgaris	-6.30	-16.36	3.99	-1.65	-6.09	2.84	-1.10	-5.37	3.20
Syringa josikaea	-6.60	-19.15	6.33	-7.45	-18.02	2.72	-1.06	-5.44	3.39
Syringa reticulata	-6.89	-19.47	5.72	-7.39	-17.73	3.23	-0.99	-5.25	3.46
Ligustrum tschonoskii	-6.63	-19.20	6.28	-7.60	-18.30	3.08	-0.97	-5.36	3.50
Forsythia ovata	-6.77	-19.55	5.87	-7.44	-17.72	2.73	-1.05	-5.50	3.29
Forsythia suspensa	-6.12	-16.36	4.09	-7.35	-17.43	3.19	-0.91	-5.26	3.49

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Table S7: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the non phylogenetic model.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Cephalanthus occidentalis	-4.96	-14.92	5.38	-7.24	-17.89	3.24	-1.20	-5.44	3.08
Viburnum buddleifolium	-14.54	-27.32	-2.15	-6.42	-16.75	4.49	-0.33	-4.81	4.32
Viburnum carlesii	-8.95	-21.76	3.97	-7.51	-18.21	3.24	-1.24	-5.64	3.15
Viburnum cassinoides	-3.71	-11.38	3.89	-5.17	-11.27	1.16	-1.47	-5.57	2.67
Viburnum lantanoides	-9.24	-16.57	-1.67	-8.47	-14.62	-2.48	-1.61	-5.72	2.45
Viburnum plicatum	-12.20	-25.12	0.40	-6.78	-16.97	3.77	-0.68	-5.11	3.94
Viburnum opulus	-6.92	-17.13	3.34	-7.13	-17.59	3.54	-1.07	-5.31	3.32
Viburnum betulifolium	-9.67	-21.96	2.29	-7.35	-18.04	2.93	-1.35	-5.71	3.06
Weigela coraeensis	-6.56	-16.50	3.63	-7.28	-17.73	3.12	-0.97	-5.39	3.55
Weigela florida	-7.68	-20.09	4.64	-7.44	-17.87	2.82	-1.02	-5.43	3.48
Weigela maximowiczii	-8.92	-19.08	1.20	-7.17	-17.88	3.39	-0.93	-5.25	3.48
Heptacodium miconioides	-6.82	-19.04	5.69	-7.43	-18.06	3.16	-1.06	-5.51	3.45
Symphoricarpos albus	-9.52	-19.78	0.77	-3.21	-8.44	2.01	-0.99	-5.31	3.30
Lonicera maximowiczii	-7.39	-19.31	5.44	-7.68	-18.06	2.94	-0.99	-5.42	3.58
Lonicera alpigena	-7.78	-20.33	4.51	-7.44	-18.17	3.04	-0.91	-5.30	3.73
Lonicera canadensis	-5.93	-18.81	7.24	-6.98	-14.79	0.81	-1.10	-5.56	3.39
Lonicera caerulea	-8.21	-21.52	5.31	-7.69	-18.25	2.78	-1.07	-5.56	3.48
Eleutherococcus sieboldianus	-5.41	-15.51	4.71	-7.38	-17.99	3.12	-0.93	-5.20	3.20
Eleutherococcus setchuenensis	-7.57	-20.49	5.35	-7.35	-17.75	2.96	-1.11	-5.57	3.36
Eleutherococcus senticosus	-5.49	-15.94	5.09	-7.28	-17.96	3.46	-0.85	-5.16	3.48
Ilex mucronata	-3.79	-11.32	3.87	-6.56	-12.55	-0.46	-1.95	-6.21	2.13
Rhododendron prinophyllum	-8.09	-20.84	4.67	-9.26	-18.33	-0.45	-1.15	-5.60	3.14
Rhododendron canadense	-2.62	-12.72	7.74	-7.23	-17.42	3.14	-0.97	-5.29	3.32
Rhododendron dauricum	-6.80	-19.00	5.68	-7.19	-17.73	3.19	-0.78	-5.16	3.84
Rhododendron mucronulatum	-7.40	-20.33	5.50	-7.54	-18.22	3.36	-0.93	-5.24	3.42
Kalmia angustifolia	-7.32	-19.73	5.25	-12.11	-20.86	-4.08	-1.88	-6.36	2.60
Vaccinium myrtilloides	-5.98	-18.81	6.75	-7.41	-15.38	0.43	-0.96	-5.29	3.52
Lyonia ligustrina	-8.15	-21.11	4.80	-10.43	-20.28	-1.38	-1.13	-5.67	3.42
Nyssa sylvatica	-8.31	-20.67	4.49	-9.52	-18.51	-0.80	-1.39	-5.88	3.14
Cornus alba	-6.41	-16.04	3.37	1.92	-5.09	9.28	-1.53	-5.67	2.62
Cornus kousa	-4.68	-14.61	5.57	-7.39	-17.85	2.97	-1.23	-5.54	3.10
Cornus mas	-6.61	-16.98	3.82	-3.77	-10.09	2.70	-1.00	-5.49	3.49
Hydrangea arborescens	-10.58	-20.66	-0.37	-7.14	-17.55	3.55	-1.00	-5.24	3.33
Hydrangea involucrata	-10.15	-20.14	-0.07	-7.34	-18.13	3.41	-1.09	-5.52	3.30
Hydrangea serrata	-9.89	-22.57	2.80	-7.40	-17.99	3.12	-1.05	-5.61	3.29
Deutzia gracilis	-7.60	-20.50	4.96	-7.50	-18.00	2.96	-0.97	-5.22	3.39
Deutzia scabra	-5.07	-15.20	5.25	-7.38	-17.61	2.97	-0.96	-5.33	3.45
Decaisnea fargesii	-9.88	-22.56	2.67	-7.29	-18.05	3.42	-1.04	-5.49	3.53
Berberis dielsiana	-6.59	-19.04	6.31	-7.55	-18.15	3.04	-1.03	-5.46	3.38
Liriodendron tulipifera	-13.64	-26.59	-1.43	-7.48	-17.99	2.87	-1.54	-6.05	2.97
Acer pseudoplatanus	-9.70	-16.44	-2.92	-9.89	-12.97	-6.82	-1.04	-4.56	2.52
Acer saccharinum	-7.59	-11.67	-3.57	-5.92	-14.96	3.57	-1.10	-5.65	3.47
Acer rubrum	-16.72	-23.81	-9.65	-0.57	-5.33	4.18	-0.11	-3.91	3.89

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Table S7: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the non phylogenetic model.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Acer barbinerve	-8.41	-20.80	4.09	-7.50	-17.88	3.24	-1.09	-5.44	3.39
Acer negundo	-11.74	-22.34	-1.06	-5.75	-15.29	4.11	-1.25	-5.65	3.01
Acer pensylvanicum	-8.87	-16.22	-1.40	-7.87	-13.96	-1.91	-2.06	-6.16	1.94
Acer platanoides	-9.84	-20.42	0.22	-7.16	-17.34	2.95	-1.08	-5.44	3.22
Acer campestre	-10.97	-21.18	-0.77	-7.11	-17.69	3.50	-0.95	-5.30	3.32
Acer tataricum	-7.79	-18.03	2.46	-5.40	-14.64	4.07	-1.15	-5.40	3.14
Acer ginnala	-7.24	-19.58	5.24	-7.49	-18.33	3.43	-1.12	-5.68	3.44
Amelanchier laevis	-8.10	-21.11	5.19	-7.37	-17.58	3.14	-1.20	-5.72	3.31
Amelanchier florida	-8.42	-18.53	1.88	-7.19	-17.84	3.50	-0.98	-5.22	3.36
Buddleja davidii	-6.63	-18.75	5.87	-7.44	-17.88	3.29	-0.89	-5.27	3.52
Buddleja alternifolia	-6.14	-18.70	6.71	-7.50	-17.98	2.95	-0.99	-5.35	3.43
Buddleja albiflora	-6.94	-19.44	5.67	-7.57	-17.97	2.86	-0.92	-5.35	3.61
Celtis laevigata	-12.78	-22.93	-2.58	-7.23	-17.80	3.21	-1.47	-5.78	2.81
Celtis occidentalis	-6.21	-18.44	6.36	-7.09	-17.45	3.03	-1.26	-5.69	3.24
Celtis caucasica	-10.47	-20.58	-0.58	-7.13	-17.53	3.27	-1.10	-5.50	3.24
Cladrastis lutea	-12.14	-22.62	-1.82	-7.49	-17.74	3.05	-1.87	-6.32	2.42
Elaeagnus ebbingei	-7.84	-20.50	4.78	-7.59	-18.36	3.17	-0.94	-5.27	3.50
Fagus crenata	-9.96	-20.36	0.39	-7.46	-17.89	2.82	-1.39	-5.68	2.90
Fagus engleriana	-10.08	-20.42	-0.09	-7.30	-17.89	3.21	-1.29	-5.55	3.13
Fagus grandifolia	-12.35	-20.21	-4.58	-9.72	-16.07	-3.46	-3.14	-7.46	0.95
Fagus orientalis	-14.05	-24.38	-3.82	-7.67	-17.96	2.80	-2.12	-6.56	2.13
Fagus sylvatica	-14.21	-15.81	-12.65	-2.65	-4.64	-0.66	-9.51	-12.05	-7.03
Fraxinus excelsior	-8.32	-18.52	1.93	-8.54	-17.44	0.30	-1.54	-5.89	2.75
Fraxinus ornus	-16.69	-27.23	-6.40	-6.19	-16.38	4.61	-0.79	-5.22	3.63
Fraxinus nigra	-8.33	-21.58	4.78	-11.81	-20.23	-3.87	-1.66	-6.24	2.85
Fraxinus pennsylvanica	-5.37	-15.49	5.02	-6.09	-15.47	3.72	-1.14	-5.50	3.25
Fraxinus americana	-7.61	-12.04	-3.03	-5.48	-14.63	4.13	-1.11	-5.73	3.57
Fraxinus latifolia	-10.54	-20.86	-0.45	-7.26	-17.74	3.42	-1.68	-6.06	2.61
Fraxinus chinensis	-7.27	-17.55	3.05	-6.59	-15.87	3.19	-0.98	-5.29	3.43
Juglans cinerea	-8.76	-19.59	2.18	-6.49	-15.82	2.86	-1.05	-5.29	3.25
Juglans ailantifolia	-9.49	-20.35	1.28	-6.42	-15.56	2.82	-1.17	-5.49	3.22
Parrotiopsis jaquemontiana	-5.61	-15.90	4.64	-7.37	-17.60	2.86	-1.06	-5.36	3.28
Pyrus ussuriensis	-8.49	-21.12	4.01	-7.50	-17.79	3.05	-1.01	-5.40	3.50
Pyrus elaeagnifolia	-9.48	-19.57	0.58	-7.28	-18.02	3.53	-1.07	-5.26	3.22
Quercus faginea	-18.47	-33.56	-5.41	-11.03	-17.86	-4.45	-3.11	-7.94	1.24
Quercus bicolor	-8.94	-19.24	1.46	-6.42	-15.74	3.46	-1.21	-5.63	3.23
Quercus alba	-9.45	-22.53	3.34	-11.13	-20.45	-2.23	-1.97	-6.64	2.55
Quercus coccifera	-18.01	-32.31	-4.98	-8.90	-18.92	0.86	-1.25	-5.73	3.27
Quercus rubra	-16.88	-23.01	-10.62	-10.78	-14.60	-6.94	-2.17	-6.10	1.72
Quercus ellipsoidalis	-13.69	-25.01	-2.52	-7.55	-17.79	2.46	-1.22	-5.78	3.27
Quercus velutina	-9.87	-23.30	3.02	-11.53	-21.17	-2.22	-1.60	-6.14	2.87
Quercus shumardii	-12.36	-22.59	-2.46	-7.18	-17.39	3.45	-1.31	-5.42	3.02
Quercus ilex	-22.78	-36.98	-10.07	-18.72	-25.67	-12.04	-1.40	-5.94	3.15

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Table S7: Estimated sensitivities of 191 tree species to three environmental cues: chilling ($\beta_{chill,j}$), forcing ($\beta_{force,j}$) and photoperiod ($\beta_{photo,j}$), along with their corresponding 2.5% (low) and 97.5% (up) uncertainty intervals (UI). Values correspond to the non phylogenetic model.

Species	$\beta_{chill,j}$	*lowUI*	*upUI*	$\beta_{force,j}$	*lowUI*	*upUI*	$\beta_{photo,j}$	*lowUI*	*upUI*
Quercus petraea	-14.19	-21.05	-7.52	-12.70	-16.43	-9.14	-1.64	-5.91	2.50
Quercus pubescens	-5.83	-19.07	7.80	-15.90	-26.67	-6.44	-0.98	-5.62	3.61
Quercus robur	-10.11	-16.66	-3.51	-11.38	-15.34	-7.53	1.99	-1.51	5.79
Rhamnus cathartica	-4.04	-11.63	3.79	-11.39	-21.57	-1.84	-1.89	-6.25	2.37
Rhamnus alpina	-13.28	-23.56	-3.29	-6.84	-17.38	3.86	-0.92	-5.18	3.57
Rhamnus frangula	-7.45	-20.31	5.55	-9.97	-19.23	-0.83	-1.15	-5.51	3.37
Salix gracilistyla	-7.77	-20.03	5.07	-7.52	-17.74	2.88	-0.98	-5.36	3.50
Salix smithiana	-4.74	-11.00	1.55	-4.61	-10.32	0.93	-2.27	-6.68	2.05
Salix repens	-11.68	-21.88	-1.57	-7.11	-17.62	3.43	-1.11	-5.42	3.22
Sambucus tigranii	-10.43	-22.84	1.55	-7.40	-17.95	3.27	-1.05	-5.56	3.38
Sambucus pubens	-10.68	-23.03	1.36	-7.42	-17.88	3.17	-1.03	-5.39	3.43
Sorbus aucuparia	-8.39	-20.03	3.44	-6.35	-11.41	-1.50	-1.11	-4.81	2.58
Sorbus torminalis	-10.89	-21.41	-0.75	-8.01	-18.33	2.39	-1.09	-5.06	2.89
Sorbus aria	-13.07	-23.69	-2.74	-6.98	-17.30	3.44	-1.08	-5.35	3.24
Sorbus decora	-8.57	-18.81	1.94	-7.34	-17.48	2.93	-1.09	-5.39	3.30
Sorbus commixta	-7.51	-17.66	2.70	-7.38	-17.75	3.10	-1.01	-5.41	3.50
Spirea alba	-5.95	-18.47	6.94	-6.51	-14.74	1.51	-1.05	-5.49	3.46
Stachyurus praecox	-7.90	-20.29	4.77	-7.55	-17.73	2.86	-1.05	-5.54	3.43
Stachyurus sinensis	-7.56	-18.17	3.53	-7.03	-17.41	3.35	-0.99	-5.43	3.44

Table S8: Model parameters estimated for 158 tree species not affected by polytomies in the phylogenetic tree, including mean, standard deviation (sd), 2.5%, 50%, and 97.5% uncertainty intervals (z-scored model, thus predictors are directly comparable to one another), alongside model diagnostics. Note that most species from well-represented genera (e.g., Quercus, Fagus, Acer), are absent from this analysis.

Parameter	*mean*	*sd*	*2.5%*	*50%*	*97.5%*	n_{eff}	*Rhat*
μ_{α}	30.01	3.75	22.73	30.00	37.26	12779.08	1.00
$\mu_{\beta_{force}}$	-5.98	1.82	-9.54	-6.00	-2.28	3683.05	1.00
$\mu_{\beta_{chill}}$	-6.20	2.09	-10.28	-6.22	-1.90	7016.47	1.00
$\mu_{\beta_{photo}}$	-1.30	0.89	-3.05	-1.31	0.45	2898.12	1.00
λ_{α}	0.64	0.12	0.38	0.65	0.85	4353.95	1.00
$\lambda_{\beta_{force}}$	0.14	0.12	0.00	0.11	0.45	3127.79	1.00
$\lambda_{\beta_{chill}}$	0.53	0.16	0.19	0.54	0.82	2083.87	1.00
$\lambda_{\beta_{photo}}$	0.58	0.28	0.04	0.61	0.98	193.31	1.02
σ_{α}	14.01	1.35	11.66	13.91	16.90	7157.78	1.00
$\sigma_{\beta_{force}}$	8.17	1.01	6.42	8.09	10.37	1490.78	1.00
$\sigma_{\beta_{chill}}$	6.87	0.86	5.35	6.82	8.67	2211.74	1.00
$\sigma_{\beta_{photo}}$	2.44	0.41	1.71	2.41	3.33	1045.71	1.01
σ_{y}	12.53	0.19	12.17	12.52	12.90	11427.98	1.00

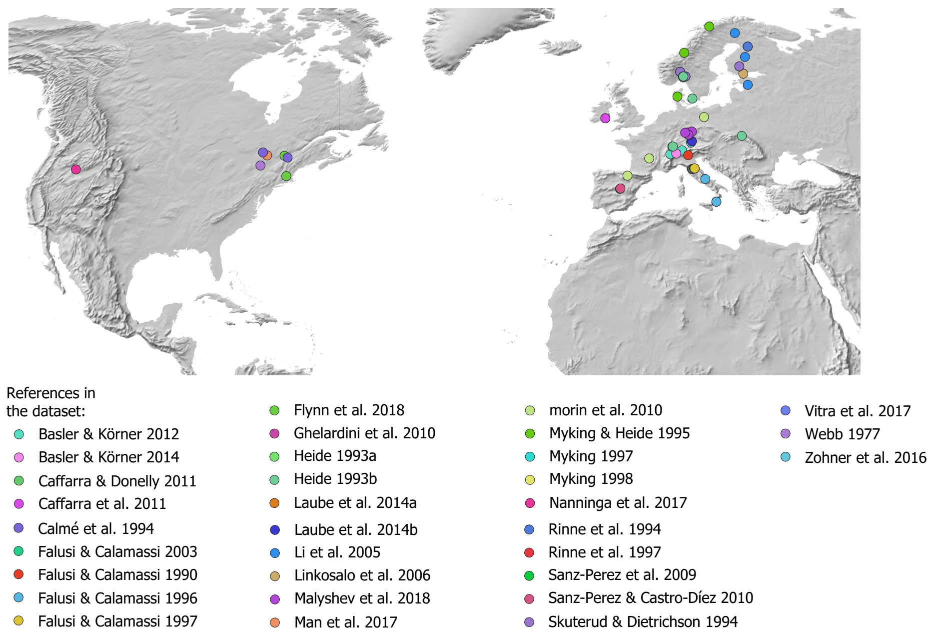

Figure S1: Map showing locations from which woody plant samples were taken for experiments in meta-analytic dataset, which is a subset of the OSPREE dataset. Dots in the map show the locations, and are colored according to the study IDs shown in the legend (see XXX for full information on study IDs).

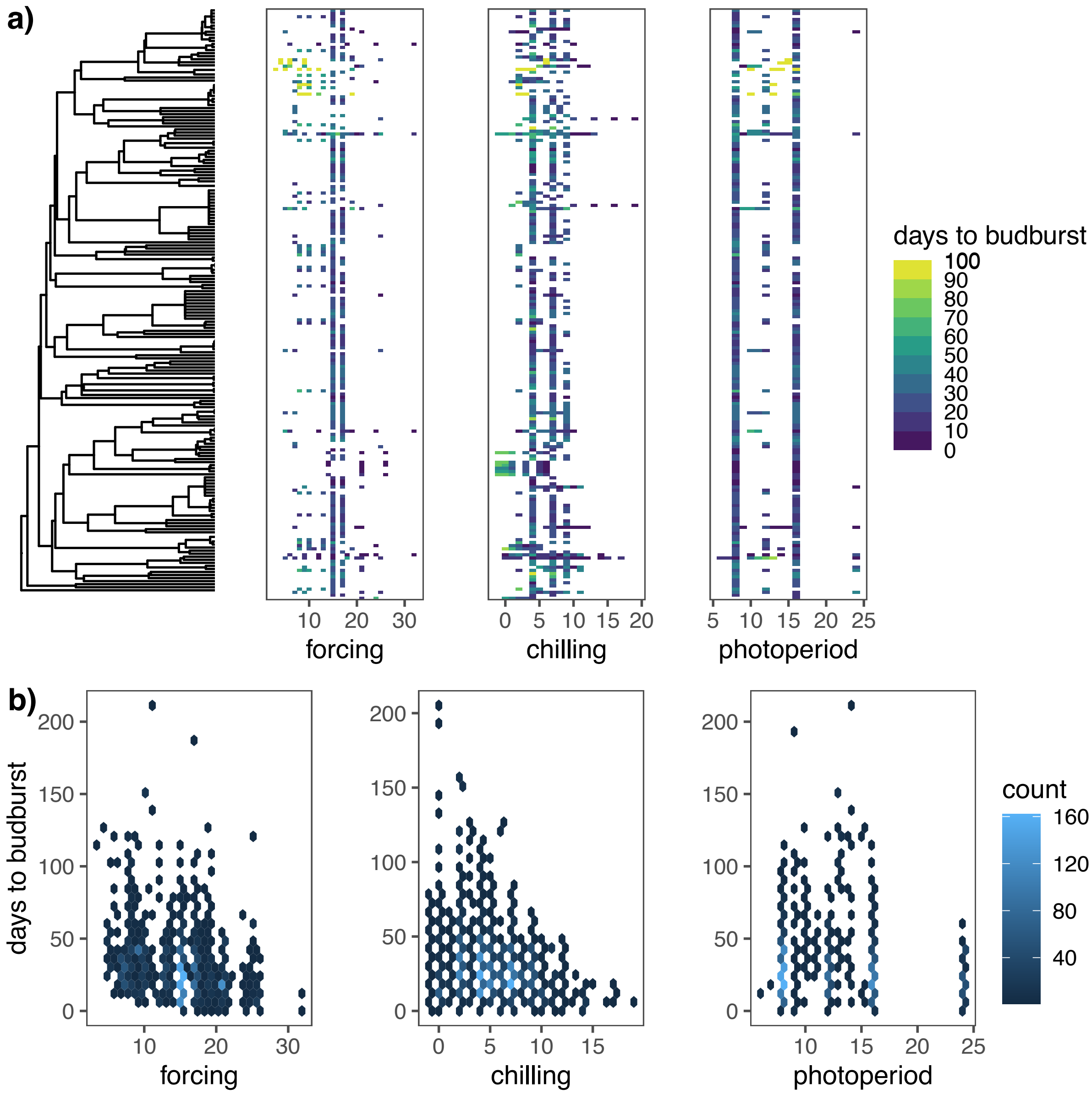

Figure S2: Distribution of data including response (days to budburst) and predictor variables (forcing in °C, chilling in Utah units, and photoperiod in hours of light per day) in our dataset. The upper panels show distribution of experimental treatments for forcing, chilling and photoperiod ordered vertically with respect the phylogenetic tree. Colors quantify the response variable. The lower panels show response vs. predictor variables with colors indicating the frequency at which a treatment-response is found in the dataset.

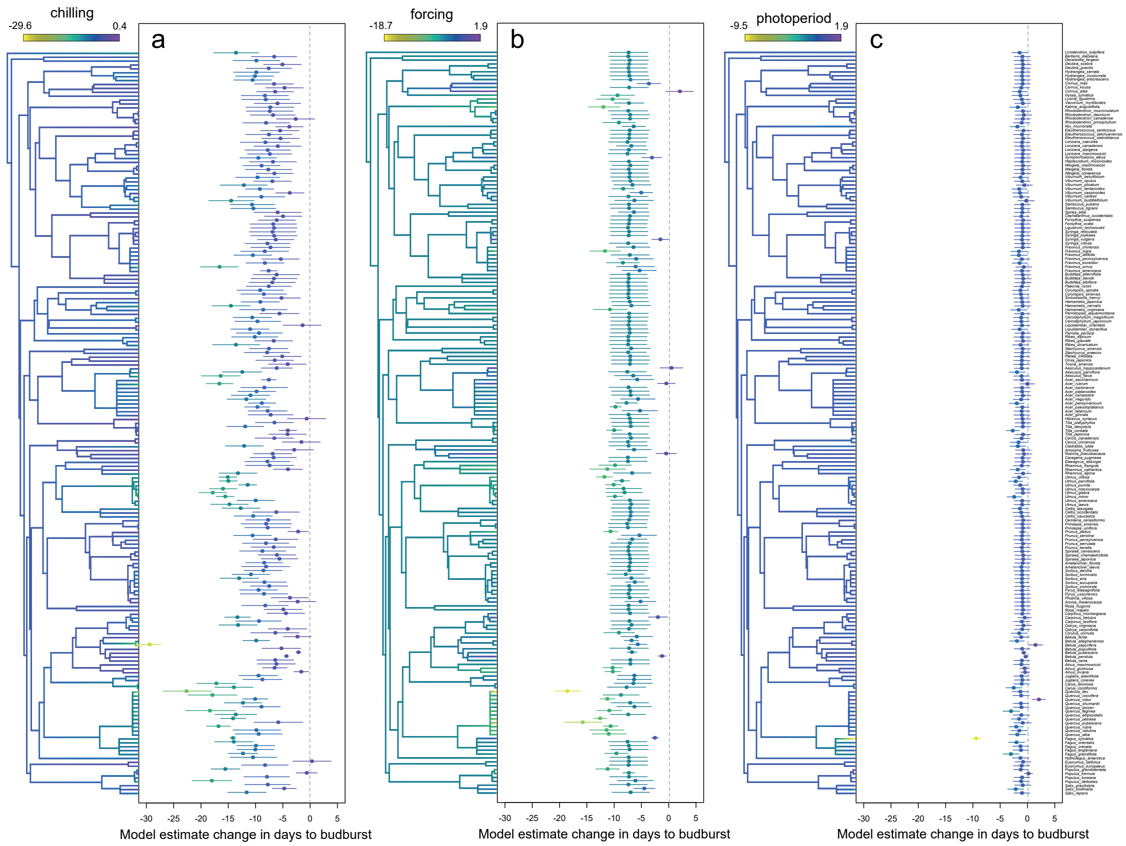

Figure S3: Non-phylogenetic phenological sensitivity to three environmental cues, chilling (a), forcing (b) and photoperiod (c) measured in change in days to budburst per standardized unit (z-transformation) of the cues across 191 tree species. Sensitivity estimates are computed by commonly used hierarchical model where phylogenetic distances are not accounted for ($\lambda = 0$). The same phylogenetic tree is shown in each panel, colored acording to an estimation of ancestral character states, being the states at the tips the species' sensitivities to a cue. Species sensitivities are shown along with 50% uncertainty Intervals in the diagrams. Note that the color scale varies in each panel. Total tree depth is 81. My.

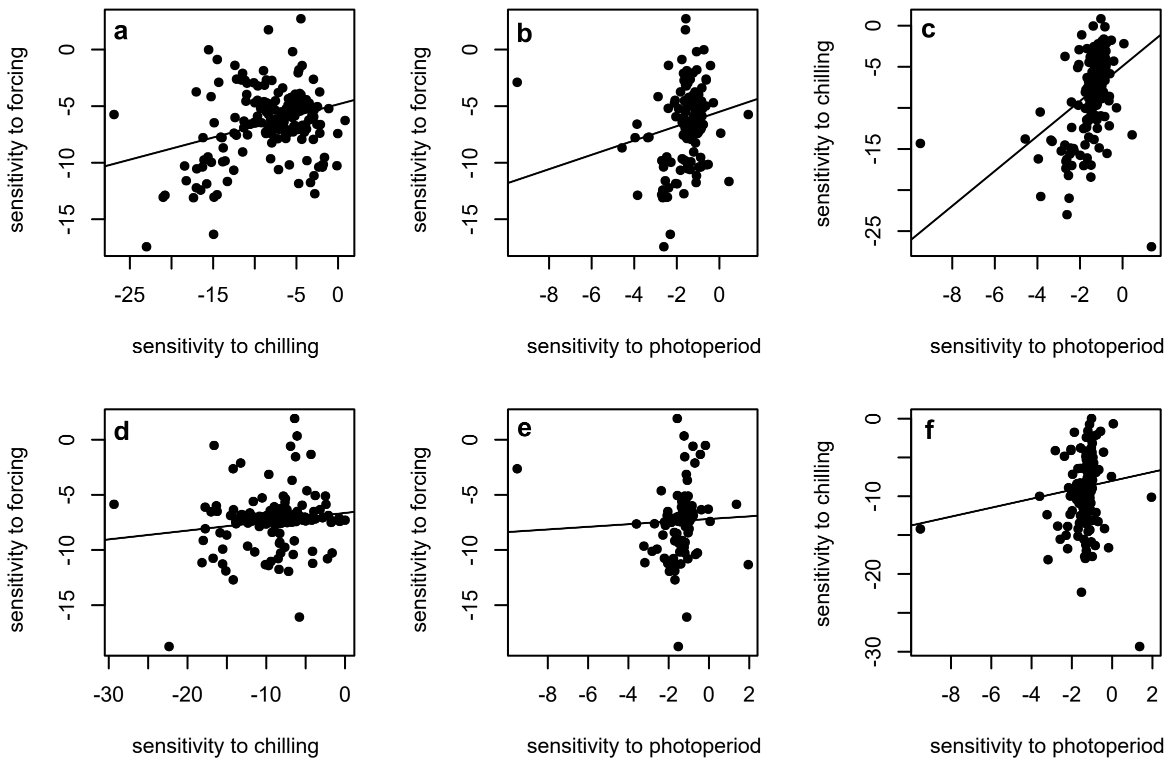

Figure S4: Correlations among estimated sensitivities to the environmental cues comparing forcing vs. chilling (a,d), forcing vs. photoperiod (b,e) and chilling vs. photoperiod (c,f). Upper panels show correlations among estimated sensitivities by the phylogenetic model and lower panels show results for the non-phylogenetic model.

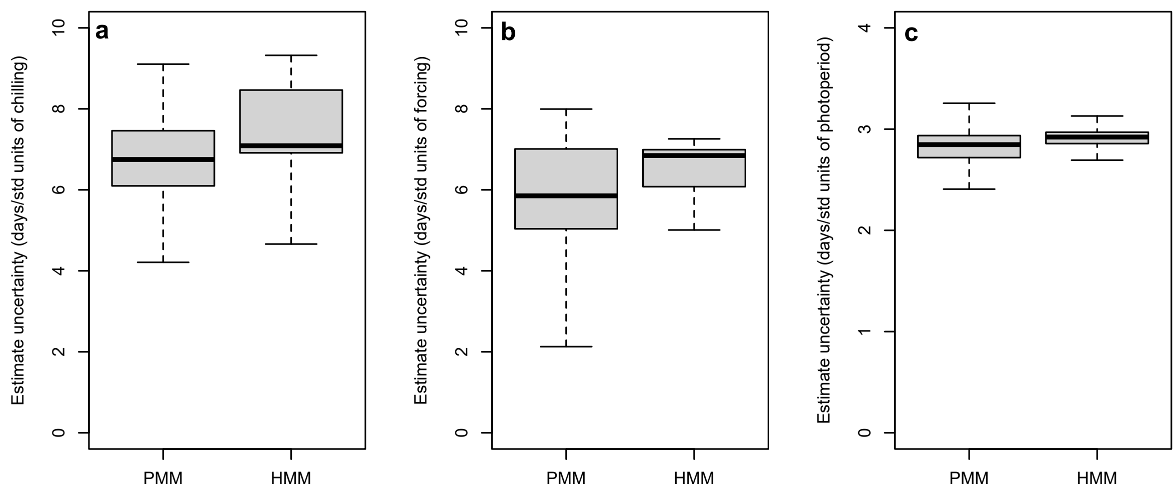

Figure S5: Comparison of uncertainty around estimated sensitivities to chilling (a), forcing (b) and photoperiod (c) of individual species between the phylogenetic model with estimated λ (lambdaest), and the non-phylogenetic model with $\lambda = 0$ (lambda0). The non-phylogenetic model increases uncertainty.

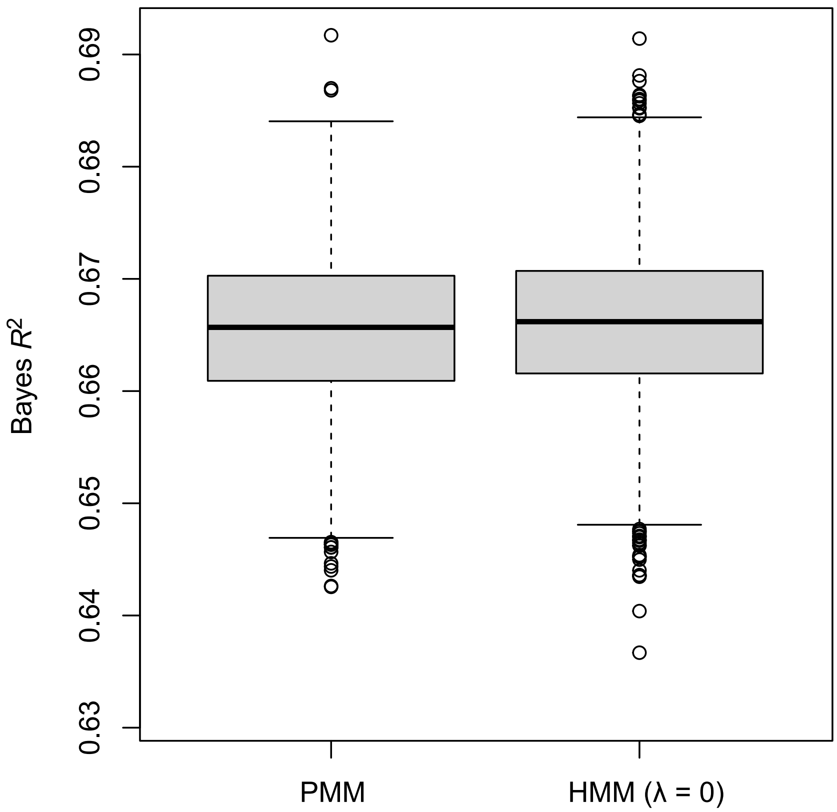

Figure S6: Comparison of overall model accuracy as measured by Bayes *R2* for the phylogenetic model (PMM) and the non-phylogenetic model (HMM). There are no differences in accuracy even if individual species estimates markedly differ between models.

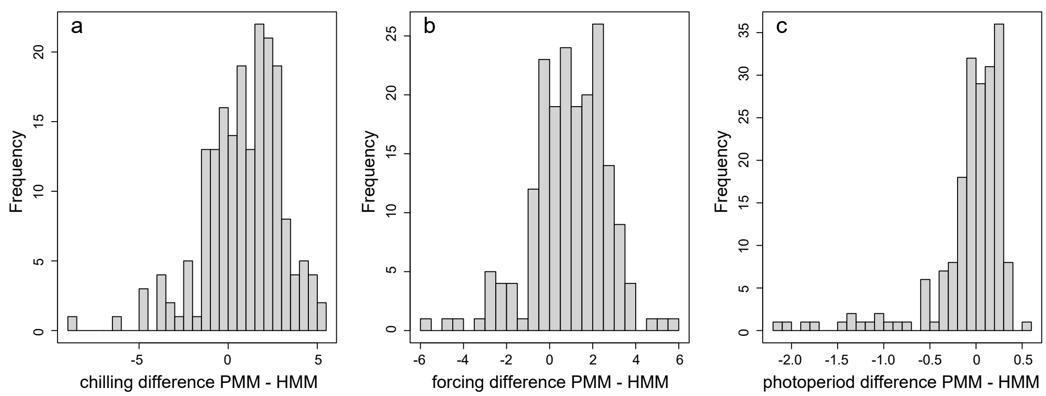

Figure S7: Bias in estimation of sensitivity to chilling (a), forcing (b) and photoperiod (c). Histograms show the difference between the phylogenetic model with estimated λ against the non-phylogenetic model with $\lambda = 0$. Positive values indicate that sensitivities estimated by the non-phylogenetic model are smaller than those estimated by the phylogenetic model.

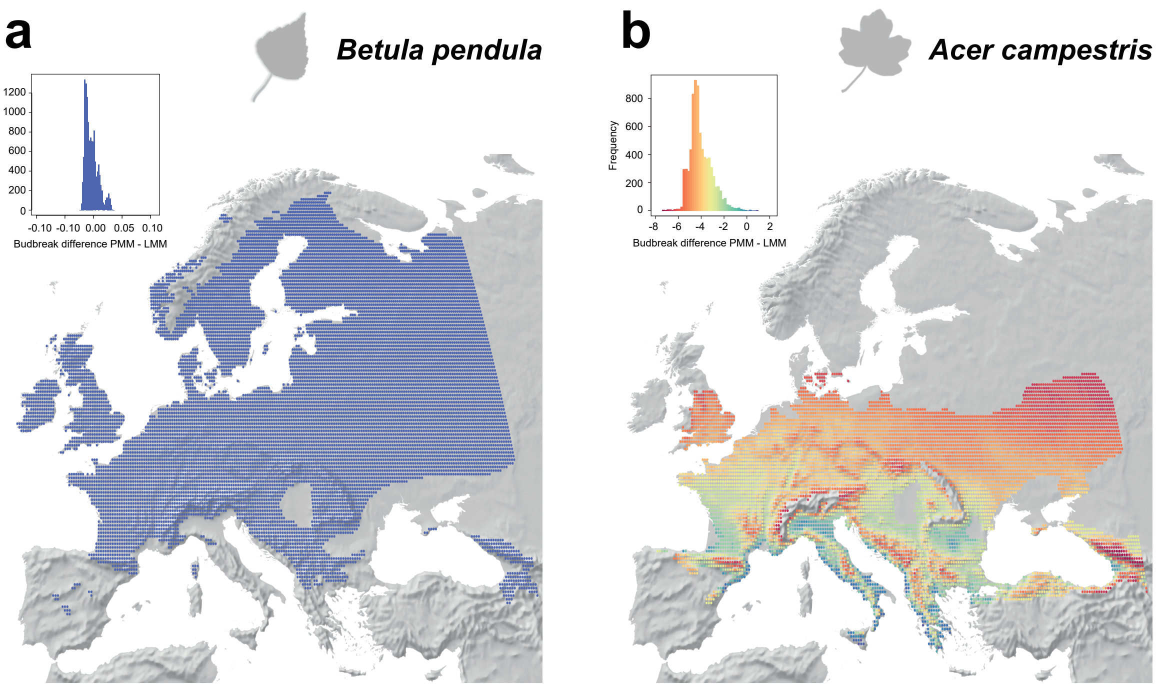

Figure S8: Maps comparing projections of phylogenetic (PMM) against non-phylogenetic (HMM) models into the European distributions of two overlapping species, one well represented in the dataset *Betula pendula* (a) and one underrepresented *Acer campestre* (b). The color scale shown in maps and histograms reflects budbreak differences between models where days are relative to start of forcing conditions, not calendar days.

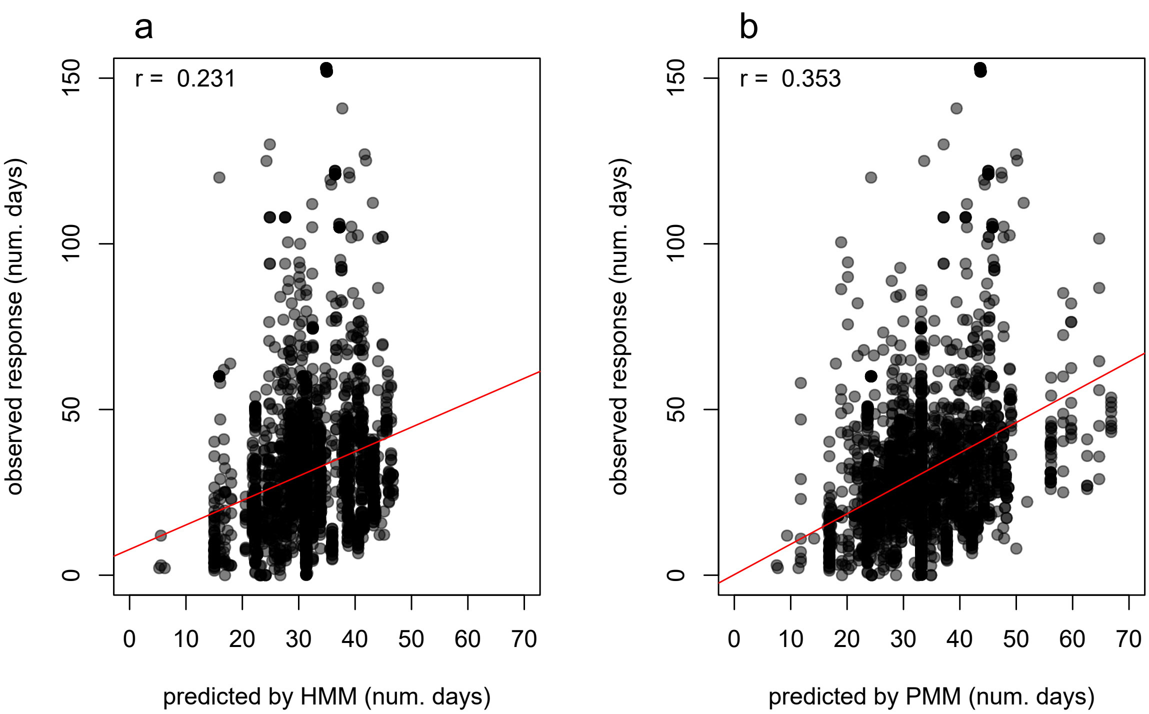

Figure S9: Comparison of observed vs. predicted values of our response variable (number of days to budburst) for left out species in our cross-validation analyses, as modelled by the new phylogenetic mixed model we present (PMM; panel a) and a more traditional hierarchical mixed model (HMM; panel b).

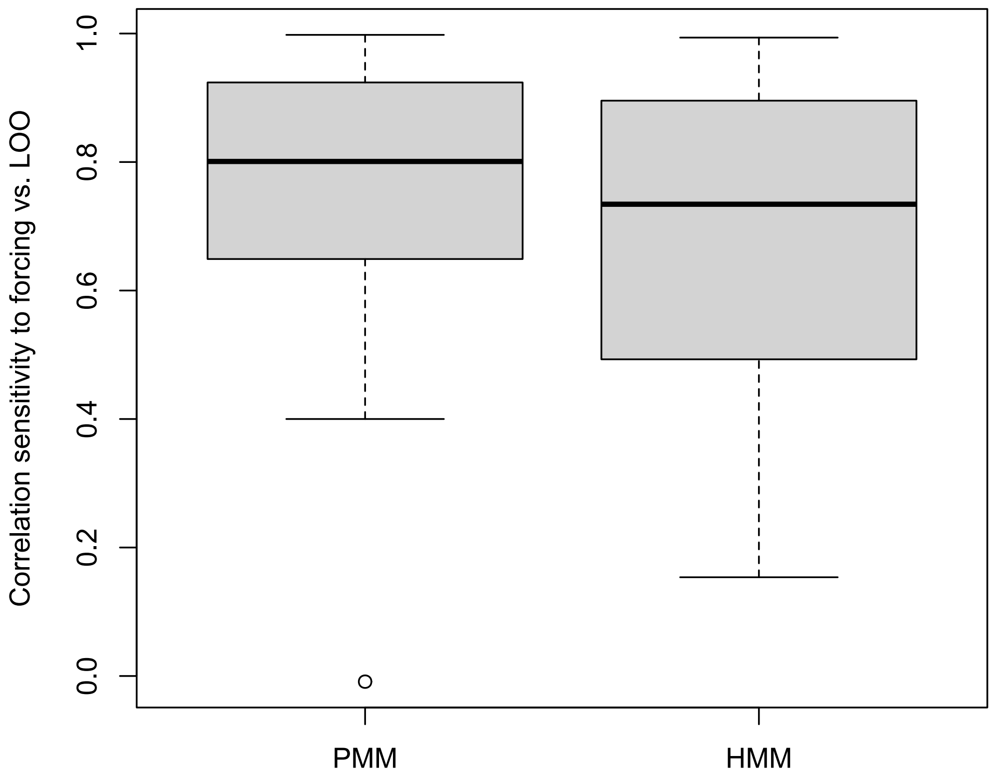

Figure S10: Comparison of correlations between estimated slopes for species in subset models after leaving out a genus, and the full model including forcing as the predictor, for both the phylogenetic mixed model (PMM) and the hierarchical mixed model (HMM).

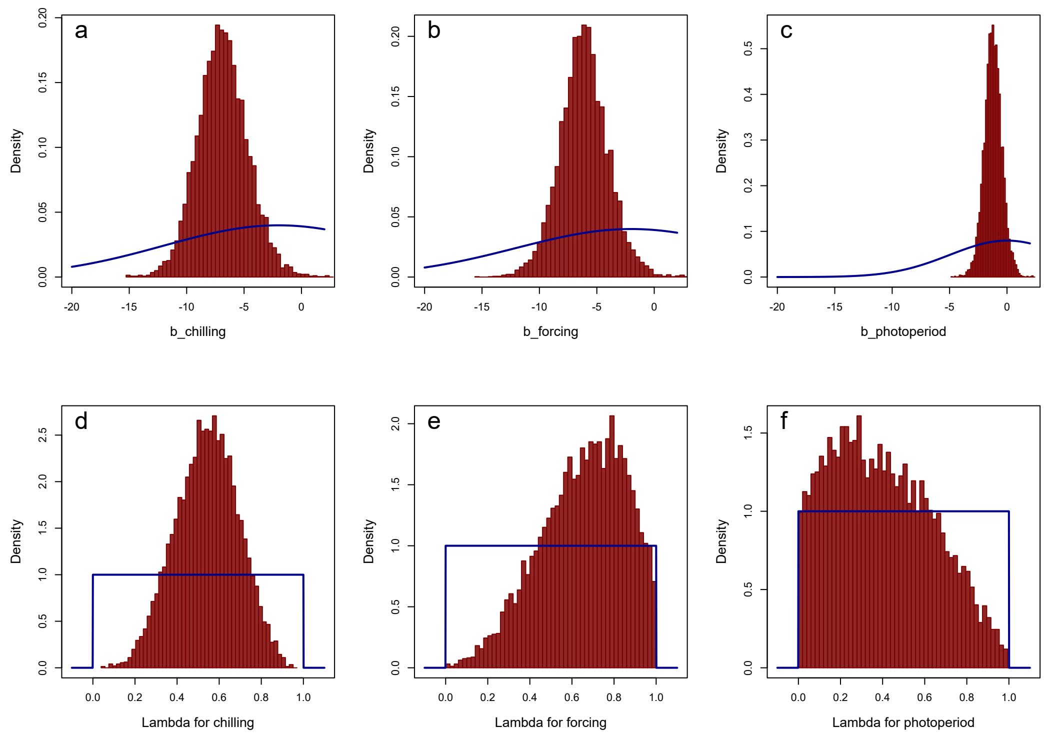

Figure S11: Marginal plots contrasting the posterior distributions (in red) of estimated sensitivities to chilling (a), forcing (b) and photoperiod (c) against prior distributions (blue). Lower panels show marginal plots for the posterior distributions of phylogenetic parameter λ fitted for chilling (d), forcing (e) and photoperiod (f). See *Stan code* section below for details on prior and parameter specification of the models.

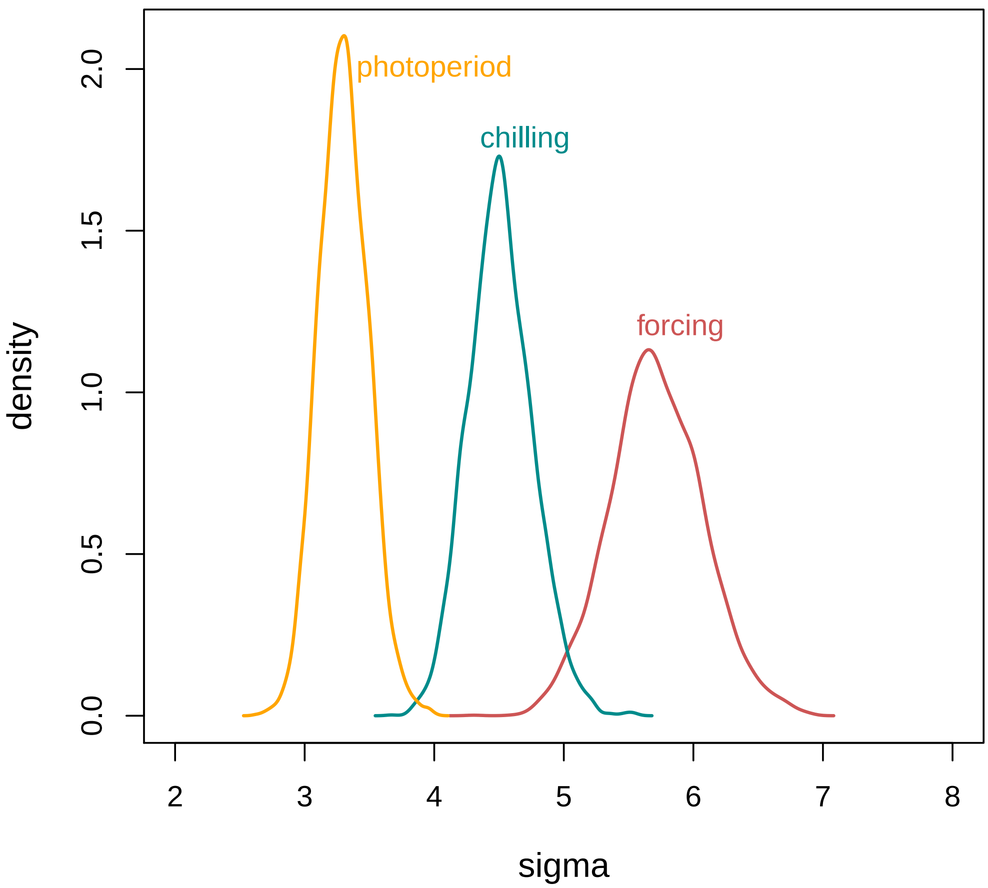

Figure S12: Estimates of sigmas using our phylogenetic model and simulated data with responses to forcing and photoperiod generated from a delta model of evolution (fastBM in phytools package), with delta set to 2 for forcing and to 0.5 for photoperiod (intercept and chilling generated from lambda model with a lambda of 1).

Stan code

Annotated example code

We wrote our model using the Stan programming language and as such, the model code consists of four program blocks. Below we have included a breakdown of our code structure for a simplified example code with a single intercept and slope and annotations for the different components of our model code. Additional annotations are denoted in the code by a double forward slash.

The Stan code begins with a function block in which the phylogenetic variance-covariance matrices are generated. Below the function defines the correlation matrix with lambda and sigma parameters and generates a matrix of the correct size and scaling.

```
functions {
  //correlation matrix with lambda and sigma
  matrix lambda_vcv(matrix vcv, real lambda, real sigma){
  matrix[rows(vcv),cols(vcv)] local_vcv; //blank matrix - size vcv
  local_vcv = vcv * lambda;

  for(i in 1:rows(local_vcv))
      local_vcv[i,i] = vcv[i,i];
      return(quad_form_diag(local_vcv, rep_vector(sigma, rows(vcv))));
  }
}
```

The data block declares the data type and includes associated dimensions and restrictions to the data. In the below example, this includes defining the overall size of the dataset, the number of species used for partial pooling, the response and predictor variables, and finally the phylogeny.

```
data {
  int<lower=1> N; //sample size
  int<lower=1> n_sp; //number of species
  int<lower=1, upper=n_sp> sp[N]; //species
  vector[N] y; // response
  vector[N] x1; // predictor
  matrix[n_sp,n_sp]Vphy;     // phylogeny
}
```

The parameters block defines the model parameters included in our model. In our simple model we include phylogenetic effects on both the intercept and slope, with lambda and sigma parameters for each, and their respective root trait values. This is in addition to parameters for the intercept, slope, and error.

```
parameters {
  real<lower=0> sigma_y; //error
  real<lower=0, upper=1> lam_interceptsa; //lambda for the intercept
  real<lower=0> sigma_interceptsa; //sigma for the intercept
  real<lower=0, upper=1> lam_interceptsb; //lambda for predictor
  real<lower=0> sigma_interceptsb; //sigma for forcing

  vector[n_sp] b; // slope of predictor effect
  real b_z; // root trait value for predictor
  vector[n_sp] a; // intercept
  real a_z; // root trait value for the intercept

}
```

Finally the model block is where we define the model structure, sampling statements, and prior distributions for our parameters. We define the prior distribution for each of the parameters listed above.

```
model {
  real yhat[N]; //predicted y value from below model

  // phylogenetic matrices generated by function model block
  matrix[n_sp,n_sp] vcv_a;
  matrix[n_sp,n_sp] vcv_b;

  // linear regression model with one intercept and one predictor
  for(i in 1:N){
    yhat[i] = a[sp[i]] + b[sp[i]] * x1[i];
}

  vcv_a = cholesky_decompose(lambda_vcv(Vphy, lam_interceptsa, sigma_interceptsa));
  vcv_b = cholesky_decompose(lambda_vcv(Vphy, lam_interceptsb, sigma_interceptsb));
```

```
  a ~ multi_normal_cholesky(rep_vector(a_z,n_sp), vcv_a);
  b ~ multi_normal_cholesky(rep_vector(b_z,n_sp), vcv_b);

  y ~ normal(yhat, sigma_y);

  // Priors
  a_z ~ normal(60, 10);
  b_z ~ normal(0, 10);

  lam_interceptsa ~ beta(1, 1);
  lam_interceptsb ~ beta(1, 1);

  sigma_interceptsa ~ normal(30, 20);
  sigma_interceptsb ~ normal(1, 5);

  sigma_y ~ normal(10, 10);

}
```

Full model Stan code

Below is the full model used to conduct our analyses. Our full model includes a single intercept and three predictor parameters, but consists of the four program blocks outlined above. Parameters listed in the parameter block are defined in the Bayesian hierarchical phylogenetic model section of the main text and in equations 1 to 3.

```
functions {
  matrix lambda_vcv(matrix vcv, real lambda, real sigma){
    matrix[rows(vcv),cols(vcv)] local_vcv;
    local_vcv = vcv * lambda;
    for(i in 1:rows(local_vcv))
      local_vcv[i,i] = vcv[i,i];
      return(quad_form_diag(local_vcv, rep_vector(sigma, rows(vcv))));
  }
}

data {
  int<lower=1> N;
  int<lower=1> n_sp;
  int<lower=1, upper=n_sp> sp[N];
```

```
  vector[N] y;  // response
  vector[N] x1; // predictor (forcing)
  vector[N] x2; // predictor (chilling)
  vector[N] x3; // predictor (photoperiod)
  matrix[n_sp,n_sp]Vphy;  // phylogeny
}

parameters {
  real<lower=0> sigma_y;
  real<lower=0, upper=1> lam_interceptsa;
  real<lower=0> sigma_interceptsa;
  real<lower=0, upper=1> lam_interceptsbf;
  real<lower=0> sigma_interceptsbf;
  real<lower=0, upper=1> lam_interceptsbc;
  real<lower=0> sigma_interceptsbc;
  real<lower=0, upper=1> lam_interceptsbp;
  real<lower=0> sigma_interceptsbp;
  vector[n_sp] b_force; // slope of forcing effect
  real b_zf;
  vector[n_sp] b_chill; // slope of chilling effect
  real b_zc;
  vector[n_sp] b_photo; // slope of photo effect
  real b_zp;
  vector[n_sp] a; // intercept
  real a_z;
}

model {
  real yhat[N];

  matrix[n_sp,n_sp] vcv_a;
  matrix[n_sp,n_sp] vcv_bf;
  matrix[n_sp,n_sp] vcv_bc;
  matrix[n_sp,n_sp] vcv_bp;

  // linear regression model with one intercept and three predictors
  for(i in 1:N){
    yhat[i] =
  a[sp[i]] + b_force[sp[i]] * x1[i] + b_chill[sp[i]] * x2[i] + b_photo[sp[i]] * x3[i];
  }
```

```
vcv_a = cholesky_decompose(lambda_vcv(Vphy, lam_interceptsa, sigma_interceptsa));
  vcv_bf = cholesky_decompose(lambda_vcv(Vphy, lam_interceptsbf, sigma_interceptsbf));
  vcv_bc = cholesky_decompose(lambda_vcv(Vphy, lam_interceptsbc, sigma_interceptsbc));
  vcv_bp = cholesky_decompose(lambda_vcv(Vphy, lam_interceptsbp, sigma_interceptsbp));


  a ~ multi_normal_cholesky(rep_vector(a_z,n_sp), vcv_a);
  b_force ~ multi_normal_cholesky(rep_vector(b_zf,n_sp), vcv_bf);
  b_chill ~ multi_normal_cholesky(rep_vector(b_zc,n_sp), vcv_bc);
  b_photo ~ multi_normal_cholesky(rep_vector(b_zp,n_sp),vcv_bp);

  y ~ normal(yhat, sigma_y);

  //Priors
  a_z ~ normal(30, 10);
  b_zf ~ normal(-2, 10);
  b_zc ~ normal(-2, 10);
  b_zp ~ normal(0, 5);

  lam_interceptsa ~ beta(1, 1);
  lam_interceptsbf ~ beta(1, 1);
  lam_interceptsbc~ beta(1, 1);
  lam_interceptsbp ~ beta(1, 1);

  sigma_interceptsa ~ normal(30, 20);
  sigma_interceptsbf ~ normal(1, 5);
  sigma_interceptsbc ~ normal(1, 5);
  sigma_interceptsbp ~ normal(1, 5);

  sigma_y ~ normal(10, 10);
}
```