

Current environments and evolutionary history shape forest temporal assembly

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Abstract

The timing of major life history events or phenologies, such as the start of growth or reproduction, often span weeks or months within a community due to species' different timings. Community ecology posits that species partition time to occupy different temporal niches and thus reduce competition for resources. These different phenologies are driven by different responses to environmental cues—such as temperature and daylength, although differences in species shared evolutionary history could also play a role. To understand these drivers of variability, we examined community-level responses to environmental cues across 47 species from eastern and western North America respectively. We focused on woody plant budburst, where the underlying cues—temperature and daylength—are well known and can be manipulated in controlled environments. Using a Bayesian phylogenetic model, we found little variation across sites, but strong variation by species. Budburst advanced in response to temperature and daylength, with these cues explaining 38.6 to 60.6% of variation and the remaining variation mostly ascribed to intrinsic differences in species traits that were strongly phylogenetically structured ($\lambda = 0.8$). These phylogenetic effects suggest an important role of additional traits that determine woody plant budburst, and could improve predictions of future phenological shifts and their effects on community dynamics and ecosystem services.

Introduction

Climate change has led to advances of about 3 days per decade in the timing of species life history events—phenology (Parmesan, 2007; Thackeray et al., 2016; Cohen et al., 2018). Different types of events and the rate of their responses to climate change, however, are highly variable. Events, such as leafout, can span a period of weeks and are shifting in response to rising temperatures at different rates (Parmesan, 2007; Fitter and Fitter, 2002; Menzel et al., 2006; Yu et al., 2010; Fridley, 2012). Understanding and explaining this variability is an important goal that remains extremely challenging. Some degree of variability is likely due to differences in climate change itself across space—as some areas warm faster than others and generate larger phenological shifts (Hoegh-Guldberg et al., 2018). But climate change alone explains a limited amount of the total variation. Recent research suggests that species-level differences in phenology drive some of this variation (Vitasse et al., 2009; Wolkovich and Cleland, 2014; Zohner and Renner, 2014; Vitasse et al., 2018). How species-level differences compare to other potential sources of variation, and what predicts them, is still largely unknown. But

understanding the drivers of species-level variation is necessary to predict the effects changes in phenology will have on community dynamics and ecosystem services.

ocal habitats—due in part to latitudinal trends in photoperiod and temperature—impose unique selective pressures, and thus may drive site-level differences in responses to cues

Differences in species phenologies can impact community structure and dynamics. Community ecology has long posited that species assemble in part through partitioning time, leading to unique temporal niches that allow species to coexist (Chesson et al., 2004; Grime, 1977), and may trade-off different pressures. Increasing research suggests that species with early temporal niches experience greater abiotic pressures, but avoid the larger competitive pressures for resources that occur later in the season (Sakai and Larcher, 1987; Gotelli and Graves, 1996; Augspurger, 2009; Pau et al., 2011). In forest communities, this niche partitioning is apparent in the forest structure, with understory species—such as shrubs and shorter tree species—starting growth earlier in the season prior to the leafout of canopy species. Communities may also be structured across space, responding to latitudinal trends in photoperiod and temperature which may impose unique selective pressures that drive site-level differences in responses to cues. But as climate change variably affects the timing of growth this may alter the temporal order of species in a community and result in novel competitive interactions between species (Cleland et al., 2012; Rudolf, 2019; Tiusanen et al., 2020), thus changing the competitive landscape and synchrony of interactions within communities.

While recent changes in climate are shaping species-level differences in phenology, for many species their temporal niches may also reflect their evolutionary history. Species traits in communities today are the result of selective pressures acting over evolutionary timescales that include the historical climates and related ancestral phenotypes that were favourable under those previous conditions (Wiens et al., 2010). This could produce greater similarity in phenological traits of more closely related species (Davies et al., 2013; Morales-Castilla et al., 2024). Understanding these evolutionary relationships is critical to predicting how species will respond to future climates.

Spring budburst offers an excellent system to test for species- and community-level patterns in phenology and environmental cues. Budburst of temperate woody plants is well studied and thus known to respond to temperatures in both the winter and spring—referred to as chilling and forcing, respectively—as well as daylength, or photoperiod (Chuine et al., 2010; Polgar and Primack, 2011; Cooke et al., 2012; Basler and Körner, 2014; Laube et al., 2014). But through decades of work, we have also found individual species to have unique phenologies—even within the same location and climate conditions. For example, in forest communities, understory species often budburst earlier than canopy trees, when light and soil nutrients are most available (Mahall and Bormann, 1978; Muller, 1978). To better understand species temporal niche partitioning, we must also isolate evolved differences among communities from plasticity. This can be done by conducting experiments in controlled environments that remove the relative effects of interannual climate variability that drive plastic variation in phenology.

Here we test the relative importance of environmental cues and evolutionary relationships in shaping species-level variation in phenology both within and across forests in North America. Using the results from two growth chamber studies in which we used a Bayesian phylogenetic approach, we detect general trends in budburst cues in deciduous forest communities and estimate the contribution of species evolutionary history to current variation in budburst. We collected samples of 47 woody plant species from four sites, in eastern and western North America, with pairs of sites on each coast spanning 4-6° latitude. Our dataset includes the diverse assemblages of tree and shrubs found in eastern and western deciduous forests, allowing us to explore differences across both sites and functional groups in eastern versus western forests. We expected sites to differ in species budburst cues, given the differences in the dominant forest composition between sites, reflecting differences in the forest architecture and resource availability.

Materials and Methods

Field sampling

We combined data from two growth chamber studies using branch clippings of North American deciduous woody plants. Such cutting experiments are a common and powerful approach to infer the responses of adult trees to environmental conditions (Vitasse et al., 2014). In our first study, we collected samples from two eastern communities—Harvard Forest, Massachusetts, USA (42.55°N, 72.20°W) and St. Hippolyte, Quebec, Canada (45.98°N, 74.01°W), from 20-28 January, 2015 (previously reported in Flynn and Wolkovich, 2018). The second growth chamber study spanned two western communities—Smithers (54.78°N, 127.17°W) and E.C. Manning Park (49.06°N, 120.78°W), British Columbia, Canada, with sampling from 19-28 of October, 2019 (not previously published). Combining the datasets from these two experiments allowed us to test for spatial variation in the phenology of woody plant communities at a larger scale and make stronger inferences for how different species vary in their cues.

We selected the dominant deciduous species in each forest community and maximized the number of species occurring across sites. We observed budburst for 47 species spanning eastern and western forest communities, with 28 species at our eastern transect and 22 species at our western transect, of which 3 species occurred at both regions (Table S3). Of the species in our eastern transect, there were 13 shrubs and 15 trees, while our western transect included 18 shrub and 4 tree species. At all sites, we tagged 15-20 healthy, mature, individuals for each species in the summer prior to sampling. Depending on the size of the individual, we collected 1-16 cuttings from 6-20 tagged plants, using a pole pruner from the ground. We kept samples cold and immediately placed them in water upon returning from the field. We conducted the eastern study at the Arnold Arboretum, Boston, MA, USA, and the western study at the University of British Columbia, BC, Canada. We used daily weather data from local weather stations to calculate the field chilling prior to collection (see Table S2).

Growth chamber study

We used growth chambers with two levels of chilling—with either no additional chilling or 30 days at 4°C for our eastern study, and 30 or 70 days of chilling at 4°C for our western study (all dark)—after which we moved plants to one of two levels of forcing—with day and night temperatures that varied to create a cool regime of 15:5°C and a warm regime of 20:10°C—crossed with two photoperiods of either 8 or 12 hours—for a total of 8 distinct treatments in each study.

Our design was similar for both eastern and western species. We had seven to ten replicates per treatment in our eastern study and eight replicates in our western study, with the exception of *Sorbus scopulina*, for which we only had six replicates per treatment. Our eastern and western studies differed only in the timing of sample collection and thermoperiodicity—alternation in day and night temperatures—in forcing treatments. By collecting samples in our eastern study in late January, they experienced considerable field chilling. But we collected the western samples in late October, with most chilling occurring under controlled conditions. In our eastern study, we also set the duration of forcing temperatures to correspond with the photoperiod treatments. While this is a widespread and common approach in phenology chamber studies, it leads to a confounding effect in the thermoperiodicity (Buonaiuto et al., 2023). Thus we applied forcing temperatures for 12 hours independent of the duration of the photoperiod treatments in our western study, and controlled for this difference in our statistical approach (see below). Further details regarding the re-cutting of samples, water changes, and rotation through chambers are presented in Flynn and Wolkovich (2018). We controlled for differences in the number of replicates across species in our statistical approach using partial pooling (see section on statistical analysis).

We assessed phenological stages of budburst using the BBCH scale, adapted for our specific species

(Finn et al., 2007). We also created photographic guides to help define each stage of the BBCH scale for our specific species (Savas et al., 2017; Loughnan and Wolkovich, 2024). Every 1-3 days, we observed each sample and recorded all phenological stages up to full leaf expansion (defined as code 17 by Finn et al., 2007). Here, we present the response in budburst date, defined as the day of budbreak or shoot elongation (defined as code 07 by Finn et al., 2007). Our eastern study spanned 82 days, with over 19320 phenological observations, while the western study spanned 113 days and 47844 phenological observations.

Statistical Analysis

We tested for differences in budburst cues across species and communities using a phylogenetic mixed effects model with partial pooling (‘shrinking’) across species. This approach accounts for both the evolutionary relatedness of our species, and estimates the species-level cues and differences across sites. We obtained species phylogenetic relatedness by pruning the Smith and Brown (2018) megatree of angiosperms (Fig. S5).

In our model, we included each of our three cues as continuous variables. To account for the greater amounts of field chilling experienced in our eastern study, we converted our chilling treatments to chill portions for each individual community using local weather station data and the chillR package (Luedeling, 2020). We calculated chill portions for both the chilling experienced in the field prior to sampling and during the experiment in our 4°C chilling chambers. We also converted forcing temperatures to mean daily temperatures in each treatment to account for differences in thermoperiodicity between the two studies (Buonaiuto et al., 2023). Finally, we z -scored each cue and site using two standard deviations to allow direct comparisons between results across parameters (Gelman, 2008). In addition to the overall predictors, we included all two-way interactions between cues and between cues and sites.

Our modelling approach allowed us to combine observations of budburst (y_i) across species (sp), to estimate both a species-level intercept (α_{sp_i}) and slope estimates (β) for individual cues, sites, and all possible interactions between cues and between cues and sites to estimate the modeled day of budburst (\hat{y}) relative to the first day of forcing conditions.

$$\begin{aligned} y_i = & \alpha_{sp_i} + \beta_{site2} + \beta_{site3} + \beta_{site4} + \\ & \beta_{chill_{sp_i}} + \beta_{force_{sp_i}} + \beta_{photo_{sp_i}} + \\ & \beta_{force \times chilling_{sp_i}} + \beta_{chilling \times photo_{sp_i}} + \beta_{photoperiod \times chilling_{sp_i}} + \\ & \beta_{force \times site2_{sp_i}} + \beta_{force \times site3_{sp_i}} + \beta_{force \times site4_{sp_i}} + \\ & \beta_{chilling \times site2_{sp_i}} + \beta_{chilling \times site3_{sp_i}} + \beta_{chilling \times site4_{sp_i}} + \\ & \beta_{photoperiod \times site2_{sp_i}} + \beta_{photoperiod \times site3_{sp_i}} + \beta_{photoperiod \times site4_{sp_i}} + \epsilon_i \end{aligned}$$

$$\epsilon_i \sim \text{normal}(0, \sigma_y^2)$$

The slopes were modelled with partial pooling at the species-level:

$$\begin{aligned}
\beta_{force_{sp}} &\sim \text{normal}(\mu_{force_{sp}}, \sigma_{force}^2) \\
&\dots \\
\beta_{photoperiod \times site_{sp}} &\sim \text{normal}(\mu_{photoperiod \times site_{sp}}, \sigma_{photoperiod \times site_{sp}}^2)
\end{aligned}$$

171 We included the phylogenetic effect of budburst timing (α_{sp}) as a variance covariance matrix (\mathbf{V}) in
172 the parameterization of the normal random vector:

$$\alpha_{sp} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \dots \\ \alpha_n \end{bmatrix} \text{ such that } \alpha \sim \text{multi-normal}(\mu_\alpha, \mathbf{V}), \tag{1}$$

$$\tag{2}$$

173 The timing of budburst ancestrally is represented as root value of the means of the multivariate nor-
174 mal distribution. For more detail on this method of phylogenetic modeling, see Morales-Castilla et al.
175 (2024).

176
177 We used semi-informative priors for each of our model parameters, validating the model code using
178 test data prior to analysis. Our model produced \hat{R} values close to 1, well mixed chains, and n_{eff}
179 values that exceeded 10% of the model iterations. Our model was fit using the Stan language (Stan
180 Development Team, 2018) with the rstan package in R (R Development Core Team, 2017), version
181 3.3.6).

182
183 We present model estimates, relative to baseline conditions of low chilling, low forcing, and short pho-
184 toperiod treatments, and—when relevant—for the Smithers community. We present results as means
185 and 90% posterior uncertainty intervals from our Bayesian phylogenetic models.

187 Results

188 On average, species budburst 27.4 days (uncertainty interval: 12.0, 46.1, all estimates are given as
189 mean \pm 90% uncertainty intervals, henceforth ‘UI,’ and budburst dates given as relative to baseline
190 conditions, see methods for more details) after the start of forcing and photoperiod treatments. The
191 empirical observations on which this modelled mean is based, span budburst days as early as such
192 as 13.6 for *Aronia melanocarpa*, and as late as day 52.1 for *Quercus velutina*. Between the earliest
193 and latest budbursting species, the difference in the mean day of budburst was 38.5 and 30.7 days
194 for the eastern and western sites respectively. Overall we found species budburst was strongly phylo-
195 genetically structured (λ of 0.8, UI: 0.6, 0.9, estimated on the intercept) and that all cues led to an
196 advance in budburst date. Of the three cues, chilling had the largest effect (-15.2, UI: -17.3, -13.2)
197 and photoperiod the smallest (-3.6, UI: -4.3, -3.0, Fig. 1). But we found a large, positive inter-
198 action between forcing and chilling (9.1, UI: 7.6, 10.5); this results in a subadditive effect where low
199 chilling is offset by high forcing conditions, and vice versa (Fig. S1 and see Table S1 for model output).

200
201 Overall we found small site-level effects compared to differences between cues. Across all species,
202 there was considerable overlap in the responses of the four sites to each cue (Fig. 1). As such, low
203 forcing, chilling, and shorter photoperiods all produced later estimated budburst dates compared to
204 higher temperature and longer photoperiod treatments across all sites and across transects (Fig. S1
205 a-c, shown for baseline conditions, see Table S1 for model output). Overall budburst dates did not

differ between sites, though eastern sites budburst marginally earlier (34.1, UI: 27.1, 40.7) compared to the western sites (46.5, UI: 39.4, 52.7, see also Table S1 for model output). This could be due to the earlier collection date of our western species, which reduced the field chilling they received relative to our eastern samples.

Budburst of individual species showed distinct differences in their timing and the relative importance of cues. Later budbursting species had slightly larger responses to chilling and forcing (Fig. 2). Despite our expectations that species responses should differ across the canopy layer, with shrubs being less sensitive to cues than trees, we did not find substantial differences across these two functional groups (Fig. S2). Shrubs, like *Cornus stolonifera*, showed small responses to chilling and forcing. But 36.7% of the shrubs, including *Menziesia ferruginea* and *Symphoricarpos alba*, exhibited the opposite response and budburst relatively late (Fig. S2). Similarly for trees, some matched our predictions for their cues, but 23.5% budburst earlier than expected. Specific tree species, such as *Quercus velutina*, did have larger chilling and photoperiod responses as predicted, and *Fagus grandifolia* had the largest photoperiod response. But overall we did not find clear differences between the cues of trees and shrubs across the four forest communities.

Our results depict the relative importance of phenological cues to variation across species, but we found the contribution of cues to budburst order and timing to be dependent on the magnitude of the cue, and to be small compared to the overall species differences unexplained by cues (represented in the modeling framework as the intercept). The rank order of species estimated budburst changed more under high cue conditions than under low cues (Fig S3). The budburst ranking for the three species that occurred in both transects remained relatively consistent across the two communities (Fig. 2), with only *Alnus incana* in the western community experiencing a large change in rank with cues (Fig. S3).

In comparing the earliest and latest budbursting species, we found relatively small differences in cues (Fig. 2). This is contrary to our prediction of greater cue requirements—especially chilling cues—for later budbursting species. For example, an early budbursting shrub, *Lyonia ligustrina*, had chilling and forcing cues of -15.4 and -10.4 respectively, which are comparable to the cue estimates of -16.6 and -10.4 for the much later tree, *Quercus alba*. Yet the model predicts these species to have a 15.9 day difference in day of budburst. This highlights how the timing of budburst across species was also strongly related to species level differences outside of cues (intercept values, see Fig. 3). Across the range of cue values, cues explained only between 38.6 and 67.0% of variation for eastern species and between 48.3 and 60.6% for western species, with the intercept—which was strongly phylogenetically structured—explaining the rest (Fig. 3).

Discussion

In our study, species temporal niches were partly explained by differences in environmental cues, but varied very little across sites or functional groups. While the timing of budburst generally advanced in response to each cue, the greatest responses were to chilling and forcing respectively. We found no evidence of site-level differences in budburst cues, as responses were similar across our sites despite their inherent differences in environments and photoperiod. There was, however, considerable variation in the importance of cues across species, driven by their evolutionary history. Budburst had a strong phylogenetic structure, with species evolutionary history and cues contributing almost equally to the phenological variation we observed. These findings highlight the need to account for evolutionary history to accurately forecast phenological responses under continued warming.

Despite differences in the composition of our sites and local environments, under controlled condi-

tions, sites differed only slightly in their phenological cues. This contrasts our expectation that local habitats—due in part to latitudinal trends in photoperiod and temperature—impose unique selective pressures, and thus may drive site-level differences in responses to cues (Keller et al., 2011). Latitudinal gradients in spring phenological shifts have been found by studies using *in situ* phenological data (Post et al., 2018; Alecrim et al., 2023). But, this work is based on long-term observations in the field, with confounding differences in study duration and start dates, variable methodologies, and geographic extent (Post et al., 2018; Alecrim et al., 2023). The lack of site-level effects that we observed suggests budburst is not shaped by local conditions, at least at our study scale.

Community composition and interspecific variation in phenology

Our species varied in their responses to environmental cues, creating large potential differences in their temporal niches and ecological roles. Species ranged from early to late budburst dates and spanned a similar period as observed in natural communities (Lechowicz, 1984; Richardson, A.D., O’Keefe, 2009). This suggests our experiment captured a realistic breadth in temperate forest budburst. Furthermore, all our focal species responded to each environmental cue, with large responses to chilling and comparatively small responses to photoperiod, trends consistent with previous studies. Cues, however, had complex interactions that appear potentially advantageous under warming climates (Heide, 1993; Caffarra and Donnelly, 2011; Flynn and Wolkovich, 2018). The interaction between chilling and forcing ensures species can budburst if warmer winters cause insufficient chilling, but will require additional forcing. Despite differences in species responses to cues, we did not find clear, generalizable trends across functional groups.

Shrubs and trees differ greatly in their physiology, filling different ecological niches. Most of our trees budburst later than the shrubs, a relative order also found by previous studies (Gill et al., 1998; Panchen et al., 2014). But about a quarter of the trees also budburst early, with timing more similar to that of shrubs. Similarly, we found a third of shrubs to budburst at similar times as the majority of our trees. These deviations from our expectations for how shrubs and trees partition their budburst timing suggests there is more nuance to these patterns than previously found. As trees species advance phenologically—resulting in earlier canopy closure and reduced light availability (Donnelly and Yu, 2019)—shrubs with small cues may have reduced fitness. But as our findings suggest many shrubs will also advance phenologically and have the potential to maintain their relative temporal niche.

Community assembly in responses to cues versus evolutionary history

Our study included the three cues—chilling, forcing and photoperiod—commonly thought to determine budburst timing, but about a third of total variation was not explained by these cues (Fig. 2), thus suggesting our model may be incomplete. This paired with the observed phylogenetic structure in budburst timing suggests there are unidentified latent traits still missing from our understanding of budburst (Webb et al., 2002; Davies et al., 2019).

Latent traits could reflect missing environmental cues or additional traits that mitigate phenological cues. Species temporal niches could be similarly influenced by other physiological or structural traits. Theories of how plants vary in their growth strategies predict phenology should correlate with other key traits, including those that facilitate greater resource use and earlier spring growth, or the greater competitive abilities needed when budbursting later (Grime, 1977). Early successional species are predicted to budburst early in the season and have traits associated with faster growth rates and resource acquisition, such as high specific leaf areas or low wood density (Wright et al., 2004; Chave et al., 2009). Incorporating phenology into a broader trait framework could thus provide insights into traits that correlate with budburst timing, and—ultimately—the drivers selecting for species phenotypes.

The evolutionary history and ancestral phenotypes of a species will also have a strong effect on their adaptive potential to future climates. Species traits are shaped over ‘deep’ timescales, with previous evolution influencing responses to the present climate. Phylogenetic trends could thus be an indication of limited evolutionary time to adapt. Some temperate species, like *Nyssa* and *Fagus*, have had a shorter geologic time to respond to their local temperatures (Lechowicz, 1984). These phylogenetic effects could skew species assemblages, favouring species with traits and cue requirements adapted for historical climates.

Predicting budburst under future climates

Our results provide new insights into the factors and ecological processes critical to forecasting future phenologies. The consistent trends we observed across communities facilitate forecasting across similar regions with limited local phenological data but similar species assemblages. The high phylogenetic structure in budburst timing could enable us to forecast trends in phylogenetically related species for well resolved and well sampled genera (Molina-Venegas et al., 2018).

Accurate forecasts of phenology, however, require an understanding of what environmental cues are most important at the population, species, and community level. As climate change leads to greater temperature cues, we are already observing advances in species budburst within diverse ecological communities, but the largest effects will occur in high latitude communities that are warming fastest and to a greater extent (Hoegh-Guldberg et al., 2018). Our results suggest that these greater rates of warming at species northern range limits will cause these communities to budburst earlier (Fig. 3), altering species interactions and creating unique selective pressures across the assemblages of species within a site. This may reshape species temporal niches and in turn alter community assembly.

Our findings also suggest the order of species budburst in a community will change with variable warming. Community dynamics are most likely to change at sites that experience greater warming. As species budburst order changes (Fig. S3), species that previously exhibited temporal niches distinct from one another will increasingly interact. This may have cascading effects on species, changing their competitive landscape, and synchrony with pollinators or herbivores.

While our findings have broad applications to plant communities, our analytical approach is widely applicable to forecasting species responses to climate change. To this end, future efforts should invest in identifying the latent traits contributing to the high phylogenetic structure of phenological events. Combining more species-rich and community-wide approaches with phylogenetic relationships allowed us to combine the effects of species evolutionary history with current ecological processes and enable us to predict changes in spring phenology under future climates.

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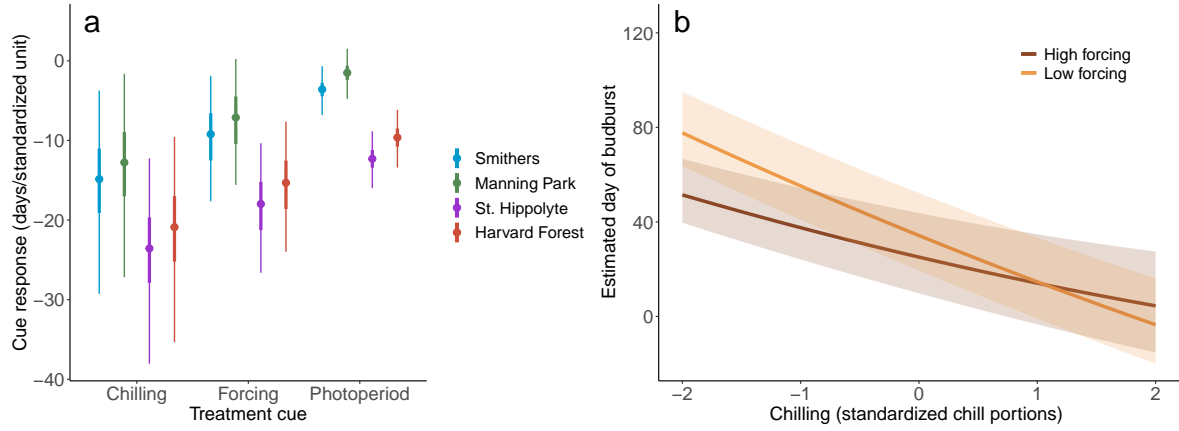


Figure 1: **a**, Posterior distributions of estimated chilling, forcing, and photoperiod responses with site level effects for individual communities. Points represent the median cue, thicker lines the 50% uncertainty interval, and the thin lines the 90% uncertainty interval. **b**, Cues interacted to produce a subadditive effect that promoted budburst under low forcing or chilling cues. variable responses that promote budburst when individual cues are not met. We standardized predictors (cues) via z -scores using two standard deviations, see methods for further details.

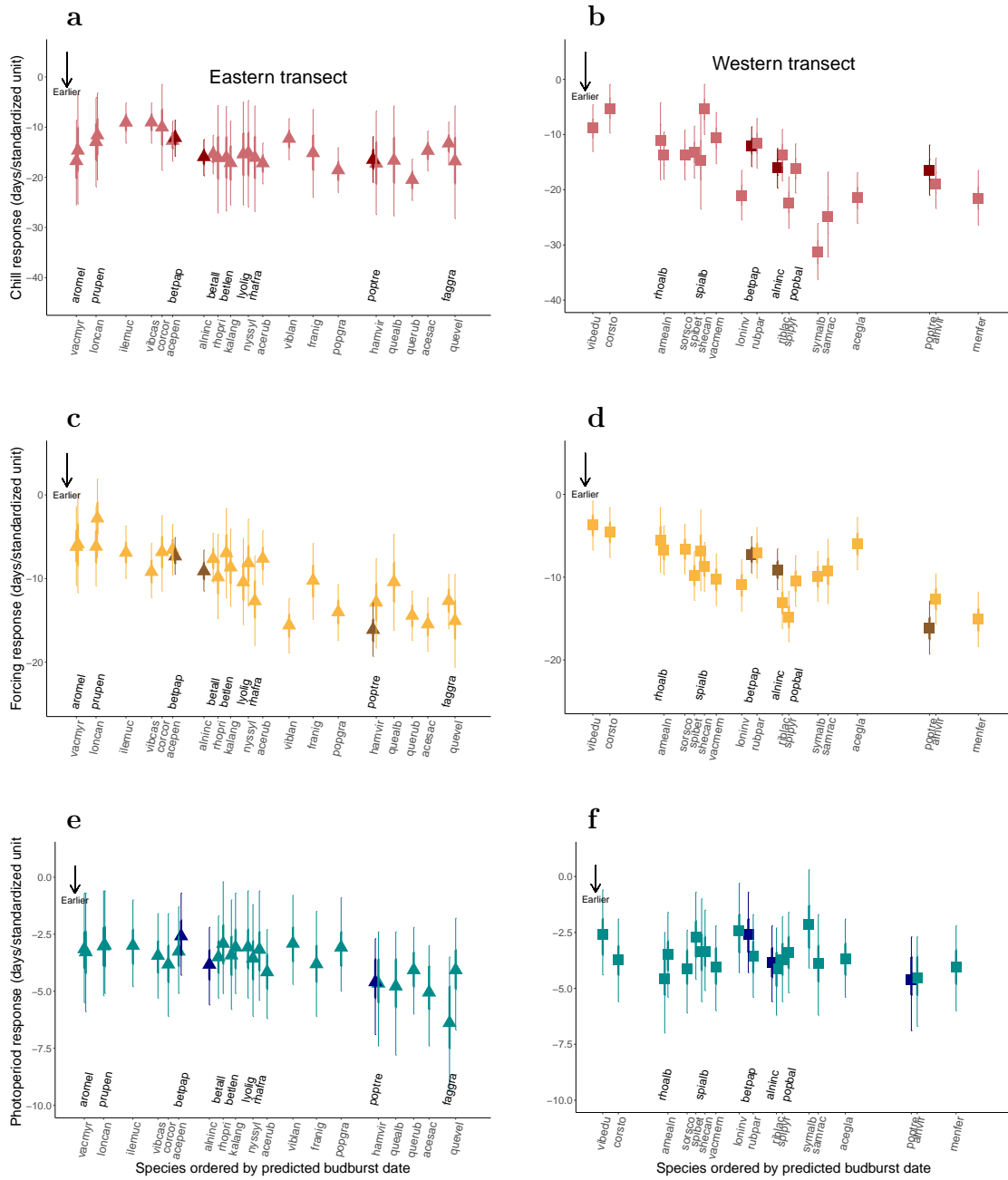


Figure 2: Estimated species **a,b**, chilling, **c,d** forcing, **e,f** and photoperiod responses ranked by increasing estimated budburst dates for both the **a,c,e**, eastern **b,d,f** and western sites. Cues are plotted on differing y-axis to better depict species differences. For each species, the thinner error bars represent the 90% uncertainty interval, and thicker bars represent the 50% uncertainty interval. Species that occur in both the eastern and western transects are depicted using darker colours. To make the results across cues directly comparable, we standardized predictors (here, cues) via z -scores using two standard deviations, see methods for further details.

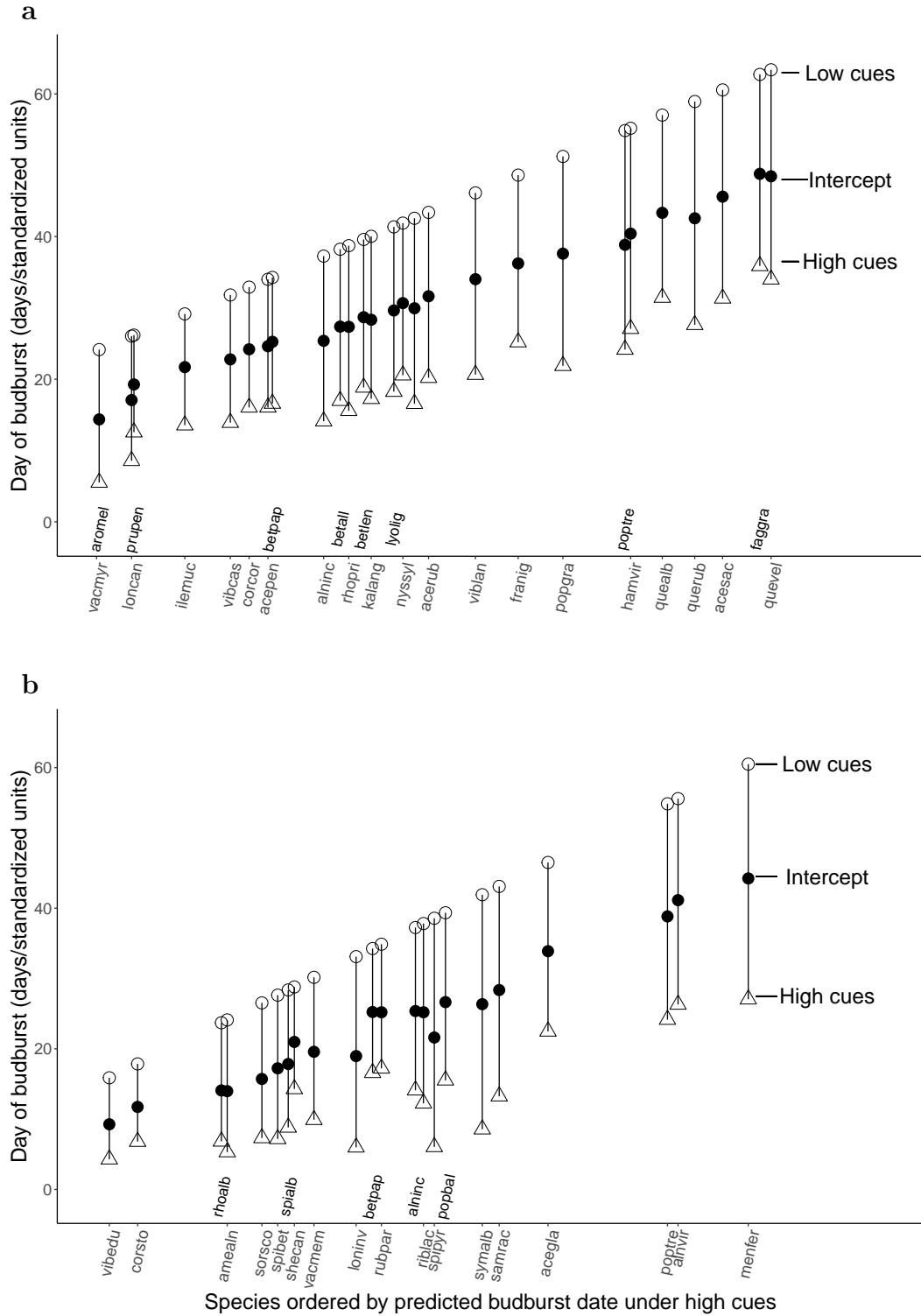


Figure 3: Comparisons of our estimated budburst based on the full model (intercept plus all cues), shown in white, versus the intercepts only (without cues), shown in black, ordered according to differences in species estimated budburst dates for both the **a**, eastern **b**, and western sites under low cue conditions, depicted as circles, and high cue conditions, depicted as triangles.