

# Differences in phenological cues responses do not explain temporal assembly of woody plant communities

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## Introduction

## Materials and Methods

### 0.1 Field sampling

We combined data from two growth chamber studies using branch clippings of North American deciduous woody plants. Our first study used samples taken from two eastern populations—Harvard Forest, Massachusetts, USA (42.55°N, 72.20°W) and St. Hippolyte, Quebec, Canada (45.98°N, 74.01°W), which we sampled from the 20-28 January, 2015. The second growth chamber study spanned two western populations—Smithers (54.78°N, 127.17°W) and E.C. Manning Park (49.06°N, 120.78°W), British Columbia, Canada, respectively, sampled from the 19-28 of October, 2019.

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

### Growth chamber study

To estimate the effects of chilling, forcing and photoperiod, 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 days or 70 days of chilling at 4°C for our western study (all dark)—after which plants were moved to one of two levels of forcing—a cool regime of 15°C:5°C and a warm regime of 20°C:10°C—crossed with two photoperiods of either 8 or 12 hours—for a total of 8 distinct treatments in each study. This design was

similar for both eastern and western species, except for the thermoperiodicity in forcing treatments. In our eastern study, we 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 (Buonaiuto2023). We applied forcing temperatures for 12 hours independent of the duration of the photoperiod treatments in our western study, w. 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. Further details regarding the re-cutting of samples, changing water in containers and, rotation through chambers, are presented in Flynn and Wolkovich (2018).

Phenological observations of budburst were assessed using the BBCH scale, adapted for our specific species (Finn et al., 2007). We observed each sample every 1-3 days 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)). In total, our eastern study spanned 82 days, with over 19320 phenological observations. The western study in turn spanned 113 and we made 47844 phenological observations across all samples.

## Statistical Analysis

To test for differences in cue responses across species and populations, we used a phylogenetic mixed effect model with partial pooling across species. This approach allowed us to account for both the evolutionary relatedness of our species, and estimate the species level cue responses and differences across sites. Species phylogenetic relatedness was obtained by pruning the ? megatree of angiosperms.

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 population using local weather station data and the chillR package (Luedeling2020). Chill portions were calculated 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 (Buonaiuto2023). Finally, we z-scored each cue and site using two standard deviations to allow results across parameters to be directly compared (Gelman2008). In addition to the overall predictors, we included all two-way interactions between cues and between cues and sites:

$$\begin{aligned} \hat{y}_i \sim & \text{normal}(\alpha_{sp_i} + \beta_{site2} + \beta_{site3} + \beta_{site4} + \\ & \beta_{chill_{sp_i}} + \beta_{force_{sp_i}} + \beta_{photo_{sp_i}} + \\ & \beta_{force \times chilling_{sp_i}} + \beta_{chilling \times photo_{sp_i}} + \beta_{photoperiod \times chilling_{sp_i}} + \\ & \beta_{force \times site2_{sp_i}} + \beta_{force \times site3_{sp_i}} + \beta_{force \times site4_{sp_i}} + \\ & \beta_{chilling \times site2_{sp_i}} + \beta_{chilling \times site3_{sp_i}} + \beta_{chilling \times site4_{sp_i}} + \\ & \beta_{photoperiod \times site2_{sp_i}} + \beta_{photoperiod \times site3_{sp_i}} + \beta_{photoperiod \times site4_{sp_i}}) \end{aligned}$$

$$\begin{aligned}\beta_{force_{sp}} &\sim \text{normal}(\mu_{force_{sp}}, \sigma_{force}^2) \\ \dots \\ \beta_{photoperiod \times site4} &\sim \text{normal}(\mu_{photoperiod \times site4}, \sigma_{photoperiod \times site4}^2)\end{aligned}$$

73 We included the phylogenetic effect as a variance covariance matrix in the parameterization of the  
74 normal random vector:

$$\boldsymbol{\alpha} = [\alpha_1, \dots, \alpha_n]^T \text{ such that } \boldsymbol{\alpha} \sim \text{multi-normal}(\mu_{\boldsymbol{\alpha}}, \mathbf{V}), \quad (1)$$

$$(2)$$

75 The timing of budburst prior to evolution is represented as root values of the means of the multivariate  
76 normal distributions. For more detail on this method of phylogenetic modeling, see Morales-Castilla  
77 et al (XXXX).

78  
79 We used semi-informative priors for each of our model parameters, validating the model code using  
80 test data prior to analysis. Our model produced  $\hat{R}$  values close to one, well mixed chains, and  $n_{eff}$   
81 values that exceeded 10% of the model iterations. Our model was fitted using the Stan language (Stan  
82 Development Team, 2018) using the rstan package in R (R Development Core Team, 2017) (version).  
83

84 We present model estimates, relative to baseline conditions of low chilling, low forcing, and short  
85 photoperiod treatments, and—when relevant—for the Smithers population.

## 86 Results

87 On average, we observed species budburst 28.1 days (uncertainty interval: 45, 15.2) after the start of  
88 our forcing and photoperiod treatments (all estimates are given as mean  $\pm$  90 uncertainty intervals,  
89 henceforth ‘UI,’ and budburst dates given as relative to baseline conditions, see methods for more de-  
90 tails). But some species, such as *Aronia melanocarpa*, budburst as early as day 13.6, and as late as day  
91 52.1 for *Quercus velutina*. The difference in timing of our earliest and latest species spanned a period of  
92 38.5 and 30.7 days for our eastern and western species respectively. Overall we found species budburst  
93 to be strongly phylogenetically structured ( $\lambda$  of 0.8, UI: 0.9, 0.6) and that all cues led to an advance  
94 in budburst date. Of the three cues chilling had the strongest effect (-15.2, UI: -17.3, -13.2) and pho-  
95 toperiod the weakest (-3.6, UI: -4.3, -3.0, Fig. 1). But we found a strong interaction between forcing  
96 and chilling (9.1, UI: 7.6, 10.5), which produced a delaying effect. The delaying effect of low chilling  
97 on budburst can therefore be offset by high forcing conditions (Fig. 2 and see Table 1 for model output).  
98

99 Overall we found population effects were small compared to differences between cues. Across all species,  
100 there was considerable overlap in the responses of our four populations to each cue (Fig. 1). As such,  
101 low forcing, chilling, and shorter photoperiods all produced later estimated budburst dates compared  
102 to higher temperature and longer photoperiod treatments across all populations (Fig. 3 a-c, shown  
103 for baseline conditions) and across transects (Fig. 3, see Table 1 for model output). Populations were  
104 similar in their overall budburst dates, but eastern populations were marginally earlier (34.1, UI: 40.7,  
105 27.1) compared to our western populations (46.5, UI: 52.7, 39.4, see also Table 1 for model output).  
106

107 Budburst of individual species showed distinct differences in their timing and the relative importance of  
108 cues. Both chilling and forcing responses varied with budburst, with later budbursting species having  
109 slightly stronger responses to each cue respectively (Fig. 4). Despite our expectations that species re-  
110 sponses should differ across the canopy layer, with shrubs being less sensitive to cues than tree species,

we did not find strong differences across these two functional groups (Fig. S3). While many of our earliest species were shrubs with weaker responses to chilling and forcing, like *Cornus stolonifera*, 36.7 percent of shrubs, including *Menziesia ferruginea* and *Symphoricarpos alba*, exhibited the opposite response and budburst relatively late (Fig. S3). Similarly for tree species, some matched our predictions for their cue responses, but 23.5 percent of our tree species budburst earlier than expected. But specific species, like *Quercus velutina*, did have stronger chilling and photoperiod responses as predicted, and of all our focal species *Fagus grandifolia* produced the strongest photoperiod response. But overall there were no clear differences between the cue responses of trees and shrubs across our 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, but small compared to overall species differences. Under high cue conditions, the rank order of species estimated budburst changed (Fig. ??). Changes in species rank order as cue strength increased were greater for our western species, with a mean change in rank order of 6, compared to our eastern species for which the mean change in rank was 4. In comparing our earliest and latest budbursting species, we found the differences in the cue responses were relatively small (Fig. 4). This is contrary to our prediction of stronger cue requirements—especially chilling cues—for later budbursting species. For example, an early (shrub) species *Lyonia ligustrina* had chilling and forcing cues of -15.4 and -10.4 respectively, which are comparable to the estimates of -16.6 and -10.4 for the much later tree species, *Quercus alba*. Yet our model predicts these species to have a 15.9 day difference in day of budburst. This highlights how the timing of budburst across species could mostly be attributed to species level differences outside of cue responses (Fig. 5). In fact, cues explained only between 38.6 and 67.0 percent of variation for eastern species and between 48.3 and 60.6 percent for western species, with the intercept explaining the rest (Fig. 5).

## Discussion

1. Across all species, relative importance of cue = varied = unique temporal niches (Fig. S2)
2. Large portion of budburst due to spp differences - need more research to understand this, if not cues what causes it? Could introduce traits and foreshadow the third chapter
3. The experimental design (which is impressive) combined with your models means that most other things some models would assign to the intercept are assigned to site, species, chill, force etc. here... and still the intercept is big. Wow!!
4. Suggests factors other than species cues and architectural growth driving budburst.

## 1 Tables and figures

Table 1: Summary output from a phylogenetic Bayesian model in which species are partially pooled and phylogeny is included on the intercept. The model includes photoperiod and site as dummy variables, while the forcing and chilling effect is included as continuous. Parameter estimates were used to estimate day of budburst for sites under low cue conditions and for Smithers only when relevant.

	mean	sd	5%	95%
Intercept	12.51	3.14	7.40	17.60
Phylogenetic effect	0.79	0.12	0.60	0.90
Forcing	-9.55	0.74	-10.70	-8.30
Photoperiod	-3.62	0.41	-4.30	-3.00
Chilling	-15.21	1.25	-17.30	-13.20
Manning Park	2.09	0.36	1.50	2.70
Harvard Forest	-6.04	1.03	-7.80	-4.40
St. Hippolyte	-8.71	0.97	-10.30	-7.10
Forcing x photoperiod	0.23	0.71	-1.00	1.40
Forcing x chilling	9.06	0.90	7.60	10.50
Photoperiod x chilling	-0.67	0.90	-2.20	0.80
Forcing x Manning Park	-1.76	0.77	-3.00	-0.50
Photoperiod x Manning Park	0.58	0.79	-0.70	1.90
Chilling x Manning Park	-0.36	1.60	-3.00	2.20
Forcing x Harvard Forest	3.81	1.22	1.80	5.80
Photoperiod x Harvard Forest	-1.96	0.86	-3.30	-0.60
Chilling x Harvard Forest	9.97	2.03	6.60	13.40
Forcing x St. Hippolyte	5.25	1.19	3.20	7.20
Photoperiod x St. Hippolyte	-2.13	0.84	-3.50	-0.70
Chilling x St. Hippolyte	8.65	1.70	5.90	11.50

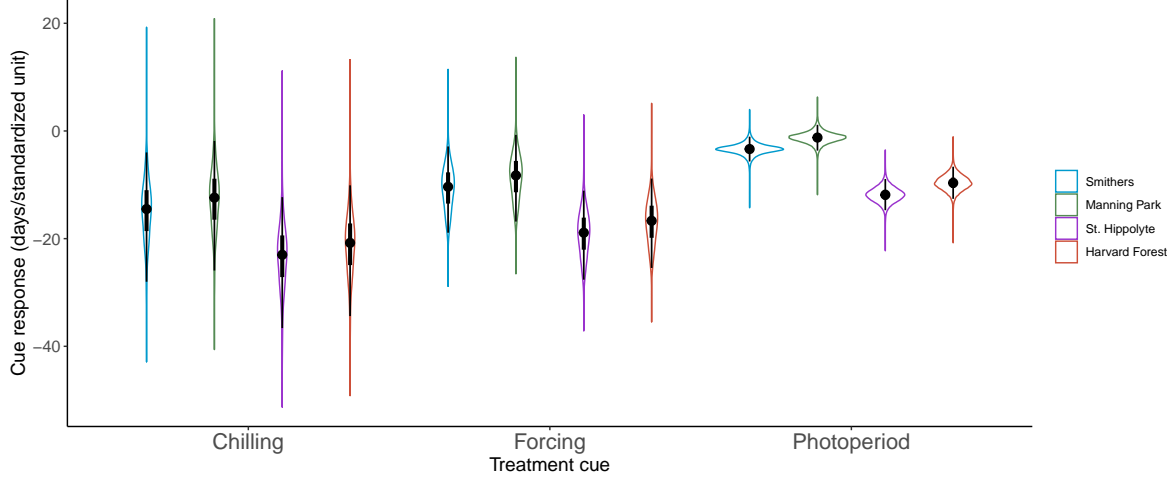


Figure 1: Posterior distributions of estimated chilling, forcing, and photoperiod responses with site level effects for individual populations. Black circles represent the median cue response, thicker black lines the 50% uncertainty interval, while the thinner black line the 90% uncertainty interval. The y-axis spans the entire range of the data. Cues were z-scored using two standard deviations.

## References

- Finn, G. A., A. E. Straszewski, and V. Peterson. 2007. A general growth stage key for describing trees and woody plants. *Annals of Applied Biology* 151:127–131.

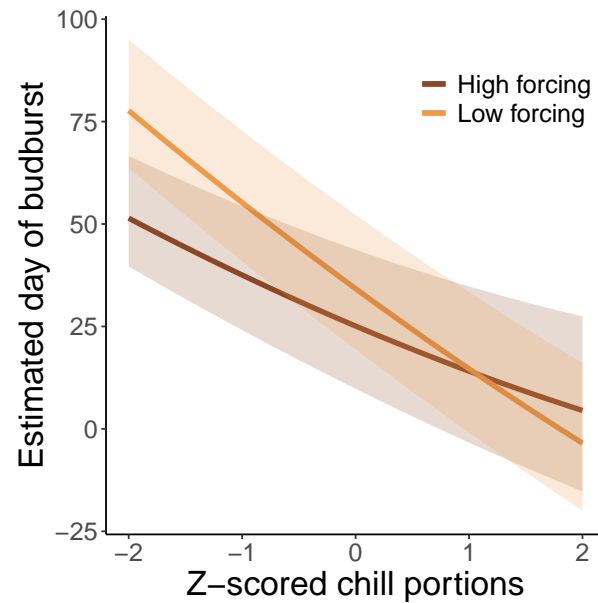


Figure 2: Estimated day of budburst of first bud in response to chill portions and forcing, estimated for our defined baseline conditions.

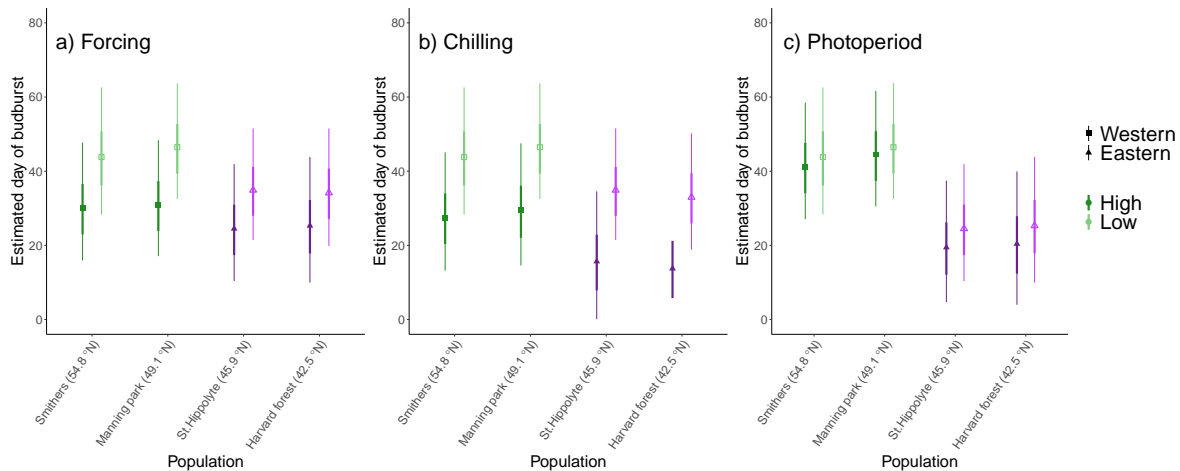


Figure 3: Estimated day of budburst of first bud in response to (a) forcing across populations under low chilling conditions and short photoperiods, (b) chilling across populations under low forcing and short photoperiods, and (c) across photoperiods under our baseline forcing and chilling conditions for species sampled from our four populations. The thin error bars represent the 90% uncertainty interval, while the thicker error bars represent the 50% uncertainty interval.

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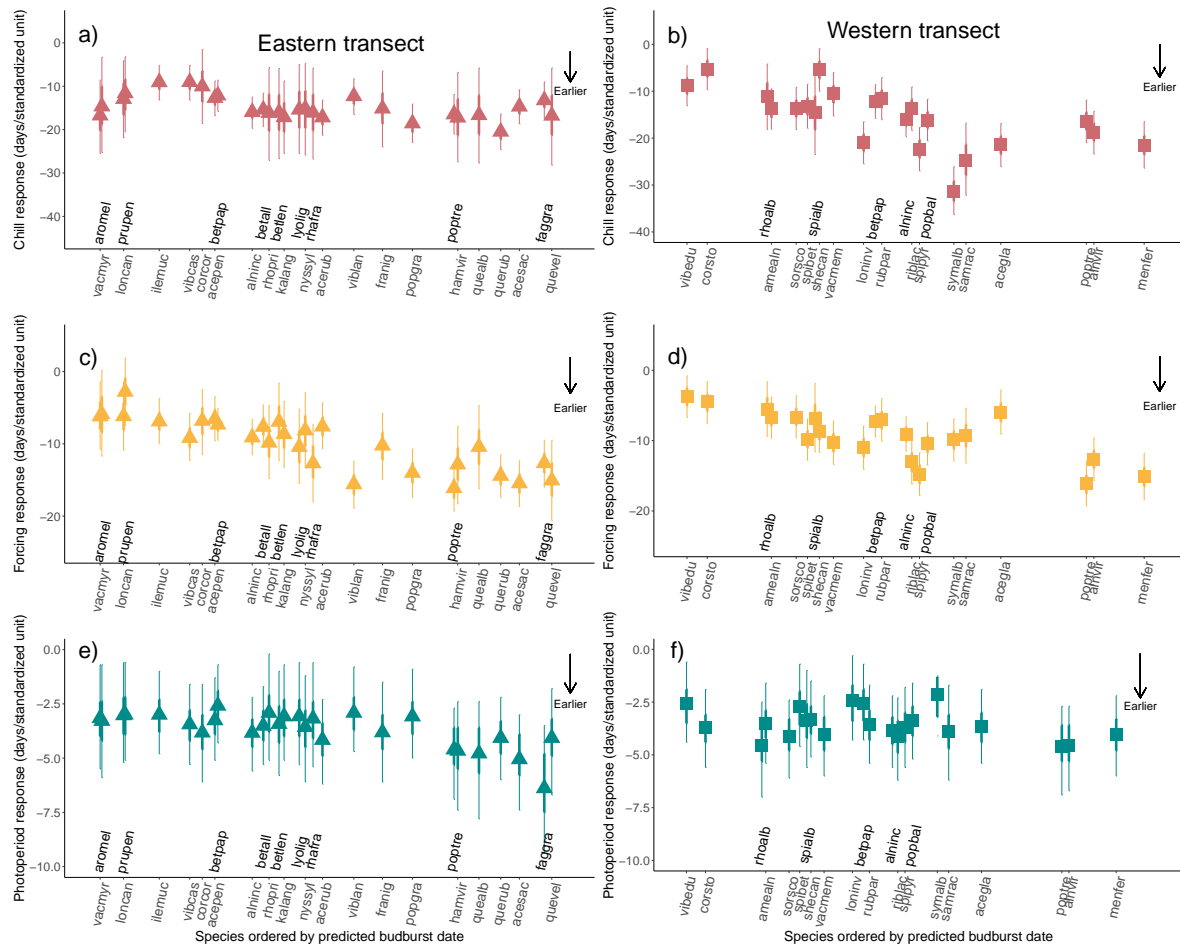


Figure 4: Estimated species' chilling (a,b), forcing (c,d) and photoperiod (e,f) responses ranked by increasing estimated budburst dates for both the eastern (a, c, e) and western (b, d, f) populations. Cues are plotted on differing y-axis to better depict species differences. For each species, the thinner error bars represent the 90% uncertainty interval, and thicker bars represent the 50% uncertainty interval. Each cue was z-scored, using two standard deviations, to make the results across cues directly comparable.

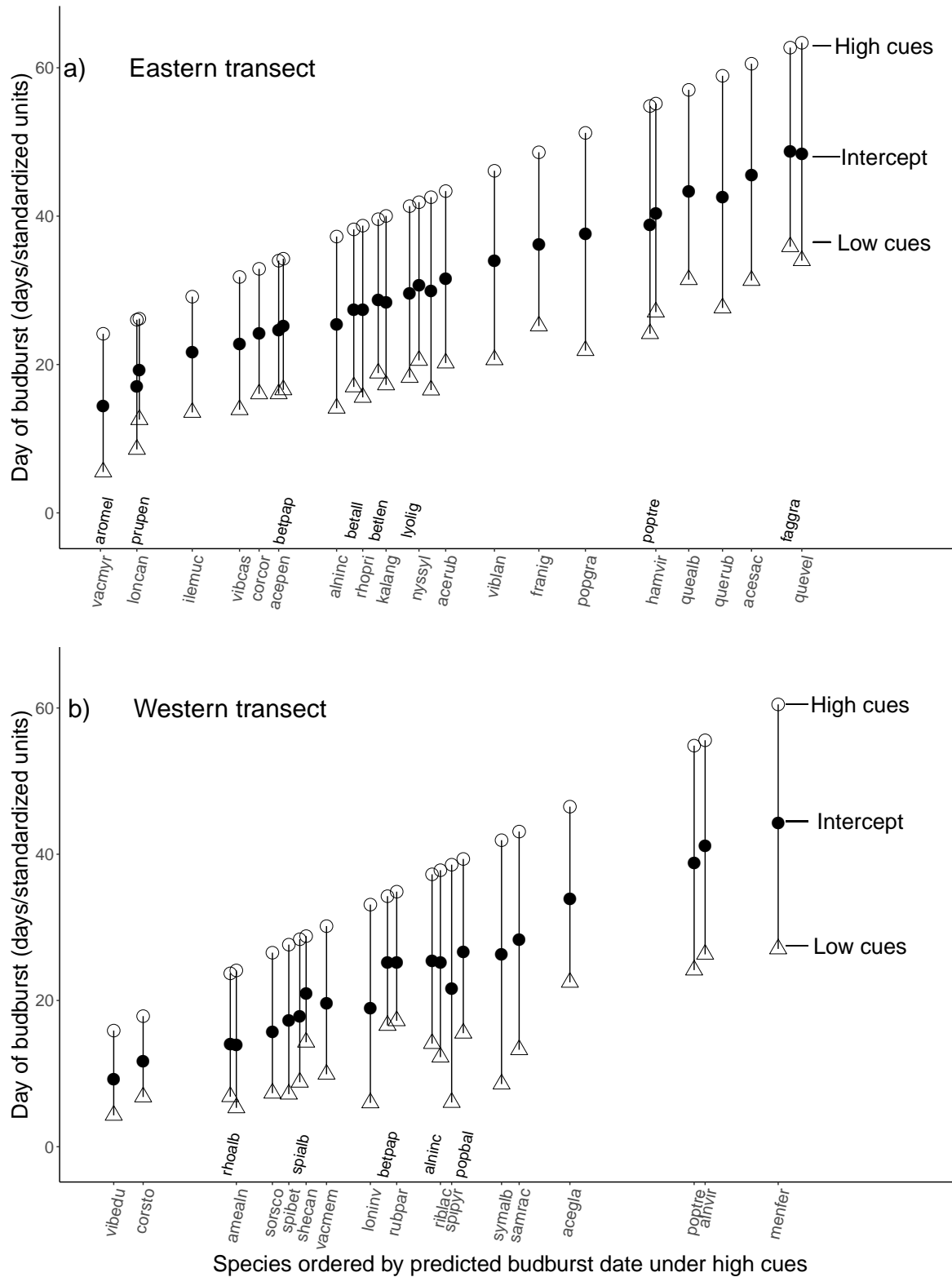


Figure 5: Comparisons of our estimated budburst based on the full model (intercept plus all cues), shown in white, versus the intercepts only (without cues), shown in black, ordered according to differences in species estimated budburst dates for both the eastern (a) and western (b) populations under high cue conditions, depicted as circles, and low cue conditions, depicted as triangles.