

1 Woody plant phenological responses are strongly associated
2 with key functional traits

3 Deirdre Loughnan¹, Faith A M Jones¹, Geoffrey Legault¹, Mira Garner²,
Darwin Sodhi³, Daniel Buonaiuto⁴, Catherine Chamberlain⁵, Ignacio Morales Castilla ⁶,
Ailene Ettinger⁷, and E M Wolkovich¹

4 April 18, 2022

5 ¹ Department of Forest and Conservation, Faculty of Forestry, University of British Columbia, 2424
6 Main Mall Vancouver, BC Canada V6T 1Z4.

7
8 ² Arnold Arboretum of Harvard University, 1300 Centre Street, Boston, Massachusetts, USA;

9
10
11 ³ Organismic & Evolutionary Biology, Harvard University, 26 Oxford Street, Cambridge, Massachusetts,
12 USA;

13
14 ⁴ XXXX

15
16 ⁵ XXXX

17
18 ⁶ Edificio Ciencias, Campus Universitario 28805 Alcalá de Henares, Madrid, Spain

19
20 ⁷ XXXX

21
22 Corresponding Author: Deirdre Loughnan deirdre.loughnan@ubc.ca
23

1 Summary

Key Words: Budburst phenology, functional traits, Trees, climate change

2 Introduction

Climate change is altering the timing of species phenologies, with changes in temporal niches reshaping ecological communities and interactions between species. In temperate systems, the observed advances in plant phenological events, such as budburst, leafout, and flowering times, are associated with changes in seasonal temperatures, particularly warming winter and spring conditions (Menzel et al., 2006; ?). But despite this strong general trend, phenological responses vary across species and geographically, and we have yet to fully understand the underlying mechanisms driving observed differences (Morin et al., 2009). As the effects of climate change become more pronounced, understanding these relationships is of increasing importance if we are to predict and preserve the diversity and services found in temperate forest ecosystems.

While we have yet to identify all drivers of selection on phenologies, considerable work has shown the importance of three abiotic cues – chilling, forcing, and photoperiod – as the primary drivers of budburst and leafout in temperate deciduous species (Chuine et al., 2016; ?; Flynn and Wolkovich, 2018). For budburst to occur, species must experience extended period of cold temperatures to break dormancy (Cooke et al., 2012), where species with higher chill requirements budburst later in the season. Spring forcing temperatures, or the temperatures needed to cue species to initiate growth after dormancy release, are also changing as temperatures warm and the timing at which suitable temperature thresholds are met occur earlier within the season. Photoperiod cues can also determine a species ability to initiate growth (Zohner et al., 2020). Species with strong photoperiod requirements are, however, expected to be more constrained in their ability to track changes in temperature and may face fitness costs and novel species interactions as a result (Guy, 2014). Previous studies support the general trend of advancing budburst in response to each cue, but with considerable variation in the relative importance of different cues across species (Chuine et al., 2016; Flynn and Wolkovich, 2018). Some woody plant species, for example, require less forcing to budburst after experiencing a cool winter with more chilling, while also having the ability to compensate for low chilling with high forcing conditions or longer photoperiods (Harrington and Gould, 2015; Flynn and Wolkovich, 2018; Caffarra and Donnelly, 2011; ?; Zohner et al., 2016). Evidence for the role of photoperiod is largely species specific (Heide, 1993; ?; Singh et al., 2017; Zohner et al., 2016), with few studies testing for its importance across species in a community (but see Flynn and Wolkovich (2018)). Species that are less dependent on photoperiod cues and able to track trends in temperatures may benefit from greater intra-annual phenotypic plasticity resulting in greater fitness outcomes under increasingly variable climates (citation?). Despite the insights that identifying these proximate drivers have provided, we still lack a generalizable and mechanistic understanding of why species and populations differ in their cue use that. Further insight on this topic is needed to predict future changes in species sensitivities and community structure.

In our efforts to understand variation in spring phenological timing, researchers have tested several potential mechanisms to identify the drivers of species cue responses. Work exploring drivers of intraspecific cue use, for example, has found age or the development stage of woody plants to be important. Younger life stages, including both seedlings and younger understory trees, budburst earlier than mature individuals in the canopy (Vitasse, 2013; Seiwa and Kikuzawa, 1991). These trends reflect both differences in the temperature sensitivities across life stages and effects of ontogenic changes as trees mature (Vitasse, 2013; Seiwa and Kikuzawa, 1991). Interspecific differences in cues, however, have been studied in relation to species' phylogenetic relatedness. Work on this topic has found strong evidence for events like flowering-time and budburst to be consistent within taxonomic families, sug-

gesting conservatism in the genetic and physiological mechanisms that determine species phenologies (Kochmer and Handel, 1986; Davies et al., 2013; Gougherty and Gougherty, 2018). Studies of woody plant phenologies across species ranges have also highlighted the importance of local adaptations, with the presence of gradients in phenological responses and presumably cue use at northern range limits (Lechowicz, 1984; Chuine and Beaubin, 2001; ?). In temperate systems for example, greater temperature variation in North America was associated with higher chilling requirements and more conservative phenological responses (Zohner et al., 2017). Studies testing for trends in cues responses across species latitudinal ranges have also observed stronger responses to photoperiod cues at lower latitudes (Zohner et al., 2016). Exploring these potential drivers of plant phenologies have illustrated the nuanced nature of phenology in shaping diverse communities, but they are still limited in the degree to which they explain the variation we observe across species and ecosystems.

Taking a functional trait approach to phenological research could help explain the variation in cue use across species and geographically (Flynn and Wolkovich, 2018; Osada, 2017). Early work on functional traits used trait data from diverse global assemblages of deciduous plants to identify associations between traits, common growth strategies, and different niche space (Westoby, 1998; Wright et al., 2004; Chave et al., 2009). The resulting leaf-height-seed scheme and the more extensive leaf economic spectrum found direct associations between several trait values and gradients in species growth rates and competitive abilities (Westoby, 1998; Wright et al., 2004; Díaz et al., 2016; Chave et al., 2009; Funk et al., 2016). While reproductive phenological traits have been identified as ecologically important for many years (Weiher et al., 1999; Laughlin, 2014), few studies have explored their role in the larger trait framework. Spring phenological traits, such as budburst and leafout, define the beginning of the growing season and period of photosynthesis, and therefore also have the potential to correlate with established growth strategies. Support for the existence of trade-offs in budburst dates and traits related to growth and resource use have been observed across plant functional groups and habitat types in a handful of studies. For example, several studies have found deciduous woody species with smaller vessel diameters and diffuse or semi-ring-porous xylem structures to leaf out earlier than species with larger vessels, as this anatomy reduces the risk of embolism during freezing events (Panchen et al., 2014; Lechowicz, 1984). In testing relationships between budburst and leaf traits of deciduous tree species in Japan, (Osada, 2017) found positive correlations between budburst date and leaf area, leaf mass, and nitrogen content by both mass and area, while (Sun et al., 2006) found deciduous species with high leaf mass per area (a trait that is the inverse of specific leaf area) to budburst earlier in deciduous oak forests in eastern China. Variation in leafout can also relate to species heights, both intraspecifically and across functional groups, with shorter individuals or understory species leafing out earlier than taller individuals or canopy species (Seiwa, 1999). To date, however, research in this area has focused on individuals at local scales, or few traits for a small number of species, limiting our ability to draw more general and causal inferences. There is also a lack of studies linking traits directly to cue sensitivity rather than phenological date. The likely associations between cue sensitivity, phenological events, and growth strategies may allow for more generalizable trends across species and sites, and better account for species variability in key environmental cue use.

To date, there have been numerous studies investigating the relationships between climate and functional traits and a wealth of literature on the separate effects of climate cues as drivers of phenology. However, the selective pressures shaping species traits under variable temperatures are also likely to act on species responses to phenological cues and define a species temporal niche. Species with a more acquisitive life-strategy have shorter rates of return on resource investments and the ability to take advantage of the greater abundance of soil nutrients and light early in the growing season. Such species face a lesser cost in initiating phenological events too early, as they can recover from early season damage (cite Cat's paper?). For example, some acquisitive species produce leaves with high leaf nitrogen content and Specific Leaf Area (SLA) and can take advantage of greater light availability by having higher rates of photosynthesis (Wright et al., 2004; Pereira and Des Marais, 2020), while also limiting the costs of tissue production (??). Acquisitive-strategy species also invest less in their

wood structure, having shorter heights and lower stem densities (Laughlin et al., 2010). Species that budburst earlier in the growing season require less spring forcing and winter chilling, and shorter photoperiods (Flynn and Wolkovich, 2018), allowing them to grow under less competition for light and soil resources. The suite of traits of acquisitive species contrasts with more conservative life-strategy species that exhibit slower, more competitive growth strategies that benefit from slower rates of return on resource investment and the longer retention of leaf tissue. A greater requirement for cue unit accumulation to trigger phenological events should align with a more conservative life-strategy as such species seek to avoid damage due to premature development.

In this study, we test for associations between plant phenological responses to environmental cues and common functional traits. Budburst data for tree species in controlled environmental studies was selected from the Observed Spring Phenology Response in Experimental Environments (OSPREE) database and paired with functional trait data from the TRY and BIEN databases (citations). This data was used to explicitly test for the relative differences in functional traits and the timing of budburst in response to experimental forcing, chilling, and photoperiod cues. Drawing on previous work and the broader trait literature, we predict that species that respond less strongly to chilling, forcing, and photoperiod conditions are more likely to have traits associated with acquisitive growth but low competitiveness, as reflected by high SLA, high leaf nitrogen content per mass (LNC), shorter heights, and lower seed mass. In contrast, species that are more responsive to chilling, forcing and photoperiods will have traits more associated with conservative growth and higher competitive abilities, such as low SLA, low LNC, greater heights and heavier seeds.

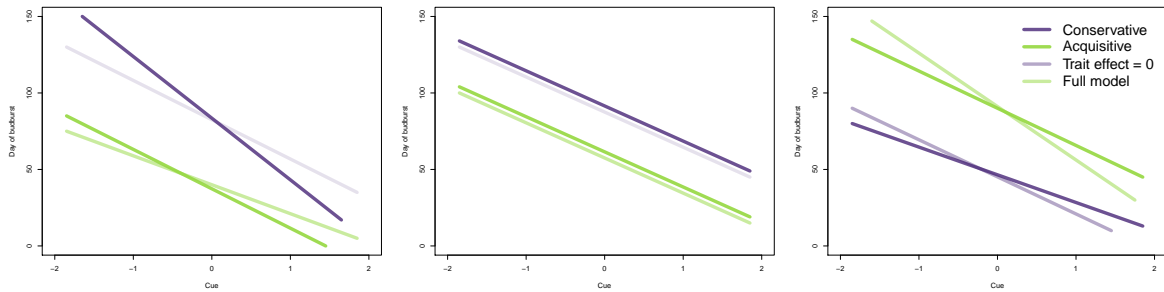


Figure 1: Conceptual figures

Using tree height as an illustrative example, we predict taller trees to be more conservative in their growth strategies and shorter species to budburst earlier and exhibit a more acquisitive growth strategy. Previous work on cue responses in woody species have consistently observed negative responses to stronger cues, resulting in advanced budburst, and therefore we expect that the estimated cue responses from our models would all be negative. Under this assumption, there could be three possible trends in the relationships between cue and trait effects on budburst date. If phenological responses align with trait variation associated axes of acquisitive to conservative growth, we predict there to be a negative trait effect, resulting in a steeper negative slope in the cue response, and a stronger cue response and advance in budburst dates with higher cues (Fig. 1). This is illustrated by the steeper slope of the solid lines for both the conservative and acquisitive species in (Fig. 1). If the more conservative species have later budburst dates than the more acquisitive species, we should also observe a negative correlation between the trait effect and the cue slopes. It is important to note that the smaller differences in slope estimates for when the trait effect is zero and the full model observed for species with low traits is due to the magnitude of the trait value and not a difference in strength of the response. If functional traits have no relation to budburst phenology, the trait effect will be estimated as zero and we could expect to see no difference in the slopes of full model and cue only model (Fig. 1).

Finally, if our model estimates a positive trait effect, potentially as a result of a trade-off in selection for budburst phenology and resource use or competitiveness, we predict the slopes of our full model to be less steep than the cue only model (Fig. 1).

3 Methods

For our analysis, we combined phenological data from the OSPREE database (?) with functional trait data from the TRY(cite) and BIEN (cite) trait databases.

The OSPREE database contains woody, deciduous species phenological data for which experimental data on phenological cues is available, and the phylogenetic relationship is well estimated. First published in 2019, this database has since been updated, and now includes the review of an additional 623 and 270 new publications from each of the following search terms:

- (budburst OR leaf-out) AND (photoperiod OR daylength) AND temperature*
- (budburst OR leaf-out) AND dorman*.

From this subsequent review, we an additional 12 papers met our selection criteria. For additional information on the construction of the OSPREE database and methods of cue estimates, see (?). Our analysis used all available budburst data for our 37 focal species, with the data originating from 28 unique studies.

Both TRY and BIEN are large databases compiling plant trait data across many individuals, species, and studies. Initially, we began by searching both databases for all available trait data for all 234 species represented in the OSPREE database.

Data was also obtained from the BIEN database using the BIEN R package (?). Data were requested or downloaded in December 2018. Our full trait datasets included data on 96 species and ten traits from the TRY database and 34 species and seven traits from the BIEN database. For our analysis, however, we only included trait data from adult individuals with a minimum height of 1.42 m and we removed all data from experiments or growing in non-natural habitats. Traits were also grouped where appropriate, for example, separate entries for SLA values with petioles, without petioles, and for which no petiole presence was specified were all categorized as a single trait in our analysis (see Table S1). Duplicated data across the datasets were removed ($n = 434905$). Finally, we subsetted the data to include only species for which we had a complete dataset for each species and trait. This resulted in a dataset of only 26 species and six functional traits. To test for correlations in our six traits and further refine our trait selection, we applied a PCA. The principle component explained 32.2% of variation while the second explained 23.4% of the variation (Fig. S1). Given the strong association between the SLA and LDMC leaf traits, and similarly between stem specific density (SSD) and height, we further reduced the number of traits in our analysis to include only height, seed mass, LNC, and SLA. By including only these four traits, we were able to increase the number of species we could include in our analysis as we had had at least one trait measurement for 37 species (height $n = 47781$, seed mass $n = 281$, LNC $n = 3853$, SLA $n = 7656$). Given the abundance of height data and overrepresentation of height measurements for six of our focal species, we randomly sampled 3000 height measurements for each of these species to include in our analysis ($n = 27318$). This reduces the effect of trait values from these frequently measured species from overwhelming the partial pooling effect in our model. In addition we excluded seed mass data from the HE Marx dataset from BIEN, as it consisted of only one value, making it challenging to include the study level effect in our model.

Joint model of trait and phenology

To understand the implications of linking traits directly to cue responses, we developed a joint hierarchical Bayesian model. Our model is composed of two sub-models, a trait model and a phenology model, that are co-estimated and linked by a shared parameter. Since each trait varied in the number of studies in which it is included as well as the number of individuals for which it is measured, we chose to model each trait separately. The first part of the model is a hierarchical intercept only model where the response variable $Y_{i,j}$ is the observed trait value of species i from study j , and is assumed to be normally distributed. We further assume that the observed trait value is composed of a “grand” species trait value $\alpha_{\text{trait},i}$ that is shared across all individuals of a species and that is independent of environment, a hierarchical grouping term on the intercept for study, $\alpha_{\text{study},j}$, to account for study-level differences in environment or observation methods, and random error. This results in the following sub-model for each trait:

$$Y_{i,j} \sim \mathcal{N}(\mu_{i,j}, \sigma_{\text{trait}}) \quad (1)$$

where σ_{trait} represents random error in the trait value (i.e., independent of study or species) and:

$$\mu_{i,j} = \alpha_{\text{trait},i} + \alpha_{\text{study},j} \quad (2)$$

with:

$$\begin{aligned} \boldsymbol{\alpha}_{\text{trait}} &= \{\alpha_{\text{trait},1}, \dots, \alpha_{\text{trait},n}\}^T \text{ such that } \boldsymbol{\alpha}_{\text{trait}} \sim \mathcal{N}(\mu_{\alpha_{\text{trait}}}, \sigma_{\alpha_{\text{trait}}}) \\ \boldsymbol{\alpha}_{\text{study}} &= \{\alpha_{\text{study},1}, \dots, \alpha_{\text{study},n}\}^T \text{ such that } \boldsymbol{\alpha}_{\text{study}} \sim \mathcal{N}(0, \sigma_{\alpha_{\text{study}}}) \end{aligned} \quad (3)$$

Parameters $\mu_{\alpha_{\text{trait}}}$ and $\sigma_{\alpha_{\text{trait}}}$ represent the mean trait value across all species and the standard deviation in trait values between species, respectively. The mean effect of study is assumed to be centered at 0 with standard deviation $\sigma_{\alpha_{\text{study}}}$.

The second part of the joint model is a hierarchical linear model where the normally distributed response variable $Z_{i,k}$ is the day of budburst for species i experiencing forcing (F_k), chilling (C_k), and photoperiod (P_k). This sub-model is linked to the trait sub-model via the shared parameters $\alpha_{\text{trait},i}$, representing the “grand” trait values of species that are independent of study. The overall structure of the phenology sub-model is similar to that of (Ettinger et al., 2020), except species’ responses to forcing ($\beta_{\text{force},i}$), chilling ($\beta_{\text{chill},i}$), and photoperiod ($\beta_{\text{photo},i}$) are treated not as single parameters but as a combination of parameters, a species-specific response that is independent of its trait value (e.g., $\alpha_{\text{force},i}$) and an effect of its trait value (e.g., $\beta_{\text{trait.force}}$) that is multiplied by $\alpha_{\text{trait},i}$ and does not differ between species. In other words, species responses to cues interact with their “grand” trait values, and we assume this interaction is independent of species identity. The phenology sub-model can thus be written as:

$$Z_{i,k} \sim \mathcal{N}(\mu_{i,k}, \sigma_{\text{pheno}}) \quad (4)$$

where σ_{pheno} represents random error in budburst day and:

$$\mu_{i,k} = \alpha_{\text{pheno},i} + \beta_{\text{force},i} \times F_k + \beta_{\text{chill},i} \times C_k + \beta_{\text{photo},i} \times P_k \quad (5)$$

with:

$$\begin{aligned} \beta_{\text{force},i} &= \alpha_{\text{force},i} + \beta_{\text{trait.force}} \times \alpha_{\text{trait},i} \\ \beta_{\text{chill},i} &= \alpha_{\text{chill},i} + \beta_{\text{trait.chill}} \times \alpha_{\text{trait},i} \\ \beta_{\text{photo},i} &= \alpha_{\text{photo},i} + \beta_{\text{trait.photo}} \times \alpha_{\text{trait},i} \end{aligned} \quad (6)$$

and all species-specific parameters are, as in the trait sub-model, given hierarchical structure whereby:

$$\begin{aligned}\alpha_{\text{pheno}} &= \{\alpha_{\text{pheno},1}, \dots, \alpha_{\text{pheno},n}\}^T \text{ such that } \alpha_{\text{pheno}} \sim \mathcal{N}(\mu_{\alpha_{\text{pheno}}}, \sigma_{\alpha_{\text{pheno}}}) \\ \alpha_{\text{force}} &= \{\alpha_{\text{force},1}, \dots, \alpha_{\text{force},n}\}^T \text{ such that } \alpha_{\text{force}} \sim \mathcal{N}(\mu_{\alpha_{\text{force}}}, \sigma_{\alpha_{\text{force}}}) \\ \alpha_{\text{chill}} &= \{\alpha_{\text{chill},1}, \dots, \alpha_{\text{chill},n}\}^T \text{ such that } \alpha_{\text{chill}} \sim \mathcal{N}(\mu_{\alpha_{\text{chill}}}, \sigma_{\alpha_{\text{chill}}}) \\ \alpha_{\text{photo}} &= \{\alpha_{\text{photo},1}, \dots, \alpha_{\text{photo},n}\}^T \text{ such that } \alpha_{\text{photo}} \sim \mathcal{N}(\mu_{\alpha_{\text{photo}}}, \sigma_{\alpha_{\text{photo}}})\end{aligned}\tag{7}$$

Parameters $\mu_{\alpha_{\text{pheno}}}$, $\mu_{\alpha_{\text{force}}}$, $\mu_{\alpha_{\text{chill}}}$, $\mu_{\alpha_{\text{photo}}}$ represent the mean budburst day, response to forcing, response to chilling, and response to photo period across all species, respectively. Parameters $\sigma_{\alpha_{\text{pheno}}}$, $\sigma_{\alpha_{\text{force}}}$, $\sigma_{\alpha_{\text{chill}}}$, $\sigma_{\alpha_{\text{photo}}}$ are the standard deviations between species.

Forcing, chilling, and photoperiod (F_k , C_k , P_k) were z-scored to account for differences in the scale of predictors across studies (?), as well as differences in the natural units for the cues. We assumed parameters had weakly informative prior distributions (generally normal or half-normal distributions) that we obtained from a series of prior predictive checks where the objective was to produce a wide but also plausible range of trait and phenology values (e.g., budburst dates between days 0 – 365). The joint model was coded in the Stan programming language (Stan citation) and fit to the trait and phenology data (see above) using the rstan package (version, citation). For all traits, model fits were deemed valid based on *Stan's* diagnostic metrics, including no divergences across 1000 iterations, high effective sample size (n_{eff}), and scale reduction factor \hat{R} close to 1 across 4 chains. We quantify 90% credible interval of posterior distributions using the highest probability density index.

We selected our priors using our prior knowledge of functional trait diversity in deciduous species and cue responses. In doing so, we assume that stronger environmental cues will result in earlier budburst dates, as reflected by negative cue values. Priors of the phenology portion of our model reflect this, and are centered on negative values.

Finally, we used a phylogenetic generalized least-squares regression model (PGLS) to test the relationship between day of budburst and individual traits. This analysis allowed us to test for phylogenetic non-independence in the phenology-trait relationship (Freckleton et al., 2002). We obtained a rooted phylogenetic tree by pruning the tree developed by (?) and performed the PGLS analysis using the mean trait values and mean posterior estimates of the cue responses from our joint model. The PGLS was run using the "Caper" package in R (?).

4 Results

In modelling each individual traits' relationship with phenological cues, our models estimated the simple geometric mean for each species-trait combination to fall within the posterior estimations (Fig. 2). For several species in the height model, however, the simple geometric mean fell outside of predicted species means after accounting for the effect of study. This was the case for *Quercus ilex*, *Quercus petraea*, *Quercus coccifera*, *Aesculus hippocastanum*, and *Rhamnus cathartica*. These model estimates may also reflect our use of a normal distribution for our traits, which may produce estimations of ecologically unrealistic zero or negative values. The use of the normal distribution in complex models such as ours, however, strikes a good balance between being biologically realistic and computationally viable, and in general our model produced realistic trait estimates that usually did not cross a zero threshold.

The parameterization of our model allowed for the separation of species and study level effects for each trait, and in doing so accounts for variation in trait data due to differences in datasources, habitats, measurement protocols, and observer error. The extent of variation in trait measurements varied considerably across species and traits 2. For example, the breadth of variation we observe in the raw height data reflects the high number of height measurements we have for most species 2. Species such as *Acer saccharum* has 3000 observations from a single study, producing a range of height values, and

a model posterior estimate that corresponds to the data mean 2. In contrast, our dataset only includes six observations of *Juglans regia* from four studies, producing a greater study level effect, as is reflected by the difference between the posterior and mean estimates 2. Our seed mass data originates from only five studies, with the majority of the data coming from a single study. We therefore see very little variation in our estimates and a high degree of overlap between the posterior estimates and the mean seed mass for most species 2.

The relationship between species height and cue responses varied across the three cues, with increasingly tall trees having more positive responses to warming, but negative responses to both chilling and photoperiod (Fig. 3). Of the three cues, height had the strongest influence on chilling, with an estimated interaction parameter of -0.5 (90% credible interval: -1, -0.1). The response to photoperiod was also negative, but the photoperiod slope was smaller at -0.3 (90% credible interval: -0.6, 0). Interestingly, forcing had a positive slope, at 0.2 (90% credible interval: -0.1, 0.5). The positive response to forcing indicates that tall trees, like *Acer pseudoplatanus*, have more positive slopes in the full model compared to models with a zero trait effect, and a much greater difference in their slopes than shorter trees like *Corylus avetana* (Fig.4). In contrast, the negative responses to chilling and photoperiod mean that the full model for taller trees will have a more negative slope than that of the model with zero trait effects.

We also found variation in the relationship between SLA and each of the three cue responses (Fig. 3), with increasing SLA leading responses to forcing and chilling to be more positive, but negative responses with increasing photoperiod. Chilling was most strongly influenced by SLA (interaction parameter: 0.3: 90% credible interval: -0.1, 0.7). Species' responses to forcing were also positively correlated with SLA values (interaction parameter: 0.2, 90% credible interval: -0.1, 0.4), however, responses to photoperiod were negative (interaction parameter: -0.2, 90% credible interval: -0.4, 0). For species with high SLA values, such as *Fagus grandifolia*, this positive trait effect in forcing and chilling responses produced a more positive slope in the full model relative to the slope when the trait effect is set to zero. The difference in the slopes of species with leaves with low SLA, such as *Quercus ilex*, is much smaller (Fig.4). The relatively small trait effect of photoperiod is reflected in the smaller difference in the slopes between the full model and the model without the effect of trait (Fig.4).

As we predicted, species log seed mass had a negative relationship with all three cue responses 3. As we observed for other trait models, seed mass had the largest influence on species responses to chilling (interaction parameter: -1.1: 90% credible interval: -2.8, 0.7). The influence of seed mass on forcing and photoperiod were also negative but relatively negligible, with slopes of -0.3 (90% credible interval: -1.4, 0.8) and -0.6 (90% credible interval: -1.6, 0.4) respectively. The negative trait effect estimated from our model produced more negative slopes, however, given the nature of the log transformation of the seed mass data, the resulting estimated day of budburst can be positive. This is observed in the response of the large seeded species *Aesculus hippocastanum* to forcing cues 4. The negative effect of the seed mass trait still produced a more negative slope in the full model compared to the slope of the model with a zero trait effect for each of the three cues (Fig. S??). The slope differences of small seeded species, like *Alnus glutinosa*, was considerably smaller. Our model also estimated the trait effect of photoperiod to produce similar slopes for both the full model and the model with a trait effect set to zero, indicating a relatively small effect of this cue (Fig. S??).

Finally, the relationship between LNC and cue responses was also in line with our predictions, producing a positive association between LNC and cue responses (Fig.3). Chilling was most influenced by LNC (interaction parameter: 0.7 :90% credible interval: 0.2, 1.2), followed by the response to forcing (interaction parameter: 0.5: 90% credible interval: 0.1, 0.9), while photoperiod again had the smallest influence (interaction parameter: 0.3 :90% credible interval: 0, 0.7). For species like *Alnus glutinosa* that produce leaves with high LNC, the positive trait effect resulted in a more positive slope in the full model relative to the slope of the zero trait effect model. In contrast, species with low LNC like *Quercus ilex* have a much smaller difference in their slopes (Fig.S??). The model estimated trait effect of LNC for photoperiod is relatively small, producing less of a difference between the full model and the zero trait effect model (Fig.S??).

The results of the PGLS analysis suggest there are mostly non-significant phylogenetic relationships

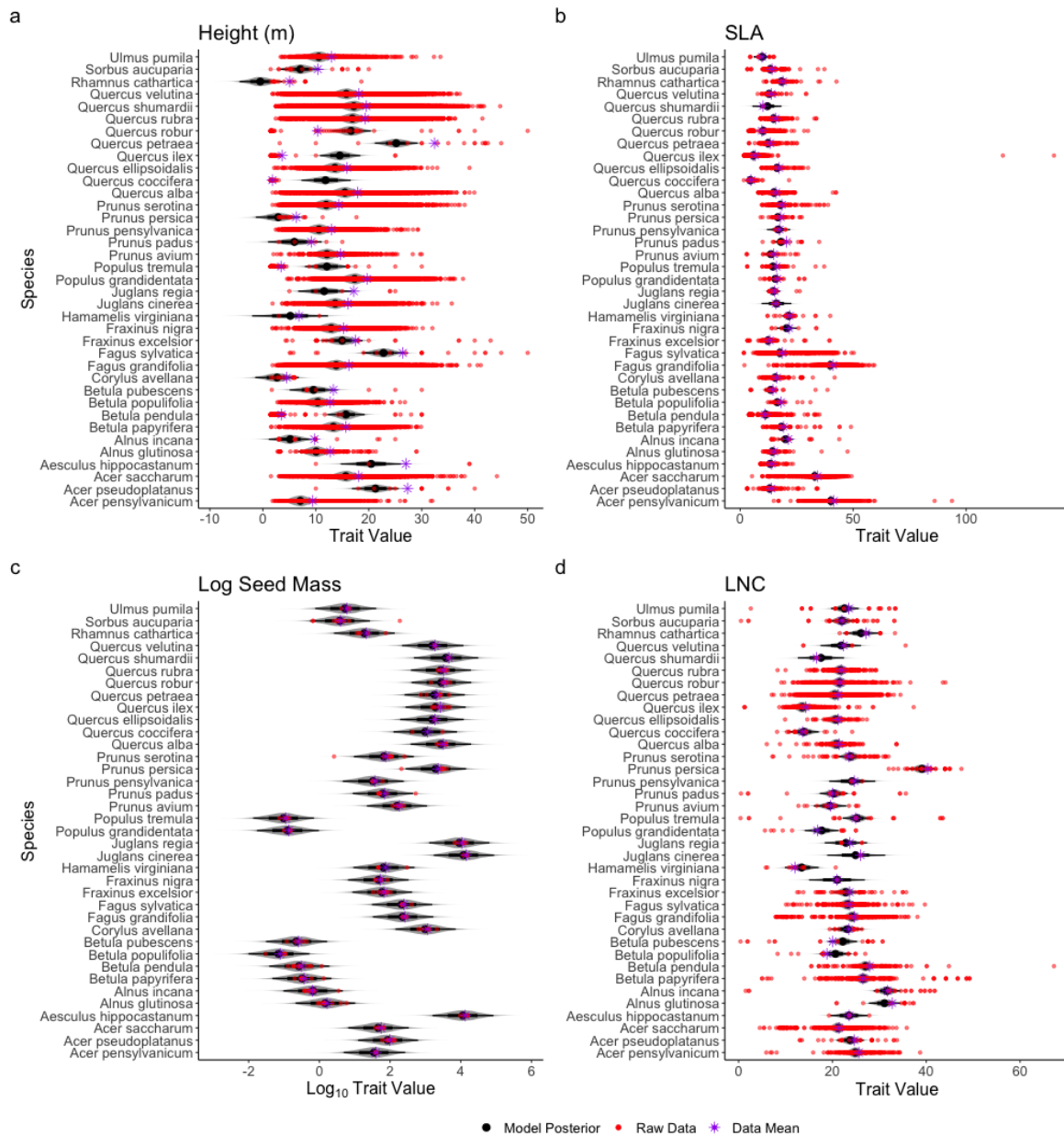


Figure 2: Comparisons of estimated model fits and raw data from joint models of trait effects on budburst phenological cues for 37 species of woody deciduous plants. Four functional traits – a. height, b. SLA, c. seed mass, and d. LNC – were modeled individually, with the calculated trait value being used to jointly model species responses to standardized chilling, forcing, and photoperiod cues. Model posteriors are shown in black, with the thicker line depicting the 66% interval and the thinner black line the 97% interval. Overall species level model posterior distributions were well aligned with the raw data, shown in red, and the species level means from the raw data, denoted as a purple asterisks.

331 between each of our four traits and chilling responses, as well as between height and forcing, and seed
 332 mass and forcing cues (SM tableX). There were no phylogenetic relationships between SLA or LNC

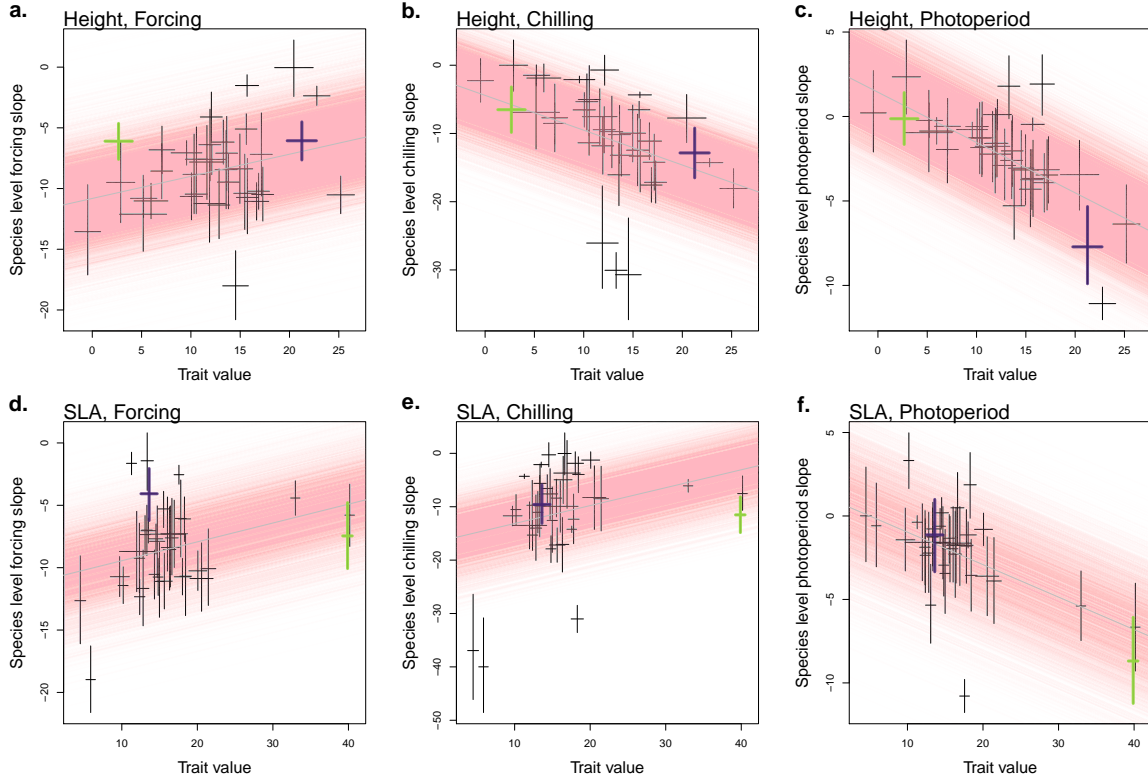


Figure 3: Estimated trait values for height (a-c) and SLA (d-f) traits, correlated against species level cue responses to forcing (a & d), chilling (b & e), and photoperiod cues (c & f). Parameters were estimated using our joint trait-phenology model, with the grey line depicting the mean linear relationship between estimated trait effects and the slope of the cue response. The pink shading represents the distribution of the posterior estimates. Our model of tree heights estimated a positive correlation between height values and the response to forcing cues in panel a. The responses in both chilling and photoperiod cue responses (b & c), however were negative. The responses to cues from our SLA model contrasted those of the height model, with the estimated SLA values positively correlating with the response in forcing and chilling (d & e), but a negative correlation in the response of photoperiod cues (f). The species used in our illustrative examples in Fig 4 are highlighted in each panel, with the relative short species, *Corylus avellana* shown in green, and the taller species, *Acer pseudoplatanus* shown in purple in panels a to c. In panels d to f, the species with small SLA values, *Fagus grandifolia* is shown in green, and the species with large SLA values, *Quercus ilex* shown in purple.

and forcing, or for any trait and photoperiod cues (SM tableX). While these results suggest there is some phylogenetic effect influencing the cue response of species for these traits, we were unable to further incorporate these effects into our current analysis given the complexity of our model.

5 Discussion

We found the functional traits of woody plant species to influence plant responses to phenological cues. Species associated with acquisitive growth strategies, producing high SLA and LNC leaves, shorter heights, and small seeds, showed advances in their budburst dates in response to increasing chilling cues. Interestingly, the relationships of traits to forcing and photoperiod cues were only partially in line with our predictions. Trees with high SLA and LNC and small seeds did show advances in

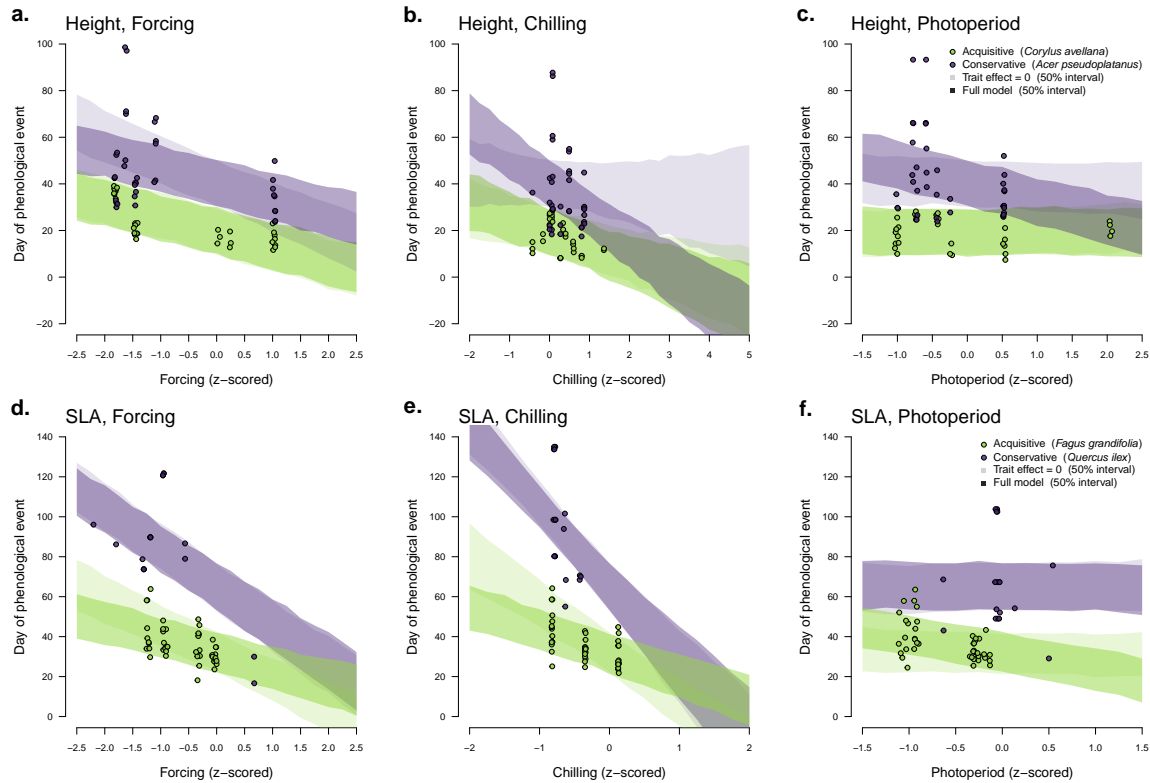


Figure 4: Comparisons of estimated cue responses of a species with an trait value associated with acquisitive growth strategies, shown in green, or conservative growth strategies, shown in purple. Associations between tree height and forcing, chilling, and photoperiod are depicted on panels a to c respectively and associations between LNC and each cue in panel d to f. The green points represent the budburst data for *Corylus avellana*, a relatively short species, while the green points are budburst data of the taller species, *Acer pseudoplatanus*. Dark bands represent the 50% credible interval for the posterior cue estimates for the full model. Opaque bands represent the 50% credible interval for the posterior cue estimates with a trait effect of zero. The positive value of the height model's forcing slope produces a less negative effect on the day of budburst when the effect of height is included, indicating that taller trees advance their budburst dates at a lower rate to rising forcing temperatures (a). The negative slopes for the height model's chilling and photoperiod cue responses produce a more negative slope for the full model, with taller trees advancing their budburst more with greater chilling and daylengths (b & c). Estimates of forcing and chilling cue responses in our SLA model were positive and produced more positive slopes in the full model, indicating that high SLA values are less responsive in their budburst to increasing forcing and chilling values (d & e). The estimate for photoperiod cues in response to SLA was negative, resulting in a more negative slope and greater advances in budburst with longer daylengths (f). The greater effect of slopes on taller trees and high SLA species is a artifact of the trait value itself being larger and not a reflection on the magnitude of the response.

budburst as forcing increased, while the response of forcing cues to height contrasted our predictions. Contrary to our predictions, our model found taller trees to require less forcing temperatures to advance their budburst. We were also surprised by the relationship between SLA and photoperiod, as species with leaves with high SLA values were estimates to have a stronger cue response and require longer photoperiods to advance budburst. But as we predicted, shorter species with small seeds and leaves with high LNC had lower photoperiod cue responses and earlier budburst. These results suggest that

phenology does generally align with established gradients in traits variation, with most traits following shifts from acquisitive and early budburst to more conservative, later budburst.

The deviation from our predicted trait-cue relationships we observed for the influence of height on forcing cues and SLA on photoperiod cues may provide interesting insight into the variable roles and trade-offs that select for plant phenotypes and cue use. While height is often associated with competition for light and therefore photoperiod, spring temperature is also an important factor influencing other wood traits that may confound resource investment into lateral growth. For example, spring temperature influences growth of the cambial meristem (?), with frost events having the potential to severely hinder tree growth and height (Clements et al., 1972; Marquis et al., 2020). Early season damage could pose a strong selective pressure for later budburst on shorter species to ensure cambial meristem development is not affected. Exploring additional traits that relate to height and wood structure may offer a more mechanistic explanation of the observed response in forcing cue use. Our results also contrasted our expectations of how photoperiod cues would relate to LNC, a trait most often associated with light availability and photosynthetic potential (Wright et al., 2004; Pereira and Des Marais, 2020). Although the general response between LNC and photoperiod was for high LNC to more less sensitive to photoperiod cues as we predicted, our model of LNC was most variable and the response to photoperiod similar to that of other traits S??. The effects of traits on cue response could also be the result of interactions between cue responses not accounted for in our analysis. Numerous growth chamber studies have observed compensatory interactions between species budburst and our three cues (Heide, 1993; Caffarra and Donnelly, 2011; ?). Greater forcing cues, for example, have been found to offset the effects of low chilling on the timing of budburst (Heide, 1993; Caffarra and Donnelly, 2011; ?). The unpredicted relationships between traits and cues may reflect underlying mechanisms a model without interactions can not differentiate given our limited understanding of cue-trait relationships. Unfortunately we were unable to include such interactions in our currently model given its complexity, but further exploration into associations between traits and cues may provide novel insights.

Across our four models, we consistently observed the strongest responses to increases in chilling, while the effects of photoperiod cues were weakest. This is in line with previous growth chamber studies, which also found chilling cues to have strong effects on budburst dates (Heide1993, Caffarra2011,Laube2014,Flynn2018). The accumulation of chill units determines the transition of plants from endodormancy, the phase in which woody plants are in a internally controlled state of inactivity during the coldest winter months, to ecodormancy, during which time growth inactivity is environmentally controlled and reflects limitations in resource availability (Cooke et al., 2012). The high fitness costs of premature growth in late winter or early spring may select for stronger responses to chilling cues. Responses in photoperiod cues, in contrast, are generally found to contribute less to the timing of budburst or are more species specific (Flynn and Wolkovich, 2018). The associations we observed between our functional traits and species cue responses, and their relative strength, supports the importance of winter chilling, forcing, and photoperiod in defining species phenologies, but suggest species will be most responsive to future changes in winter temperatures, while spring temperatures and daylengths will play a lesser role in shaping woody plant growth strategies.

To date, studies of functional traits that include phenology have generally tested for correlations between phenological events, such as budburst and flowering, and other functional traits. While studies of traits from single species have not observed associations between budburst and functional traits (Kitamura et al., 2007), multispecies studies have found similar results as our own. In their study of deciduous woody plants in Japan, (Osada, 2017) also observed correlations in budburst dates and leaf and wood traits, with a positive correlation between species leaf mass area (the inverse of SLA) and later budburst (Osada, 2017). Few studies to date have also explored the links between traits, phenology, and environmental cues, but there is some evidence suggesting these associations are generalizable. Work synthesizing the importance of traits and environmental cues across diverse plant functional groups also found traits, such as height and SLA, to explain observed differences in flowering phenology (?). Advances in first-flowering time were also strongest for shorter plants, with high SLA (?), which aligns with the positive correlation we observed between these traits and the timing

of budburst. Our findings provide early evidence for complex interactions between trait syndromes, phenology, and environmental cues, highlighting key areas for future research to directly test for their underlying mechanisms.

A challenge of inferring the role of functional traits in relation to abiotic cues are a traits' likelihood of having multiple roles in species interactions and in mediating environmental conditions. Such diversity in the role a trait plays could facilitate or limit the adaptive potential of species phenologically to future climates, as there may be stronger selection of these alternate roles. Warming winter and spring temperatures are expected to result in species chilling requirements being met earlier (Guy, 2014), while warming springs will cause forcing temperature thresholds to also be met earlier. Our results suggest species with acquisitive growth strategies will best be able to respond to such changes, advancing phenologically and budbursting earlier in the spring. Species that are most able to initiate growth in the spring and tolerate late frost events, will be more likely to track these changes in temperature and benefit from longer growing seasons and reduced competition. This could favour species that produce less costly leaves, with high SLA, as the loss of tissue to late season frosts would incur a lower fitness cost (?). These leaves are more easily decayed, contributing to fast cycling of resources within a community (). Selection on the timing of budburst may also be constrained by species traits. Leaves with low LNC and less photosynthetic machinery for example, may cause species to be limited by photoperiod length and their photosynthetic capacity. As daylengths remain constant, species with strong photoperiod responses will be constrained in their ability to advance their timing of budburst with rising temperatures. These effects of traits on future changes in species phenologies may alter species' temporal niche and ultimately change the competitive landscape and species interactions within deciduous forests.

In addition to allowing us to infer ways in which traits and phenology may alter native plant communities, our findings provide insights into the potential influence of invasive species. The same traits that allow native species to track changes in temperature infer a greater fitness and adaptive advantage to invasive species as well. Invasive species are generally thought to be more sensitive to seasonal variation, with a greater ability to shift their phenologies (Wilsey et al., 2011; Fridley, 2012). Our results imply that invasive species with traits associated with high growth rates, such as SLA, greater LNC and photosynthetic potential, and less investment in wood anatomy and reproduction through seed mass, are most likely to benefit from less chilling and warmer forcing temperatures. As species with this phenotype track changes in temperature and budburst earlier in the growing season, they can benefit from early seasonal priority effects and the less competitive temporal niche at this time (?). Invasive woody plant species can have higher rates of leaf production and differences in wood anatomy traits associated with faster growth (?). This can alter the competitive dynamics within a forest, with the greatest fitness impacts to species with less competitive traits such as smaller sized seeds (Fried et al., 2019). Communities within which native and invasive species phenological niches are most similar are, however, most resistant to invasion (?). The relative importance of phenology in determining resource availability and coexistence of native and invasive species within a community is likely shaped by functional traits and the more complex processes they are proxies for.

For our analysis we combined data from two large datasets, with the aim to include as many diverse and well studied woody plant species as possible. By including species trait measurements across the leaf and wood economic spectrum, however, we were only able to find a relatively small number of species with at least one trait measurement across commonly measured traits. The subset of species included in this study reflects the diversity of available trait data, but is a relatively small subset of the diversity of woody plant species and most indicative of the responses of commonly measured species. The trait and budburst data we used were also collected independently of one another, and therefore may reflect a greater amount of variation than would be expected if measurements were taken from the sample populations or individuals. Including study effects in our trait model accounted for these sources of variability in our model estimates. The relationships we observed therefore reflect general trends in trait relationships that scale across populations and species. Future studies should still aim to include a greater diversity of species and functional traits. For example including traits related to wood structure and defense compounds could provide new insights into the influence of temperature on

vessel development and the potential for biotic pressures from herbivory to also influence phenology. To further understand if the trends we observed occur at finer ecological scales, future studies should also aim to include trait and phenological data that are measured from within the same populations. As more functional trait data becomes available and sampling efforts extend beyond temperate ecosystems, we will gain a more complete picture of the global variability in species trait and cue responses and apply this to future research into the role of phenology as a functional trait.

6 Conclusion

In modeling the joint relationships between functional traits and cue responses in budburst, we found associations between functional traits and species responses to budburst date with varying temperature and light cues. In general, traits associated with acquisitive growth strategies were less responsive to chilling, forcing, and photoperiod cues, while species with more conservative traits required stronger cues. These findings provide novel insights into the potential for species of these growth strategies to respond to future changes in climates and community structure. The varying responses between height and forcing, and between SLA and photoperiod, highlight potential gaps in our current understanding of how traits mediate abiotic conditions and suggest complex relationships between traits, phenology, and environmental cues. Better understanding the underlying mechanisms shaping species phenologies and overall fitness is necessary if we are to predict how species will respond to climate change and the cascading effects of these changes on trophic interactions and ecosystem services.

- How might traits constrain/facilitate future shifts in phenology?
- our findings do support the idea that phenology is an important functional trait
- traits and relationships to increased frost risk, increased drought stress, increased herbivore pressure
- novel competitive communities
- How might ecosystem functioning shift if species track temperature? How to our results relate to seasonality and frost risk?
- What does it mean if more competitive/invasive species respond to warming and start bb earlier - outcompete species and lead to compressed temporal niche?
- Relate our results to invasion success
- What do our results suggest for the relationship between cue use and traits?
 - Do we find relationships between cues and traits?
 - Do these trends agree with an acquisitive/conservative tradeoff?
- How do our results relate to previous studies? Huang et al. 2018 - found several growth strategies - all combinations of early- fast, early-slow, late-fast etc - but looked at flowering Osada 2017 - bb later for sp with greater LMA, thickness, Narea - driven by differences across deciduous and evergreen spp; Deciduous alone: bb positively correlated with leaf mass, area, vessel diam in cross spp comparisons Kitamura et al 2007 - found no relationship between budburst of their focal oak species and SLA, LNC, etc. Low sla - associated with aridity - Sun, S., D. Jin, and R. Li. 2006. LMA neg correl with leafout; larger LMA = earlier
- What do our results suggest for the bigger picture?

- 491 – How might traits constrain/facilitate future shifts in phenology? - our findings do support
- 492 the idea that phenology is an important functional trait - traits and relationships to in-
- 493 creased frost risk, increased drought stress, increased herbivore pressure - novel competitive
- 494 communities
- 495 – How might ecosystem functioning shift if species track temperature? How to our results
- 496 relate to seasonality and frost risk?
- 497 – What does it mean if more competitive/invasive species respond to warming and start bb
- 498 earlier - outcompete species and lead to compressed temporal niche?
- 499 – Relate our results to invasion success
- 500 • Limitations/strengths?
- 501 – we assume stronger cues mean earlier bb but really it's more complicated than this
- 502 – broad approach means lose detail and compromise - traits come from different populations
- 503 to the phenology data
- 504 – disconnect between trait data - observational - and phenology data that is in a controlled
- 505 environment
- 506 – limited data may have reduced diversity of traits/strategies - may not be enough to detect
- 507 predicted trends – reframe this as less of a limitation and more of a future direction
- 508 – Why we think mean height values were different from geometric mean values for some
- 509 species. Talk about the influence of accounting for the study effect.

References

- Caffarra, A., and A. Donnelly. 2011. The ecological significance of phenology in four different tree species: Effects of light and temperature on bud burst. *International Journal of Biometeorology* 55:711–721.
- Chave, J., D. Coomes, S. Jansen, S. L. Lewis, N. G. Swenson, and A. E. Zanne. 2009. Towards a worldwide wood economics spectrum. *Ecology Letters* 12:351–366.
- Chuine, I., and E. G. Beaubien. 2001. Phenology is a major determinant of tree species range. *Ecology Letters* 4:500–510.
- Chuine, I., M. Bonhomme, J. M. Legave, I. García de Cortázar-Atauri, G. Charrier, A. Lacointe, and T. Améglio. 2016. Can phenological models predict tree phenology accurately in the future? The unrevealed hurdle of endodormancy break. *Global change biology* 22:3444–3460.
- Clements, J. R., W. Fraser, J., and C. W. Yeatman. 1972. Frost Damage to White Spruce Buds. *Canadian Journal of Forest Research* 2:62–63.
- Cooke, J. E., M. E. Eriksson, and O. Junttila. 2012. The dynamic nature of bud dormancy in trees: Environmental control and molecular mechanisms. *Plant, Cell and Environment* 35:1707–1728.
- Davies, T. J., E. M. Wolkovich, N. J. Kraft, N. Salamin, J. M. Allen, T. R. Ault, J. L. Betancourt, K. Bolmgren, E. E. Cleland, B. I. Cook, T. M. Crimmins, S. J. Mazer, G. J. McCabe, S. Pau, J. Regetz, M. D. Schwartz, and S. E. Travers. 2013. Phylogenetic conservatism in plant phenology.
- Díaz, S., J. Kattge, J. H. Cornelissen, I. J. Wright, S. Lavorel, S. Dray, B. Reu, M. Kleyer, C. Wirth, I. Colin Prentice, E. Garnier, G. Bönsch, M. Westoby, H. Poorter, P. B. Reich, A. T. Moles, J. Dickie, A. N. Gillison, A. E. Zanne, J. Chave, S. Joseph Wright, S. N. Sheremet Ev, H. Jactel, C. Baraloto, B. Cerabolini, S. Pierce, B. Shipley, D. Kirkup, F. Casanoves, J. S. Joswig, A. Günther, V. Falczuk, N. Rüger, M. D. Mahecha, and L. D. Gorné. 2016. The global spectrum of plant form and function. *Nature* 529:167–171.
- Ettinger, A. K., C. J. Chamberlain, I. Morales-Castilla, D. M. Buonaiuto, D. F. Flynn, T. Savas, J. A. Samaha, and E. M. Wolkovich. 2020. Winter temperatures predominate in spring phenological responses to warming. *Nature Climate Change* 10:1137–1142.
- Flynn, D. F. B., and E. M. Wolkovich. 2018. Temperature and photoperiod drive spring phenology across all species in a temperate forest community. *New Phytologist* 219:1353–1362.
- Freckleton, R. P., P. H. Harvey, and M. Pagel. 2002. Phylogenetic analysis and comparative data: A test and review of evidence. *American Naturalist* 160:712–726.
- Fridley, J. D. 2012. Extended leaf phenology and the autumn niche in deciduous forest invasions. *Nature* 485:359–362.
- Fried, G., M. Carboni, L. Mahaut, and C. Violle. 2019. Functional traits modulate plant community responses to alien plant invasion. *Perspectives in Plant Ecology, Evolution and Systematics* 37:53–63.
- Funk, J. L., J. E. Larson, G. M. Ames, B. J. Butterfield, J. Cavender-Bares, J. Firn, D. C. Laughlin, A. E. Sutton-Grier, L. Williams, and J. Wright. 2016. Revisiting the Holy Grail: Using plant functional traits to understand ecological processes. *Biological Reviews* 92:1156–1173.
- Gougherty, A. V., and S. W. Gougherty. 2018. Sequence of flower and leaf emergence in deciduous trees is linked to ecological traits , phylogenetics , and climate. *New Phytologist* 220:121–131.
- Guy, R. D. 2014. The early bud gets to warm. *New Phytologist* 202:7–9.

- Harrington, C. A., and P. J. Gould. 2015. Tradeoffs between chilling and forcing in satisfying dormancy requirements for Pacific Northwest tree species. *Frontiers in Plant Science* 6:1–12.
- Heide, O. M. 1993. Daylength and thermal time responses of budburst during dormancy release in some northern deciduous trees. *Physiologia Plantarum* 88:531–540.
- Kitamura, M., T. Nakamura, K. Hattori, T. A. Ishida, S. Shibata, H. Sato, and M. T. Kimura. 2007. Among-tree variation in leaf traits and herbivore attacks in a deciduous oak, *Quercus dentata*. *Scandinavian Journal of Forest Research* 22:211–218.
- Kochmer, J. P., and S. N. Handel. 1986. Constraints and Competition in the Evolution of Flowering Phenology. *Ecological Monographs* 56:303–325.
- Laughlin, D. C. 2014. The intrinsic dimensionality of plant traits and its relevance to community assembly. *Journal of Ecology* 102:186–193.
- Laughlin, D. C., J. J. Leppert, M. M. Moore, and C. H. Sieg. 2010. A multi-trait test of the leaf-height-seed plant strategy scheme with 133 species from a pine forest flora. *Functional Ecology* 24:493–501.
- Lechowicz, M. J. 1984. Why Do Temperate Deciduous Trees Leaf Out at Different Times? *Adaptation and Ecology of Forest Communities*. *The American Naturalist* 124:821–842.
- Marquis, B., Y. Bergeron, M. Simard, and F. Tremblay. 2020. Growing-season frost is a better predictor of tree growth than mean annual temperature in boreal mixedwood forest plantations. *Global Change Biology* 26:6537–6554.
- Menzel, A., T. H. Sparks, N. Estrella, E. Koch, A. Aaasa, R. Ahas, K. Alm-Kübler, P. Bissolli, O. Braslavská, A. Briede, F. M. Chmielewski, Z. Crepinsek, Y. Curnel, Å. Dahl, C. Defila, A. Donnelly, Y. Filella, K. Jactzak, F. Måge, A. Mestre, Ø. Nordli, J. Peñuelas, P. Pirinen, V. Remišová, H. Scheffinger, M. Striz, A. Susnik, A. J. Van Vliet, F. E. Wielgolaski, S. Zach, and A. Züst. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology* 12:1969–1976.
- Morin, X., M. J. Lechowicz, C. Augspurger, J. O’keefe, D. Viner, and I. Chuine. 2009. Leaf phenology in 22 North American tree species during the 21st century. *Global Change Biology* 15:961–975.
- Osada, N. 2017. Relationships between the timing of budburst, plant traits, and distribution of 24 coexisting woody species in a warm-temperate forest in Japan. *American Journal of Botany* 104:550–558.
- Panchen, Z. A., R. B. Primack, B. Nordt, E. R. Ellwood, A. Stevens, S. S. Renner, C. G. Willis, R. Fahey, A. Whittemore, Y. Du, and C. C. Davis. 2014. Leaf out times of temperate woody plants are related to phylogeny, deciduousness, growth habit and wood anatomy. *New Phytologist* pages 1208–1219.
- Pereira, C. G., and D. L. Des Marais. 2020. The genetic basis of plant functional traits and the evolution of plant-environment interactions. *International Journal of Plant Sciences* 181:56–74.
- Seiwa, K. 1999. Changes in leaf phenology are dependent on tree height in *Acer mono*, a deciduous broad-leaved tree. *Annals of Botany* 83:355–361.
- Seiwa, K., and K. Kikuzawa. 1991. Phenology of tree seedlings in relation to seed size. *Canadian Journal of Botany* 69:532–538.
- Singh, R. K., T. Svystun, B. AlDahmash, A. M. Jonsson, and R. P. Bhalerao. 2017. Photoperiod- and temperature-mediated control of phenology in trees – a molecular perspective.

- 593 Sun, S., D. Jin, and R. Li. 2006. Leaf emergence in relation to leaf traits in temperate woody species
594 in East-Chinese *Quercus fabri* forests. *Acta Oecologica* 30:212–222.
- 595 Vitasse, Y. 2013. Ontogenic changes rather than difference in temperature cause understory trees to
596 leaf out earlier. *New Phytologist* 198:149–155.
- 597 Weiher, E., A. Werf, K. Thompson, M. Roderick, E. Garnier, and O. Eriksson. 1999. Challenging
598 Theophrastus: A common core list of plant traits for functional ecology. *Journal of Vegetation*
599 *Science* 10:609–620.
- 600 Westoby, M. 1998. A leaf-height-seed (LHS) plant ecology strategy scheme. *Plant and Soil* 199:213–227.
- 601 Wilsey, B. J., P. P. Daneshgar, and H. W. Polley. 2011. Biodiversity, phenology and temporal niche
602 differences between native- and novel exotic-dominated grasslands. *Perspectives in Plant Ecology,*
603 *Evolution and Systematics* 13:265–276.
- 604 Wright, I. J., M. Westoby, P. B. Reich, J. Oleksyn, D. D. Ackerly, Z. Baruch, F. Bongers, J. Cavender-
605 Bares, T. Chapin, J. H. C. Cornelissen, M. Diemer, J. Flexas, J. Gulias, E. Garnier, M. L. Navas,
606 C. Roumet, P. K. Groom, B. B. Lamont, K. Hikosaka, T. Lee, W. Lee, C. Lusk, J. J. Midgley,
607 Ü. Niinemets, H. Osada, H. Poorter, P. Pool, E. J. Veneklaas, L. Prior, V. I. Pyankov, S. C. Thomas,
608 M. G. Tjoelker, and R. Villar. 2004. The worldwide leaf economics spectrum. *Nature* 428:821–827.
- 609 Zohner, C. M., B. M. Benito, J. D. Fridley, J. C. Svenning, and S. S. Renner. 2017. Spring predictability
610 explains different leaf-out strategies in the woody floras of North America, Europe and East Asia.
611 *Ecology Letters* 20:452–460.
- 612 Zohner, C. M., B. M. Benito, J. C. Svenning, and S. S. Renner. 2016. Day length unlikely to constrain
613 climate-driven shifts in leaf-out times of northern woody plants. *Nature Climate Change* 6:1120–
614 1123.
- 615 Zohner, C. M., L. Mo, T. A. M. Pugh, J.-F. Bastin, and T. W. Crowther. 2020. Interactive climate
616 factors restrict future increases in spring productivity of temperate and boreal trees. *Global Change*
617 *Biology* pages 1–14.