

Phenological sensitivity as a mediator of plant interactions

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Motivation and Dissertation Framework

Phenology, the timing of annual life cycle events, allows organisms to synchronize important life history transitions with optimum environmental conditions (Forrest & Miller-Rushing, 2010). Phenology is an important mediator of ecosystem processes (Cleland *et al.*, 2007; Piao *et al.*, 2007) and species interactions (Leverett, 2017; Yang & Rudolf, 2010), and plays a major role in determining species' range limits (Chaine & Beaubien, 2001). Driven by anthropogenic climate change, pronounced shifts in phenology observed across a broad range of taxa have been reported, with plant phenology shifting by 3-5 days on average per decade (Menzel *et al.*, 2006; Parmesan & Yohe, 2003; Root *et al.*, 2003). Phenological sensitivity to climate change, defined as the shift in phenological event date per degree of temperature change, varies among taxa, and there is evidence that within given communities, species' phenologies are shifting at different rates (Cleland *et al.*, 2012; Ovaskainen *et al.*, 2013). These differential sensitivities are likely to have far reaching effects on community interactions, but our ability to predict these second order effects remains limited.

In my proposed dissertation, I seek to advance our understanding of how phenology influences species interactions under changing climate conditions. Sitting at the nexus of traditional community ecology and global change biology, my proposed dissertation will explore 1] how differences in sensitivity to environmental conditions can produce significantly different phenological patterns and 2] how differential phenological responses alter community interactions.

In **Chapter I**, I use experimental manipulations and statistical modeling to evaluate the current evolutionary hypotheses regarding flower-leaf phenological sequences in temperate woody plant species, and investigate differential phenological sensitivity between flower and leaf buds as a potential mechanism that structures these patterns.

In **Chapter II**, I turn my attention to seed germination phenology, where I probe the

effect of variable stratification periods and incubation temperature on germination of a large suite of temperate plants, to determine interspecific differences in their phenological response to changing climate, and to evaluate the likelihood of germination rank changes under future climate scenarios.

In **Chapter III**, I expand the scope of my inquiry in chapter II by compiling a global database of experimentally manipulated germination trials and using meta-analysis techniques to better understand the reaction norm of germination phenology in response to environmental manipulations.

In **Chapter IV**, I perform a direct test of the impact of phenological shifts on community interactions by using alternate climatic treatment to manipulate the germination phenologies of two species growing in a pairwise competition experiment.

Background

In my dissertation, I focus on the phenological transition between dormancy and growth in the spring, a time in which biological activity makes plants most susceptible to mortality, but if survived, has the potential to significantly increase the overall fitness of the organism (Rathcke & Lacey, 1985). This phenological transition takes place in both seeds and buds of perennial plants, and is mediated by a complex combination of environmental factors, evolutionary tradeoffs, and physiological processes. These factors, along with an understanding of the statistical frameworks that are used to model spring phenology, are critical background to my dissertation work, and I discuss each one briefly below.

Eco-physiology and Evolution of Spring Phenology: Plants sense and interpret a complex set of environmental cues that signal the changing of the seasons, and can respond by fine-tuning their phenological transitions accordingly (Vitasse *et al.*, 2013). For plants growing in temperate regions, it is widely accepted that phenological transitions are responses to the interaction of the exogenous environmental conditions, temperature and photoperiod (Forrest & Miller-Rushing, 2010), with endogenous cues like circadian clocks (Visser *et al.*, 2010). Temperature and light are also considered to be the main drivers of seed germination (Finch-Savage & Leubner-Metzger, 2006). In the temperate zone, both seeds and buds generally cycle through a state of dormancy, a temporary state in which metabolic activity is minimized, preventing organism growth, development, or activity. Dormancy allows organisms to persist in harsh environments by conserving energy during periods that are unfavorable for biological functioning, which, in temperate regions, are the cold months of winter. There is a complicated taxonomy of dormancy in seeds (Baskin & Baskin, 2004), and the most common dormancy class in the temperate regions of the world is physiological dormancy (PD), in which a physiological inhibition mechanism is present in the embryo that

prevents radical emergence (Finch-Savage & Leubner-Metzger, 2006). While, globally, there are several climactic factors that contribute to dormancy break, in our region this transition from dormancy to growth tends to be mediated by exposure to a prolonged period of cool temperatures (chilling or stratification), followed by warm (forcing or incubation) temperatures. It should be noted that the first visible sign that dormancy is broken is germination or budburst, so as such, it is difficult, and even controversial, to mark where dormancy ends and growth begins (Bewley, 1997; Long *et al.*, 2015).

It has been suggested that the major selective forces dictating spring phenology are shared by both spring germinating seeds, and by buds. The adaptive benefits of early phenological transition, an extended growing season, predator avoidance, and reduced competition for resources are balanced by the higher risk of mortality due to biotic and abiotic factors, resulting in stabilizing selection (Rathcke & Lacey, 1985). For flower buds, the availability of pollinators may be an additional selection factor. As such, the phenological optimum evolves in relation to other functional traits and life history tradeoffs.

While the selective forces, environmental conditions and conceptual framework for the transition from dormancy to growth may be quite similar for seeds and buds, there is evidence that the physiological mechanisms regulating these processes are quite different. In buds, short day conditions and the end of the season induce dormancy by isolating meristematic cell interactions through heavy deposits of callose in the plasmodesmata (Rinne *et al.*, 2011; Sager & Lee, 2014). Winter chilling degrades the callose, reengaging cellular integration for the transition to growth under suitable conditions.

In seeds, callose has been shown to play a secondary role in dormancy by maintaining a physical, seed coat imposed dormancy (Leubner-Metzger, 2003), but it is the hormone abscisic acid (ABA), that is generally thought to initiate and maintain dormancy (Baskin & Baskin, 2014; Fenner, 2000). It has been hypothesized that the balance of ABA and the growth promoter gibberellic acid (GA_3) acting at different parts of a seed's "life" are the primary regulators of dormancy and germination in seeds (Kucera *et al.*, 2005; Leubner-Metzger, 2003). Environmental treatments such as cold or warm stratification and afterripping, have been shown to contribute to the degradation of ABA, and an upregulation and increased sensitivity to GA_3 , as well as ethylene and brassinosteroids, which promotes germination (Kucera *et al.*, 2005).

Model of Spring Phenology: Many models have been developed to use temperature to predict phenology in woody plants (Chuine *et al.*, 2002), while seed science most commonly uses a single model, the thermal time or cardinal temperature model, or its variant the hydrothermal time model which includes water potential as a parameter (Bradford, 2002). The thermal time model of germination describes the relationship between time, temperature and germination fraction at sub-optimal temperatures.

$$\theta_T(g) = (T - T_b)t_g$$

where $\theta_T(g)$ is thermal time to germination, T is the treatment temperature, T_b is the base temperature below which germination rate is 0 and t_g is the time to a given germination fraction. If not observed experimentally, T_b can be inferred through statistical methods by regressing the reciprocal of germination time against a given germination fraction and determining the x-intercept (Pritchard *et al.*, 1999). If supra-optimal temperature are included in the experiment, which would be indicated by a reduction in germination rate at higher temperatures, a constant K_t is added to the equation to modify the thermal time parameters by the following equation:

$$\theta_T = (k_T(T - T_o))(T - T_b)t_g$$

where T_o is the optimum temperature.

While this model is widely toted for its biological accuracy in predicting the germination phenology of non-dormant seeds (Bradford, 2005), the standard thermaltime model is less effective for phenological predictions with dormant species (Batlla & Benech-Arnold, 2015).

Several attempts have been made to modify this modeling framework to better incorporate a dormancy module. Conceptually, dormancy break treatments reduce T_b or (ψ_b in the hydrothermaltime variant) allowing for a more rapid accumulation of thermaltime and more rapid germination. This framework has been applied to include afterrippingening (Meyer *et al.*, 2000), and cold stratification (Batlla & Benech-Arnold, 2003; Pritchard *et al.*, 1996), but has not been broadly applied outside of agriculture or horticulture, and its effectiveness for a diversity of taxa remains unknown (Steadman & Pritchard, 2004). By evaluating the change in germination rate at different dormancy break treatment levels, one can determine a coefficient which reflects the rate of change in T_b . The equation is formulated below:

$$T_b = (\beta(t_s)) + T_b(o)$$

where β is constant rate of decline, t_s is the stratification time, and $T_b(o)$ is the base temperature without dormancy treatment.

Chapter I: The significance of flower-leaf sequences in an era of global climate change

Introduction

Why do some tree species seasonally flower before leafing out? This sequence, known as hysternanthy, proteranthy, or precocious flowering, is readily apparent in many ecologically and commercially important species and has been described as the characteristic flower-leaf sequence (FLS) of temperate deciduous forests (Rathcke & Lacey, 1985). Most of the current hypotheses regarding FLS's suggest that they are critical to the reproductive or physiological

functioning of woody plants (Gougherty & Gougherty, 2018). Several authors suggest that the hysteranthous FLS is a trait critical for wind-pollination efficiency (Friedman & Barrett, 2009; Whitehead, 1969). Others suggest that flowering first is an adaptation to reduce water stress and maintain floral hydration (Franklin, 2016), though this hypothesis has emerged primarily from the dry-deciduous tropics where hysteranthous is also common (Franklin, 2016; Janzen, 1967). Still others suggest the hysteranthous FLS is an adaptation to allow for extremely early flowering and is correlated with other early flowering traits such as seed size, dispersal time and cold tolerance (Bolmgren *et al.*, 2003; Gougherty & Gougherty, 2018; Primack, 1987). It is also possible that FLS's are highly conserved, and the preponderance of hysteranthous in the temperate zone is a product of phylogenetic representation of the region rather than an adaptive quality to the trait. These functional hypotheses suggest that FLS's may have an important role in mediating both inter and intra-specific competition for pollen, and variation in FLS's could be considered a critical life history tradeoff.

Despite the rich theoretical attention FLS has received in the literature, data about FLS is limited. The most comprehensive source of data we have regarding FLS comes from categorical, qualitative descriptions in regional flora and guide books. A few long term empirical datasets in which FLS is properly reported as a continuous variable can be found, but these are rare, as flower and leaf phenology have generally been treated and observed separately (Wolkovich & Ettinger, 2014). In part I of this chapter I ask, given the available data:

1. What is the association between FLS and several other life history traits (pollination syndrome, shade tolerance, plant height, flowering time, duration of fruit maturation) pertinent to the established hypotheses? Are these results sensitive to data quality, observational ambiguity, and modeling choices? Does treating FLS as a continuous rather than categorical variable result in a model more robust to the aforementioned factors?

Treating FLS as a categorical trait may mask important characteristics of FLS such as the range variability of FLS offset between species, individuals, populations and years. As far as I know, there have been no attempts to empirically quantify this variability. Improving our understanding of the variability of this pattern would aid significantly in evaluating the evolutionary hypotheses for FLS, and serve to generate hypotheses for the eco-physiological mechanisms behind these patterns. In part II of this chapter I ask:

1. What is the range in variability of FLS between species, years and individuals?
2. Is variability of FLS a product of differential sensitivities to environmental cue combinations between flower and leaf buds?

Methods:

Part I: I obtained species level descriptions of floral-foliate sequences and trait information from the regional guidebook Michigan Trees (Barnes & Wagner, 1981,2004) and its companion volume Michigan Shrubs and Vines (Burton V. Barnes, Christopher W. Dick, 2016) (hereafter: MTSV) and the United States Forest Services Silvics Manual Vol. 2 (Burns *et al.*, 1990) (hereafter: USFS). All categorical traits were reclassified as binary: FLS (0 leaf first, 1 flower first), shade tolerance (0 intolerant, 1 tolerant), pollination syndrome (0 insect, 1 wind). I developed three alternative classifications for FLS: physiological (only taxa with “flowers before leaves” classified hysteranthous), intermediate (taxa with “flowers before leaves” and “flowers before and flowers before/with leaves” classified hysteranthous) and functional (taxa with “flowers before leaves”, “flowers before/with leaves” and “flowers with leaves” classified hysteranthous). In total, 196 and 82 woody species, in MTSV and USFS respectively, were included in my analysis. To investigate the phylogenetic signal of hysteranthous and control for phylogenetic structure in the datasets, I used a published angiosperm phylogenetic tree (Zanne *et al.*, 2013), pruned to match the species list from the MTSV and USFS data. Species not in the tree were added at the generic root. I used a generalized linear modeling framework (Ives & Garland, 2010) to build a logistical regression model corrected for phylogenetic structure using the R package phylolm (Ho & Ane, 2014). The model was run with 599 bootstrapped re-sampling iterations for each dataset (Wilcox, 2010). Continuous predictors were rescaled by subtracting the mean and dividing by two standard deviations to allow for a reasonable comparison of effect sizes between the binary and continuous predictors in this model (Gelman & Hill, 2007). Models were run on each dataset for each classification of FLS for sensitivity analysis.

To model with FLS as a continuous response, I used a long term phenological dataset from Harvard Forest in Petersham, MA (O’Keefe, 2015) (hereafter: HAFO) and calculated the average FLS lag time for 21 species which overlapped the MTSV species list. With the same modeling framework, I modeled the association between the original MTSV predictors and the Harvard Forest continuous FLS data. I also ran a model in which mean FLS lag time was coded as a binary variable ($FLS < 0$ = leaf first, $FLS > 0$ = flower first) to directly assess the effect of binary vs. continuous FLS data.

Part II: I first plotted the interannual dynamics of FLS offset in the HAFO dataset using the R base statistical package to establish a basic understanding of the typical variability in FLS, which was significant. In October of 2017, I obtained cutting of dormant twigs from 12 woody plant species from Harvard Forest in Petersham MA. Twigs were transported to the Weld Hill Research Building in Boston, MA, re-cut in water, and placed into 250 ML Erlenmeyer flasks. Six replicates of each species were randomly assigned to different growth chamber temperature and photoperiod combinations. Twigs received one of two

levels of chilling (four or eight weeks at 4°C), combined with one of two forcing treatments (24°C/18°C or 18°C/12°C day/night temperatures on 12 hour cycles) and one of two photoperiod treatments (8/16 or 12/12 day/night) for a 12 way full factorial design. Flasks were moved between chambers every two weeks to reduce the influence of growth chamber effect artifacts on the results. Twigs were monitored for flower and leaf phenology using the BBCH scale (Finn *et al.*, 2007) every two-three days for four months.

I currently use a multilevel, Bayesian, survival analysis framework to analyze these data. Survival analysis is the appropriate framework for this experiment as there was a considerable number of twigs that did not burst buds, but were determined to be still living at the conclusion of the experiment. Dead twigs, or those which were determined to have had no flower buds at the outset of the experiment are excluded from the analysis. I predict that the FLS offset will vary significantly between treatment combinations and that this variation will be traceable to flowering and leaf phenology being differentially sensitive to the environmental factors. My initial model is a varying slope/intercept model by species, with interactions between each predictor (forcing, chilling, photoperiod) and phenophase (leafing or flowering). With this formulation, the interactions between each phenophase and predictor will reveal differences in the response to the treatments between floral and leaf phenophases.

Status and Preliminary Results:

What is the association between FLS and several other life history traits? Are these results sensitive to data quality, observational ambiguity, and modeling choices?: In the categorical models, there is a consistent relationship between early flowering time and hysteranthly, indicating that early flowering is more likely to be associated with a hysteranthous FLS. Seed development time showed a negative relationship, suggesting that more rapid seed development is associated with hysteranthly. Pollination syndrome showed a general positive trend with hysteranthly, indicated the likelihood of hysteranthly is increased in wind pollinated taxa. In some versions of the model, increasing height and shade tolerance display a weak positive association with hysteranthly, but there is little confidence in these estimates. All traits except flowering time varied considerably in significance, sign, and strength, depending on data source and modeling choices. See figure 1 for effect size plots.

The phylogenetic signal for FLS also varied depending on the data and modeling choices (with estimated D statistics of 0.05, 0.16, 0.29, 0.64, 0.11, 0.12 for MTSV-functional, MTSV-intermediate, MTSV-physiological, USFS-functional, USFS-intermediate and USFS-physiological respectively). Since values close to 0 indicate a high likelihood of Brownian phylogenetic structure and values closer to 1 indicate random structure, no clear characterization of the phylogenetic structure can be made to to the variability across datasets and FLS classifica-

tions.

In the continuous model, pollination syndrome was the strongest predictor of FLS, with a strong, positive relationship between wind pollination and hysteresis. Shade tolerance and early flowering also displayed a strong positive association with hysteresis (see figure 2b). The continuous model was robust to FLS classification with all three classification schemes yielding comparable effect sizes. This was not the case when the mean FLS offset values in HAFO were classified as binary (see figure 2a), with model output again displaying high variability in effect size strength and sign. These findings demonstrate the advantage of treating FLS as a continuous response variable, and also lend support to the pollination syndrome, early flowering hypotheses. It is not surprising that multiple hypotheses find support in this analysis, as FLS is a complex trait that may have developed independently in different selection environments.

Is variability in FLS a product of a differential sensitivity to environmental cue combinations between flower and leaf buds?: As seen in the example plots of *Quercus rubra* phenology at Harvard Forest (Fig. 3), there is considerable interannual and inter-individual variation in FLS. Additionally, for this species, there appears to be a temporal trend in which FLS has shifted towards a hysteresis pattern over time. This phenomenon could be correlated with climate change, and should be investigated further.

Preliminary analysis of my experimental result confirms there is considerable variability in FLS offset in different environments (see figure 4). Because of many non-response values in the data spread unevenly across species and treatments, the estimates of my initial model have low confidence and other modeling approaches need to be attempted. Below I present other modeling frameworks I will attempt:

1. Rather than modeling flowering and leafing sensitivities as interactions, use offset (as determined in part I) as a response variable.
2. Use a logistic regression framework with phenology as a binary response.
3. Run individual species models for only the species with the most data.

Implications

This project will advance a current idea that is gaining traction in the literature that phenological phases must be considered in concert with each other in order to anticipate the implications of phenological shifts on the overall fitness of organisms. This chapter includes the largest taxonomic exploration of FLS in the temperate zone to date, and preliminary results demonstrate the advantage of modeling FLS's as a continuous trait. Additionally, part II of this project will identify a mechanism to account for fine-scale variability in phenological

sequences, generating a strong working hypothesis for further study of coordination and constraints in separate phenological constraints.

Chapter II: The germination response to varying stratification regimes of a suite of temperate herbaceous species

Introduction

Seed germination is an important component of plant community interactions. The timing of germination influences resource use, and interactions with competitors, predators, and mutualisms (Gioria *et al.*, 2018; Koerner *et al.*, 2008; Rathcke & Lacey, 1985). Dormancy not only allows seed to survive through a single inhospitable winter, but can let seeds persist in the environment for many years until conditions are favorable, expanding these community demographic battles across time (Long *et al.*, 2015). As mentioned above, it is commonly understood that in our region, dormancy is released by a period of exposure to cool temperatures known as cold stratification.

The cold stratification requirement for dormancy release has been identified in a large number of North American temperate plant taxa, and stratification treatments are employed widely in both plant science and industry (Hartmann *et al.*, 2011). The required stratification period has been shown to differ between species (ranging from just a few days to many months (Luna *et al.*, 2009)), vary significantly depending on temperature and between seed populations (Steadman & Pritchard, 2004), and affect the germination speed and final germination percentage of a cohort. While cold stratification is commonly found as an experimental treatment in the literature and has been shown to advance germination, studies which evaluate the germination response across a range of stratification periods or temperatures are rarer (Batlla *et al.*, 2009). As a result, the dynamics of the germination response to variable stratification regimes are poorly characterized for the vast majority of plant species.

Cold stratification in the lab serves as a proxy for the natural exposure to chilling conditions that a seed would experience while overwintering in the field. With global climate change, changes to the severity and duration of winter will alter the natural stratification period experienced by seeds (Walck *et al.*, 2011). While winters are generally predicted to be warmer and shorter (Pachauri & Meyer, 2014), the number of days which the stratification conditions are met may increase, decrease, or shift temporally, differentially affecting the germination phenology of plant species depending on their geographic position, and the dynamics and sensitivity of their response to temperature (Walck *et al.*, 2011).

In this chapter I ask:

1. How do varying stratification periods effect the germination rate of a suite of plant

species?

2. How do stratification periods and incubation temperatures interact in germination time courses?
3. Is the stratification requirement best characterized by an optimum (can seeds be over-stratified) or a threshold?
4. To what degree is germination rank between species affected by varying stratification regimes?

Proposed methods

Experimental Protocols: In the summer of 2018, I procured seeds of 14 temperate eastern North America herbaceous plant species of both native and non-native origins from plant nursery stock or collections (see figure 5) and dry-stored in cool conditions until the start of the experiment. In mid-August 2018, I checked all seeds for the presence of an embryo using a float test (Baskin & Baskin, 2014), and imbibed them in distilled water for 20 hours. I then randomly divided seeds of each species into cohorts of 15-20, depending on seed availability, and placed them on wetted sterile sand in 8 cm plastic petri dishes. I assigned three replicates of each cohort to a combination of stratification duration (10 levels: 0, 14, 28, 35, 42, 49, 56, 63, 77, 100 days) and incubation (two levels, low temperature: 20 °C day/10 °C night or high: 25 °C day/15 °C night) treatments, making for a 20-level full factorial treatment design. For stratification, I wrapped petri dishes in aluminum foil and placed them in a germination chamber in the dark at 4 °C. At the end of each stratification duration, I transferred cohorts to incubation conditions in growth chambers. I observed germination fractions every other day for 25 days, and moistened as needed. By measuring the germination fraction over time, I will generate germination time courses, plots demonstrating change in germination percentage over time, for each species and each treatment.

Statistical analysis: Using the germination time courses for each species or population respectively, I will calculate the rate of change for T_b as a function of stratification duration. From these data, I will assess each species' sensitivity to stratification, and use this information to predict how germination rank may change under different stratification scenarios. I will also examine whether species with different characteristics, such as life history and habitat requirements, differ in the strength of their response to the environmental treatments.

Status/preliminary results

Project Status: The experimental procedures are underway, and expected to conclude in December 2018. Parital time courses from the first four treatment levels of experiment one can be seen in figure 6. As expected, this limited data indicates that stratification accelerates germination rate and increases final germination percentages.

Implications

This chapter will significantly expand the scope of our understanding of species' germination response to climate change. Because of the large numbers of species and treatment levels in these experiments, this study will provide high-resolution information regarding the dynamics of germination phenology in response to stratification across a suite of interacting wild plant species, an approach which has been hitherto restricted to single-species studies or domestic species. This study will be unique for its ability to directly compare these responses among species, advancing our understanding of the effects of phenological shifts on plant interactions.

OEGREs: A meta-analysis of Observed Environmental Germination Responses in Experiments

Introduction and Questions:

Seed germination is a critical life history stage for plant life, and as such, there is a long history, over 2000 years, of germination research (Baskin & Baskin, 2014; Fenner, 2000). More contemporary work has produced a large body of literature detailing the germination requirements and dormancy classes (physiological, morphological, physical, morpho-physiological dormancy and their subclasses) for a vast number of species across an array of taxonomic and geographic space (see Baskin & Baskin (2014) for examples). Many comprehensive books and review papers have been written on the subject, and germination research continues at a rapid pace around the globe, but there are still large gaps in our knowledge (Baskin & Baskin, 2014). As mentioned above, our understanding of the kinetics of the germination response to environmental conditions remains in its infancy. Without a better understanding of a more complete range of germination responses to different environmental states, it is difficult to predict the extent of climate change impact on plant regeneration. While few individual studies systematically investigate responses to a wide range of environmental conditions, the large body of germination literature could be leveraged to this end. In this chapter, I propose

a meta-analysis to more broadly address the questions I laid out in chapter II:

1. How do varying environmental treatments affect the germination time courses of plant species?
2. How do various environmental treatments interact to affect seed germination?
3. Do phylogenetic, geographic or life-history patterns explain variation in germination responses?

In addition to these fundamental biological questions, I will also use this project to address several important questions about germination research methodologies.

Proposed methods:

Due to the acknowledged importance of temperature in mediating seed dormancy and germination, my primary interest is to evaluate the effects of stratification and incubation treatments on germination, but I intend to also include other environmental factors, such as water status, soil properties, afterripening, and scarification treatments in my analysis.

Data collection: I performed a search of the Web of Science database using the keywords “germination” and “stratification”, and excluded meeting abstracts, abstracts of published items (abstract only) and proceedings papers. The search returned 1,208 papers. For each paper, I read the abstract, methods, and figures to identify studies that fit for inclusion in my analysis.

Inclusion criteria: To be included in the study, papers were required to:

- Report a temporal germination response in addition to a final germination percentage.
- Manipulate a temperature variable (cold or warm stratification).

Currently, I excluded papers that were not fully accessible from my analysis, but I intend to access them through the inter-library loan system.

Because of the large volume of papers, I will randomly sample 200 papers that meet the selection criteria to build a database, using ImageJ to scrape data from the relevant figures. The response variables I will capture include any measurement or index of germination rate as well as final germination percentages. The predictors I capture in addition to the specific environmental treatments in the paper will include: seed provenance (continent, latitude, longitude, altitude, biome), seed age, year of collection and maternal environment, dormancy class (if applicable), non-environmental treatments (chemical/hormone application), life history and population native status.

Analysis: Upon completion of the database, I will use a multilevel, Bayesian modeling framework to assess the impact of varying temperature regimes on germination behavior. I intend to run several models with different grouping factors, including taxonomic and regional. I will also query the database to address methodological questions and make suggestions to improve experimental designs moving forward.

Project status:

As of October 2018, I have evaluated 610 papers of which 241 were determined fit for inclusion. Assuming this 39.5 percent inclusion rate remains consistent, I expect that 450-500 studies will be fit for inclusion.

Implications

This meta-analysis will provide the first comprehensive quantification of the range of responses of seed germination phenology to variable environmental conditions. The identification of these species specific reaction norms, along with broad-scale taxonomic, geographic, and trait based patterns in germination phenology, will have important application for improving predictive models in an era of climate change. The resulting open-access database will also be an invaluable resource for researchers to use to ask questions about the ecology and evolution of seed germination, and will highlight new frontiers for seed science research with regard to environmental control of germination phenology.

Chapter IV: Seasonal priority effects: Germination phenology as a mediator of plant competition

Introduction

Priority effects, a class of interspecific interaction in which the effect of species on one another depends on the order in which they arrive at a site, are a cornerstone of community assembly theory (Fukami, 2015). These historical contingencies have been shown to alter the structure and function of communities, even driving communities to alternate stable states (Fukami & Nakajima, 2011). Recent theory has suggested that it is not just species' arrival times that determine the course of interactions, but significant priority effects can be determined by the phenological differences between species already resident to a site, a subcategory of historical contingency known as seasonal priority effects (SPE) (Wainwright *et al.*, 2012). Like traditional priority effects, SPE's can operate through niche preemption, in which the species with earlier phenology reduces the amount of resources available for species

with more delayed phenological activity, or niche modification, in which earlier phenological initiators modify the environment, determining the growth conditions that the later species will experience (Fukami, 2015).

Most of the evidence for seasonal priority effects comes from observation studies correlating earlier phenology with competitive dominance or invasion success (Gioria *et al.*, 2018). However, early phenology may be linked with other traits associated with superior competitive ability (Dickson *et al.*, 2012), and the strength of priority effects have been shown to vary according to species identities (Cleland *et al.*, 2015) and competition environments (Kardol *et al.*, 2013). While some studies have succeeded in experimentally linking seasonal priority effects with competitive dominance (Wainwright *et al.*, 2012), or have inferred seasonal priority effects through sequential planting studies (Koerner *et al.*, 2008), the relative strength of SPE's influence on competition between species has yet to have been quantified in any systems.

With the evidence for significant interspecific differences in phenological sensitivity to variable climates, it is likely that climate change will alter the germination lag times or even rank between species. If SPE's do indeed significantly mediate species interactions, these phenological shifts would be expected to have strong implications for community dynamics. In this final chapter I ask:

- What are the effects of varying SPE's on the competitive dynamics between two species in a controlled environment?

Proposed Methods

Based on results from chapter II, I will select two species for a pairwise competition experiment. The two species will be selected based on the following criteria:

1. They have similar growth requirements and would be likely to be found in the same habitat in nature.
2. Their germination rank changes or the lag between their respective germination phenology shifts by more than 7-10 days given different stratification/incubation combinations.

I will sow seeds of each species in a soil medium at varying relative and overall densities following a response surface design detailed in Inouye (2001), (see figure 7). This design has been shown to be the most effective for differentiating between the effects of intra vs. interspecific competition and integrating data with theoretical models of competition. I will randomly assign replicates of each density to two different stratification/incubation regimes

that have previously been shown to alter the germination rank of the species, thus manipulating the strength of the seasonal priority effects in the competitive system.

After the given stratification period and 25 days of incubation, I will transfer all pots to a greenhouse for the duration of the experiment (12 weeks). Every four weeks, I will measure the height of each plant and take standardized photos of each pot to allow for an estimation of percent cover of each species. The measurement will be applied for a biomass estimation using models found in Axmanová *et al.* (2012). At each measurement interval, I will measure, harvest, dry, and weigh five plants of each species that were not included in the response surface to better calibrate the biomass models. At the conclusion of the experiment, I will harvest, dry, and weigh all plants for a final biomass calculation.

Analysis: I will use the repeat measures of biomass to calculate and compare the relative growth rate (RGR) (Connolly & Wayne, 2005) of each species under the different priority effect manipulations. I predict that if the first species to germinate is a superior competitor, the stronger priority effect treatment will increase its dominance and ability to suppress the growth of the second germinating species. If the second germinating species is the superior competitor, I predict that its dominance will be reduced in the stronger priority effect treatment when compared with the weaker priority effect treatment. All in all, the first germinating species should have a higher RGR in the stronger priority effect treatment and the second germinating species should have a higher RGR in the weaker priority effect treatment.

Implications

This chapter will serve as one of the first major proofs of concept for the role of seasonal priority effects in determining competitive interactions. This study will allow for the direct quantification of the proportionate strength of phenological priority effects to other competitive effects in the context of resource competition, clarifying the reported association between rapid germination and competitive dominance. Furthermore, it will be one of the first priority effect competition studies in which germination rank was manipulated through natural manipulation (temperature) rather than sequential sowing, further demonstrating the relevance of this area of study in the context of global change.

Timeline

Time	Task
Fall 2018	
ch.1	Write article for part 2
ch.2	Complete experimental data collection
ch.3	Complete OEGRES initial inclusion survey
Spring 2019	
ch.1	Analysis of part 2
ch.2	Data analysis
ch.3	Begin data scraping
ch.4	Select species and treatment for response surface
Summer 2019	
ch.1	Write article for part 2
ch.2	Continue data analysis
ch.3	Continue data scraping
ch.4	Continue preparations for response surface trials
Fall 2019	
ch.2	Continue data analysis
ch.3	Continue data scraping
ch.4	Initiate treatments, begin competition experiment
Spring 2020	
ch.2	Data analysis
ch.3	Data cleaning
ch.4	Continue experiment
Summer 2020	
ch.2	Conclude Data analysis
ch.3	Data cleaning
ch.4	Begin data analysis
Fall 2020	
ch.2	Write article
ch.3	Modeling
ch.4	Continue data analysis
Spring 2021	
ch.3	Continue Modeling
ch.4	Continue data analysis
Summer 2021	
ch.3	Write article
ch.4	Continue data analysis
Fall 2021	
ch.4	Write article
Spring 2022	Defense

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Figures

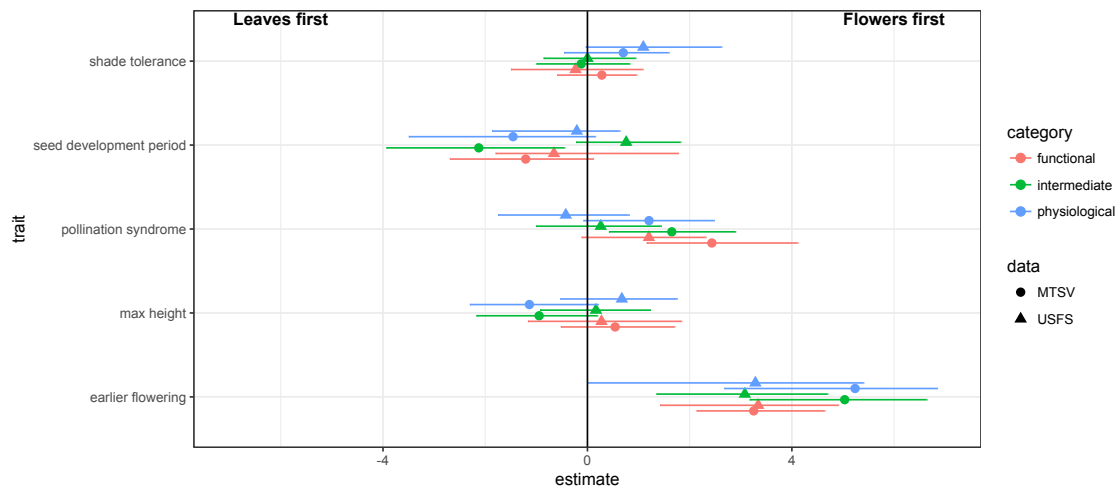


Figure 1: Predictor effect size comparisons (means and 95% bootstrap intervals, scaled predictors) with two different data sources (USFS and MTSV) and three different binary classifications of flower-leaf sequences (flower first= 1, leaf first= 0). Results are sensitive to both data source and modeling choices.

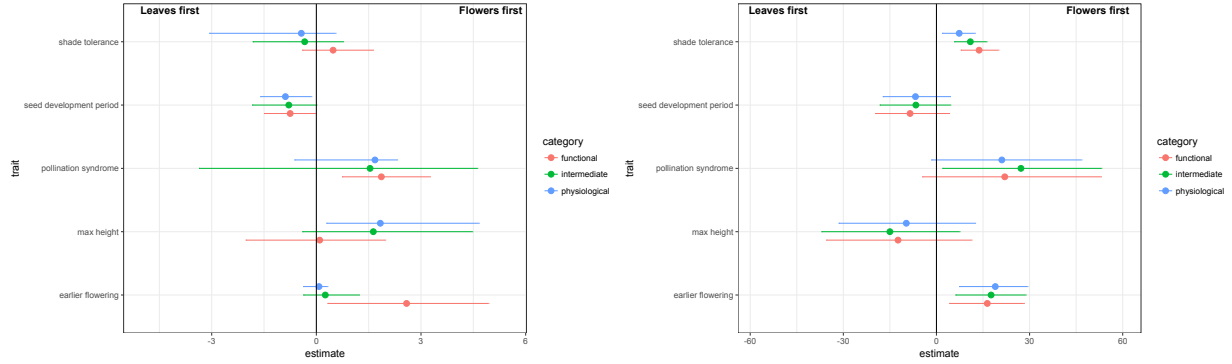


Figure 2: Effect sizes (means and 95% bootstrap intervals) for a model integrating MTSV predictors with observed response variables (mean FLS offset in days) in Harvard Forest with three different classifications of FLS. In panel (A) mean offset was re-coded as a binary response (offset < 0 = seranthous, > 0 hysteranthous) and in panel (B) mean offset in days is continuous data. Treating FLS data as continuous reduces model sensitivity to FLS classification choices.

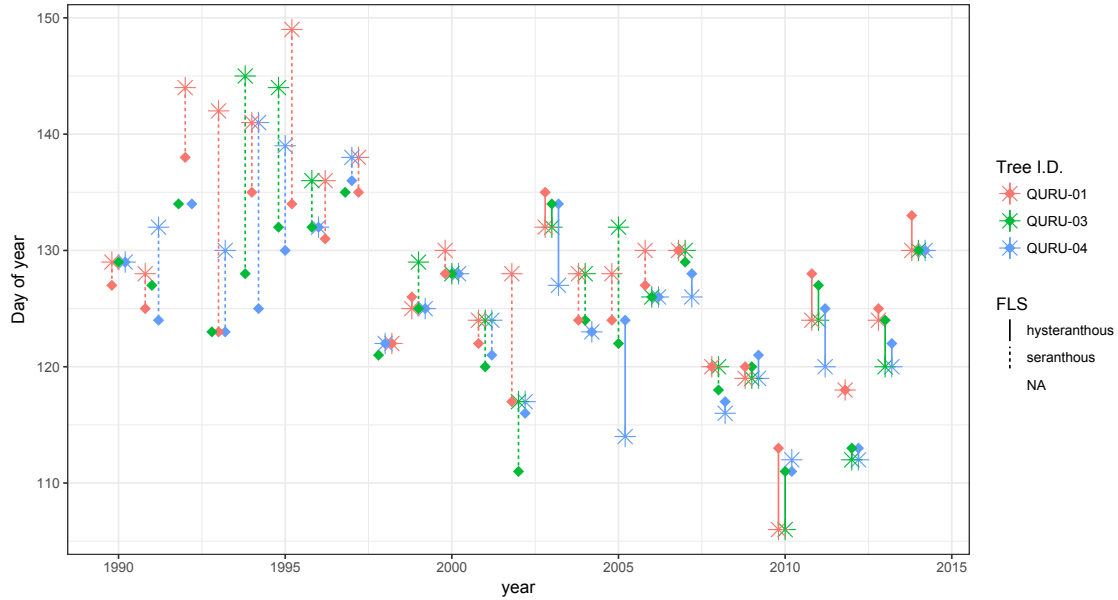


Figure 3: Plots showing interannual variability in FLS for three *Quercus rubra* individuals at Harvard Forest from 1990-2015. Star points indicated flower budburst, and diamonds leaf budburst. Solid offset lines indicate years of flowering buds bursting first (hysteranthous) and dashed lines indicate years in which leaf buds burst first (seranthous)

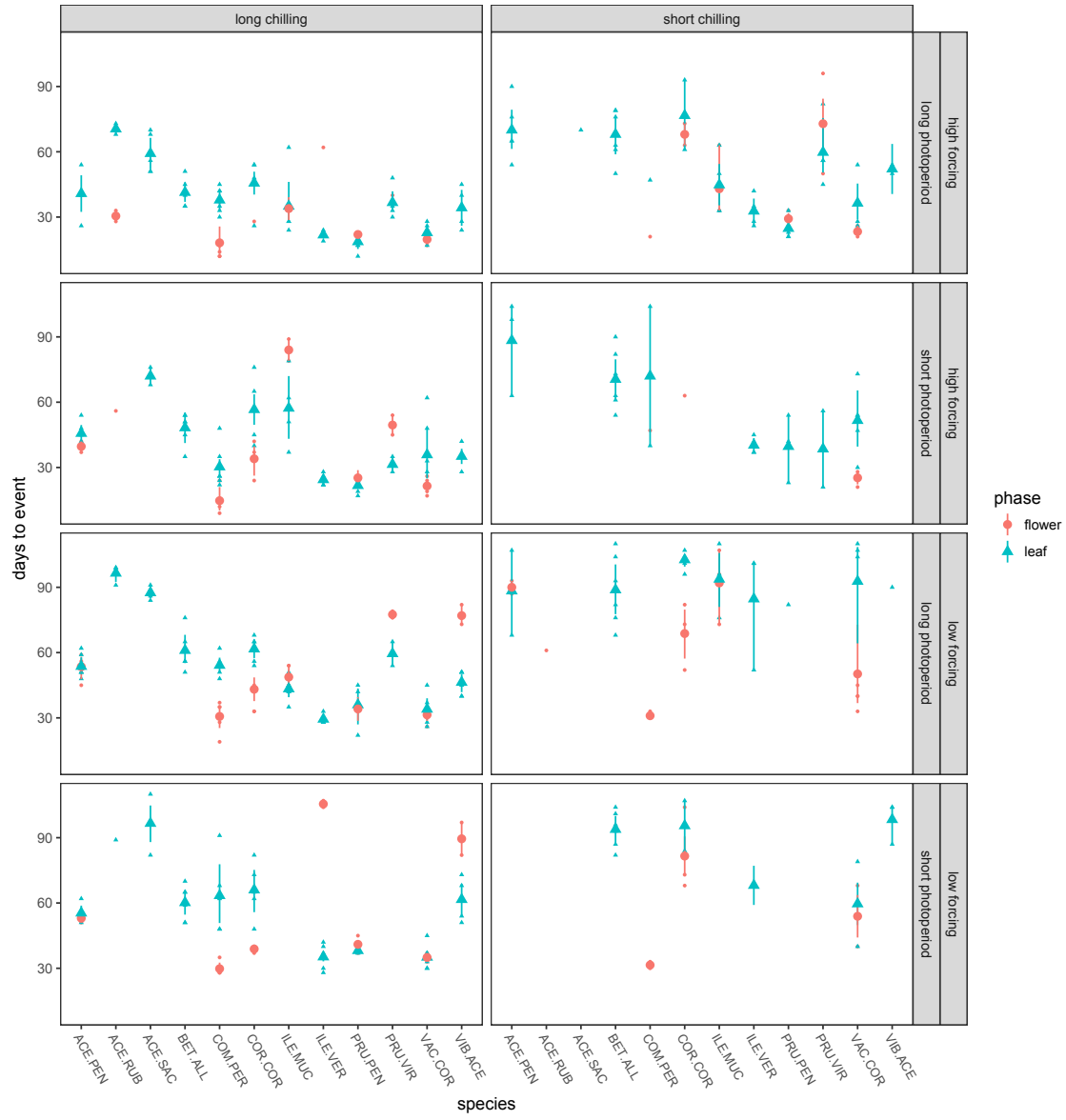


Figure 4: FLS variability (mean and standard deviation flowering and leafout time) for 12 species under different temperature and photoperiod regimes.

Species	Provenance	Life history	Habitat
<i>Anemone virginiana</i>	Minnesota	perennial	E/F
<i>Asclepias syriaca</i>	New York	perennial	O/E
<i>Carex grayi</i>	Minnesota	perennial	E/F
<i>Carex grisea</i>	Minnesota	perennial	E/F
<i>Cryptotaenia canadensis</i>	Minnesota	perennial	E/F
<i>Eurybia divaircata</i>	New York	perennial	E/F
<i>Hesperis matronalis</i>	U.S.	biennial	O/E
<i>Impatiens capensis</i>	Minnesota	annual	E/F
<i>Oenothera biennis</i>	New York	biennial	O/E
<i>Phlox divircata</i>	Texas	Perennial	E/F
<i>Polygonum virginianum</i>	Minnesota	Perennial	E/F
<i>Silene stellata</i>	Minnesota	Perennia	E/F
<i>Silene vulgaris</i>	Massachusetts	Perennial	O/E
<i>Thalictrum dioicum</i>	Minnesota	Perennial	E/F

Figure 5: Species information: species, seed provenance, life history, and habitat preference (O=Open, E=Edge, F=Forested)

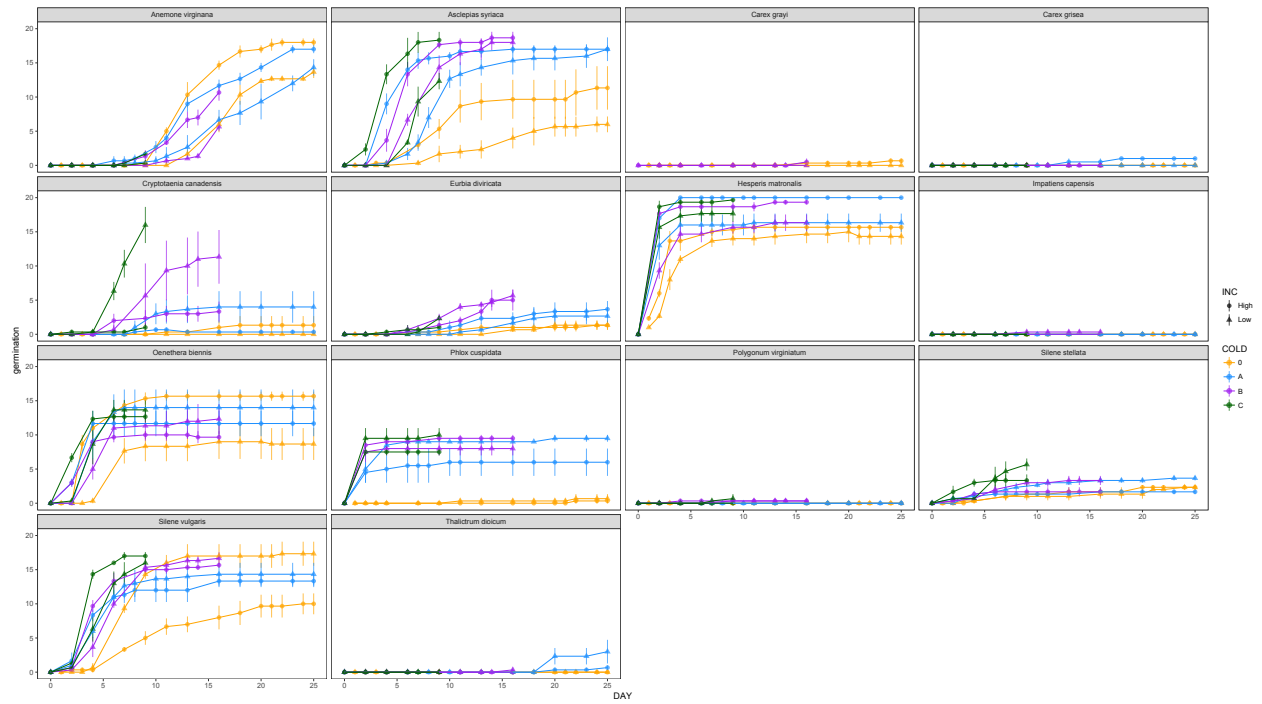


Figure 6: Germination time courses for 14 temperate zone plant species after receiving 0,14(A),28(B),35(C) days of cold stratification. The y axis is average number of seeds germinated.

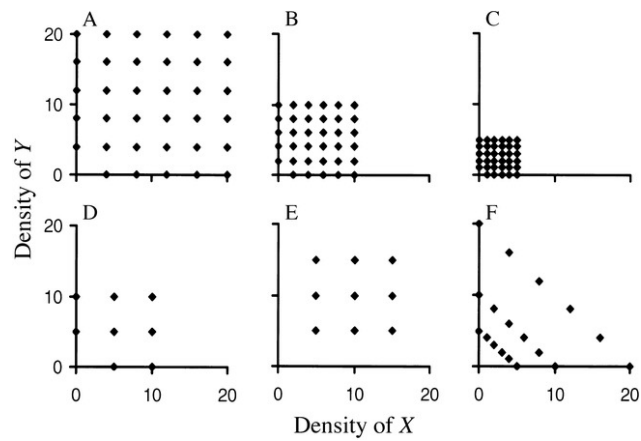


Figure 7: Example of different response surface experimental designs from Inouye, 2001.