**Proposal for Research**

**Life stage specific temperature tolerance in horsenettle (*Solanum carolinense*) and**

**The effects of snow on flowering phenology in upper Midwestern prairies**

**Submitted to the Department of Biological Sciences**

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**Comparison of temperature tolerance by region and life stage in *Solanum carolinense***

***Abstract***

Solanum carolinense (horsenettle) is a part of the Solanaceae (nightshade) family and originally was common throughout the Southeastern United States. It has since spread to much of the continental U.S., including Texas and Minnesota. Since the distribution of this species spans remarkably different climates, horsenettle is ideal for studying the evolution of temperature tolerance for both extreme cold and extreme heat. My proposed research aims to address differences in temperature tolerance regionally and mechanisms of plant adaptation in response to changing temperatures associated with climate change. To understand how horsenettle has managed to adapt to extreme high temperatures and extreme low temperatures, I will compare temperature tolerance between individual plants from Texas and Minnesota for both the sporophytic (diploid) and gametophytic (haploid) life stages. Previous research has shown an overlap between temperature tolerance traits in the sporophytic and gametophytic life stages and in examining both stages, I will determine if this is consistent for temperature tolerance traits in horsenettle. This research will improve our understanding of temperature tolerance evolution which is critical due to the uncertainty of how crops or wild species will cope with climate change.

***Introduction***

Global climate change is altering local temperature regimes and affecting the ranges acceptable for biota. As local temperature regimes change, plants must either shift ranges or adapt to the local conditions (Kawecki and Ebert 2004, Wolkovich et al. 2012, Cooper et al. 2018, Moran 2020). The overarching question for this proposed study is how do plants adapt to changing temperature conditions? Adaptation is the result of natural selection acting on variation among genetically based phenotypes of the same species. As conditions change, adaption will occur if phenotypes that are more suitable for the conditions are more successful in survival and reproduction and therefore, are favored by natural selection (Kawecki and Ebert 2004).

Since angiosperms have alternation of generations, selection can occur at the gametophytic stage (haploid stage; pollen or ovule) and/or the sporophytic stage (diploid stage; zygote, seedling, or mature plant) (Walsh and Charlesworth 1992). I am interested in understanding how the set of traits associated with temperature tolerance evolve. Does selection for temperature tolerance occur in the sporophytic stage, gametophytic stage, or both?

Recognizing the underlying mechanisms for selection are particularly important for understanding adaptation of plants in new environments or a changing climate. Previous studies have shown an overlap in temperature tolerance between the sporophytic and gametophytic stages, meaning that thermotolerant plants produce relatively thermotolerant pollen (Zamir, Tanksley and Jones 1982, Hedhly, Hormaza and Herrero 2005, Zhou et al. 2017, Poudyal, Rosenqvist and Ottosen 2019). Furthermore, selection for tolerance traits in the gametophyte stage has led to evolutionary shifts in the sporophyte stage (Mulcahy 1979, Hedhly et al. 2005). These studies support the hypothesis that the combination of selection at the sporophytic and gametophytic life stages contribute to the evolution of temperature tolerance in angiosperms.

Almost all previous studies concerning climate adaptation have focused on crop species and overall, little attention has been paid to non-crop species. This is problematic because restoration and conservation efforts involve adaptation processes of non-crop species. Wang et al. (2012) conducted a meta-analysis in which the authors compared crop and non-crop species and found a difference between the two in physiological responses to temperature and CO2 levels. The authors went on to mention that their analysis was limited because of understudied groups of plants and necessitated further research of responses to climate change (Wang et al. 2012). Furthermore, novel tolerance mechanisms discovered in non-crop species might provide insight for crop breeding.

*Study Species*

*Solanum carolinense* is an invasive, non-crop species, native to the southeastern United States that now spans much of temperate North America (Sylwester 1946). The pervasiveness of *Solanum carolinense* suggests that this species easily adapts to different conditions. For this study, I will compare temperature tolerance in populations of *Solanum carolinense* in Texas and Minnesota, and exploit plants from a wide range of local temperature thresholds (Fig. 1).

*Solanum carolinense* is not native to TX or MN and currently these states are on the outer reaches of the range for this species. As is common for exotic species first forming colonies, the populations in MN and TX are relatively small and are likely in the process of adapting to local conditions. This is an example of contemporary evolution, coined by Hendry and Kinnison in 1999, which is short-term evolution of traits and is common among invasive species. For exotic species, like *Solanum carolinense*, contemporary evolution may be assisting expansion as the rapid evolution of adaptive traits improves survival in novel environments (Stockwell, Hendry and Kinnison 2003, Colautti and Lau 2015). Since the climates are vastly different in TX and MN, I hypothesize that the adaptation of tolerance to extreme temperatures in these regions deviates. I expect that the northern plants are adapting to extreme cold and southern plants are adapting to extreme heat. With this proposed study, I intend to elucidate the mechanisms of contemporary evolution specific to temperature tolerance in *Solanum carolinense*.



Figure 1. Range of *Solanum carolinense* and locations for the origins of the plants that will be used in this study.

The objective of this study is to examine the relative effects of selection in the gametophytic and sporophytic stages for temperature tolerance in *Solanum carolinense.* I will test two null hypotheses that there is no difference in temperature tolerance between the northern and southern horsenettle populations for both life history stages. The expected alternative hypothesis is that southern plants will be more tolerant of high temperature stress in both gametophytic and sporophytic life stage and vice versa for the plants originating in Minnesota. I also hypothesize that selection for temperature tolerance is reinforced in sporophytic and gametophytic stages due to overlap in gene expression (Tanksley, Zamir and Rick 1981, Willing and Mascarenhas 1984, Beaudry et al. 2020).

**Methods**

***Horsenettle collection***

Twenty-six rhizomes from individual plants were collected from four populations in Collin county, TX, where mean monthly temperatures range from 18°C to 43°C. Thirty-three rhizomes from individual plants were collected from two populations in Houston county, MN with a mean monthly temperature ranging between -14°C and 29°C. The rhizomes were grown to maturity, all vegetative material was cut back to the rhizome, and the rhizomes were stored in soil at 4°C, mimicking a dormant period prior to the proposed study.

***Greenhouse Experimental Design***

In January, I began transitioning plants from dormancy to growing conditions in the greenhouse. Twenty-six northern plants were randomly selected to pair the 26 southern plants. The rhizome of each individual plant was divided into four ramets (genetically identical sections of rhizome capable of growth), to produce four clones labeled ramets A, B, C, and D. All four ramets will eventually be planted in narrow cone-shaped containers, separated spatially and temporally. Temporal staggering will be achieved by starting all ramet A before ramets B, C, and D for all individual plants.

To control for inconsistent conditions throughout the greenhouse, the plants will be arranged in a randomized block design (Fig. 2). Each block will consist of five or six pairs. Each pair will include one MN ramet and one TX ramet, randomly assigned to the left or right side of the pair. Each week, one block will be started until all five blocks for ramets A, B, C, and D are growing. Once the plants reach maturity (approximately eight weeks after start), sporophytic and gametophytic data will be collected. The experimental unit is the mean of the four ramets for one individual plant. Since the ramets are effectively clones, they will not be used as individual experimental units to avoid pseudoreplication (Hurlbert 1984).





Figure 2. Random block design with a leaf symbolizing a ramet. Blue indicates a ramet from a Minnesota plant and red symbolizes a ramet from a Texas plant. Small, shaded red box represents a pair. Large, red box outlines a block. Black box with circles used to represent structure that holds cone shaped containers, in which ramets will be planted.

***Sporophytic tolerance***

Sporophytic tolerance will be analyzed using vegetative tissues, specifically leaves. I will measure temperature tolerance by the level of damage observed before and after temperature treatments. The parameters that will be used to quantify temperature tolerance are cell membrane stability and net photosynthesis. All parameters will be used for both high and low temperature tolerance measures. These parameters are commonly used for observing physiological responses to stress in sporophytic tissues (Gajanayake et al. 2011, Poudyal et al. 2019). These parameters were selected based on available resources and evidence in previous studies showing responses in these variables to temperature stress.

The Texas plants are expected to preform better under high temperature stress than the Minnesota plants. Therefore, the cell membrane stability and net photosynthesis are expected to be higher in the Texas plants than the Minnesota plants. Conversely, the Minnesota plants are expected to perform better in cold stress conditions than the Texas plants and therefore, are expected to have a higher cell membrane stability and net photosynthesis when subjected to cold treatments.

*Cell membrane stability*

Cell membrane stability (CMS) will be measured using the conductivity of a solution containing a specific quantity of leaf material following the protocols from Gajanayake et al. (2011) and Fang and To (2016). Stressful conditions can reduce the integrity of cell membranes in plants, causing cytoplasm to leak into the solution and raise the conductivity (Gajanayake et al. 2011). The conductivity, measured in μS, will be recorded after the temperature treatment and then again after a maximum damage treatment (Fig. 3).

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Figure 3. Schematic describing protocol using conductivity to measure cell membrane stability for the heat stress treatment.

First, 20 leaf disks from one leaf selected based on predetermined criteria will be divided between two test tubes with 10 mL of RO water. For the high temperature treatment, one test tube with leaf material will placed in a water bath at 50°C for 20 minutes and the control test tube will remain at room temperature (Fig. 3). The same protocol will be used for the cold temperature tolerance treatment except one test tube will be placed in a refrigerator for 72 hours, while the control remains at room temperature (Fig. 4). The conductivity will be measured after the test tubes return to room temperature.

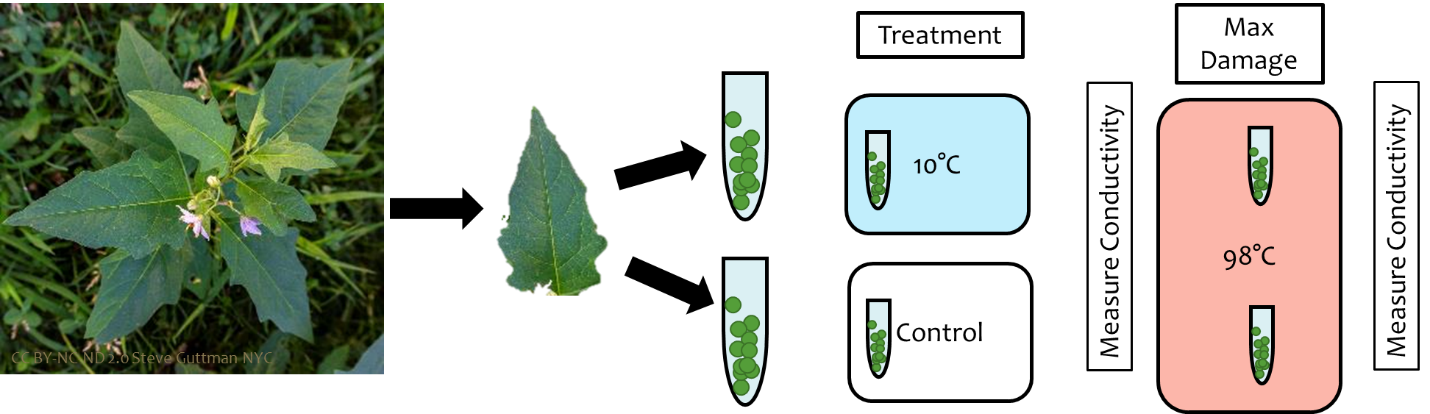


Figure 4. Schematic describing protocol using the conductivity to measure cell membrane stability for the cold stress treatment.

For the maximum damage condition, the test tubes for both the treatment and control groups will be placed in a water bath at 98°C for 30 minutes, followed by a conductivity measurement. The maximum damage condition is used to determine a baseline for comparison to the damage caused by the treatments. The ratio of conductivity after the treatment to after maximum damage will then be used to quantify cell membrane stability.

*Photosynthesis*

Photosynthesis will be measured before heat treatment, after a temperature stress treatment, and following a recovery period (Fig. 5), as described by Poudyal et al. (2019). Photosynthesis will be measured using a Li-COR infrared gas analyzer after the plant is dark adapted for 45 minutes following protocol modified from Mishra et al. (2019). Photosynthesis will be reported through the quantum efficiency of photosystem II using the ratio of variable fluorescence and maximum fluorescence (Fv/Fm) in units of μmol/m2s. Photosynthesis will also be measured before, during, and after a cold treatment.

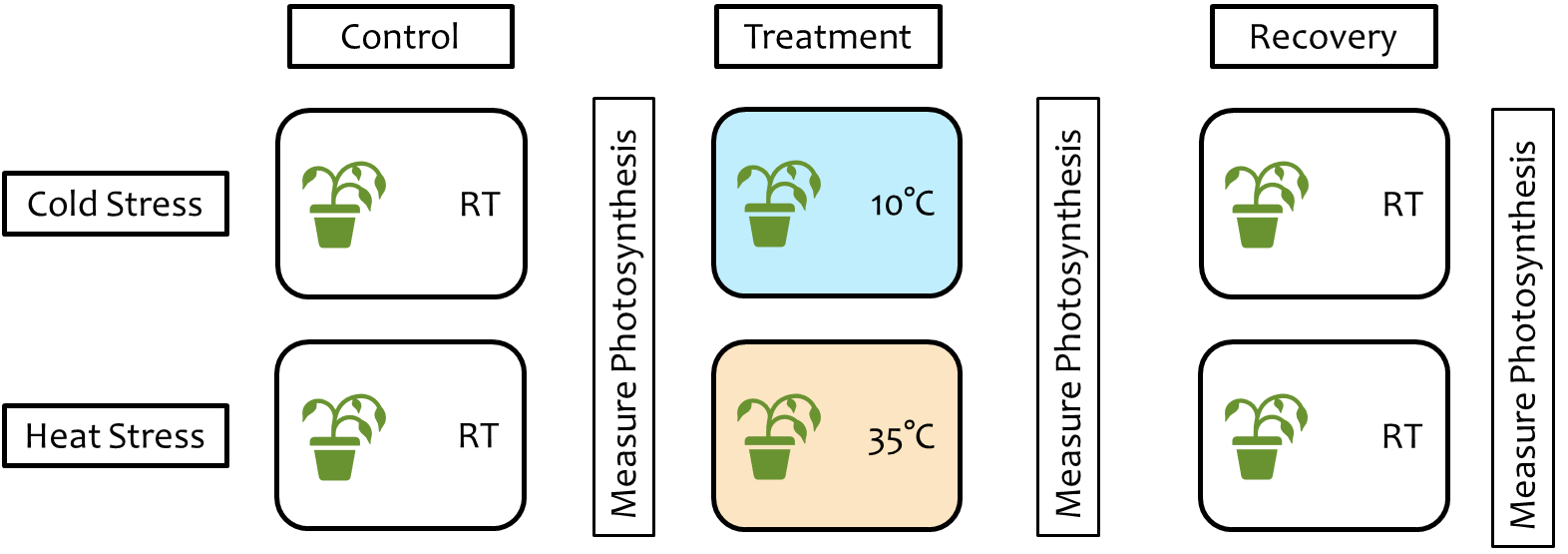


Figure 5. Schematic describing protocol to measure photosynthesis for cold and heat stress treatments.

***Gametophytic tolerance***

*Pollen tube growth rate and viable pollen*

Gametophytic tolerance will be analyzed following the protocol of Gajanayake et al. (2011). Pollen success relies on pollen tube growth through the length of the style for fertilization at the ovule. Therefore, pollen tube growth rate will be measured as an indication of pollen fitness. The length of pollen tubes will be recorded after 24 hours in incubation at one of five temperatures: 10°C, 15°C, 25°C, 30°C, and 40°C. We will use a light microscope to photograph the pollen tubes on the agar plates. ImageJ will be used to measure the lengths of the pollen tubes in the pictures taken. We will fit a curve to the growth rates at all temperatures to determine low, optimal, and high temperature limits for pollen tube growth. We will also count the total number of pollen grains to determine the proportion of viable pollen.

***Data Analysis***

Data analysis will be conducted in R. Variables reported as proportions will be arcsin sqrt transformed before analysis. Mixed model analysis of variance with region nested and genet as a random effect will be used for the analysis of each variable. Correlation analysis will be used to determine the relationships between temperature tolerance traits for the sporophytic and gametophytic stages.

**Expected Results**

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Figure 6. Pilot data for cell membrane stability under high temperature treatment. Experimental unit was one leaf from individual plant. Outliers identified by Grubb’s test excluded. T-test of arcsin sqrt transformed cell membrane stability proportion had p-value 0.028.

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Figure 7. Expected results for cell membrane stability under low temperature treatment.

The expected outcome for cell membrane stability is that the southern population has a higher stability than the northern population when exposed to a high temperature treatment. Pilot data collected in fall aligned with this expected outcome (Fig. 6). The opposite is expected for cell membrane stability exposed to the cold treatment (Fig. 7). These results would support the hypothesis that southern horsenettle populations are more tolerant of high temperatures and northern populations are more tolerant of low temperatures for the sporophytic life history stage. The null hypothesis would be supported if there is no difference in cell membrane stability between plants from the northern and southern provenances.

The expected outcome for net photosynthesis is that the southern populations will have a constant net photosynthesis for the control, heat stress, and recovery treatments (Fig. 8) while, the northern population will have a constant net photosynthesis for cold stress (Fig. 9). A constant net photosynthesis or at least higher net photosynthesis is indicative of normal functioning under stress. These net photosynthesis outcomes would support the hypothesis that southern populations are more tolerant of high temperature stress and vise versa for northern populations.

The expected outcome for the measures of gametophytic tolerance are that the southern population has a threshold of pollen tube growth and viability at increased temperatures when compared to the northern population (Fig. 10). This outcome would support the alternative hypothesis that southern populations are more tolerant of high temperature than the northern population in the gametophytic life history stage.

Figure 8. Expected outcome for net photosynthesis for the control, heat stress, and recovery treatments of northern and southern horsenettle populations.

Figure 9. Expected outcome for net photosynthesis for the control, cold stress, and recovery treatments of northern and southern horsenettle populations.

***Gametophytic Tolerance***

Figure 10. Expected outcome for pollen tube growth rate or pollen viability with curves defining the minimum, maximum, and optimal pollen tube growth temperatures for northern and southern populations.

**Pollen competition in response to temperature stress in *Solanum Carolinense***

***Abstract***

Selection for certain traits occurs at the sporophytic (diploid) and gametophytic (haploid) life stages in angiosperms. For the gametophytic life stage, competition between pollen grains for fertilization is severe when there are large numbers of pollen grains deposited on the stigma of a flower. Certain pollen grains may outperform others based on their tolerance to environmental conditions, compatibility with the receiving plant, viability, and pollen tube growth rate. Additionally, the process is rapid compared to competition throughout a plant’s development in the sporophytic stage. If selection for temperature tolerance traits is strong in the gametophytic stage, evolution in temperature tolerance may be a more rapid process than would be expected for selection at only the sporophytic stage. My proposed research is to examine the siring success of pollen grains from Texas and Minnesota plants when pitted against one another on one stigma and exposed to high and low temperature stress. Studying the performance of pollen grains will give us insight into how plants adapt to extreme temperature conditions and how influential selection in the gametophytic stage is to temperature tolerance traits. ***Introduction***

Competition not only occurs between plants for resources such as nutrients, light, and water but also between gametes for fertilization. Once deposited on the stigma, pollen grains begin to produce pollen tubes which grow down the length of the style and into the ovary, where sperm is discharged into ovules. Because of the enormous number of pollen grains produced and deposited on the stigma, competition between the male gamete is an effective evolutionary mechanism (Ottaviano, Sarigorla and Villa 1988). There are several traits that determine the fitness of the male gamete including competition for resources in the anther, viability, pollen tube growth rate through the style, overall germination time, and selective fertilization at the ovary (Ottaviano et al. 1988). Variability in these traits suggest that fertilization at the ovule in not random (Sarigorla et al. 1992). Pollen selection can inevitably alter the sporoyphitic stage as well, due to the genetic overlap between the two stages (Tanksley et al. 1981, Willing and Mascarenhas 1984, Beaudry et al. 2020).

Competition among pollen grains is further complicated by conditions in the style, or stylar discrimination (Harder et al. 2016, Cruzan and Barrett 2016). Stylar discrimination can completely halt pollen tube growth for certain pollen grains. One case where this occurs is through the self-incompatibility (SI) system in several angiosperms, including *Solanum carolinense*. In the SI system, the pistil produces specific ribonucleases (S-RNases) that degrade RNA in pollen tubes that are genetically similar at the multiallelic S-locus, or S-allele (Mena-Ali and Stephenson 2007, Mena-Ali, Keser and Stephenson 2009). Degradation of RNA terminates pollen tube growth, preventing self-crossing and favoring fertilization with outcross pollen. Similarly, temperatures can influence pollen siring success. Zamir, Tanksley, and Jones (1981) found that pollen grains from a wild species of tomato found at high elevations in the Andes were more successful in fertilization at low temperatures than a cultivated variety. Following these findings, I am proposing to conduct gametophytic competition experiments, where pollen from Texas and Minnesota *Solanum carolinense* plants will compete for fertilizations under specific temperature treatments.

The objective of this study is to examine siring success of northern and southern horsenetlle plants under high and low temperature stress. My null hypothesis is that there is no difference between the siring success of pollen from TX and MN plants under high and low temperature stress. My alternative hypothesis is that northern plants will outcompete southern plant at low temperature treatments and vice versa due to adaptation to temperature conditions of the region from which they originate.

***Methods***

*Plant Collection*

The plant collection is the same as mentioned in part 1, except one more population of northern plants will be added, totaling 58 individual plants from MN and 26 from TX. Prior to the pollen chase experiment, the S-allele variant for each plant will be determined using PCR with primers of the six known variants in horsenettle (Mena-Ali et al. 2009). In addition to the S-alleles, microsatellite sequences common in *Solanum* species will be used to further differentiate genotypes (SOURCE).

All plants will be removed from dormancy, placed in the greenhouse, and grown to maturity. All plants will then be crossed with one another to determine compatibility, since the self-incompatibility system can render a pair incapable of fertilization. Then, all plant vegetative material will be cut back to the rhizome and returned to dormancy for eight weeks. Following the dormancy period, the plants will be removed, placed in the greenhouse, and grown to maturity a second time. I will then collect pollen from one northern and one southern plant and evenly disperse the pollen on the stigma of a plant that is compatible with both pollen doners. Then, I will place the plant at either the low temperature condition (15°C) or the high temperature condition (35°C) for the length of time required for fertilization (about 48 hours). After fertilization, I will return the plant to room temperature and allow the ovary to mature and fruit. Once the fruit is mature, I will collect the seeds and begin the process of germination. Once seedlings are grown from the germination of each seed, I will use PCR and microsatellite sequencing to determine the paternity of each seed. The pollen donor that sired the most seeds is the winner of the pollen competition and considered to have higher fitness, given the conditions.

***Data Analysis***

Data analysis will be conducted in R. A heterogeneity G-test will be used for both the high and low temperature treatments to test the null hypothesis that there is no difference in the proportion of seeds sired between MN and TX plants. A chi-square heterogeneity test analyzing a 2 x 2 contingency table will then used to compare the siring success of pollen by region and temperature treatment (Travers and Mazer 2001).

***Expected Results***

I expect that the pollen from Texas plants will outperform the pollen from Minnesota plants when pollen tube growth and fertilization occur in high temperature conditions (Fig. 11). I expect the opposite for low temperature conditions. These results would support my alternative hypothesis.

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Figure 11. Expected results for pollen competition. Proportion of seeds sired for MN and TX plants when exposed to high temperatures and low temperatures. Error bars indicate standard error. **The effects of winter precipitation on flowering phenology**

***Abstract***

Shifting flowering phenology in response to climate change has been well documented, especially for the effect of changing temperatures on flower timing. In the Midwest, precipitation patterns are also expected to change with increasing greenhouse gasses, yet few studies have shown a phenological sensitivity to precipitation changes. However, tundra and alpine studies have shown strong relationships between flowering phenology and winter precipitation. Based on these patterns, we hypothesized that northern latitudes with substantial snowfall would have similarly strong relationships between winter precipitation and flowering phenology. We combined a historical data set of first flowering dates in Minnesota tallgrass prairie with climatic data to construct a structural equation model, testing hypotheses about the relationships between winter precipitation and temperature variables and flowering phenology. While temperature had a strong effect on flowering phenology for most species observed, winter precipitation had a significant relationship with only three of nineteen species. The three species affected by snow were later flowering species which is inconsistent with our prediction that winter precipitation affects early flowering phenology. These results further our understanding of the climatic cues that drive flowering phenology and improve our ability to predict how climate change will impact prairie species.

***Introduction***

Shifting flowering phenology, or flower timing, is an important biotic effect caused by climate change that has been well documented in many parts of the world (Cleland et al. 2007, Miller-Rushing et al. 2007, Parmesan 2006, Schwartz, Ahas and Aasa 2006, Wolkovich et al. 2012). Changes to flowering phenology can influence plant-pollinator interactions if asynchrony between flower timing and pollinator emergence occurs (Cleland et al. 2007, Kharouba et al. 2018, Visser and Gienapp 2019, Kharouba and Wolkovich 2020). Several environmental cues trigger flowering such as temperature, amount of moisture, and photoperiod. Since climate change can influence these cues, flowering phenology is likely to change.

Shifting flowering phenology has been strongly associated with temperature in prairies (Dunnell and Travers 2011, Reed et al. 2019). Reed et al. (2019) found advancement of phenological events due to recent temperature increases in the Pacific Northwest. Dunnell and Travers (2011) found mixed responses to temperature changes in the Midwest. Since temperature did not explain phenological responses for all species, other environmental cues may be important. Precipitation is also predicted to increase in the Midwest (Pachauri and Meyer 2014) and therefore may also be involved in shifting flowering phenology.

The upper Midwest has long, harsh winters with precipitation primarily in the form of snow. Snow could affect flowering phenology by inhibiting bud emergence while snow cover remains and by releasing large quantities of moisture into the soil upon snow melt. Studies in montane and tundra environments have shown that snow affects phenology and in some case is more important than temperature. Though there is evidence that snow affects flowering phenology for tundra and montane species. Inouye et al. (2002) found a significant relationship between date of first bare ground and first flowering for *Delphinium barbeyi.* Sherwood et al. (2017) manipulated snowpack at montane plots and found that reduced snowpack was correlated to earlier bud emergence but also increased frost damage due to exposure to freezing air temperatures. Bjorkman et al. (2015) found that snowmelt was strongly related to flowering in arctic tundra species. Though there is evidence of snow influencing flowering phenology in montane and tundra ecosystems, as far as we know, there have been no studies that have examined the effects of snow on flowering phenology in prairie species.

The objective of this study was to assess the direct and indirect effects of temperature and snow on flowering phenology. Our hypothesis was that increased snowpack and later snow melt will delay flowering.

***Methods***

We used historical data collected by O.A. Stevens from 1910 to 1961 and subsisted by Steven Travers from 2012 to 2020 for a record of the day of year when the first flowering was observed for a species. These data were collected at Bluestem Prairie, a tall grass prairie in Clay county Minnesota. To be included in this study, a species was required to have at least five records with one record in the 1900’s and one in the 2000’s. There were 24 species that met these criteria, all of which were perennial herbs.

We used climate data collected at a NOAA (National Atmospheric and Oceanic Administration) station at the Fargo International Airport, which is 32 km west of Bluestem Prairie. Climate data at this station was first collected in 1942 and therefore the years 1942 to 1961 and 2012 to 2020 were included in this study. The raw climate dataset contained maximum and minimum temperature, snowpack, and snowfall which were used to calculate the climate variables used in the model.

For the temperature variable, we used Accumulated Degree Growing Unit (AGDU). Growing units are defined as the difference between the average daily temperature and 35°F. Average daily temperatures below 35°F were set to zero (McMaster and Wilhelm 1997). The AGDU variable was calculated as the day of the year when the sum of growing units surpassed 300, which is typically toward the end of march for the upper Midwest. Therefore, years with a warmer spring will have a lower value for AGDU and vice versa.

Three variables were used for measures of winter precipitation. Total snowfall (TSNOW) was calculated as the sum of daily snowfall over the first 90 days of the year. Date of first bare ground (DOBG) was the day of the year when the snowpack first reached zero. Eight of the years observed had one to two days of late season snowpack, which were excluded. The final winter precipitation variable was snowpack on day X (SPDX), which is designed to represent the snowpack just prior to the growing season. To calculate SPDX for each species we used linear regression and model selection to identify the day in March with snowpacks that best predicted the first flowering day (FFD) for that species. SPDX values increase with increasing snowpack and decrease with decreasing snowpack on the selected day of March. The most predictive day was determined separately for each plant species. We used this variable to maximize the explanatory power of snowpack on flowering in a month when temperatures and snowpack are rapidly changing. Each of the four climate variables were not independent of each other.

Using these climate variables and first flowering day (FFD) we constructed a path diagram defining the relationships between the variables (Fig. 12a). The path diagram was then used for Structural Equation Modeling (Grace 2006) to assess the strength and significance of each relationship for each species. We used the *lavaan* package in R (Rosseel 2012) for analysis. The model included regressions for each endogenous variable, variances within all variables, and residual covariances between the exogenous variables. We considered both direct and indirect effects. In addition to the full path diagram, we also created reduced path diagrams that omitted either DOBG, SPDX, or AGDU. Akaike Information Criterion (AIC) was then used to select the model that best represented the data.

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(b)

(a)

Figure 12. Full path diagram (a) and reduced path diagram excluding DOBG (b). The reduced path diagram was used for the structural equation modeling.

***Results***

Model selection based on AIC values indicated that the model excluding DOBG (Fig. 12b) was the best explanatory model. Based on the chi-squared statistic estimating goodness of fit, the model excluding DOBG was a good representation of the relationships among the exogenous and endogenous variables for all but five species (*Anemone patens, Caltha palustris, Lithospermum canescens, Campanula rotundifolia,* and *Amorpha canescens*). These five species were removed from further analysis. The regression coefficients, describing the strength and direction of each relationship, were attained for each species through path analysis and are presented in Figure 13 and Table 1.

The direct relationship between AGDU and FFD was significant in 12 out of 19 species analyzed. All twelve had positive regression coefficients, indicating that warmer temperatures earlier in the year led to earlier flowering. The five first flowering species had strong and significant relationships between AGDU and FFD. Later flowering species with significant regression coefficients were scattered throughout the growing season, but typically had weaker relationships. For the direct effect of AGDU on SPDX, only 5 of 19 were significant and all regression coefficients were weakly positive. Winter temperatures (AGDU) also had indirect effects on flowering time (FFD) through intermediary effects on the snowpack in March (SPDX) for 1 species (*Zigadenus elegans*).

The relationship between snowfall in the winter months (TSNOW) and snowpack in March (SPDX) was positive and significant for all species. Both variables describe winter precipitation and therefore were predictably related. Only three out of the 19 species had a significant relationship between SPDX and FFD. In one species (*Cypripedium candidum*) the path coefficient was negative indicating that relatively large amounts of winter snowfall led to earlier flowering relative to years when there was less winter snowfall. However, in the other two species (*Zigadenus elegans* and *Rosa arkansana*) the coefficient was positive. There were significant indirect effects of TSNOW on FFD for the same three species through its effects on SPDX (Table 1).

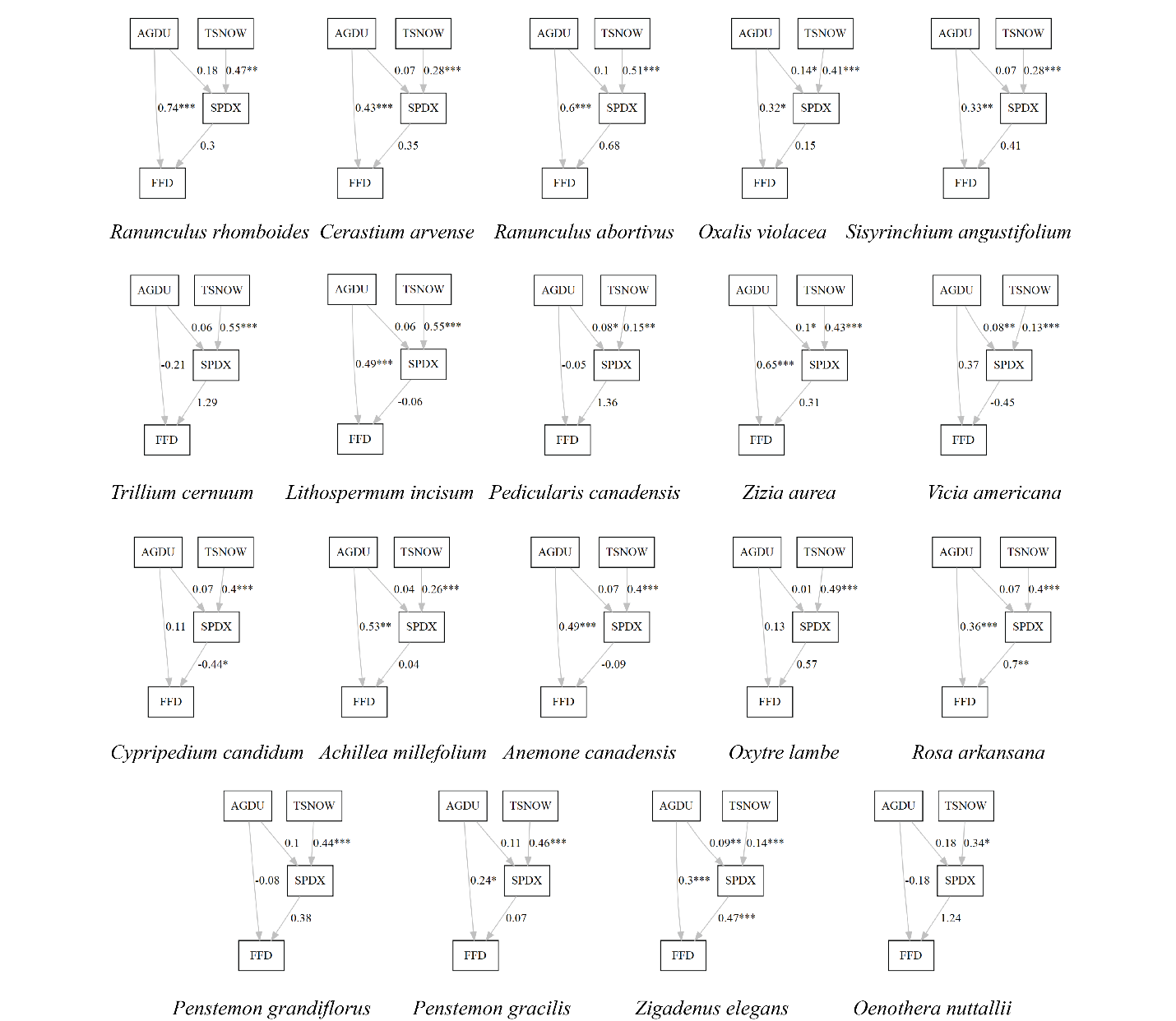


Figure 13. Path diagrams with direct effect estimates labeled. Number of asterisks indicate level of significance for p-value: \*p ≤ 0.05, \*\*p ≤ 0.01, \*\*\*p ≤ 0.001.

Table 1. Statistical summary of regression coefficients for direct and indirect effects for reduced model. AD = indirect effect for TSNOW on FFD mediated by SPDX, BD = indirect effect for AGDU on FFD mediated by SPDX. Number of asterisks indicate level of significance for p-value: \*p ≤ 0.05, \*\*p ≤ 0.01, \*\*\*p ≤ 0.001.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Species | A  SPDX~TSNOW | B  SPDX~AGDU | C  FFD~AGDU | D  FFD~SPDX | AD | BD |
| *Ranunculus rhomboides* | 0.471\*\* | 0.178 | 0.737\*\*\* | 0.295 | 0.139 | 0.053 |
| *Cerastium arvense* | 0.281\*\*\* | 0.066 | 0.427\*\*\* | 0.348 | 0.098 | 0.023 |
| *Ranunculus abortivus* | 0.508\*\*\* | 0.098 | 0.595\*\*\* | 0.679 | 0.345 | 0.066 |
| *Oxalis violacea* | 0.405\*\*\* | 0.139\* | 0.319\* | 0.146 | 0.059 | 0.020 |
| *Sisyrinchium angustifolium* | 0.281\*\*\* | 0.066 | 0.334\*\* | 0.405 | 0.114 | 0.027 |
| *Trillium cernuum* | 0.553\*\*\* | 0.056 | -0.211 | 1.288 | 0.712 | 0.072 |
| *Lithospermum incisum* | 0.553\*\*\* | 0.056 | 0.486\*\*\* | -0.061 | -0.033 | -0.003 |
| *Pedicularis canadensis* | 0.151\*\* | 0.083\* | -0.048 | 1.359 | 0.205 | 0.113 |
| *Zizia aurea* | 0.427\*\*\* | 0.102\* | 0.652\*\*\* | 0.307 | 0.131 | 0.031 |
| *Vicia americana* | 0.134\*\*\* | 0.081\*\* | 0.371 | -0.452 | -0.060 | -0.037 |
| *Cypripedium candidum* | 0.398\*\*\* | 0.074 | 0.113 | -0.438\* | -0.174\* | -0.032 |
| *Achillea millefolium* | 0.257\*\*\* | 0.036 | 0.529\*\* | 0.042 | 0.011 | 0.002 |
| *Anemone canadensis* | 0.398\*\*\* | 0.074 | 0.491\*\*\* | -0.092 | -0.037 | -0.007 |
| *Oxytre lambe* | 0.493\*\*\* | 0.008 | 0.133 | 0.573 | 0.283 | 0.004 |
| *Rosa arkansana* | 0.398\*\*\* | 0.074 | 0.364\*\* | 0.700\*\* | 0.279\*\* | 0.052 |
| *Penstemon grandifloras* | 0.438\*\*\* | 0.097 | -0.077 | 0.382 | 0.167 | 0.037 |
| *Penstemon gracilis* | 0.459\*\*\* | 0.106 | 0.241\* | 0.067 | 0.031 | 0.007 |
| *Zigadenus elegans* | 0.144\*\*\* | 0.091\*\* | 0.301\*\*\* | 0.467\*\*\* | 0.067\* | 0.043\* |
| *Oenothera nuttallii* | 0.340\* | 0.178 | -0.177 | 1.236 | 0.421 | 0.220 |

***Discussion***

We built a path diagram describing the relationships between temperature, winter precipitation, and first flowering date variables. From the climatic and flowering variables, we created one full model and three reduced models describing the hypothesized relationships between these variables. The model that omitted DOBG was the best model, indicating that when snow melts, is not important in predicting flowering. An explanation for why plants flower regardless of when the ground becomes bare is that plants can change the length of earlier developmental phases ensuring that flowering occurs around the same time each year (Sherwood et al. 2017).

After applying structural equation modeling, we determined that variables related to snow are not correlated to flowering phenology for most species. Only 3 of 19 species had significant regression coefficients for the direct effect of SPDX on FFD. Those same three species also had significant regression coefficients for the indirect effect of TSNOW on FFD through SPDX. Curiously, all three species were later flowering species and the responses to snow were different. *Rosa arkansana* and *Zigadenus elegens* had negative regression coefficients meaning that increased snowpack in March led to later flowering. This would be expected if snow cover influenced emergence and early development. Conversely, *Cypripedium candidum*, in the Orcidaceae family, had a positive regression coefficient meaning that increased snowpack led to earlier flowering. This may be due to the moisture released during snowmelt. Moisture from snowmelt can supply plants late into the season (Wang et al. 2018) and may trigger early flowering in this species.

Though snow didn’t have an effect on flowering for most species, temperature did. Twelve of 19 species had a significant regression coefficient for the effect of AGDU on FFD. All significant relationships were positive, indicating that higher temperatures early in the year led to earlier flowering. This is consistent with the findings of other studies examining flowering phenology in temperate prairies (Dunnell and Travers 2011, Reed et al. 2019).

Future research directions could include examining the length and timing of other developmental stages of prairie plants to discover exactly how winter precipitation and other variables influence phenological patterns. An analysis of the relationship between soil moisture and flowering phenology may also further our understanding of the environmental cues that drive flowering phenology.



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