Changes in Plant Phenology in the Central United States in Response to Climate Change

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CHANGES IN PLANT PHENOLOGY IN THE CENTRAL UNITED STATES IN RESPONSE TO CLIMATE CHANGE

by

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Plant phenophases are highly sensitive to changes in temperature, precipitation, and photoperiod and have recently been identified as an indicator of climate change. Flowering time in particular appears to be sensitive to changes in temperature and plants around the world have already been observed flowering earlier than previously recorded. To determine how plants in the Midwest and Great Plains have reacted to climate change from the 1880s to present, 1,926 plant specimens made up of 10 species were examined to determine their phenophase and date of collection for each specimen was recorded. Analysis of these specimens shows that flowering time has become earlier over time for all species except for *V. pedatifida*. These changes in flowering time will have a profound effect on the diversity of plant communities in the regions mentioned above and will likely also affect many wildlife species, specifically pollinators.
Introduction

Phenology is described as the timing of key life events and, when used in the context of vegetation, is considered to mean the timing of plant lifecycle phases. These phases are also known as phenophases and include budding, leaf senescence, and flowering period (Calinger et al. 2013). The flowering period is most often used when tracking phenological changes in vegetation because of a high sensitivity to changes in climate such as temperature, precipitation, and amount of sunshine per day (Panchen et al. 2012, Franks et al. 2007). Because of this high sensitivity, plant flowering times have the ability to reflect changes in climatic conditions and have been considered an indicator of climate change (Calinger et al. 2013, Cannell et al. 1999, Beaubien and Johnson 1994, Bradley et al. 1999).

Past studies have already shown that plants today are, on average, flowering earlier than previously recorded (Bradley et al. 1999, Calinger at el. 2013, Fitter and Fitter 2002, Franks et al. 2007, Henry and Molau 1997, Panchen et al. 2012, Primack et al. 2004, Sparks et al. 2000). There is a lot of variability between each individual plant species as to how much the flowering period has advanced because of climate change: annuals are more likely to flower earlier than perennials even if they belong to the same genus (Fitter and Fitter 2002), insect-pollinated plants flower sooner than wind pollinated plants (Fitter and Fitter 2002), and plant species in the northern latitudes have also been found to be more responsive than species near the equator (Bradley et al. 1999, Henry and Molau 1997). Responsiveness to change also depends on what environmental factors a plant uses as a signal to start flowering. Plants that are controlled by photoperiods would be less likely to change phenophase behavior than plants that react to temperature and precipitation cues (Bradley et al. 1999).
Plants with the ability to adapt quickly to a change in climate could start growing and taking in nutrients before other plants get access to that space or nutrients (Fitter and Fitter 2002). However, flowering earlier could also expose plant species to adverse environmental conditions like frost which greatly inhibit plant health and reproduction (Calinger et al. 2003). These potential effects of changing flowering times open up the opportunity for individual plant species to out-compete other species and take over an ecosystem which could result in species a loss of species richness, or extinction, and increase the prevalence of mono-culture ecosystems (Calinger et al. 2003).

Being able to predict or anticipate changes to plant ecosystems would help develop strategic management goals and provide information on what communities would be the most vulnerable to climate change. Native prairie grassland habitat has already been on the decline due to increases in agricultural land use and the prevalence of invasive species. Vegetation zones are predicted to move northward as temperature increases possibly causing some plant species to not be able to adapt quickly enough to avoid being overtaken by more southern species (Thorpe 2011). Climate change is also likely to favor invasive species because of their capacity for rapid dispersal and evolution which further endangers native grassland ecosystems (Thorpe 2011). More studies on how different species are changing flowering times in response to changes in climate would guide habitat managers in restoration and management plans (Schramm 1990).

Shifts in plant species within an ecosystem can also have a negative effect on wildlife populations. Plant species in the Great Plains are expected to move northward in response to climate change (Thorpe 2011). In fact, the USDA plant hardiness zones in the Great Plains have already shifted northward—Nebraska has gone from an equal distribution of zone 4 and 5 in
1990 to majority zone 5 in 2012—and these zones are projected to continue moving north (Laukaitis 2012; Figure 1). The individual species within each zone, however, are not likely to move together as one group. One previous study found that plant species over the past 18,000 years, when exposed to changes in climate conditions, have had differential movements instead of moving as one group (Overpeck et al. 1992). These differential movements could cause a disruption in the relationship between wildlife and plant species (Root and Schneider 2002).

These disruptions between plants and wildlife are likely to have the greatest impact on pollinators. Pollinator populations are already declining due to changes in agriculture—increased land area used for agriculture and increased use of insecticides—across the country and as a result, pollinators are relying more on naturally occurring vegetation (Nicholls and Altieri 2013). Many of these pollinators have co-evolved with specific species of plants and/or will only inhabit an area if there is a wide variety of plant species (Nicholls and Altieri 2013). If plant ecosystems become less diverse, they will not be able to provide habitat for a variety of pollinators which may contribute to shift in pollinator movement and overall pollinator decline (Nicholls and Altieri 2013). Changing flowering times could also increase the occurrence of pollinator mismatch. Pollinator mismatch occurs when plants flower either too early or too late and they miss that window where migrating pollinators are in that area (Amano et al. 2010). If flowering times are changing, or change in the future, that would change the behavior of pollinators and may affect the health of endangered pollinator populations. Pollinator mismatch can also negatively impact plant communities because plants that rely on pollinators for reproduction would no longer be able to reproduce and sustain a healthy population. A decline in these might create an unstable plant ecosystem because plants that use pollinators for
reproduction have been shown to be more resilient because of greater genetic diversity (Travers et al. 2011).

Herbarium specimens are typically used when conducting studies on flowering times because plants are often collected when in full flower and have been steadily collected since the 1800s so they provide a reliable and long-term data source (Primack et al. 2004). Herbarium specimens are often referred to as plant mounts and consist of a dried, flattened plant that has been mounted on a sheet of paper and usually has a label that contains information on when and where the plant was collected. Plant specimens are also collected throughout the United States which allow for the detection of any differences that can occur within a species range while studies that look at live plants in one location would not be able to detect such differences (Borchert 1996). Evidence also suggests that differences seen in herbarium specimens mirror those seen in real life and that assessment of phenological response to temperature using herbarium specimens shows no statistical difference than field observations (Borchert 1996, Robbirt et al. 2011).

The purpose of this study is to determine if the phenology of native vegetation in the Midwest and South Central United States have changed within the past 150 years and whether or not any changes are correlated to climate change. Overall increases in temperature have an impact on plant phenophases; however, the minimum temperatures specifically, seem to have the largest impact. A study on grassland vegetation and global warming concluded that minimum monthly values are increasing faster than the maximum monthly values for each season of the month (Alward et al. 1999). In addition, the spring season minimum monthly values affect flowering times greater than any other season (Alward et al 1999).
Methods

Plant selection was based on a detailed review of botanical information on shrubs and forbs that are native to Nebraska, attract pollinators, and have flowering times of 1 to 2 months (Lindgren 2010, Panella 2017). 10 species met these criteria, including *Ceanothus americanus*, *Ceanothus herbaceus*, *Prunus americana*, *Prunus virginiana*, *Viola pedatifida*, *Penstemon grandiflorus*, *Cornus obliqua*, *Ostrya virginiana*, *Gymnocladus dioicus*, and *Lithospermum canescens*.

Once the specific species were determined I did a search on the Intermountain Region Herbarium Network database (http://intermountainbiota.org/portal/collections/harvestparams.php) which has pictures of specimens from herbarium collections across the United States. This search was narrowed to an area between 32.5-47.5° latitude and 80-102.5° longitude. This included the states of Nebraska, North and South Dakota, Minnesota, Wisconsin, Michigan, Illinois, Indiana, Iowa, Ohio, Oklahoma, Tennessee, Kentucky, Missouri, Arkansas, and parts of Texas, Colorado, Alabama, Mississippi, and Louisiana. These states were then split into different climate regions in accordance with the National Oceanic and Atmospheric Administration, NOAA, U.S. temperature regions (Figure 1). The regions that fit into my latitudinal and longitudinal search were the central, west north central, east north central, and south climate regions. From this search I found 863 individual specimens in the Intermountain Herbarium Network that included the month, day, and year, the latitude and longitude coordinates of where it was collected, and a picture of the plant mount.

I also looked at physical specimens available at the Keim Hall Herbarium and Bessey Herbarium at the University of Nebraska-Lincoln. Many of the specimens in each herbarium were collected in Nebraska and neighboring states or the central and west north central climate regions (Figure
These two resources added 1,036 specimens that fit into the search area for a total count of 1,926 specimens that were available for analysis.

For each plant I determined whether they were flowering by comparing the number of flowers to the number of flower buds or fruit. If there were more flowers than buds or fruit I considered the plant to be flowering and if there were more buds or fruit than flowers then the plant was considered non-flowering (Calinger et al. 2013). I disregarded any specimens that contained more fruits than flowers and specimens that were clearly not flowering at the time of collection. Some specimens did not have any flowers on the plant mount but flowers were found in packets that had been attached to the plant specimen. These specimens were considered to be flowering at the time of collection. For all of the plants I recorded the date and the location of collection, and any identifiable number or code that was given to that individual specimen.

Temperature was used to represent climate change because temperature changes have been shown to play a significant role changes in flowering time (Fitter and Fitter 2002, Panchen et al. 2012, Sparks et al. 2000, Waggoner 1974). Minimum monthly temperatures are increasing at a faster rate than maximum monthly temperatures and the spring season monthly minimums, specifically, have the greatest effect on flowering time (Alward et al 1999). I used monthly temperature data from the NOAA website that goes from 1895 to present day in the central, west north central, east north central, and south climate regions (Figure 2). For each year, I calculated the average minimum monthly temperature between January and March.

For the data analysis I used a linear regression with three different sets of variables: year as the independent variable and flowering date as the dependent variable, year as the independent variable again and average minimum monthly temperature as the dependent variable, and
average minimum monthly temperature as the independent variable and median flowering time as the dependent variable. The first analysis was used to determine if flowering dates were changing with respect to year and was done for each species in all regions and each region with all species included. The second analysis was used to determine if average minimum monthly temperature between January and March were changing with respect to year and was done for each region. The final analysis was conducted to see if there was any causation between flowering times and average minimum monthly temperatures for January through March. This analysis was conducted on the data for the central climate region because that region contained the most data points.

**Results**

Nine of the 10 plant species progressively had earlier flowering dates over the 150-year study period when looking at data for all climate regions combined. *Viola pedatifida* was the only plant species that trended toward a later flowering date for all climate regions combined—a change of 3 days (Table 1; Figure 3). *Ceanothus americanus* and *Ostrya virginiana* had the greatest change in flowering dates for all climate regions combined—*Ceanothus americanus* is flowering earlier by 33 days and *Ostrya virginiana* is flowering earlier by 29 days (Table 1; Figure 4; Figure 5). The data for species flowering date were also split up into each climate region. The central climate region had 8 of 10 species with earlier flowering dates, one species with no change—*Prunus virginiana*—and one species with too little data points to draw a conclusion—*Ceanothus herbaceus* (Table 1). The other three climate regions had a lot of variability of changes in flowering dates with some species flowering earlier and some flowering later.
Each climate region had earlier average flowering dates with all species data combined (Table 2). The central climate region had the greatest change in flowering date for all species combined (27 days earlier) and the east north central climate region had the smallest change in flowering date for all species (8 days earlier) (Table 2; Figures 6-9). All climate regions had earlier flowering times for all species data combined. Also, average minimum monthly temperatures for January through March for each climate region increased over the 150-year study period (Table 2). The east and west north central climate regions had the largest increases (3.24°C and 3.02°C, respectively) and the central and south climate regions had the smallest increases (1.1°C and 1.01°C, respectively) (Table 2; Figures 10-13).

The analysis of flowering date vs. average minimum monthly temperatures for January through March for the central climate region showed no causation between temperature changes and flowering time changes. Statistical analysis showed a significant relationship (P=0.04) between average minimum monthly temperature and flowering date but temperature, as the independent variable, explained an extremely low percentage of variation (r²=0.037) in flowering date (Figure 14).

**Discussion**

The results of this study support the findings of previous studies in that plants have been progressively flowering earlier over the last 100+ years; however, my findings did not support previous studies that stated minimum monthly temperatures are the key factor affecting changes in flowering time (Alward et al. 1999, Bradley et al. 1999, Calinger et al. 2013, Fitter and Fitter 2002, Franks et al. 2007, and Molau 1997, Panchen et al. 2012, Primack et al. 2004, Sparks et al. 2000). Mean minimum monthly temperatures for January through March explained only 3.7%
of the variation in flowering date of the selected species. Other factors appear to be the principal drivers of the change in flowering date over the last 150 years.

The variety of flowering date changes for all species in each region support previous studies that found plant responsiveness to changes in climate varies between each species (Bradley et al. 1999, Calinger et al. 2013, Fitter and Fitter 2002). This variation among individual plant species may also result in the geographic movement of plant species as shown by previous studies that mapped vegetation changes in North America (Overpeck et al. 1992). Differential movement and variability in flowering date will cause a disruption of the relationship between plants and wildlife species (Amano et al. 2010, Calinger et al. 2013, Fitter and Fitter 2002, Root and Schneider 2002).

Focusing on Nebraska, these changes in flowering dates may also have an effect on native pollinators. The Mottled Duskywing, which is a tier 1 species of concern in Nebraska, lays its eggs on *Ceanothus americanus* (Pannella 2017, Schneider et al. 2018). If *Ceanothus americanus* continues to flower earlier, the likelihood of pollinator mismatch between these two species will increase and this mismatch could result in the Mottled Duskywing losing its ability to reproduce. There is also an evolutionary relationship between *Lithospermum canescens* and the Hobomok skipper, which is a tier 2 species of concern in Nebraska (Schneider et al. 2018). *Lithospermum canescens* relies on the Hobomok Skipper for cross-pollination. If *Lithospermum canescens* continues flowering earlier, the chance of pollinator mismatch would increase and result in *Lithospermum canescens* losing its method of reproduction. The Hobomok Skipper would also lose access to a major food source.
Conclusion

Flowering dates for 9 of 10 species examined are getting earlier and average minimum monthly temperatures are also increasing for all climate regions examined; however, this increase in temperature did not correlate with earlier flowering dates. While it is clear that plants are flowering earlier, there are likely other factors besides temperature that are causing this shift in flowering times. These changes in flowering times corroborate previous studies that have found flowering times in the UK and eastern U.S. have been getting earlier (Bradley et al. 1999, Calinger et al 2013, Fitter and Fitter 2002, Franks et al. 2007, Henry et al 1997, Panchen et al. 2012, Primack et al. 2004, Sparks et al. 2000).

Future studies are needed to identify other factors that may be affecting flowering dates and to expand on the number of species that have been evaluated. Other factors could include temporal patterns of precipitation and the occurrence of drought. Temporal patterns of precipitation may have an effect on flowering date if precipitation does not coincide with plant growth. Drought would have a similar effect on flowering date by inhibiting plant growth due to lack of soil moisture and precipitation. If I were to do this study again, I would look at a greater number of specimens to improve statistical power, look at other climate factors like drought, and do more research into the possible link between flowering times and pollinator behavior.

Access to the Intermountain Herbarium Network was crucial to the success of this study. Having plant mounts posted online made it possible to get a lot of data from across the country that would have not been possible if just looking at physical plant mounts. Further digitization of herbariums is recommended in order to improve access to herbarium data. Most herbariums have not placed records of plant specimens online which greatly inhibits the access to plant
mount data that is needed to replicate studies like this one. Safety of herbarium specimens is also a concern. Physical plant mounts are vulnerable to fire damage and online records of these specimens would be a good backup in case of an accidental fire in a herbarium.
References


Panella, Melissa J. (Editor). 2017. Conservation strategy for Monarchs (Danaus plexippus) and at-risk pollinators in Nebraska. Nebraska Monarch and Pollinator Initiative, Nebraska Game and Parks Commission, Lincoln, NE.


### Table 1: Change in flowering time for all species in each region and all regions combined.

<table>
<thead>
<tr>
<th>Species</th>
<th>Central</th>
<th>South</th>
<th>East North Central</th>
<th>West North Central</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. americanus</td>
<td>-20*</td>
<td>-26*</td>
<td>-87*</td>
<td>-16*</td>
<td>-33*</td>
</tr>
<tr>
<td>C. obliqua</td>
<td>-12</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>-9</td>
</tr>
<tr>
<td>C. herbaceus</td>
<td>NA</td>
<td>+14</td>
<td>+20*</td>
<td>-12</td>
<td>-22</td>
</tr>
<tr>
<td>G. dioicus</td>
<td>-21*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>-4</td>
</tr>
<tr>
<td>L. canescens</td>
<td>-28*</td>
<td>-3</td>
<td>-14</td>
<td>-4</td>
<td>-24*</td>
</tr>
<tr>
<td>O. virginiana</td>
<td>-23*</td>
<td>+16*</td>
<td>NA</td>
<td>+4</td>
<td>-29*</td>
</tr>
<tr>
<td>P. americana</td>
<td>-21*</td>
<td>-17*</td>
<td>+2</td>
<td>-9</td>
<td>-24*</td>
</tr>
<tr>
<td>P. grandiflorus</td>
<td>-24*</td>
<td>-18</td>
<td>NA</td>
<td>-1</td>
<td>-3</td>
</tr>
<tr>
<td>P. virginiana</td>
<td>0</td>
<td>NA</td>
<td>+9</td>
<td>-29*</td>
<td>-18</td>
</tr>
<tr>
<td>V. pedatifida</td>
<td>-7</td>
<td>NA</td>
<td>NA</td>
<td>+5</td>
<td>+3</td>
</tr>
</tbody>
</table>

Table 1: Change in flowering time for all species in each region and all regions combined. NA values were for regions that did not contain enough data for that species to draw a conclusion on changes in flowering dates. Positive values represent later flowering dates and negative values represent earlier flowering dates. Asterisks denote statistically significant values ($R^2$ values ranging from 0.116 to 0.825 and $P$-values ranging from <0.001 to 0.017) and all others were non-significant values ($R^2$ values ranging from <0.001 to 0.089 and $P$-values ranging from <0.001 to 0.645).

### Table 2: Change in flowering date and change in average minimum monthly temperature for all climate regions.

<table>
<thead>
<tr>
<th>Climate Region</th>
<th>Change in Flowering Time (Days)</th>
<th>Change in Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>-27*</td>
<td>+1.1</td>
</tr>
<tr>
<td>East North Central</td>
<td>-8</td>
<td>+3.24*</td>
</tr>
<tr>
<td>West North Central</td>
<td>-12</td>
<td>-3.02*</td>
</tr>
<tr>
<td>South</td>
<td>-10</td>
<td>+1.01</td>
</tr>
</tbody>
</table>

Table 2: Change in flowering date and change in average minimum monthly temperature for all climate regions. Positive values represent increases in temperature or later flowering date and negative values represent decreases in temperature or earlier flowering date. Asterisks denote statistically significant values ($R^2$ values ranging from 0.072 to 0.1981 and $P$-values all <0.001) and all others are non-significant values ($R^2$ values ranging from 0.006 to 0.043 and $P$-values ranging from <0.005 to 0.51). Some lower $R^2$ values were considered significant because of the variety in flowering date ranges for each plant species in the four climate regions.
Figure 1: USDA Plant Hardiness Zone Map

Figure 2: NOAA U.S. temperature regions used to organize plant mount locations and temperature data.
Figure 3: Viola pedatifida flowering dates vs. years in all regions. Linear regression trendline start day is 128 which corresponds to May 8 and the end day is 131 which corresponds to May 11. This is a change of 3 days.
Figure 4: *Ceanothus americanus* flowering dates vs. years in all regions. Linear regression trendline start day is 189 which corresponds to July 8 and the end day is 156 which corresponds to June 5. This is a change of 33 days.
Figure 5: *Ostrya virginiana* flowering dates vs. years in all regions. Linear regression trendline start day is 123 which corresponds to May 4 and the end day is 94 which corresponds to April 4. This is a change of 29 days.

\[ y = -0.2004x + 497.72 \]

\[ R^2 = 0.1512; \text{ P-value} = 0.001 \]
Figure 6: All species flowering dates versus years in the central region. The start date for the linear regression trendline is 159 Julian days which corresponds to June 8 and the end date is 132 Julian days which corresponds to May 12. This is a change of 27 days.
Figure 7: All species flowering dates versus years in the east north central region. The start date for the linear regression trendline is 158 Julian days which corresponds to June 7 and the end date is 150 Julian days which corresponds to May 30. This is a change of 8 days.

Flowering Times for All Species Examined In the East North Central Region

\[ y = -0.0633x + 276.68 \]

\[ R^2 = 0.0062; \ P-value = 0.510 \]
Figure 8: All species flowering dates versus years in the west north central region. The start date for the linear regression trendline is 147 Julian days which corresponds to May 27 and the end date is 137 Julian days which corresponds to May 17. This is a change of 10 days.

\[ y = -0.0699x + 277.49 \]

\[ R^2 = 0.016; P\text{-value} = 0.002 \]
Figure 9: All species flowering dates versus years in the south region. The start date for the linear regression trendline is 135 Julian days which corresponds to May 15 and the end date is 123 Julian days which corresponds to May 3. This is a change of 12 days.

\[ y = -0.0936x + 311.58 \]

\[ R^2 = 0.0116; \text{ P-value} = 0.257 \]
Figure 10: The average minimum monthly temperature for January through March vs. years for the central region. The starting point of the regression line is -4.39°C and the end point is -3.29°C. This is a change of 1.1°C.

\[
y = 0.0101x - 23.425 \\
R^2 = 0.043; P\text{-value} = 0.028
\]
Figure 11: The average minimum monthly temperature for January through March vs. years for the east north central region. The starting point of the regression line is -13.63°C and the end point is -10.61°C. This is a change of 3.02°C.

Regression equation: 

\[ y = 0.0245x - 60.055 \]

\[ R^2 = 0.145; \text{ P-value } < 0.001 \]
Figure 12: The average minimum monthly temperature for January through March vs. years for the west north central region. The starting point of the regression line is -12.95°C and the end point is -9.71°C. This is change of 3.24°C.
Figure 13: The average minimum monthly temperature for January through March vs. years for the south region. The starting point of the regression line is 1.02°C and the end point is 2.03°C. This is a change of 1.01°C.

\[ y = 0.0082x - 14.517 \]

\[ R^2 = 0.047; \text{ P-value} = 0.015 \]
Figure 14: The median flowering date for all species in the central region vs. average minimum monthly temperatures for January through March for the central region. The graph shows a decrease in flowering date of 2.73 days for each 1°C increase.

$y = -2.4176x + 135.87$

$R^2 = 0.0367; P\text{-value} = 0.043$