Investigating the Effects of Climate Change on the Phenology of *Achillea millefolium*, *Aquilegia coerulea*, and *Penstemon cyanocaulis*

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Abstract

As the effects of climate change are starting to unearth themselves, the impacts can be observed by tracking the patterns of cyclical natural phenomena also known as phenology, and monitoring how they have changed over time. These cycles are at the crux of making ecosystems viable for their local biodiversity, and understanding the ongoing change allows for further understanding of the ecosystem's change over time. In this study, we look at the ordinal flowering dates of the *Achillea millefolium*, *Aquilegia coerulea*, and *Penstemon cyanocaulis* over the past century. Our data give insight into how warmer temperatures occurring earlier in the year are changing the cycle of flowering plants in the western United States. This framework encourages more investigation into the changes in plant phenology throughout different regions due to climate change.

Keywords: climate change, phenology, conservation, ecology, *Achillea millefolium*, *Aquilegia coerulea*, *Penstemon cyanocaulis*

1 INTRODUCTION

Phenology is the study of cyclical natural phenomena. Scientists use it to examine how plant and animal life, as well as various natural occurrences, vary with seasonal and climatic changes. Studying phenology allows us to observe how certain cycles change over time with relation to environmental factors, such as climate. From 1907 to 2007, the World Meteorological Organization recorded a 0.74°C increase in average global temperature. It has been shown that warming temperatures in Colorado have caused earlier flowering times in several rare plant species[1] and that several alpine species in Colorado are blooming earlier[2]. However, to our knowledge, individual, common plant species at lower elevations across Colorado have yet to be investigated. In this research, we examine the bloom times of three common flowering plants in Colorado to see if warming temperatures have an impact on when these species bloom.

We begin by looking at the bloom times of *Achillea millefolium*. This species is found in many regions throughout North America, Europe, and Oceania, and typically blooms during the summer months[3]. A study examining the flowering time of *A. millefolium* in the alpine region of Europe concluded that a lowland environment was better for the reproduction of this plant species. Given that temperatures are generally higher at lower elevations, this corresponds with the preferred warmer temperatures for *A. millefolium* taxon to bloom[4].

There is little published information on *A. millefolium*'s response to climate change; however, one study done by Sebastià et al. in the subalpine grasslands of the Pyrenees Mountain range in Europe found that the biomass of *A. millefolium* increased significantly after a short period of warming and drought, suggesting that this species thrives in warmer temperatures[5]. Another study performed in the Snowy Mountains range of Australia, by Johnston and Pickering, revealed that altitude impacted the flowering times of *A. millefolium*, with shorter flowering periods earlier in the year at higher altitudes[6]. This suggests that this species has decreased fitness, or less successful reproduction, in cooler temperatures; both features of high altitudes.

We also examine how warming temperatures in the state of Colorado may impact the flowering time of the Colorado blue columbine, *Aquilegia coerulea*. When studying the phenology of *A. coerulea*, it is important to note the variation in the ecosystems in which the

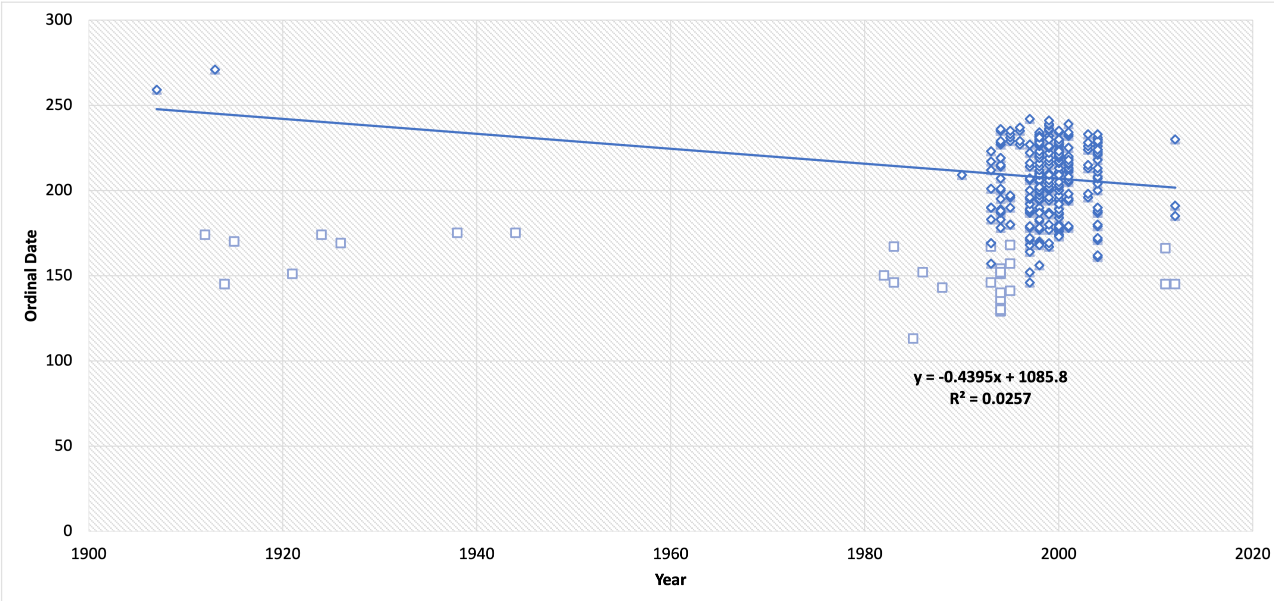

Figure 1. *A. millefolium* ordinal flowering date in Colorado between 1907 and 2012.

species occurs naturally. In a recent study, the change in flowering time for various species was found to be dependent on both temperature and altitude, with high elevation individuals showing no significant shift of flowering time in response to the changing climate[7]. It is possible the flowering times for the Colorado blue columbine may vary significantly throughout various regions at different altitudes, making it more difficult to detect the impact of warming temperatures.

The rapid responses of flowering time to the warming temperatures are due to phenotypic plasticity, or change in an organism's phenotype in response to environmental changes[8]. While there have been studies focusing on the effects of climate change on the alpine species, *A. coerulea*'s response has not been widely studied.

Penstemon cyanocaulis continue in this trend; like many other flowering species in the same climatic region, the flower times are predicted to become earlier in the year as climate change progresses and the regional temperature and climate patterns of the Rockies grows warmer. One 2011 study analyzed *P. cyanocaulis* growing in the Rocky Mountain region of the Colorado River Basin to develop a predictive model using various climate data, including precipitation, surface air temperature, and water runoff, to determine bloom-date changes[9]. They determined that earlier snowmelt dates and higher spring temperatures led to earlier bloom dates of this species. Another study analyzed the effects of climate change on flowering phenology in Gunnison County, CO[10]. The flowering phenology of two spring seasons were analyzed in the context of the previous winter's snowmelt date. The researchers determined that yearly changes in phenology and growth of the flowers were related to soil temperatures and snowmelt date. A separate study done specifically on the genus *Penstemons*, tested the effects of January temperature fluctuations on germination timing[11]. The majority of species exhibited earlier germination when winter temperatures were higher, including *P. cyanocaulis*.

In this research, the null hypothesis (H_0) was that the bloom times (as determined by the collection date in herbarium specimens of *A. millefolium*, *A. coerulea*, and *P. cyanocaulis*), do not change over time. That is, changes in bloom time are due to chance. We predict that blooming will occur earlier in the year over time because of cues from warming temperatures.

2 METHODS

The data for all species were collected from the Rocky Mountain Herbarium Specimen Database[12]. After filtering out the data for the plants that were not flowering, leaving only the data for the flowering plants as well as the flowering and fruiting plants, the ordinal date of the blooming time was calculated to show how many days into the year each species of flower bloomed. Ordinal date considers January 1st as 1 and allows us to determine if recorded bloom times occurred earlier or later in the year over time. For all three species, there were collections that spanned more than a century and were from many locations in Colorado. With these data, we then tested our null hypothesis that bloom time, as measured by ordinal date of collection, did not change over time using a linear regression test, with ordinal date of flowering time as the dependent variable and

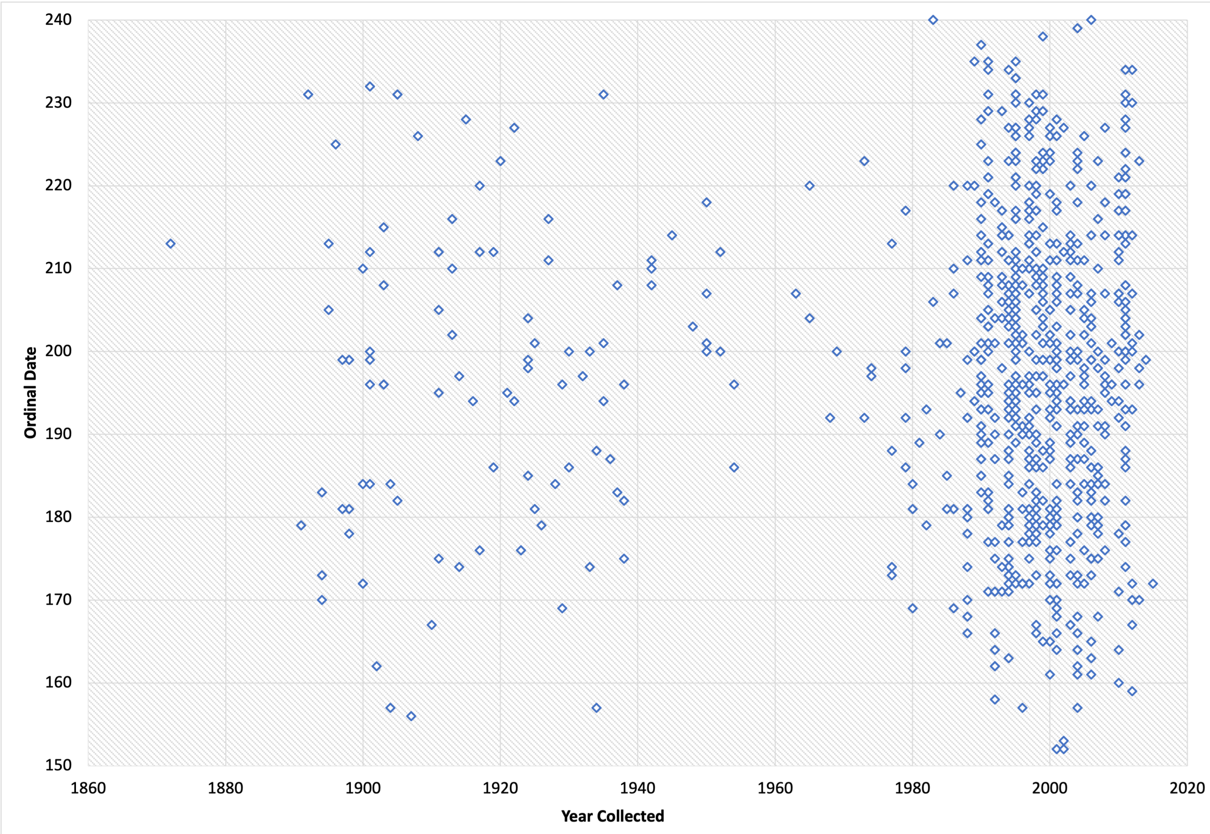

Figure 2. *A. coerulea* ordinal flowering date in Colorado between 1892 and 2014.

year as the independent variable.

3 RESULTS

3.1 *Achillea millefolium*

Figure 1 shows the relationship between collection date (ordinal date) and collection year (n = 344). The regression, $y = 0.4395x + 1085.8$, is statistically significant. Since the p-value (p = 0.003) is less than 0.05, we rejected the null hypothesis. Using the equation of the regression line, we calculated that the ordinal date in 2021 would likely be approximately 198, which is 61 days earlier than the first recorded bloom time in 1907. R^2 = 0.03.

3.2 *Aquilegia coerulea*

Figure 2 depicts ordinal date and year for *A. coerulea* (n = 458). The p-value of p = 0.42 and R^2 = 0.001 shows that the relationship between ordinal date and year is not statistically significant. Thus, we do not reject the null hypothesis of no change in ordinal date over time.

3.3 *Penstemon cyanocaulis*

The total number of data points and specimens cataloged for *P. cyanocaulis* was n = 46 (Figure 3). The relationship between year and ordinal date was statistically significant with $p < 0.003$ and R^2 = 0.19. Using the equation of the regression line ($y = -0.194x + 532.91$), we calculated that the ordinal date in 2021 would likely be approximately 142, which is 32 days earlier than the first recorded bloom time in 1912.

4 DISCUSSION

Overall, our results partially support the hypothesis that blooming of common Colorado wildflowers is occurring earlier over time. Two of the three species had significantly negative slopes of collection date across years, using data that spanned over a century.

The results show that there is a relationship between bloom time of *A. millefolium* and year recorded, supporting previous findings that there is a relationship between warming temperatures and bloom time of this plant taxon. However, the R^2 value was low, indicating that a very small proportion of the variance for the measurements of the dependent variable (ordinal date of bloom time) can be explained by the relationship be-

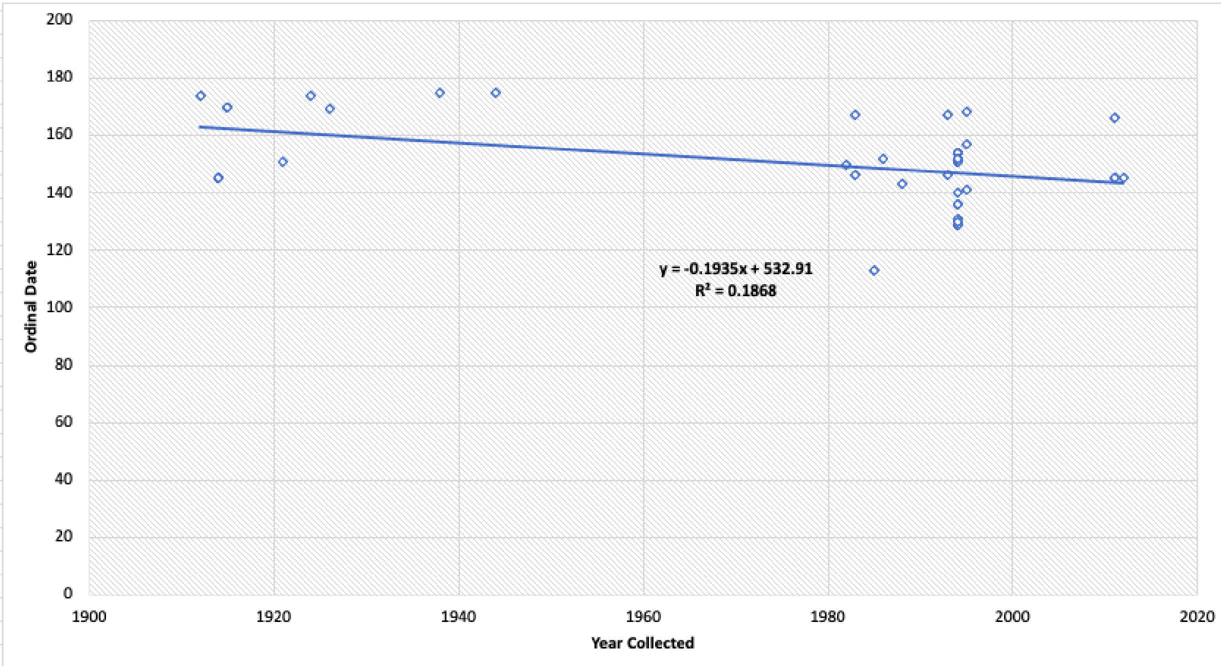

Figure 3. *P. cyanocaulis* ordinal flowering date in Colorado between 1914 and 2012.

tween ordinal date and the year recorded. This shows a limitation to this approach in using the ordinal date of the bloom time to infer a relationship between warming temperatures and bloom time of this species. First, collection date is an imperfect measure of flowering time, since we do not know when during the window of time it was flowering the collection took place. Second, *A. millefolium* can grow at many different elevations and across the state; thus, even if temperature perfectly predicts bloom time, we would expect there to be variability caused by location. Third, there is a large gap in the data for this species, during which time the bloom dates of the flowers could have shown a different pattern throughout; this lack of data limits the confidence with which it can be interpreted.

Finally, there could be other, unknown variables at play. For instance, *A. millefolium* could flower based on environmental or genetic markers other than temperature; this marker that varied in the same manner as temperature over the recorded time shown, indicating that there could be confounding variables in this study that impact its validity. If this is the case, we are concluding that warming temperatures cause premature blooming in this species, when in fact, it is another environmental factor that causes the premature blooming. There may even be a blooming trigger that is completely unrelated or less directly related to the climate, such as the presence or absence of a certain insect species. If any of these are the reason for the pattern we observed, then we would be making a Type I error in concluding a relationship between the bloom time of *A. millefolium* and climate change.

On the other hand, if precipitation or some atmospheric condition impacts bloom time of *A. millefolium*, then we can likely link climate change to the cause of earlier blooming, as climatic change also impacts precipitation and other atmospheric conditions.

While a Type I error is technically possible, it is unlikely as previous research discussed in the introduction shows a relationship between the bloom time of *A. millefolium* and climate. Human-caused climate change is likely the cause of premature blooming of this species, with variability caused by direct (precipitation, temperature) and indirect (soil health, presence or absence of insect species) effects.

As for *A. coerulea*, there is failure to reject the null hypothesis. Thus, the year the data were collected has no relationship to the date of collection for *A. coerulea* in the state of Colorado. This suggests that there is no significant change in the flowering time of the *A. coerulea* in response to warmer temperatures due to climate change. This may be because not all species use temperature as a cue to begin flowering, but may use photoperiod, which is the amount of illumination an organism receives in a day. Of course, day length does not change from year to year, so if this is the cue for flowering, there would be no change in collection date over time.

Alternatively, it is possible that *A. corulea* is affected by temperature but we failed to detect it; that is, our analysis yielded a Type II error. This may be due to the high variability seen in Figure 2, likely caused by the fact that these specimens were collected from many different populations over a wide geographic area. Ideally, the observed species would be in one concentrated area. Using observations on individual populations over time may have provided a better indicator for the possible effect of temperature on the species' flowering date. This would minimize the variation seen in this data set and would improve the understanding on the changing climate's effects on Colorado's state flower.

Regarding *P. cyanocaulis*, the significant linear regression with a negative slope indicates that over the 100 years of data, the ordinal date of blooming for this species has continued to shift earlier in the year. The overall trend exhibited by the significant slope gives strong evidence that there have indeed been changes to the phenology of *P. cyanocaulis*, despite the mild fluctuations in bloom date from year to year. Additionally, there is a period in the data in which there is an absence of *P. cyanocaulis* samples collected. This gap in the data means that there is uncertainty as to what occurred during this period in history. However, the distribution of the data was different enough, showing that climate change is changing the flowering dates of *P. cyanocaulis*. Based on these results of a pattern that has occurred over the last 100 years, and that the globe is still warming due to climate change, we predict that the flowering date will likely continue to shift to earlier in the year.

While all three of these species of flowering plants can be found in Colorado and the Western states, their response to the warming climate differs among them. These differences may be attributed to additional influences on blooming time, such as day length, soil or precipitation conditions, etc. It will require further research to determine the specific triggers for bloom date for each species.

This method of studying the relationship between plant phenology and climate change is becoming more common as herbarium data is now easier to access through public databases. However, there are still some issues to consider with this method. First, it is entirely dependent on what data happened to be collected on a particular species over time. There is also no guarantee that there is sufficient data for a particular species, as the species could span a more extensive range than surveyed. Additionally, although we found a significant change in flowering date over time for two species, and over this same period temperatures have been warming, this does not prove causality. However, given that many species are cued by temperatures, it seems likely that these species are responding to climate change.

Premature blooming as the result of warming temperatures can impact the entire ecosystem. For instance, various insects may miss out on pollination if they have a different cue than temperature. This affects not only the population of those insects but the flowering plants as well, as fertilization and seed dispersal will not be possible without the presence of pollinators. Further research on the factors that impact flowering times can help inform conservation decision-making and how best to preserve important species and ecosystems.

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6 EDITOR'S NOTES

This article was peer-reviewed.

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