Effects of spatial clustering on alpine plant flowering phenology during a dry year

Summer 2026 Full-Time Independent Research / REU

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Abstract

Climate change is shaping interactions within alpine ecosystems. Increase in global temperatures and decrease in snowpack are shifting phenology and raising concerns about future plant productivity, competition, and community dynamics. Phenological shifts are occurring more prominently in cold, high-elevation environments, making alpine plants the most susceptible to warming. As advanced snowmelt timing is causing alpine plants to flower earlier and changing the length of the growing season, the interactions between spatially clustered and non-clustered, or isolated, plants are becoming more important for understanding alpine community reorganization. While spatially clustered plants can facilitate each other to promote community resilience to climate change, isolated plants face greater risk to spring frost events, topographic exposure, and other variables. Variation in slope and aspect influence incident solar radiation at the soil surface, impacting the patchiness of snowpack, direction of snowmelt streamflow, vegetation growth, and plant distribution. Using field data from the 2026 year, this study addressed the changes in flowering phenology at a NSF-Long Term Research in Environmental Biology (NSF-LTREB) site at Mount Baldy (38.978725°N, 107.042104°W), located northwest of Gothic, Colorado. I predicted that (H1) compared to 2015 and 2025 data, isolated plants will flower earlier than clustered plants due to lack of moisture retention and thermal buffering, (H2A) that due to lack of soil moisture this season's early snowmelt will shorten flowering duration or alternatively (H2B) that rain and monsoons will extend the length of flowering duration, (H3) plants on south-facing slopes will exhibit earlier first flowering dates than north-facing plants, and (H4) the flowering time of plants has advanced since 2015. Twice a week from June–July, open flowers were counted amongst four species, *Heterotheca villosa* (HETVIL), *Ivesia gordonii* (IVEGOR), *Lupinus argenteus* (LUPARG), and *Senecio crassulus* (SENCRA). 200 individual plants were counted, 50 per species, and 25 clustered and isolated. With a final sample size of n=38, Gaussian curves were fitted for each species to estimate phenology and to predict when clustered and isolated plants flowered this season in comparison previous years; linear regressions were also run to model effects of clustering and plant size on first flowering date, separately. The 2026 curves were compared with 2015 phenology curves to identify the effects of clustering over time. Snowmelt date and aspect were separately compared with flowering duration and the first flowering dates using a linear regression model. Clustering, plant size, snowmelt date, and topographic aspect did not have a strong effect on the first flowering date or flowering duration for each species. However, within SENCRA, stronger clustering effects were consistent with our hypothesis (H1) that clustered plants would flower earlier than isolated plants. (H1) was supported by SENCRA, but not supported by HETVIL, IVEGOR, and LUPARG; the rest of the hypotheses (H2, H3, H4) were rejected by all species.

Introduction

Above the mountainous treeline are alpine environments, containing highly specialized plants that adapt and respond to demanding conditions such as drought, freezing temperatures, and high UV radiation (Körner, 2003). These high-elevation systems are tolerant of a wide range of harsh environmental conditions, and visually heterogeneous (Körner, 2003), characterized by variable physical terrain and below-ground processes that diversify the climate (Grabherr et al., 2010). Combined with the amount of solar radiation exposure, topography largely shapes plant life at altitude (Körner, 2003), dictating vegetation growth, plant distribution, and soil nutrients density (Singh, 2018). While species richness generally decreases along elevational gradients (Guo et al., 2013), alpine environments harbor many endemic species and therefore contain unique biodiversity. Topography (both slope and aspect) can influence vegetation cover and species richness (Nadal-Romero et al., 2014). Between north and south-facing slopes, south-facing slopes are more likely to be abundant in plant species richness of the two due to differences in solar radiation (Nadal-Romero et al., 2014), and west-facing slopes are found to be warmer than east-facing slopes (Singh, 2018). While the complexity of alpine environmental heterogeneity can dictate the amount of snowpack and the direction in which snowmelt flows in, it can also generate microclimates that facilitate resiliency to drought stress and specific ecological niches (Pérez-Giraldo et al., 2026).

Since the nineteenth century, average global temperatures have risen substantially, and in response, ecological processes have shifted (Arnell et al., 2019). Not only has this impacted the microclimate of various ecosystems (Rafferty et al., 2020), but climate change is also shifting the phenology of plants around the world (Badeck et al., 2004). Phenology is crucial because it drives plant productivity, competition, and community interactions (Badeck et al., 2004). Alongside a rise in air temperatures, the warming of soil temperatures during late winter and early spring and earlier drying of soils after snowmelt has advanced the spring onset for alpine plants (Richardson et al., 2018). This shift has affected the flowering time of plants and, in turn, has resulted in a mismatch between some plants and pollinators (Miller-Rushing et al., 2010). Sensitivity to warming is dependent on the life history of a plant (Varpe, 2017). While some plants are utilizing environmental cues to shift the timing of reproduction (Inouye, 2008), other plants are failing to acclimate to the changing climate. Phenological responses to temperature are greater at colder regions and altitudes, making alpine plants the most likely to be most stressed by phenological change (Rafferty et al., 2020).

As temperatures increase, it is important to also consider the effects of extreme droughts in alpine sites. Alpine communities are especially influenced by moisture, which is dependent on snowmelt and snow depth (Winkler et al., 2018). Importantly, flowering phenology is closely related to snowmelt timing as timing can determine the length of the growing season (Winkler et al., 2018). However, due to varied phenological sensitivities, not all plants flower simultaneously after snow melts (Dawson-Glass et al., 2025). Following global warming trends, the annual amount of snowmelt has considerably decreased within montane ecosystems of the western United States (Mote et al., 2005). Less snowmelt results in less soil moisture, changing the composition of alpine communities (Walker et al., 1995). Without the temperature buffering of snowpack, high-elevation plant life is at risk from spring freezing events

(Wheeler et al., 2014). These frost events are correlated with less fruit production, potentially due to limited pollen, which is possibly exacerbated by pollinator mismatch. Earlier snowmelt time can reduce plant performance and fitness, increasing probability of herbivory and damage (Wheeler et al., 2016). Due to harsh summer conditions, alpine plants are also threatened by dehydration because of lack of snowmelt hydration and increased evapotranspiration due to direct sunlight exposure (Rosbakh et al., 2017). This positive correlation between drought severity and altitude indicates that alpine plant mortality is likely becoming more frequent. Drought can impact plant vegetative traits, decreasing specific leaf area, increasing likelihood of leaf damage, and increasing lack of resistance to desiccation (Rosbakh et al., 2017, Wheeler et al., 2016). Extreme climate conditions may ultimately lead to changes in community structure and influence thermophilization, the process of heat-tolerant species gaining dominance as global temperatures arise (Rosbakh et al., 2017).

While the abiotic environment is important to consider, a biotic factor that facilitates community resilience to climate change is spatial clustering of individuals (Anthelme et al., 2014). The environmental heterogeneity of alpine ecosystems drives microclimate and functional trait differences amongst clustered and non-clustered plants (Stark et al., 2017). Clustering is a variable that influences growth, fitness, and phenology (Xu, 2025). It also has significant effects on leaf surface temperature and surface temperature buffering, implying that clustered plants may be more resilient to climate change because of thermal buffering (Ramsey, 2025). Phenologically, clustered plants are more likely to flower later than non-clustered plants (Xu, 2025), influencing peak flowering times. Clustered plants also tend to be more stress-tolerant than non-clustered plants, with non-clustered plants exhibiting higher demand for nutrients and competition (Losapio et al., 2018). At higher, exposed sites, positively interacting plants tend to exhibit more facilitative responses compared to low elevation sites (Choler et al., 2001), which are encouraged by earlier snowmelt (Anthelme et al., 2014). Spatially clustered plants can impact the concentration of higher-order interactions, which are interactions among multiple species (Gibbs et al., 2025). In particular, alpine communities are mostly characterized by stress-tolerant species that support the plant assembly, thus the spatial clumping in the alpine assembly structure (Losapio et al., 2018). Species with similar morphologies may be able to prevent desiccation or frost events (Maestre et al., 2009, Choler et al., 2001).

Nurse or cushion plants, species that benefit other plants (Filazzola & Lortie, 2014), also buffer extreme temperatures and facilitate the alpine (Anthelme et al., 2014). In fact, within unproductive ecosystems, cushion plants may increase species richness, along with the fitness and growth of other species within these clusters (Cavieres et al., 2014). However, this facilitation may not be enough to withstand high abiotic stressors. Plants are highly sensitive to global warming, with low elevation fast species plants migrating upward the elevation gradient (Anthelme et al., 2014). As microclimates are shifting across montane ecosystems, it is unpredictable how beneficial plant clustering can be in buffering rapid snowmelt.

At the Rocky Mountain Biological Laboratory, this year represents a 1-in-500 year anomaly record-low snowpack (*200- to-1,000-Year Snow Anomaly Observed in Colorado Mountains*, 2026). Given the particularly dry 2026 season, studying phenology is both interesting and informative for understanding

how alpine communities are responding to climate-change driven stress. There are few research studies that address the influence of plant clustering, and even less around the effect of topographic heterogeneity on flowering phenology. This research aims to specifically extend previous phenology studies at Mount Baldy by Rebecca Dalton (2015) and Hillary Xu (2025) with the question: how is the flowering phenology of clustered and non-clustered Mount Baldy alpine plants responding to a particularly dry and unusual year? This study will address how alpine plant phenology at Mount Baldy compares to 2015 and 2025 in the context of the current dry season, and with only two years of existing phenology data at this site, a third year of data will contribute to understanding long-term changes of flowering phenology and alpine community assembly in the Rocky Mountains.

I hypothesize that (H1) because of an increased lack of thermal buffering, non-clustered plants will flower relatively earlier than clustered plants compared to 2025. I also hypothesize that (H2A) early snowmelt will be associated with shorter flowering duration due to reduced soil moisture. Alternatively, it is possible that (H2B) earlier snowmelt is associated with longer flowering duration because of moist weather such as rain or monsoons. Considering the heterogeneity of the site's topography, I hypothesize that (H3) south-facing plants will exhibit earlier first flowering dates than north-facing plants as a result of warmer surface temperatures. Lastly, I hypothesize that (H4) the flowering time of plants has advanced since 2015. This study aims to extend past research around alpine community assembly and function, to discern the role of environmental heterogeneity in plant success, and to understand climate change's role in phenology.

Methods

1.1 Study Site

Fieldwork was conducted at the Mount Baldy (38.978725°N, 107.042104°W) Long Term Research in Environmental Biology (LTREB) site in the Colorado Rocky Mountains, United States. The project took place from late June 2026 to mid-August 2026.

1.2 Phenology

Twice a week from early to late July, open flowers were counted based on the previous phenology protocol written by Rebecca Dalton in 2015. This protocol is to "count the total number of open flowers on each capitulescence", disregarding flowers with brown, dried out petals with no visible anthers.

Four species: *Heterotheca villosa* (HETVIL), *Ivesia gordonii* (IVEGOR), *Lupinus argenteus* (LUPARG), and *Senecio crassulus* (SENCRA) were considered, with around 50 individuals each counted. Of the 50 individuals, 25 were clustered, and 25 were non-clustered. Plants were located within 30 meters of the focal plots. In accordance with Dalton and Xu, clustering was defined by a group of different species growing within two finger lengths. Position, left (L). middle (M), and right (R), were recorded along the slope of the site. The majority of the 200 tagged individuals were located outside of LTREB plots, with the exception of a few plants. Individuals were haphazardly selected based on their landscape position along the site's elevational gradient.

Plant size (height, length, width) were also measured. Height (cm) was measured as the height of the plant from the soil to the top of the plant. Length (cm) was measured as the length of the plant along the longest axis. Width (cm) was measured as perpendicular to length. The equation πabh was used for plant size, where a = 0.5*length (cm), b = 0.5*width (cm), and h = height (cm).

1.3 GPS

Individual plants were plotted on a Trimble DA2 GPS unit for mapping and spatial analysis with an accuracy of ±60 cm (Figure 1).

1.4 Data Analysis

Calculating Flowering Metrics

(H1 & H4) Phenology comparison methods were followed according to Hillary Xu in 2025 (Xu, 2025). We determined how flowering dates differed among clustered and isolated individuals for each tagged plant in comparison to 2025 preexisting phenology data collected by Xu, and in general with Dalton in 2015. The phenology curves of HETVIL, IVEGOR, LUPARG, and SENCRA plant species and individuals were generated in R version 4.6.0 (R Core Team, 2026) and fitted using a Gaussian curve using a nonlinear least squares algorithm by plant species, clustering, and tag numbers (Figure 2). From the curves, we extracted the first flowering day, peak flowering, flowering duration, and the maximum number of flowers open on a given day (see Section 1.5 Hypotheses Test).

Flowering times of isolated tagged plants were compared with flowering times of clustered tagged plants across 2026 and 2025, as 2015 did not contain clustering data. Tagged plants that were lost or eaten, had never exhibited reproductive structures, had a flowering duration relative error (the standard error of the standard deviation divided by the standard deviation) greater than two, or simply did not have enough non-zero data (plants with less than three non-zero data points) were excluded from models during quality control. A total of n=38 plants were retained after quality control (Figure 5).

Due to the early start of the growing season, the number of open flowers for IVEGOR, LUPARG, and SENCRA from the beginning of the season were not recorded. The first half of their curves (first flowering days) were estimated using the Gaussian distribution. Additionally, because of the timing of our research study, we were unable to record the peak flowering for HETVIL, so the second half of its phenology curve was not created. We only used HETVIL that flowered, and from that tag group, only modeled the HETVIL of which we caught their first flowering dates (arranged by day). This reduced our HETVIL sample size from n=38 to n=31.

Snowmelt Data Extraction

(H2) After analyzing Plant Labs snow cover maps from 2017–2026 (John et al., 2022), we produced maps (Figure 1) of estimated snowmelt dates for Mt. Baldy. Snowmelt dates were determined as the first day snow was absent on each pixel (only high quality pixels). The first snow-free date for each tagged plant was identified by extracting snowmelt data from each plant coordinate in QGIS version 3.44.11 (Nyall Dawson et al., 2026).

Extracting Slope Aspect

(H3) Slope aspect (southness) was calculated and extracted using a digital elevation model (DEM) with R package *rSDP* (Breckheimer, 2023). Again, tags with a flowering duration relative error greater than two were not considered.

1.5 Hypotheses Test

Packages *dplyr* (Wickham, François, et al., 2014), *stats* (R Core Team, 2026), *tidyr* (Wickham, Vaughan, et al., 2014), *readxl* (Wickham & Bryan, 2015), *purrr* (Wickham & Henry, 2015), *DHARMa* (Hartig, 2016), *visreg* (Breheny & Burchett, 2017), and *minpack.lm* (Timur V. Elzhov, Katharine M. Mullen, Andrej-Nikolai Spiess, Ben Bolker, 2022) were used. Graphs were created using *ggplot2* (Wickham, 2016), and *ggpubr* (Kassambara, 2026).

Nonlinear Least-squares Models

Nonlinear least-squares models identified maximum number of open flowers, peak flowering, and first and last flowering dates using the nlsLM function (package *minpack.lm*) and formula: avg_flowers_day ~ k*exp(-0.5*((day - m)/sd)^2). m = day with peak flowering, sd = standard deviation in days, and k = maximum number of open flowers. Flowering duration was calculated using the formula: 2*sd. First flowering date was calculated using m - (2*sd). Separately, first flowering dates for HETVIL were determined as ffd = day.

Linear Models

For each hypothesis, we fit linear models separately with parameters identified from nonlinear least-squares models as response variables (first flowering date and flowering duration; peak flowering not considered since we were unable to record HETVIL peak flowering data).

Modeling Hypotheses

(H1) Linear regressions were run for each species to find a significance, if any, for clustering and separately, plant size. A *DHARMa* residual test was performed for each species' tags to check model assumptions, view the relationship between predictors and residuals, and also verify if heteroscedasticity was present. QQ plot residuals were also generated to check the deviation and distribution of data points relative to the regression line. (H2) The first snowmelt-free date and clustering was used to predict the flowering duration of individual plants in a linear regression. Of the four species HETVIL, IVEGOR, LUPARG, and SENCRA, HETVIL was excluded from the analysis because of a lack of beginning and end HETVIL data. (H3) Similar to the linear regressions for the first hypothesis, we looked to see if there was any significant effect of slope aspect for each plant species' first flowering date. (H4) 2026 first flowering and peak flowering dates for each individual plant were compared with 2015 individual plants. We identified a single plant for each species that exhibited the earliest peak flowering date and also accounted for their first flowering dates.

Results

2.1 Phenology Modeling

From the species level Gaussian curves (Figure 2), we found that in 2026, clustered IVEGOR flowered earlier than isolated IVEGOR by 2.65 days. Clustered LUPARG flowered earlier than isolated LUPARG by 11.26 days. Clustered SENCRA flowered slightly earlier than isolated SENCRA by 0.93 days. HETVIL could not be determined because there was not enough data for non-zero open flowers.

In 2025 (Figure 3), isolated and clustered IVEGOR first flowered on relatively the same day (day 0.84). 2025 LUPARG standard deviation data seemed to contain errors, so flowering time comparisons for clustered and isolated LUPARG were determined by peak flowering date. Thus, clustered LUPARG peak flowered earlier than isolated LUPARG by 8.73 days. Clustered SENCRA also flowered earlier than isolated SENCRA by 0.06 days. Overall, clustered plants seemed to flower relatively earlier than isolated plants; 2026 clustered plants flowered earlier than 2025 clustered plants.

On an individual level, single-variable regressions were run for each plant by species (Table 2). Clustering had a significant effect on the first flowering date for SENCRA ($p = 0.0383^*$, $R^2 = 0.36$) (Figure 6) as clustered SENCRA flowered 5.473 days earlier than isolated SENCRA. Clustering did not significantly affect the first flowering date for the rest of the species. While clustered plants flowered earlier than isolated plants by 7.877 days, clustering was not significant for LUPARG's first flowering date ($p = 0.273$, $R^2 = 0.13$) (Figure 7). Clustering was also not significant for IVEGOR's first flowering date ($p = 0.325$, $R^2 = 0.097$). Clustered IVEGOR flowered 6.946 days earlier than isolated IVEGOR (Figure 8). Unlike the other species, isolated HETVIL (Figure 9) flowered 1.512 days earlier than clustered HETVIL ($p = 0.476$, $R^2 = 0.018$).

Plant size was also considered as a predictor of the first flowering date for each species, but was overall found to not have a statistically significant effect (Table 2, Figures 17-20).

2.2 Snowmelt and Flowering Duration

Linear regressions modeled the effects of both snowmelt date and clustering, which were found to not have strong effects (Table 3), simultaneously on flowering duration across species. Snowmelt date ($p = 0.665$) and clustering ($p = 0.753$) for IVEGOR (Figure 10) was not significant ($R^2 = 0.04$) for its flowering duration. Snowmelt date ($p = 0.772$) and clustering ($p = 0.241$) were also not a significant predictor ($R^2 = 0.22$) for LUPARG (Figure 11) flowering duration. Snowmelt date ($p = 0.631$) and clustering ($p = 0.376$) did not have a significant effect ($R^2 = 0.21$) on SENCRA's (Figure 12) flowering duration. Again, HETVIL was not accounted for because there was not enough data to measure its flowering duration.

2.3 Slope Aspect and First Flowering Date

Overall, slope aspect was not a strong predictor for the first flowering date for each plant (Table 4). While there visually was a negative relationship (Figure 13) between slope aspect (south) and first flowering date for HETVIL, slope aspect (south) did not have a strong effect ($p = 0.44$, $R^2 = 0.02$). Similarly, the slope aspect (south) for IVEGOR (Figure 16) was not significant ($p = 0.557$, $R^2 = 0.03$). Slope aspect (south) was also not a very good predictor ($p = 0.2389$, $R^2 = 0.14$) for LUPARG first flowering date (Figure 14), and similarly for SENCRA ($p = 0.468$, $R^2 = 0.05$) (Figure 15).

2.4 Phenology Comparison with 2015 and 2025

The earliest first flowering and peak flowering dates for each species were compared between 2026 and 2025 (Figure 5 and 21) In 2015, the earliest peak flowering date for HETVIL was at day 212, with the first flowering date being 1.5 days before the peak flowering date. Though we were unable to measure the peak flowering date for HETVIL in 2026, we found that the earliest first flowering date was day 191. 2015 IVEGOR's earliest peak flowering date was day 198 and the first flowering date was 1.33 days earlier. 2026 IVEGOR experienced peak flowering on day 173, and first flowering 7.83 days prior to the peak flowering date. 2015 LUPARG peaked on day 207 and first flowered on 1.83 days before peaking. In 2026, the earliest LUPARG peaked on day 181 and first flowered 7.42 days prior to peak flowering. 2015 SENCRA peaked on day 216 and first flowered 2.05 days before peaking while 2026 SENCRA peaked on day 187 and first flowered 8.14 days before peaking.

Discussion

The findings of our study reveal that while hypothesis 1 was partially supported, hypotheses 2, 3, and 4 were rejected. As hypothesized (H1), clustered SENCRA flowered earlier than isolated SENCRA. While clustered IVEGOR and LUPARG flowered earlier than their isolated counterparts during 2026, we discovered that clustering and plant size was not important for their first flowering dates. Interestingly, isolated HETVIL flowered earlier than clustered HETVIL, but again, clustering or plant size were not significant predictors. Overall, clustered plants from 2026 flowered earlier than clustered plants from 2025 and exhibited a smaller number of open flowers. (H2) In combination, snowmelt date and clustering also did not have a strong effect on plant flowering duration. (H3) Slope aspect (south) was also not important for determining first flowering dates. (H4) While we also determined that 2026 HETVIL, IVEGOR, and SENCRA flowered earlier than 2015 HETVIL, IVEGOR, and SENCRA, we interestingly found that 2026 LUPARG flowered later than 2015 LUPARG.

Notably, our 2026 sample size had substantially decreased from n=200 to n=38 (Figure 5) and may not have been large enough to detect significant clustering, plant size, snowmelt date, and slope aspect effects on all species. Had our sample size been larger or had there been more non-zero data collected, it is possible that more of our hypotheses would have been supported. Though our study design opted for an equal number of clustered and isolated plants per species, at our site we observed that SENCRA tended to grow alone. In comparison with the other species, we concluded that locations where SENCRA is clustered may overall be more moist and favorable, resulting in earlier flowering. We could test this by conducting the same phenology study again, but with SENCRA and other Asteraceae plants to see if there is similarity in clustering effects. Clustering for HETVIL, IVEGOR, and LUPARG may not have had as important of an effect as it did on SENCRA due to varied life histories as different genetic and environmental factors can influence life histories in complex environments like the alpine (Wilczek et al., 2010). Limitations of seed dispersal could also impact the strength of clustering for plants.

For all species, we learned that the snowmelt date for each plant did not have a strong influence on their flowering duration. While we found these results particularly surprising, we believe that they should be interpreted carefully as the range in distance and topography of plants chosen may not have been

sufficient or variable enough to account for any significant effects. It is possible that the end of flowering is determined by other environmental features such as the timing of summer rains. Had we chosen a more diverse snow gradient, the model might have better reflected the dry year's early and low snow conditions on flowering duration.

We were also surprised to find that the slope aspect (south) did not have a significant effect on the first flowering dates for each plant. Although not statistically significant, the results suggest that IVEGOR flowered the earliest at a lower slope aspect (south) than HETVIL, LUPARG, and SENCRA. Similar to snowmelt, had we chosen plants at more variable elevations, we believe we would have observed a stronger influence of slope aspect.

This year's IVEGOR flowering much later than 2015's IVEGOR raises important questions for why IVEGOR is flowering later than the other species, who are flowering much earlier compared to last decade's sample size. We observed that IVEGOR finished flowering earlier than the HETVIL, LUPARG, and SENCRA, suggesting that perhaps the flowering duration of IVEGOR is growing shorter over time due to climate change.

While we could not make comparisons between clustered and isolated plants from 2026 and 2015, we observed that the timing of first flowering date and peak flowering have advanced substantially in the past 11 years. HETVIL, IVEGOR, LUPARG, and SENCRA first flowered around 30 days earlier than 2015, and experienced peak flowering 15-25 days earlier (Figure 2 and 4).

As the effects of climate change are growing worse in the alpine, phenology is becoming more crucial to study (Rafferty et al., 2020). 2026 was a very dry and unusual year, with record-low snowmelt, drought conditions, and shifted phenology. In 2025, clustering was a significant predictor of the first flowering date (Figure 3). However, in 2026 clustering only seemed to matter for SENCRA, which suggests that facilitation alone may simply not be enough to counteract the climate-driven stress that Mount Baldy plants are experiencing, raising implications for other alpine plants in the Colorado Rocky Mountains. Our study also reveals that there are other factors that may affect the flowering phenology of alpine plants. We conclude that while clustering, plant size, snowmelt date, and aspect are important variables to study, other environmental variables such as soil moisture, functional traits, and leaf area index should also be considered for phenology (Walker et al., 1995, Stark et al., 2017, Valencia et al., 2016). Future research should consider a larger and more variable sample size and range for modeling.

Data Archiving Statement

As part of the RMBL Data Archiving, Curation, and Vouchers, I will participate in workshops and training for spatial and non-spatial metadata and archiving. My Data Management Plan includes a description of the datasets being archived, the dissemination methods, and the timeline for datasharing. I will use the RMBL template metadata form. I will use the default data repository Environment Data Initiative (EDI), unless my mentors request a different repository.

All data will be stored on the Blonder Lab Google Drive and will eventually be made public on the Baldy Github per NSF data release requirements.

Environmental Impacts

Mount Baldy is a Long Term Research in Environmental Biology (LTREB) site funded by the National Science Foundation (NSF). While my project will end after the 2026 summer, my principal investigator, Benjamin Blonder, will continue carrying out research at Mount Baldy until 2030 (estimated) across 100 vegetation plots of tagged plants. Soil at the Mount Baldy site may be lightly disturbed, along with soil along an off-trail route necessary for reaching the plots. Mitigation measures include removing shoes at the site and avoiding trampling/erosion of the landscape. Site plants will not be removed. Around 200 individuals of plant species will be impacted throughout the study via counting and measurement.

Relationship to Existing Research

My project has little to no potential for conflicts with other RMBL projects. This project is in collaboration with mentors Benjamin Blonder, Ian Breckheimer, and Alexandra Campbell and will re-use data from Becky Dalton and Hillary Xu. Research at Mount Baldy is approved through principal investigator Benjamin Blonder's permit via RMBL. His NSF research application was amended in 2024 and will occur from March 1, 2025 to February 28, 2030 (estimated). This project is supported by the US National Science Foundation under award DEB-2425575.

RMBL Importance

RMBL is nothing like any other place I have been. I initially chose to work at RMBL for its emphasis of conducting scientific research outside and in collaboration with scientists who have been coming back for decades, but found myself hooked by its community. RMBL scientists and staff have research interests that intersect with mine in fields such as spatial ecology, biology, and machine learning. Having this opportunity to carry out my first-ever research project in the Colorado Rocky Mountains is something that I would not be able to do without RMBL's resources and support.

Acknowledgements

Thank you to Hillary Xu for teaching me how to do phenology research, for allowing me to use her 2025 dataset, and for being a wonderful friend. To Ali Campbell, for her mentorship. Without her patience in hiking Baldy with me each day, helping me count flowers, and teaching me R, I would not have been able to complete this project; shout out Jennifer. To both Ali and Hillary, thank you a million times over for the emotional support, ice cream, and Teen Wolf. I wouldn't have survived the summer without you two. I am also grateful to Ben Blonder and Ian Breckheimer for their additional mentorship and belief in me to do science. I would also like to thank the Spatial Ecology Laboratory, especially Sophia Todorov and Amanda Henderson, for the silly animal cards, introducing me to spatial ecology, and for supporting me with GPS and GIS. Additionally, I am grateful for Kaysee Arrowsmith for checking in on my physical and emotional health. Thank you to Rebecca Dalton for her 2015 dataset, and for beginning this Baldy

phenology process. Lastly, thank you to my Oh-Be-Joyful cabinmates, Adele Havlick, Lily Lehnhardt, Linda Herrera, and honorarily, Stella Green and Carlos Pineda, for the peak and unforgettable memories.

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Tables and Figures

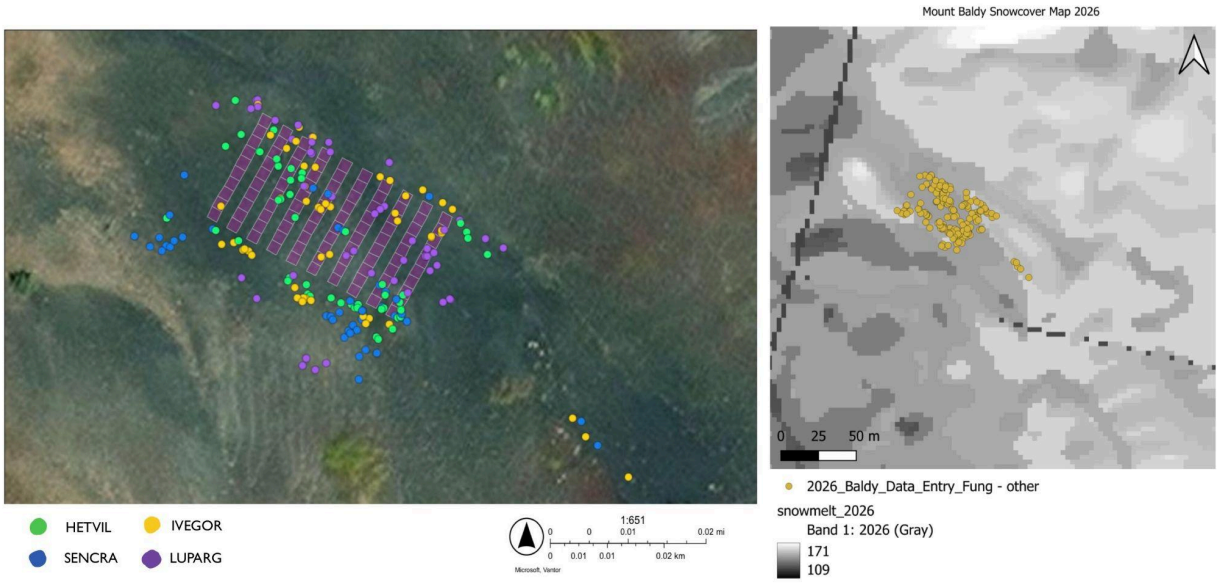

Figure 1. On the left, site location map. Four plant species are represented by four colors. 190 individual plants are depicted by dots as 10 plants were lost. On the right, Mount Baldy Snowcover Map 2026. Individual plants are represented by yellow dots, and the grayscale legend gradient represents the first snow-free date of the year for each pixel.

Predictor Variables	Values	Formula
Clustering	0, 1	clustering
Year	2015, 2025	year
Slope Aspect (S)	-1 to 1	slope_aspect_s
Plant Size	πabh	plant_size
Snowmelt Day	Day of Year	snowmelt_date

Table 1. Predictor Variables, values, and formulas used in the study.

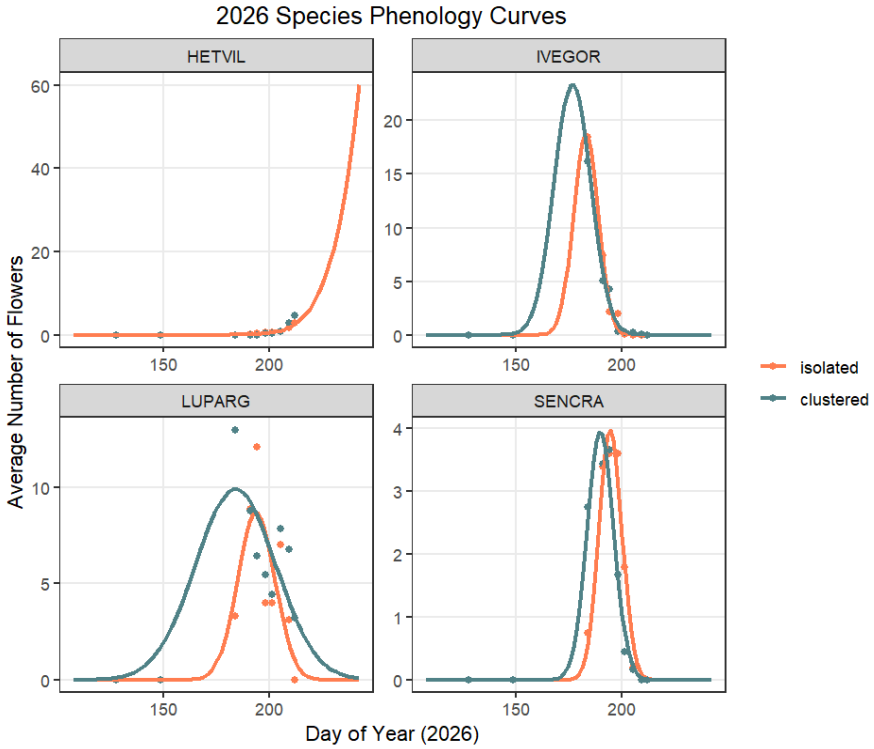

Figure 2. 2026 Species Phenology Curves. Species phenology curves for the 2026 year across four isolated and clustered species: HETVIL, IVEGOR, LUPARG, and SENCRA.

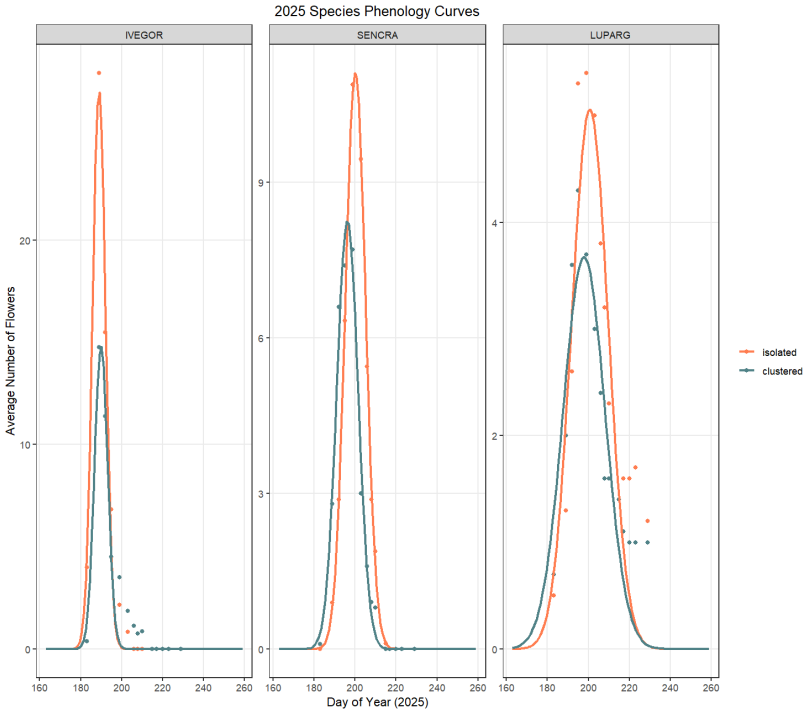

Figure 3. 2025 Species Phenology Curves. Species phenology curves for the 2025 year across three isolated and clustered species: IVEGOR, LUPARG, and SENCRA. Credit: Hillary Xu.

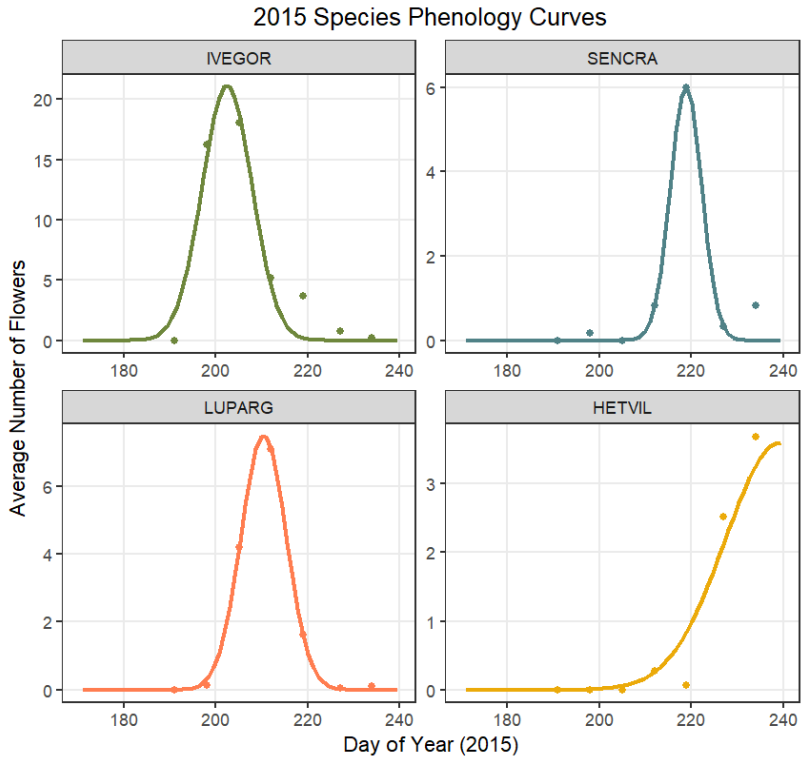

Figure 4. 2015 Species Phenology Curves. Species phenology curves for the 2015 year across four species: IVEGOR, SENCRA, LUPARG, and HETVIL. Credit: Rebecca Dalton.

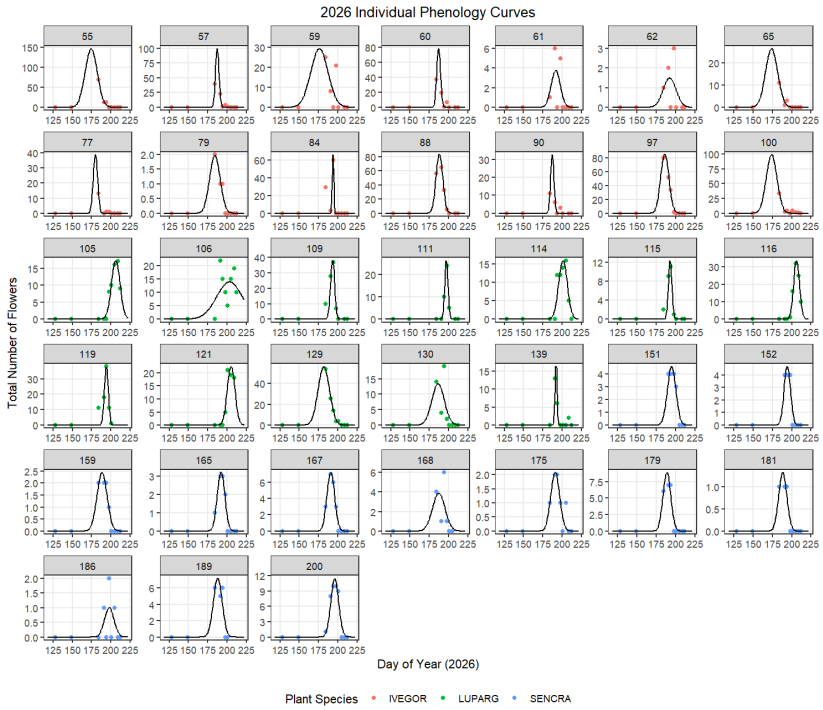

Figure 5. 2026 individual phenology curves per tag. HETVIL = Tags 1–50, IVEGOR = Tags 51–100, LUPARG = Tags 101–150, and SENCRA = Tags 151–200.

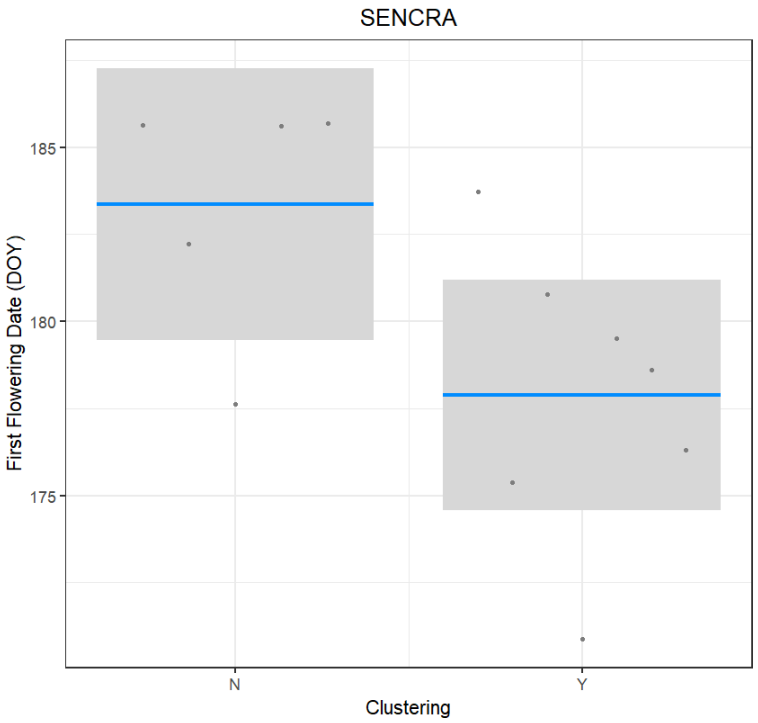

Figure 6. Clustering as a predictor for SENCRA's first flowering date (2026). Points = data, blue = model predictions.

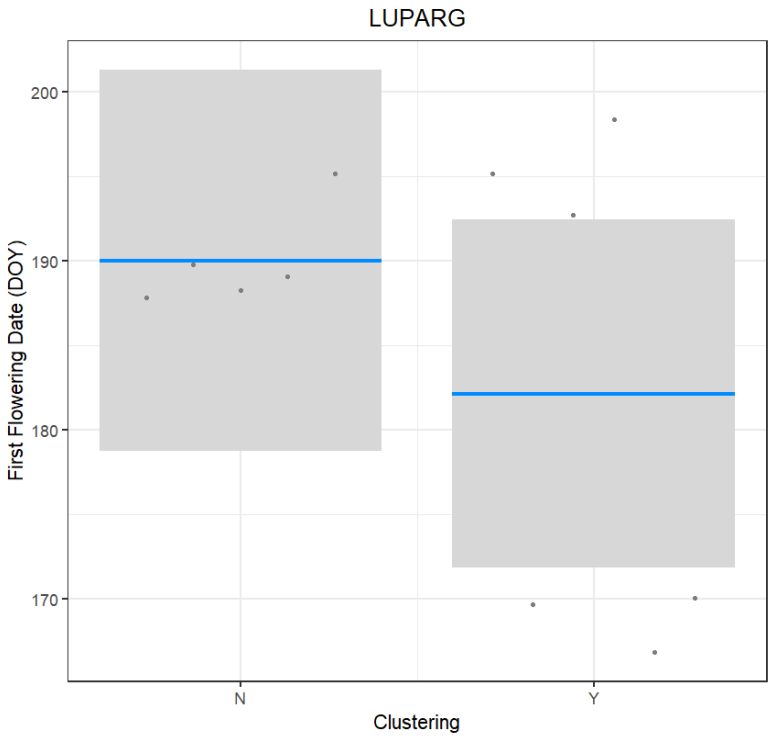

Figure 7. Clustering as a predictor for LUPARG's first flowering date (2026). Points = data, blue = model predictions.

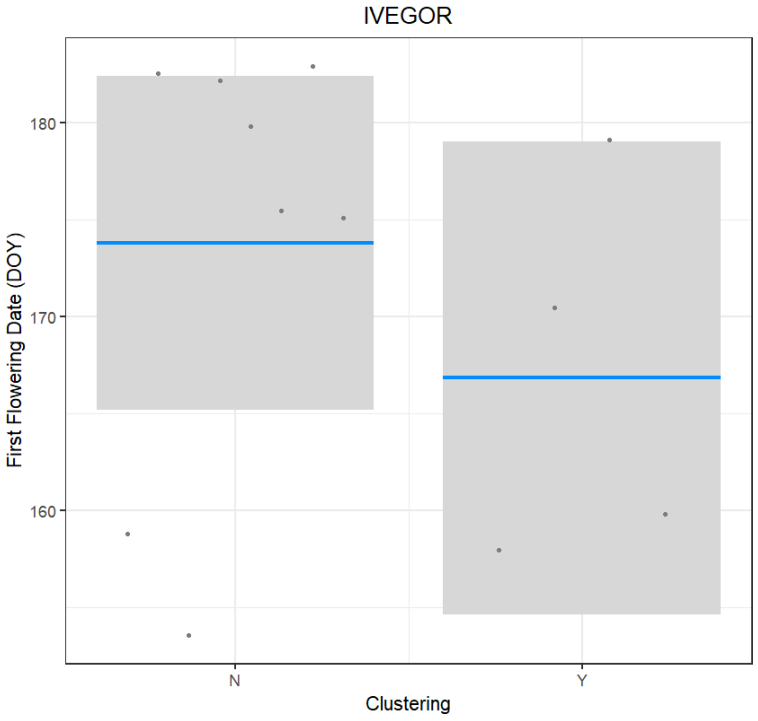

Figure 8. Clustering as a predictor for IVEGOR's first flowering date (2026). Points = data, blue = model predictions.

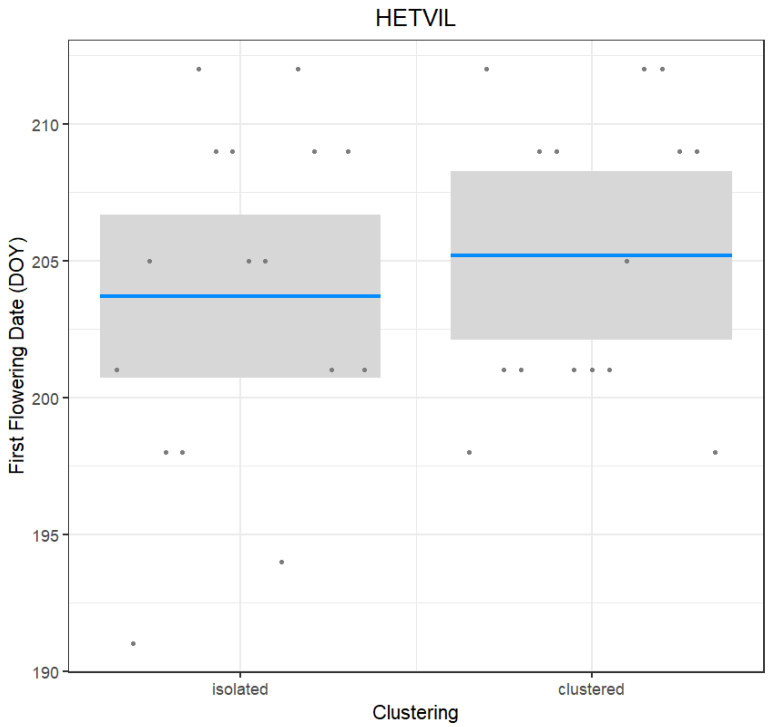

Figure 9. Clustering as a predictor for HETVIL's first flowering date (2026). Points = data, blue = model predictions.

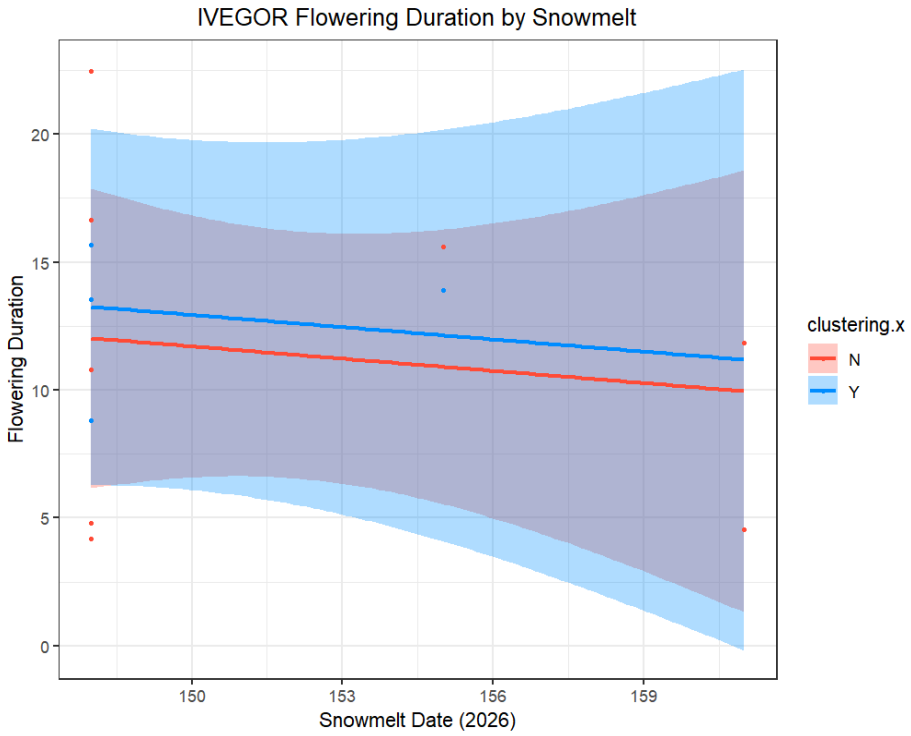

Figure 10. Snowmelt date as a predictor for IVEGOR flowering duration (2026). Points = data, blue and red = model predictions.

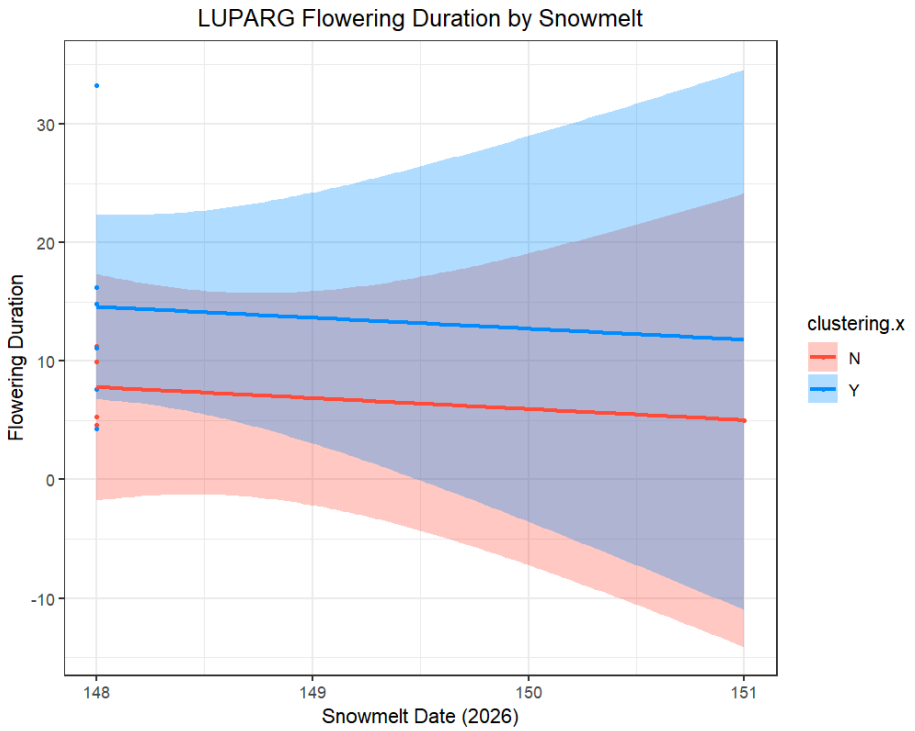

Figure 11. Snowmelt date as a predictor for LUPARG flowering duration (2026). Points = data, blue and red = model predictions.

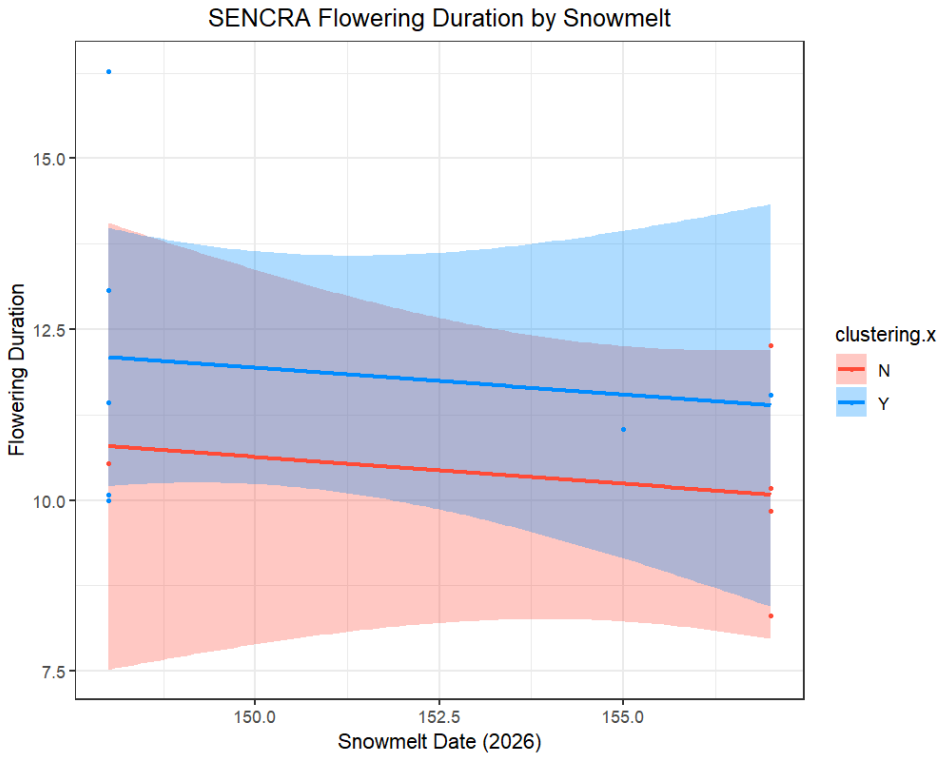

Figure 12. Snowmelt date as a predictor for SENCRA flowering duration (2026). Points = data, blue and red = model predictions.

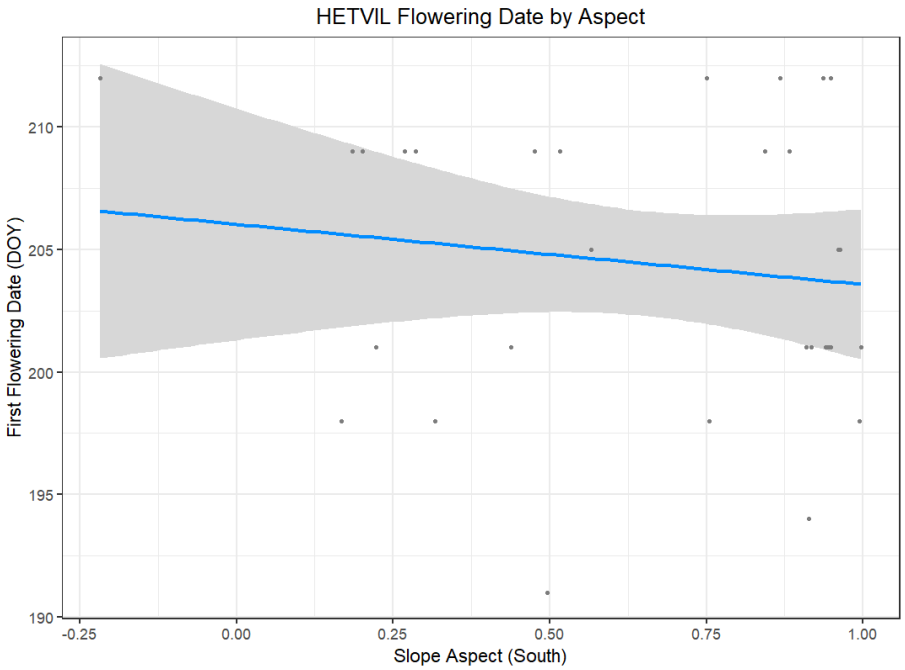

Figure 13. HETVIL Flowering Date by Aspect (2026). Points = data, blue = model predictions.

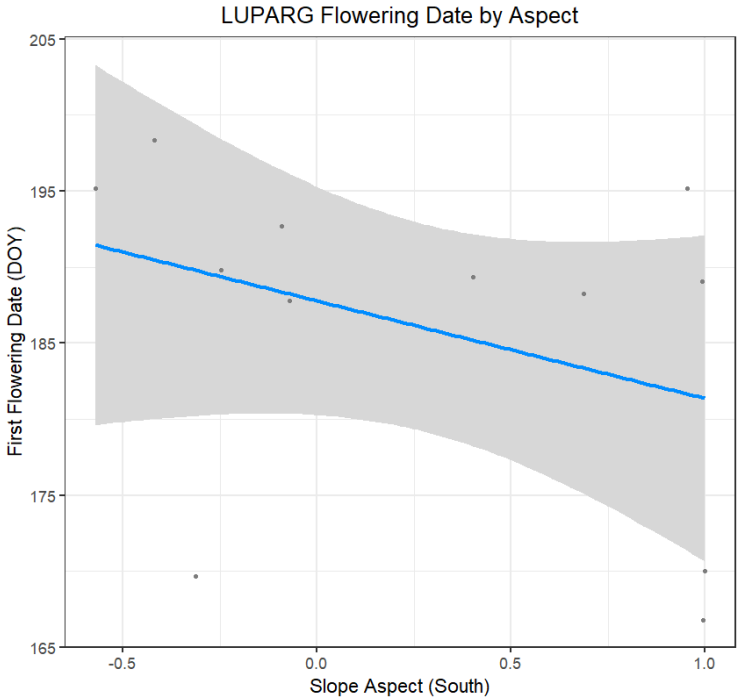

Figure 14. LUPARG Flowering Date by Aspect (2026). Points = data, blue = model predictions.

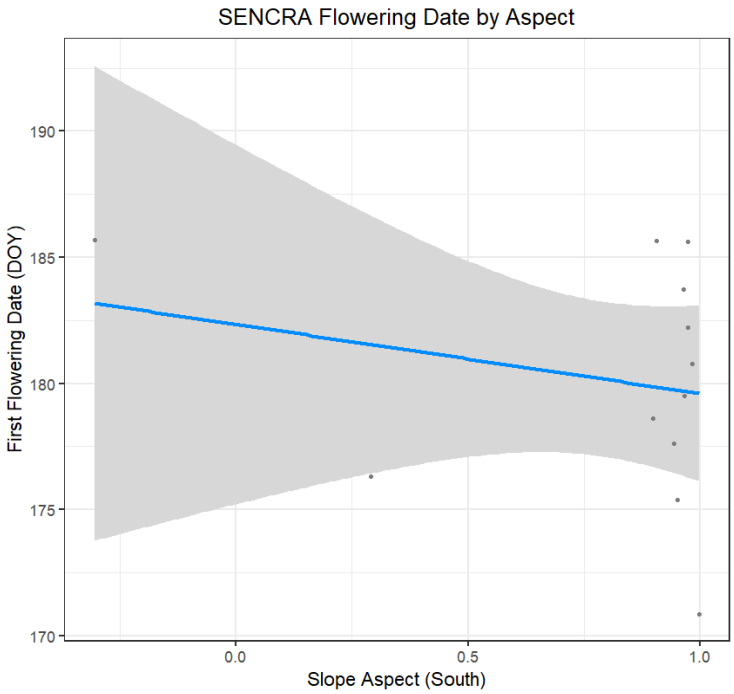

Figure 15. SENCRA Flowering Date by Aspect (2026). Points = data, blue = model predictions.

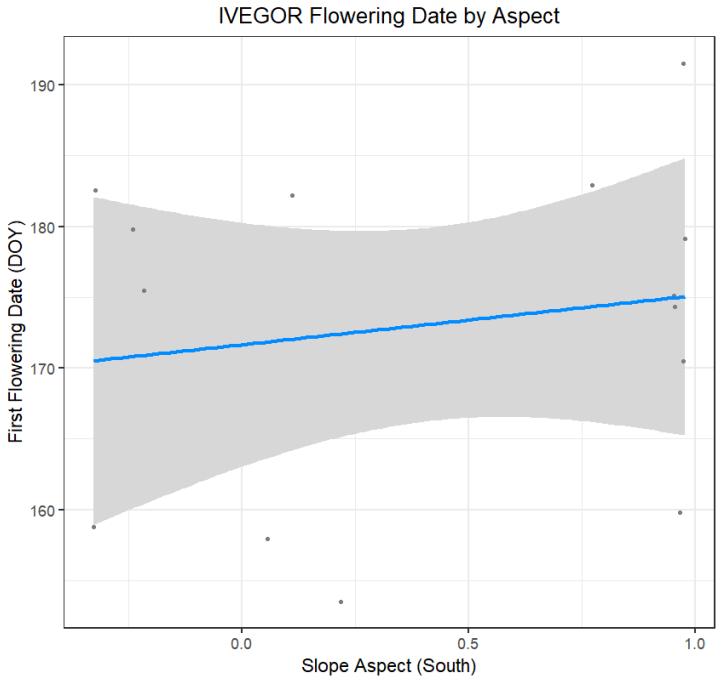

Figure 16. IVEGOR Flowering Date by Aspect (2026). Points = data, blue = model predictions.

Predictor Variables	Estimate	Standard Error	Degrees of Freedom	Multiple R Squared	p-value
clustering	1.512	2.095	29	0.01765	0.4792

[HETVIL]					
plant_size [HETVIL]	-0.001642	0.001850	29	0.02645	0.382
clustering [IVEGOR]	-6.946	6.708	10	0.09683	0.3249
plant_size [IVEGOR]	5.557e-04	1.193e-03	10	0.02123	0.6514
clustering [LUPARG]	-7.8777	6.748	9	0.1315	0.2731
plant_size [LUPARG]	-8.058e-04	7.977e-04	9	0.1018	0.3388
clustering [SENCRA]	-5.473	2.295	10	0.3626	**0.03829***
plant_size [SENCRA]	7.111e-04	9.152e-04	10	0.05693	0.4552

Table 2. The results of the linear regressions run for Hypothesis 1 separately depicting the effect of clustering and plant size on species' first flowering date. Bold = significant.

Predictor Variables	**Estimate**	**Standard Error**	**Degrees of Freedom**	**Multiple R Squared**	**p-value**
snowmelt_date [IVEGOR]	-0.1593	0.3562	9	0.04141	0.665
as.factor(clustering.x)Y [IVEGOR]	1.2298	3.7953	9	0.04141	0.753
snowmelt_date [LUPARG]	-0.9258	3.0934	8	0.2172	0.772
as.factor(clustering.x)Y [LUPARG]	6.7794	5.3580	8	0.2172	0.241
snowmelt_date [SENCRA]	-0.07859	0.15827	9	0.2074	0.376
as.factor(clustering.x)Y [SENCRA]	1.30640	1.40140	9	0.2074	0.376

Table 3. The results of the linear regressions run for Hypothesis 2 depicting the effect of clustering and snowmelt date on the flowering duration of each plant species.

Predictor Variables	Estimate	Standard Error	Degrees of Freedom	Multiple R Squared	p-value
slope_aspect_S [HETVIL]	-2.460	3.144	29	0.02068	0.44
slope_aspect_S [IVEGOR]	3.480	5.761	12	0.02951	0.557
slope_aspect_S [LUPARG]	-6.419	5.125	10	0.1356	0.239
slope_aspect_S [SENCRA]	-2.738	3.630	10	0.05383	0.468

Table 4. The results of the linear regressions run for Hypothesis 3 depicting the effect of slope aspect (south) on the first flowering date of each plant species.

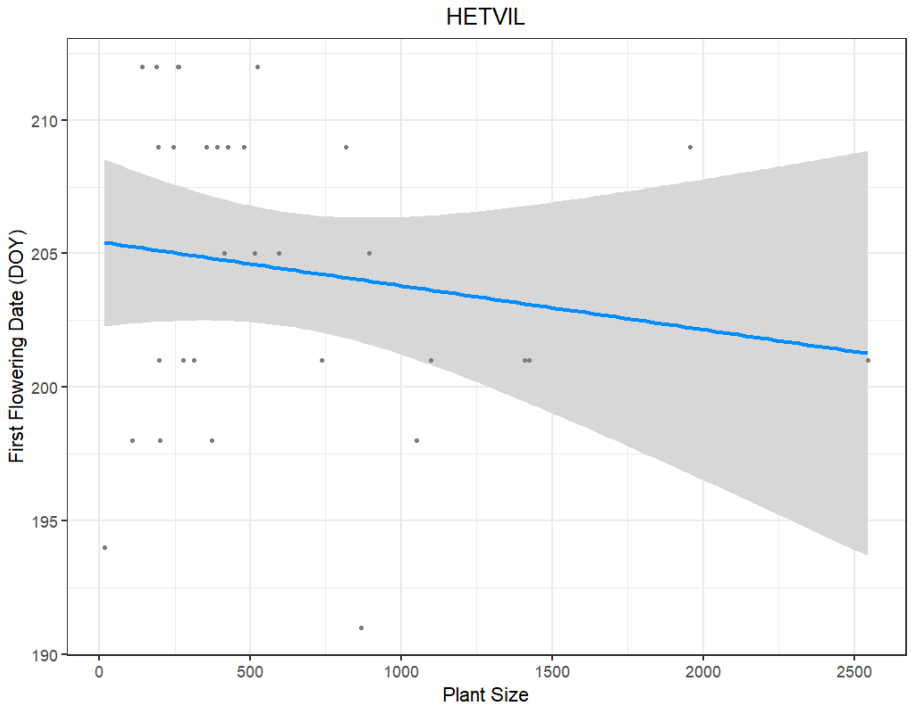

Figure 17. Plant size as a predictor for HETVIL first flowering date (DOY). Points = data, blue = model predictions.

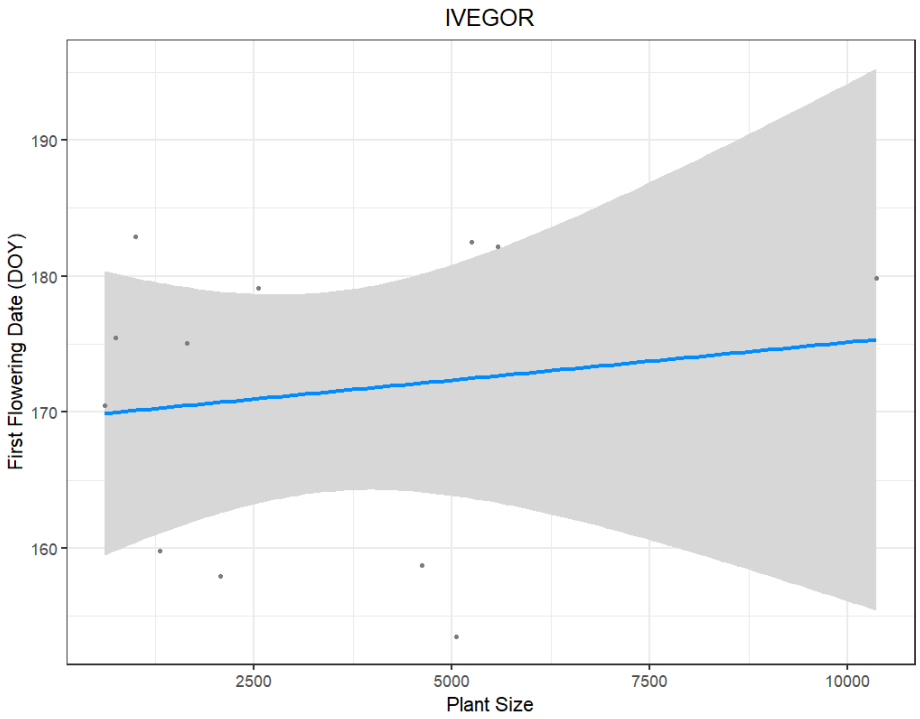

Figure 18. Plant size as a predictor for IVEGOR first flowering date (DOY). Points = data, blue = model predictions.

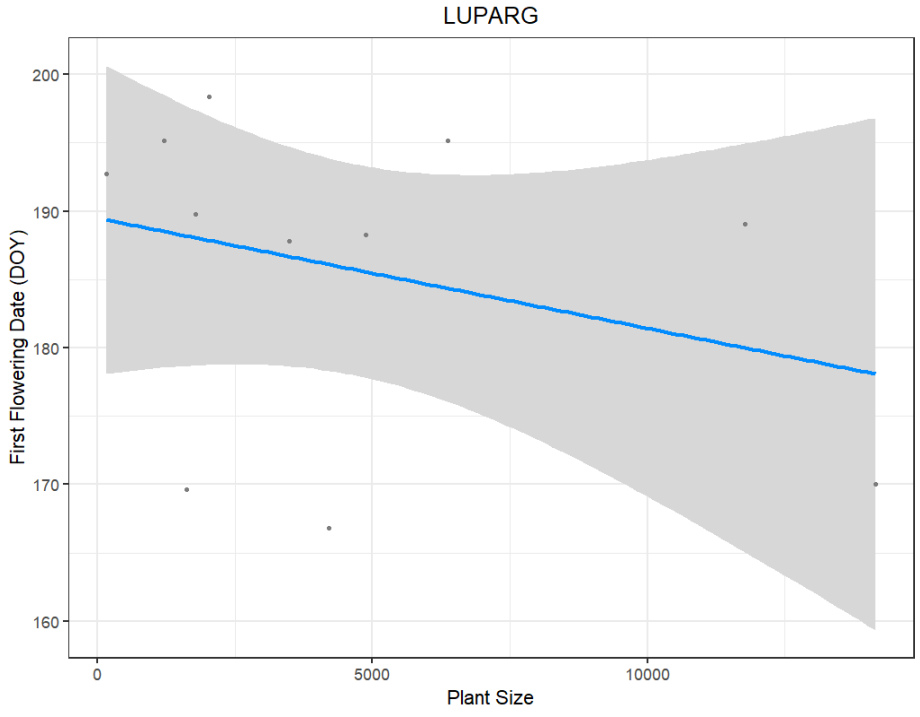

Figure 19. Plant size as a predictor for LUPARG first flowering date (DOY). Points = data, blue = model predictions.

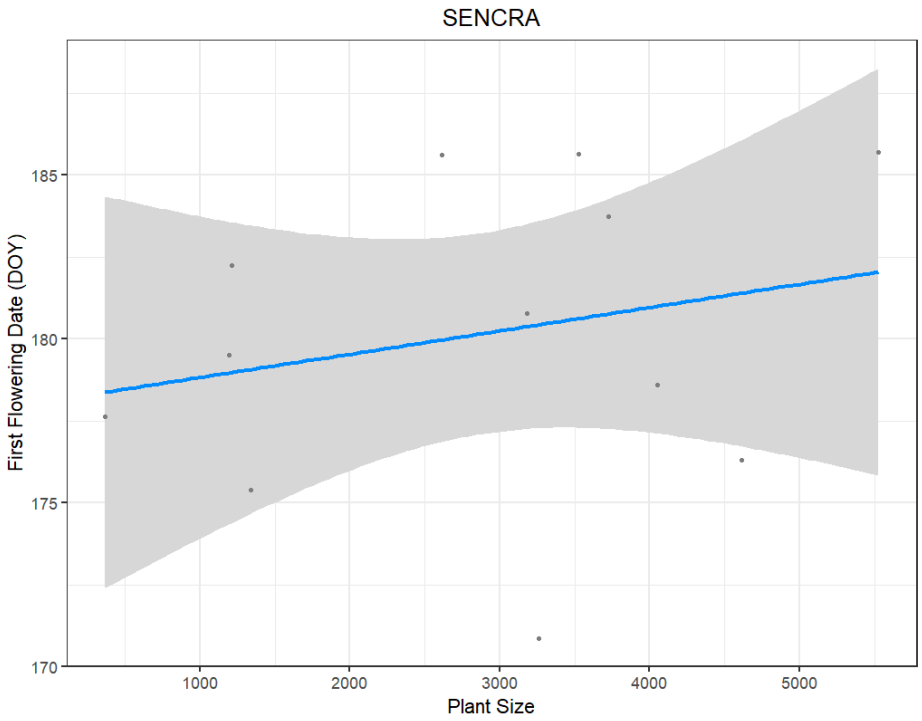

Figure 20. Plant size as a predictor for SENCRA first flowering date (DOY). Points = data, blue = model predictions.

Figure 21. 2015 individual phenology curves per tag.