

The Effect of Climate Change on Plant Communities in the Rocky Mountains: How floral traits differ along an elevational gradient and in reciprocally transplanted communities

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## **ABSTRACT**

Alpine zones are characterized by climatic conditions that can vary over short vertical distances. Therefore, elevational gradients have been used to study how changes in climate can influence plant form, function, and diversity. In my study, I examined floral traits in native communities along an elevational gradient as well as in a novel experimental set of transplant communities to understand how shifts in temperature and elevation influence floral traits. I measured flower diameter, flower radius, flower length, height of the highest flower and number of flowers (count) at a variety of sites in Washington Gulch. At three different experimental transplant sites, I sampled each transplanted and control plot. I also sampled at long-term research sites of Dr. Brian Enquist and Department of Energy (DOE) sites in the vicinity of Crested Butte, Colorado. I predicted that flower diameter, flower radius, flower length and height of the highest flower will increase at higher elevations because alpine plants typically have larger floral structures to compensate for the paucity of pollinators in the alpine and because water availability is better in alpine environments as opposed to lowland habitats. Conversely, I expect the number of flowers to decrease as elevation increases because there are fewer pollinators and harsher environmental conditions like heightened wind velocities which stunt growth.

*Helianthella quinquenervis* and *Potentilla pulcherrima* did not show any discernible trends for diameter, height or length along the gradient but both had compelling findings embedded in the data for certain sites. Significant differences were found between sites for each trait but further analysis is required to contextualize these variations. This project is unique in that we measured native plant communities that were transported to higher and lower elevation sites and also quantitatively compared different flower morphologies and attributes in these varied settings.

## INTRODUCTION

Alpine climates are characterized by a variety of inhospitable conditions that cause various direct abiotic and indirect biotic challenges to plant growth. Increased elevation involves shifts in annual temperatures, longer-term snow cover, intensified UV radiation, greater wind velocity, increased precipitation and decreased nutrient availability (Billings, 1974; Langenheim, 1962). Across the alpine ecosystems, due to changes in exposure, timing of snowmelt, and elevation, abiotic conditions can dramatically change over relatively short vertical distances. Thus, elevational gradients have been used to study how changes in climate can influence plant form, function, and diversity. Elevation is generally thought to represent the most important factor in studies on phenotypic variation in mountain plant communities (Kieltyk, 2018; Stöcklin et al., 2009; Langenheim, 1962).

Along an elevation gradient, plant communities vary both taxonomically and trait-wise, in response to changing environmental conditions (Sundqvist et al., 2013). While there are apparent examples of elevation changes, such as the transition from spruce-fir forests to smaller shrubs and herbaceous plant communities at higher elevations, more obscure developments in the functional composition of plants, such as the evolution of pendulous flowers in *Anisodus luridus* as a possible adaptation to abiotic aspects of its harsh alpine environment, also occur (Wang et al., 2010; Körner, 2003; Read et al., 2014).

Most importantly, studying functional traits along elevational gradients is paramount as we attempt to predict the concomitant responses of plant communities to global environmental changes (Barros et al., 2016; Read et al., 2014; Sundqvist et al., 2013). Specifically, floral traits, including color, shape, display size, symmetry and corolla length are not as well studied. These traits are presumed to be evolutionary adaptations to pollinators, directly affecting pollinator behavior and are integral to the reproductive success of the plant (Peng et al., 2012).

Previous work, while limited in scope, has focused on the comparison of different floral traits including flower color, flower size, and anthers and stigma arrangement (Campbell, 1996; Tourjee et al., 1995). Kasagi and Kudo (2001) compared the coefficients of variation of corolla morphology and anther-stigma distances of two *Phyllodoce* species among populations selected along different snowmelt gradients finding no clear directional trends along snowmelt gradients in either species and that traits were more variable among populations at each site than among sites in both species. Similarly, Peng et al. (2012) set out to characterize patterns of flower morphology in the subnival belt of the Hengduan Mountains to analyze how these traits affect the reproductive success of plants. They found that large flowers were the most common, followed by medium and small flowers, the majority of gathered flowers were actinomorphic (radially symmetric like a daisy) as opposed to zygomorphic (bilaterally symmetric like a snapdragon) and most flowers were oriented upward as opposed to downward or horizontal. These findings, characteristic for generalists, are consistent with the theory that generalization in pollen systems evolves when pollinators are infrequent or unavailable, a common phenomenon in the alpine ecosystems (Waser et al., 1996).

In this study, I examine floral trait measurements both along an elevational gradient and in a novel experimental set of transplant communities to predict how shifts in temperature and elevation influence floral traits. I predict that flower diameter, flower radius, flower length and height of the highest flower will increase at higher elevations because alpine plants typically have larger floral structures to compensate for the paucity of pollinators in the alpine and because water availability is better in alpine environments as opposed to lowland habitats. Conversely, I expect the number of flowers to decrease as elevation is increased because there are fewer pollinators and harsher environmental conditions like heightened wind velocities which stunt growth. These manipulated blocks of land will enable me to understand how various

plant communities respond to different climate scenarios. In terms of the broader elevational gradient, this experiment should provide further insight into whether shifts in temperature and elevation influence floral traits and whether or not these changes are species specific. In the context of the transplants, this project will provide a better understanding of whether floral traits change when populations are shifted along an elevation gradient and whether the traits resemble the species site origin or destination.

## METHODS

### *Survey Sites*

I recorded floral trait measurements in the transplanted and untouched blocks of land at three varied elevation sites located near Crested Butte, Colorado. The lowest site is Upper Montane (2,900 m; 38.93248 N, -107.01018 W), located 3.2 kilometers north of Crested Butte on Washington Gulch Road, adjacent to the boundaries of the Gunnison National Forest. This large and open montane meadow is mostly comprised of herbaceous vegetation including perennial plants, grasses and forbs within shrub communities of *Potentilla fruticosa* and *Artemisia tridentata*. The middle site is Pfeiler (3,200 m; 38.96046 N, -107.03262 W), located 12.9 kilometers north on Washington Gulch Road within the boundaries of the Gunnison National Forest. This subalpine meadow is generally characterized by perennial plants and grasses and is surrounded by a meadow of *Veratrum californicum*. The highest site is Monument (3,300 m; 38.97274 N, -107.04908 W), located 16.0 km north on Washington Gulch Road within the boundaries of the Gunnison National Forest and on the lower slopes of Mt. Baldy (3,537 m). Rocky soil and alpine plants like *Sedum integrifolium* are ubiquitous throughout this alpine meadow. The growing season for these sites typically spans from June-August with snow present from November to May. In July and August of 2017, the average temperature difference between Upper Montane and Monument was 1.5°C. In addition to sampling floral traits at these aforementioned sites outside of the transplants, I measured floral traits in several different meadows located on Cinnamon Mountain (3,473 m; 38.99467°N / 107.07048°W), Mt. Baldy (3, m; 38.99400°N / 107.046°W) and in the Department of Energy (DOE) plots near Pfeiler (3,116 m; 38.57017 N, -107.01045 W).

### *Site Setup / Turf Transplants*

Upper Montane, Pfeiler and Monument each have five blocks of five turfs (0.5m<sup>2</sup> blocks of land). Each turf was either transplanted downslope (warmed), upslope (cooled), within the same block and site (transplanted control), or not transplanted (untouched controls, both netted and unnetted) in July and August of 2017. Each transplant is covered by a net except the unnetted control (one per block), thereby eliminating any biotic interactions with pollinators.

### *Data Collection*

In the summer of 2018, there were few flowers present in most sites and in most of the turfs due to an intense drought and heightened temperatures. Given the paucity of flowers, it was challenging to find flowers that were both healthy and easy to measure. I tended to select flowers that were radially symmetric where I could measure diameter and length consistently across species. In the turfs, I measured five floral traits (flower diameter, number of flowers, height of the highest flower, flower radius and flower length) for each different, healthy individual of a certain species. Across the various sites, I conducted the same methodology but aimed to measure between 10-15 different healthy individuals of each species.

### *Statistical Analyses*

I ran a Shapiro-Wilk test of normality on each of my traits in my site data to see whether the data was normally distributed and found the data to be significantly not normal ( $p < 0.05$ .) I also ran Kruskal-Wallis Rank Sum tests on my site traits (diameter (mm), height of the highest flower (cm), and length (mm)) as the residuals are not normally distributed and the variances are heteroscedastic. If the Kruskal-Wallis Rank Sum test indicated a p-value of  $< 0.05$ , meaning that significant differences exist between at least two groups, I followed this test with a Pairwise Wilcoxon Rank Sum Test to find the differences. In order to prevent any additional type I errors,

I made adjustments to the p-values using the *p.adjust.method* option with the Bonferroni correction in RStudio Version 1.1.453.

## RESULTS

### *Sampling Distribution*

The majority of samples were taken at Monument, Cinnamon and Baldy (highest elevation sites) because the flowers were healthier and more varied (Figure 4). The sampling of each site occurred once and was conducted near peak flowering time for that site. *Potentilla pulcherrima* and *Senecio crassulus* were the most frequently sampled species while *Linum lewisii* was the least sampled species due to its relatively rapid flowering window and brittle structure when measured (Figure 5). *Potentilla pulcherrima* and *Helianthella quinquenervis* were the most widely distributed species across the gradient as they were found in all six sites (Figure 5).

### *General Findings for Helianthella quinquenervis and Potentilla pulcherrima*

*Helianthella quinquenervis* had the largest average diameter at Monument while the diameter of *Potentilla pulcherrima* remained fairly uniform along the gradient after Pfeiler (Figure 6). The average heights of *Helianthella quinquenervis* and *Potentilla pulcherrima* did not show a discernible trend along the gradient (Figure 7). There were no discernible trends observed for the length of *Helianthella quinquenervis*. *Potentilla pulcherrima* might be increasing in length after Pfeiler (Figure 8). The exclusion of Pfeiler DOE is necessary as there is only one measurement for *Helianthella quinquenervis* at this site.

### *Species level findings along the gradient*

By comparing species that had sufficient measurements across the gradient, I found that diameters tended to remain constant or slightly increase with increasing elevation (Figure 9). Conversely, most species tended to be shorter with increasing elevation except *Hymenoxys hoopesii* (Figure 10). There was no overall observable trend in lengths of species across the

gradient but the lengths of *Helianthella quinquenervis*, *Hymenoxys hoopesii* and *Potentilla pulcherrima* may be slightly increasing (Figure 11).

### *Statistical Analyses*

#### *Species level*

The Kruskal-Wallis Rank Sum test with diameter (mm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in diameter among different elevations in the gradient for all species (Kruskal-Wallis chi-squared = 17.122,  $df = 5$ ,  $p < 0.001$ ). The Pairwise Wilcoxon Rank Sum Test (post-hoc) showed that the diameters were significantly different between Monument and Pfeiler DOE ( $p < 0.001$ ).

The Kruskal-Wallis Rank Sum test with height of the highest flower (cm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in flower heights among different elevations in the gradient for all species (Kruskal-Wallis chi-squared = 86.778,  $df = 5$ ,  $p < 0.001$ ). The Pairwise Wilcoxon Rank Sum Test (post-hoc) showed that the heights were significantly different between Baldy and Monument ( $p < 0.001$ ), Baldy and Pfeiler ( $p < 0.001$ ), Baldy and Upper Montane ( $p < 0.001$ ), Cinnamon and Monument ( $p < 0.001$ ), Cinnamon and Pfeiler ( $p < 0.001$ ), Cinnamon and Upper Montane ( $p < 0.001$ ) and Monument and Pfeiler DOE ( $p = 0.00105$ ).

The Kruskal-Wallis Rank Sum test with length (mm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in length among different elevations in the gradient for all species (Kruskal-Wallis chi-squared = 17.962,  $df = 5$ ,  $p = 0.002995$ ). The Pairwise Wilcoxon Rank Sum Test (post-hoc) showed that the lengths were significantly different between Monument and Pfeiler DOE ( $p = 0.0024$ ) and Pfeiler and Pfeiler DOE ( $p = 0.0207$ ).

### *Helianthella quinquenervis* findings

The Kruskal-Wallis Rank Sum test with diameter (mm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in diameter among different elevations in the gradient for *Helianthella quinquenervis* (Kruskal-Wallis chi-squared = 13.204, df = 5,  $p = 0.02154$ ). The Pairwise Wilcoxon Rank Sum Test (post hoc) showed that the diameters of *Helianthella quinquenervis* were not significantly different at each site along the elevational gradient.

The Kruskal-Wallis Rank Sum test with height of the highest flower (cm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in height among different elevations in the gradient for *Helianthella quinquenervis* (Kruskal-Wallis chi-squared = 16.302, df = 5,  $p < 0.001$ ). The Pairwise Wilcoxon Rank Sum Test (post hoc) showed that the heights of *Helianthella quinquenervis* were significantly different between Baldy and Monument ( $p = 0.034$ ).

The Kruskal-Wallis Rank Sum test with length (mm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in length among different elevations in the gradient for *Helianthella quinquenervis* (Kruskal-Wallis chi-squared = 14.036, df = 5,  $p = 0.01538$ ). The Pairwise Wilcoxon Rank Sum Test (post hoc) showed that the lengths of *Helianthella quinquenervis* were not significantly different at each site along the elevational gradient.

### *Potentilla pulcherrima* findings

The Kruskal-Wallis Rank Sum test with diameter (mm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in diameter among different elevations in the gradient for *Potentilla pulcherrima* (Kruskal-Wallis chi-squared = 19.441, df = 5,  $p = 0.00159$ ). The Pairwise Wilcoxon Rank Sum Test (post hoc)

showed that the diameters of *Potentilla pulcherrima* were significantly different between Cinnamon and Pfeiler DOE ( $p = 0.0261$ ), Monument and Pfeiler DOE ( $p = 0.0261$ ), Cinnamon and Upper Montane ( $p = 0.0077$ ) and Monument and Upper Montane ( $p = 0.0368$ ).

The Kruskal-Wallis Rank Sum test with height of the highest flower (cm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in height among different elevations in the gradient for *Potentilla pulcherrima* (Kruskal-Wallis chi-squared = 17.277,  $df = 5$ ,  $p = 0.004004$ ). The Pairwise Wilcoxon Rank Sum Test (post hoc) showed that the heights of *Potentilla pulcherrima* were not significantly different at each site along the elevational gradient.

The Kruskal-Wallis Rank Sum test with length (mm) as the response variable and elevation (m) as the predictor variable indicated that there were significant differences in length among different elevations in the gradient for *Potentilla pulcherrima* (Kruskal-Wallis chi-squared = 20.936,  $df = 5$ ,  $p < 0.001$ ). The Pairwise Wilcoxon Rank Sum Test (post hoc) showed that the lengths of *Potentilla pulcherrima* were significantly different between Cinnamon and Pfeiler DOE ( $p = 0.0041$ ) and Monument and Pfeiler DOE ( $p = 0.0050$ ).

## DISCUSSION

### *General Findings*

Southwest Colorado experienced an intense drought and higher average temperatures during the summer of 2018 which made sampling much more difficult as there were fewer flowers at the lower elevation sites and of these flowers, the peak flowering date was earlier. Despite these limitations, I managed to sample healthy individuals of *Helianthella quinquenervis* and *Potentilla pulcherrima* at each of the six sites along the elevational gradient. It is possible that the wide distribution of *H. quinquenervis* across the Washington Gulch gradient results from a decline of different seed predators (use *Helianthella* flowers as hosts) since 1979 caused by fewer opportunities for oviposition in flower heads (Inouye, 2008). Likewise, the ubiquity of *P. pulcherrima* across the gradient is not surprising given that long, dry seasons at lower altitudes can favor rapid reproduction for *P. pulcherrima* (Stinson, 2004).

### *Helianthella quinquenervis (Site)*

*H. quinquenervis* did not show any visible trends along the gradient for diameter, height or length in natural communities. This finding is not surprising as plants with wide elevational ranges experience myriad selective pressures at both low and high elevations resulting in non-linear responses for certain traits along the elevational gradient (Frei et al., 2014a). However, there are some interesting findings embedded throughout the gradient like the largest average diameter of *H. quinquenervis* at Monument. This occurrence could be related to climatic conditions at the site like increased precipitation and slope/aspect or could result from greater investment in floral structures caused by fewer pollinators in the alpine (Fulkerson et al., 2012; Totland, 1993; Bergman et al., 1996). For instance, Malo and Baonza (2002) studied the *Cytisus scoparius* flower size along an elevational gradient in the mountains of Central Spain and found that flower size had a unimodal relationship with elevation, displaying its maximum size at the

intermediate elevation site. However, my post-hoc analysis suggests that the diameters did not significantly vary along the elevational gradient and that the larger diameter at Monument is not representative of more ideal conditions ( $p > 0.05$ ). Likewise, lengths of *H. quinquenervis* were not significantly different at the sites along the gradient, a surprising finding given the variation in local climates, which directly affect flowering timing and pollinator activity across the gradient. The average height of *H. quinquenervis* was shorter at Baldy as opposed to Monument, a finding consistent with other studies such as Kiletyk (2018), which found a decrease in *S. minuta* height with increasing elevation. Interestingly, the height of *H. quinquenervis* was only significantly different between the highest site (Baldy) and the middle site (Monument). Further analysis is required to evaluate the reasoning behind this difference.

#### *Potentilla pulcherrima* (Site)

*P. pulcherrima* does not display any evident trends along the gradient for diameter or height, however, its average diameter and height measurements are particularly compelling (Figure 6, Figure 7, Figure 8). At Pfeiler, the diameter seems to remain fairly constant along the remainder of the gradient, however, four significant differences exist between sites along the gradient, namely a difference between Cinnamon and Upper Montane. This finding suggests that floral structures vary significantly along the gradient and that there is greater investment in these structures at higher elevations like Cinnamon (Figure 6). The height of *P. pulcherrima* is the highest at Monument suggesting that height likely had a unimodal relationship with elevation, showing its maximum size at the intermediate level site (Figure 7). Interestingly, there may be somewhat of an increase in length of *P. pulcherrima* after Pfeiler (Figure 8). Although there are evident site differences between Cinnamon and Pfeiler and Monument and Pfeiler DOE, further statistical analysis is required to better ascertain these changes in length.

### *Species level findings*

One of the most compelling findings was the significant difference in height of the highest flowers among all species along the gradient. Given that seven sites were significantly different from one another we can conclude that tremendous variation in height occurred on a species level. Whether this is simply due to a conglomeration of the variations in height for each species or whether there is an actual trend present requires further study.

### *Future Study*

More in-depth analysis is required for understanding how diameter, height, length and the number of flowers differ among communities throughout the elevational gradient. To analyze the difference in number of flowers along the gradient, I need to utilize phenology data taken weekly at each transplant site. At the moment, I can assume that variations in climate, including varying levels of precipitation and different snowmelt times are responsible for the fluctuating measurements along the gradient. These are only several of many confounding factors that can affect the measurements along the gradient. Additionally, once the site data is analyzed in more detail, I can begin to analyze the transplant data to determine whether the flowers in the transplants reveal traits that are indicative of their site origin or final destination.

## **ACKNOWLEDGMENTS**

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## FIGURES

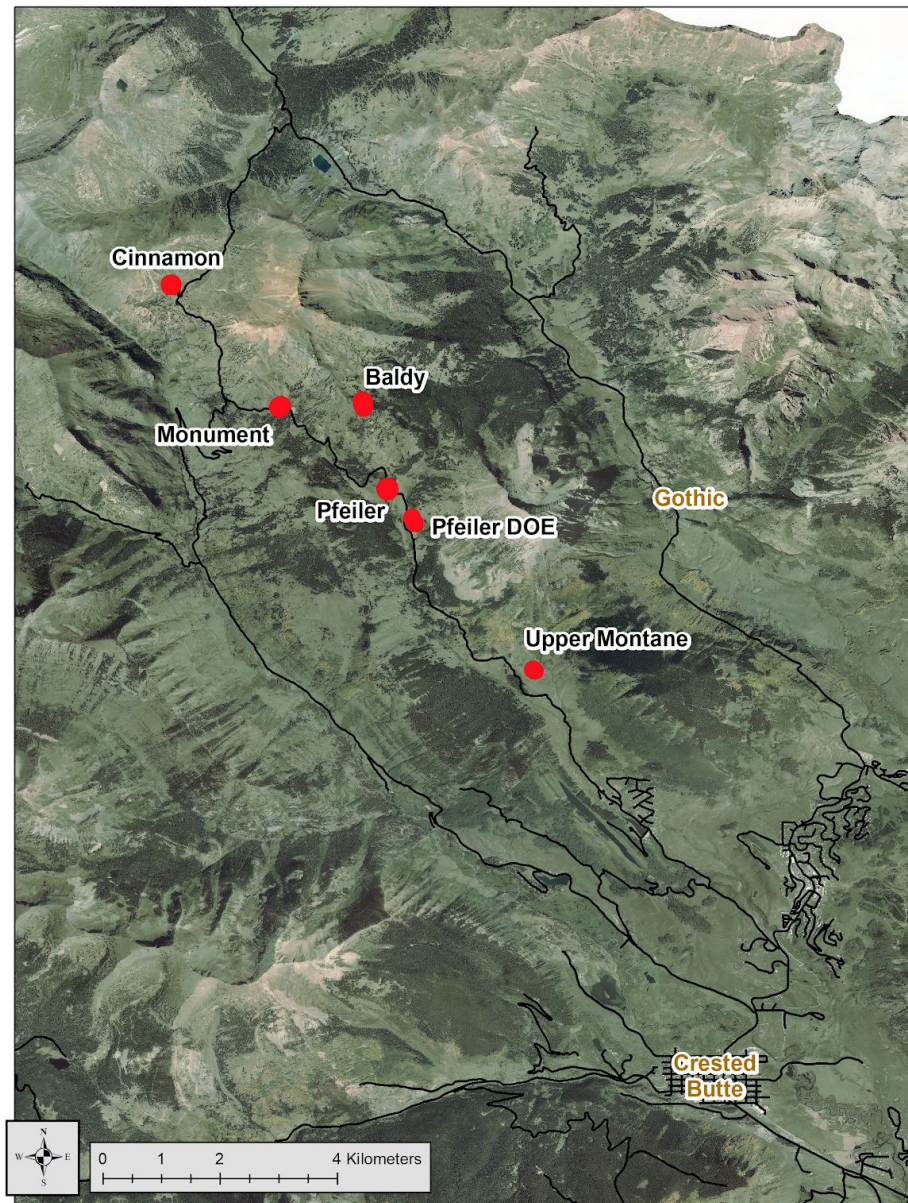


Figure 1. Map indicating study sites along Washington Gulch in the vicinity of Crested Butte, Colorado.

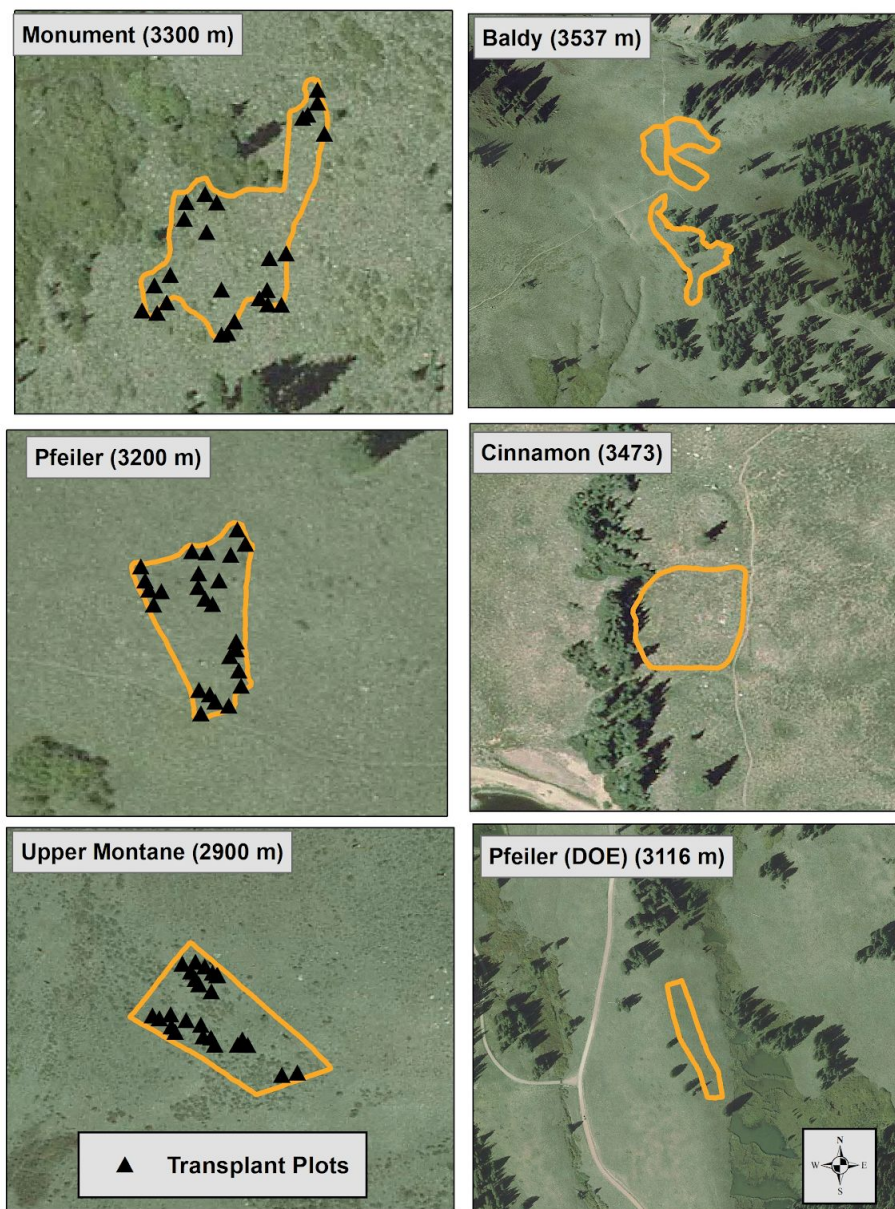


Figure 2. Map showing transplant sites in addition to sites without transplants. Transplant plots indicated by a black triangle.

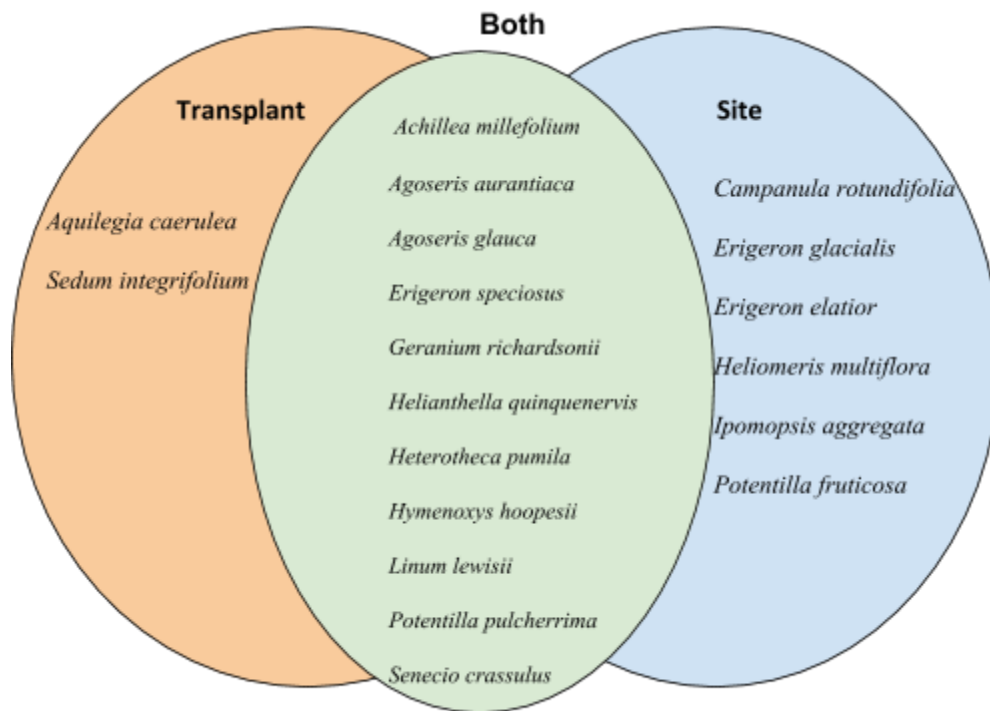


Figure 3. Species measured in the transplants, at the sites and in both locations.

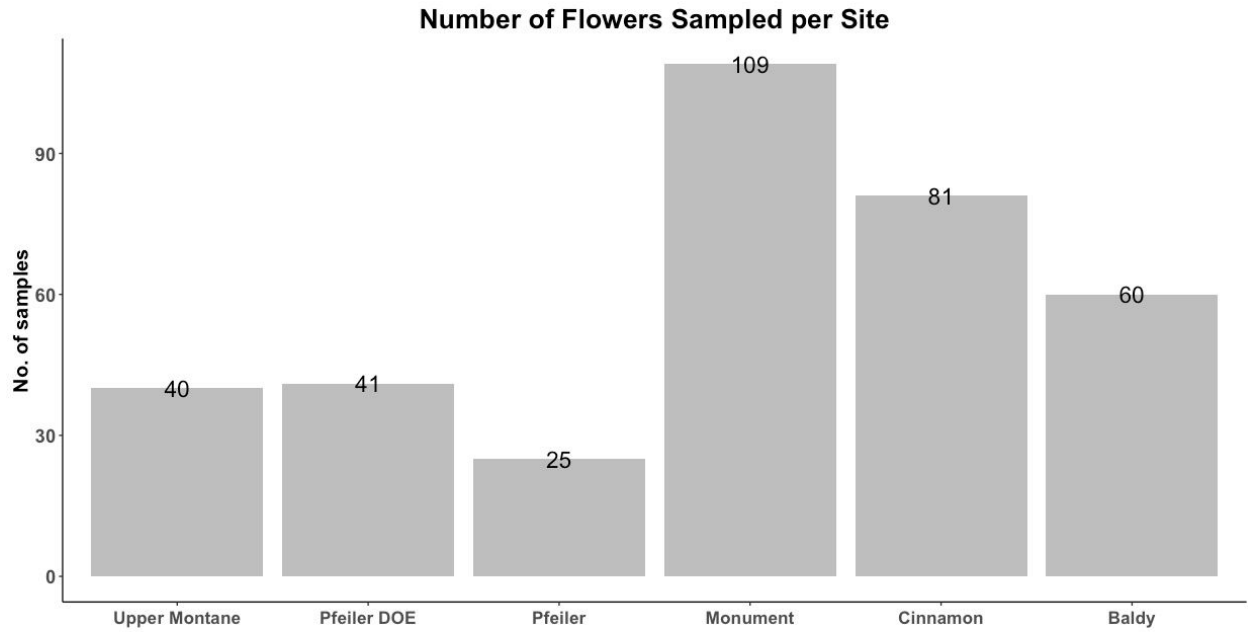


Figure 4. Number of flowers sampled at each site along the gradient. Sites listed in order of increasing elevation. Transplant data not included.

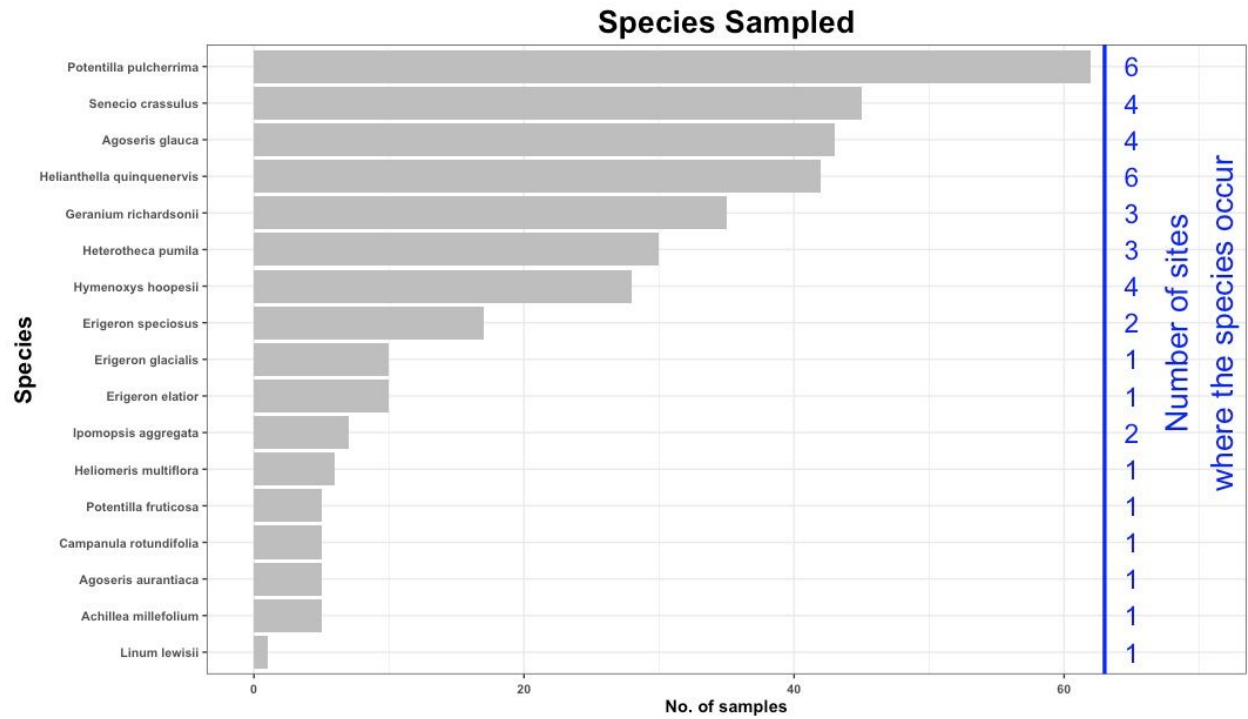


Figure 5. Number of each type of species sampled. Column on the right side displays number of sites where each species occurs. Transplant data not included.

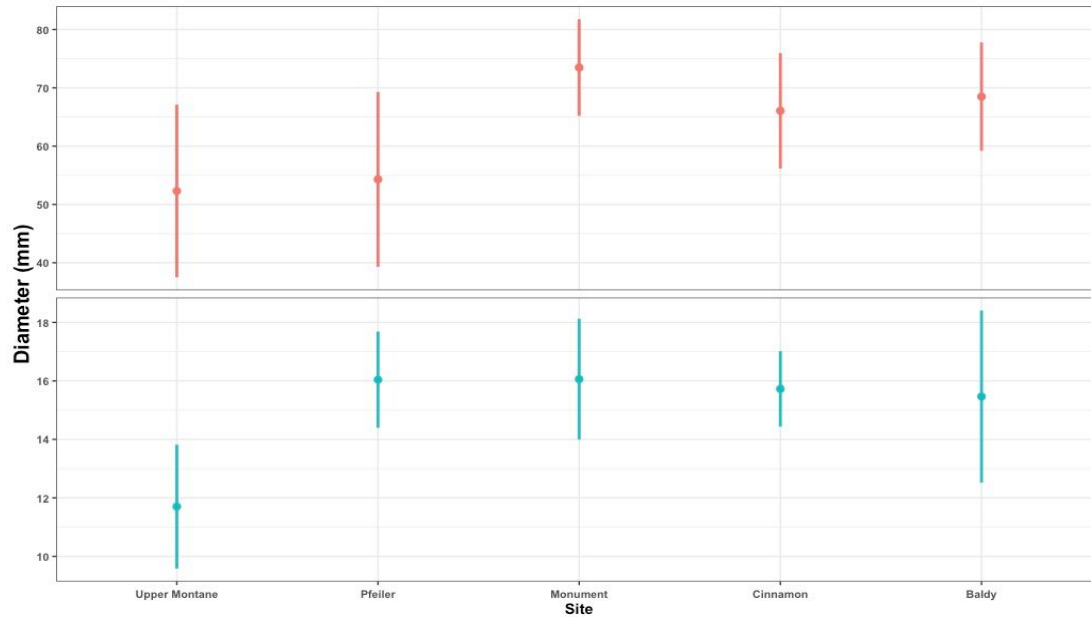


Figure 6. Diameter (mm) in response to changes in elevation (shown as sites) for *Helianthella quinquenervis* (red) and *Potentilla pulcherrima* (blue) Transplant data not included.

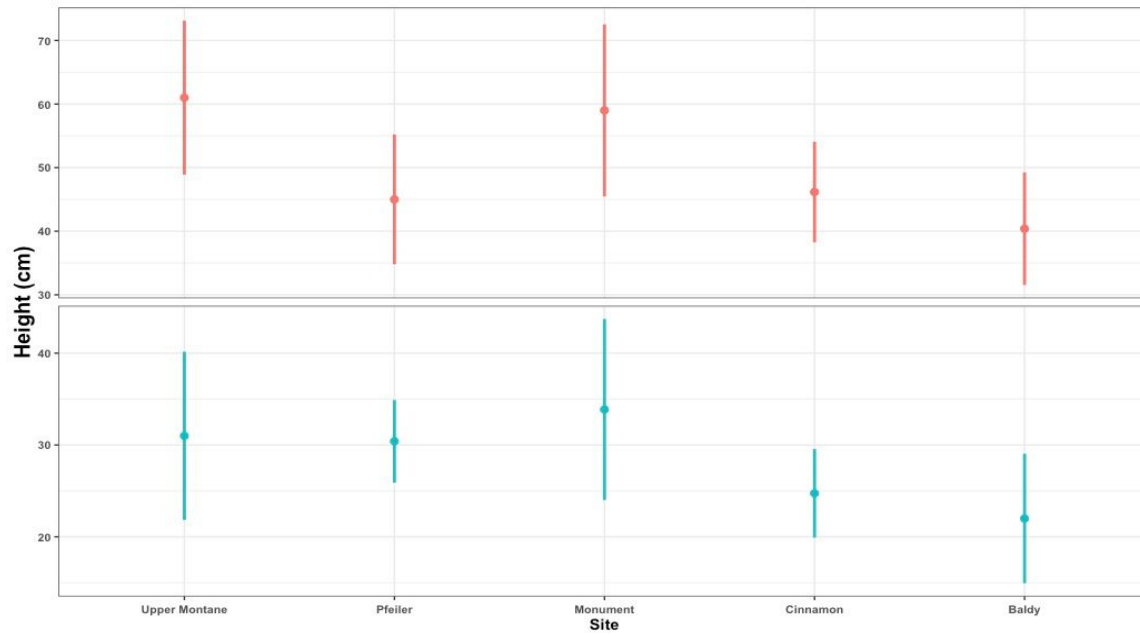


Figure 7. Height (cm) in response to changes in elevation (shown as sites) for *Helianthella quinquenervis* (red) and *Potentilla pulcherrima* (blue). Transplant data not included.

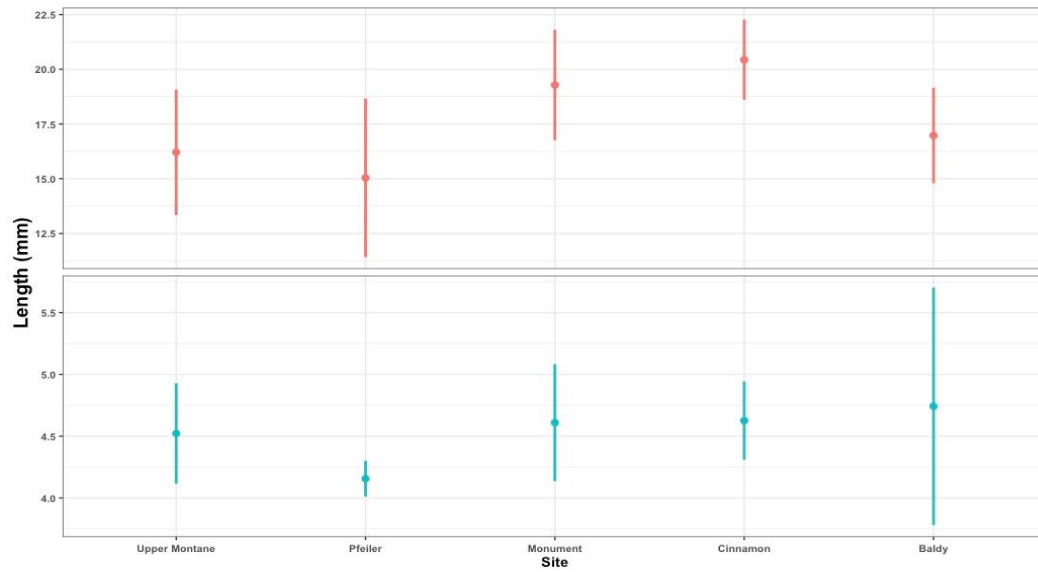


Figure 8. Length (mm) in response to changes in elevation (shown as sites) for *Helianthella quinquenervis* (red) and *Potentilla pulcherrima* (blue). Transplant data not included.

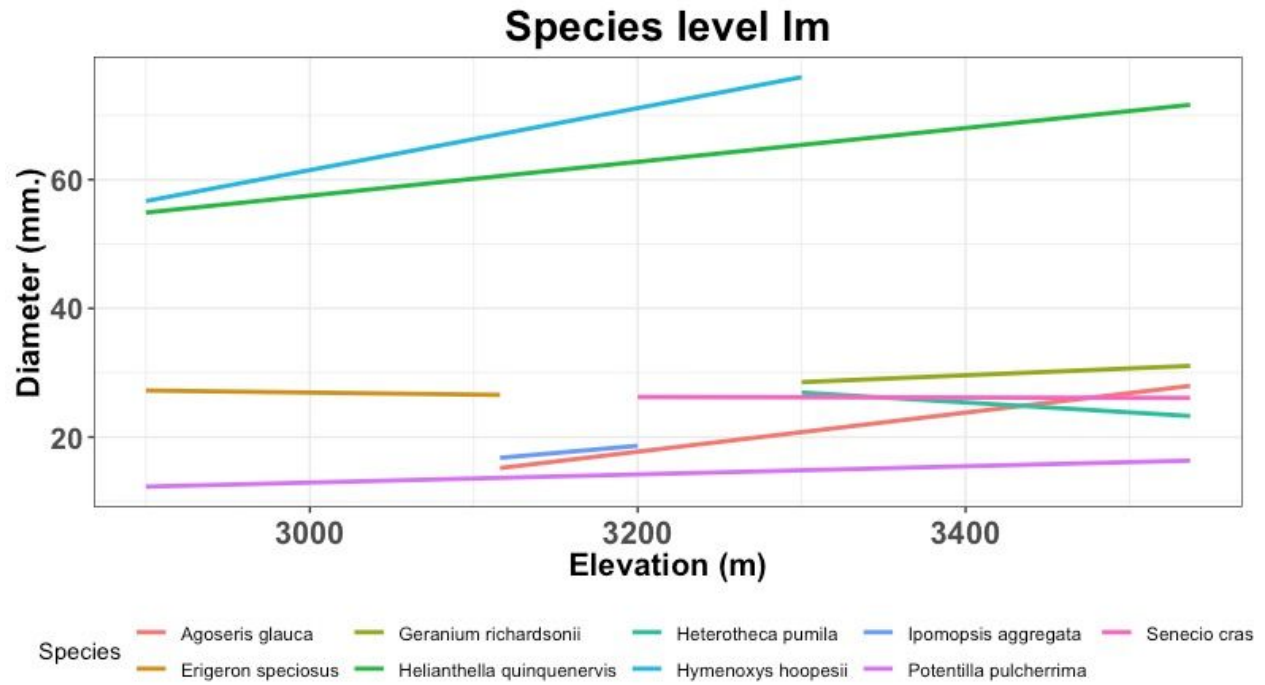


Figure 9. Species level findings for the changes in diameter (mm) of species that are widely distributed across sites along the elevational gradient. Transplant data not included.

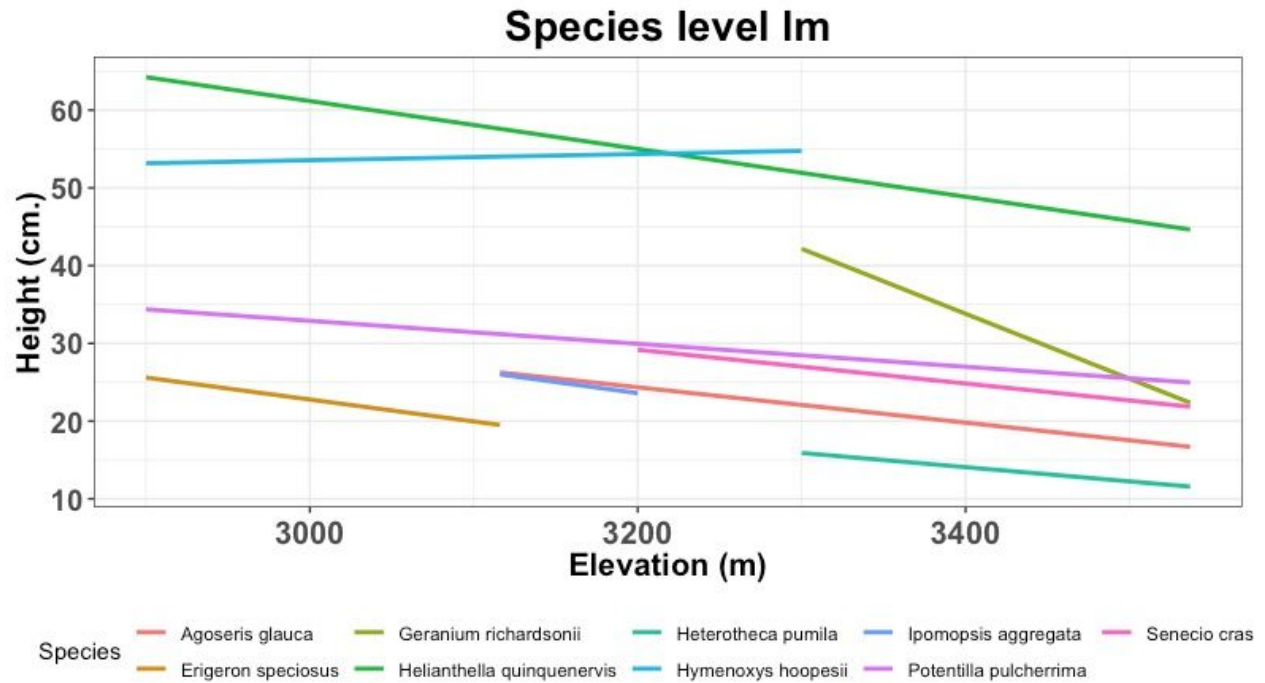


Figure 10. Species level findings for the changes in height (cm) of species that are widely distributed across sites along the elevational gradient. Transplant data not included.

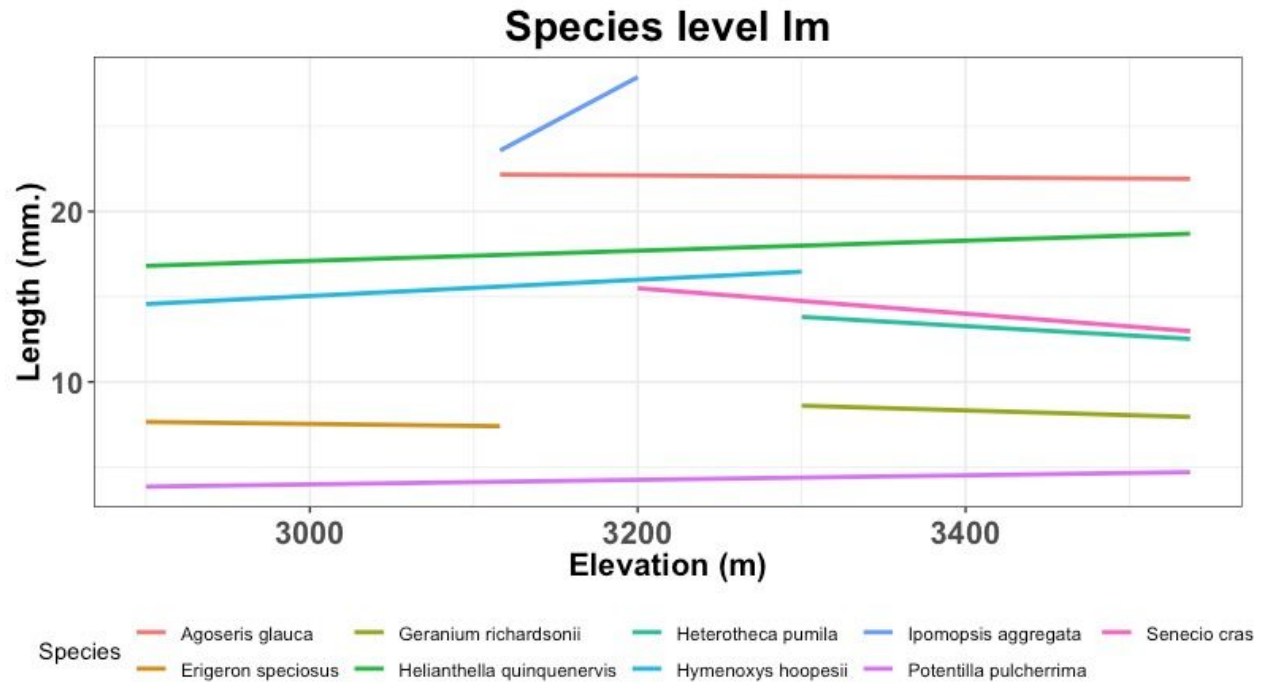


Figure 11. Species level findings for the changes in length (mm) of species that are widely distributed across sites along the elevational gradient. Transplant data not included.