PICCC FINAL PROJECT REPORT

SEPT 29, 2016

1. ADMINISTRATIVE

Project Name: Understanding how climate change is affecting Hawaii's high-elevation ecosystems: an assessment of the long-term viability of Haleakala silverswords and associated biological communities.
Agreement number: F12AP00802
Project Period: 9/17/12-6/30/16
Principal Investigator: Paul Krushelnycky **Institution**: University of Hawaii at Manoa
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Collaborators: Lloyd Loope, Lucas Fortini, Jesse Felts, Donald Drake, Forest Starr, Kim Starr, Thomas Giambelluca, Matt Brown
Total Cost: $107,450

2. PUBLIC SUMMARY

Climate change is expected to cause many plant and animal species to migrate, and others to decline or go extinct if they can't move sufficiently to keep up with changing conditions. Mountain-top species are thought to be especially vulnerable because they have limited potential to make such shifts. The Haleakala silversword, also known as ahinahina, occurs near the top of Haleakala volcano on the island of Maui, Hawaii, and is an ideal species with which to investigate plant responses to changing climate conditions. Long-term monitoring data allowed us to determine that the population has undergone a decline of approximately 60% in recent decades, and that this has corresponded to drier conditions that have developed on the mountain. A population model constructed with these data led to predictions of a high risk of extinction, over the next century, for most of the population if recent demographic trends continue. The likelihood that these trends will continue depends in large part on future rainfall patterns on the mountain, which at this stage are uncertain. Given this uncertainty, it seems prudent to plan for warmer and drier climate scenarios. Our investigations into the factors that influence silversword seedling drought tolerance suggest that some genetic differences among sub-populations may exist, but that more variation arises from the conditions that seedlings experience during development. Differences in weather and climate conditions across the plant's range also appear to contribute to patterns of seedling survival after outplanting. These findings have led to subsequent work in collaboration with land managers at Haleakala National Park, in which survival rates will be monitored in outplanting plots across wider environmental gradients. These include wetter areas of the park where silverswords grew in the past, and where they may be better able to withstand warmer and drier conditions in the future.

3. PROJECT REPORT

A. INTRODUCTION

a. TECHNICAL SUMMARY

The Haleakala silversword plant, or ahinahina, is an ideal taxon with which to develop a better understanding of the vulnerability of Hawaii's high-elevation ecosystems to climate change, and may inform responses among mountain-top biological communities more broadly. Our goals were to develop a demographic model for the silversword in order analyze demographic patterns and make population projections, collect local climate data with which to evaluate associations with demographic processes and rates, and test the potential roles of genetic differentiation and phenotypic plasticity in influencing seedling drought tolerance. We completed these goals, finding worrisome recent demographic trends. Based on decadal censuses, the total population has declined by approximately 60% from a peak around 1990, with decadal-scale population changes strongly associated with rainfall averages. Annual rates of population growth, estimated with a stage-based population matrix model, suggested more detrimental trends for the lower elevation portion of the silversword range, especially after about 1999. If similar demographic rates continue, the lower part of the population, which supports approximately 90% of plants, is projected to be at high risk of extinction within the next 100 years. Many vital rates for lower elevation plants were negatively associated with warmer temperatures, lower rainfall, and higher evaporative demand. Therefore, future patterns of precipitation, which are uncertain for upper Haleakala, will be of central importance to future population status and trends. In silversword seedlings, variation in traits often associated with ability to tolerate water stress were linked to some degree to the source location of seeds, and additionally arose via phenotypic plasticity. However, a greenhouse drought experiment and outplanting experiment suggested a weaker role for genetic differentiation in influencing plant survival, instead emphasizing the effects of phenotypic plasticity and variation in environmental conditions experienced. These findings led to recommendations to further test outplant survival across a wider range of environmental conditions and sites on Haleakala volcano, directly influencing current and future management strategies of resource managers at Haleakala National Park. The unusually detailed nature of this case study should also provide insight into mechanisms and processes of plant response to climate change more generally, particularly in alpine environments.

b. PURPOSE AND OBJECTIVES

Consistent with predictions about the vulnerability of mountain-top biological communities to climate change, evidence has been mounting that the endemic alpine plant, the Haleakala silversword, or ahinahina (*Argyroxiphium sandwicense macrocephalum*), is experiencing dramatic population declines in recent decades that are tied to drier and possibly warmer conditions. This iconic plant has been the subject of unusually detailed study and monitoring, and forms the foundation of a diverse community. It is therefore an ideal taxon with which to develop a better understanding of the potential impacts of climate change in Hawaii’s high-elevation ecosystems, and may reflect more widespread but undetected changes among co-occurring species that have little associated information regarding status and trends. Moreover, identifying the causes and mechanisms of silversword mortality and population decline is necessary for developing effective management strategies for this important taxon under future climate scenarios.

Our goals for this project were three-fold. First, to develop and implement a robust long-term monitoring protocol, and to develop an associated demographic population model, that will allow current and future demographic analyses and projections. Second, to maintain a recently-installed network of climate stations spanning the silversword range, that will help parameterize and inform demographic analyses on silverswords, as well as provide a more detailed climate picture relevant to other elements of the subalpine and alpine ecosystems at Haleakala. Third, to experimentally test the roles of genetic differentiation and phenotypic plasticity in influencing silversword seedling drought tolerance and mortality. The last objective arose in response to prior data indicating an elevational gradient in mortality among silverswords at Haleakala, with plants at the lower end of the range experiencing stronger population declines. Different mechanisms could account for this spatial pattern, including elevational gradients in evaporative water demand or other sources of external stress, as well as spatial differences in inherent drought or temperature tolerance in plants, stemming from either local adaptation or phenotypic plasticity. The relative importance of these drivers could significantly influence the design of future mitigation and restoration strategies for natural resource managers in Haleakala National Park and surrounding state forest reserves. Each of the three the original objectives for the project were met.

c. ORGANIZATION AND APPROACH

A) For the first objective, we established four new demography plots to complement and address some of the shortcomings of 11 pre-existing, smaller demography plots installed in 1982. These new plots span the entire elevational range of silverswords, and each encompasses a larger area and larger number of plants (approximately 300) to overcome bias that may result from the clumped nature of silversword demographic processes. Annual population changes in these new plots were compared to annual changes in three silversword sub-populations surrounding each plot for the first two years of the project, to verify that the demographic rates measured in the plots appear representative of wider regional patterns. We also repeated a population-wide census conducted roughly every decade since 1971, last performed in 2001, to obtain a current total population estimate. Using the combined demographic data sets from the historic and new demography plots, we constructed a stage-based matrix population model for the Haleakala silversword. A stage-based model was used instead of other approaches, such as Integral Projection Models, because most of the early demographic data included only size-class information. We used this model to calculate annual vital rates for lower and upper elevation subsets of the demographic data, as well as sensitivities and elasticities of these rates. We attempted to correlate the resultant vital rates with available climate data, and used the model to make projections of population trends.

B) For the second objective, we visited each of the six climate stations periodically to download data, replace batteries and dessicant, check instrument function, and replace instruments or loggers as needed. Downloaded data were collated and summarized into hourly averages for the variables measured or computed: rainfall, air temperature, relative humidity, soil moisture, soil temperature and vapor pressure deficit.

C) For the third objective, we used a combined greenhouse and outplanting experiment to test factors underlying potential variation in seedling drought tolerance and survival. Using two mobile greenhouses placed at the lower and upper ends of the silversword's elevational range, we grew silversword seedlings from seeds, and then tested the effects of growth elevation (low, high), moisture availability (low, high watering treatment), and source elevation (low, mid, high elevation sub-populations) on growth and development of morphological traits associated with drought tolerance for a subset of plants. We next applied progressive drought to another subset of plants, and assessed the effects of growth elevation, water treatment, source elevation, and drought elevation on seedling longevity and physiological performance. The final subset of plants was outplanted at the end of the growth period into three plots in the field, at low, middle and high elevation. Survival of these plants was monitored monthly through the end of the second wet season after outplanting (23 months). Patterns of survival were analyzed for the effects of growth elevation, water treatment, source elevation, outplant site, and weather conditions at each outplant site.

B. PROJECT RESULTS

Demographic patterns

The most recent full population census, completed in 2013, yielded an estimate of 39,355 plants for the entire Haleakala silversword population. When compared to the previous four decadal censuses, a long pattern of recovery followed by several decades of decline was revealed (Fig. 1). Decadal-scale population growth rates were strongly correlated with rainfall averages during the inter-census periods (Fig. 2). The dramatic reversal in the silversword population trajectory around 1990 coincides with an upward shift in the frequency of the trade wind inversion (TWI) in Hawaii at that time, which on average created sunnier and drier conditions in silversword habitat.

The four new demographic plots recorded three years of annual population growth during the project period. Comparison of these growth rates with those of surrounding sub-populations in the first two years indicated that the plots should generally be representative of wider regional patterns. While annual changes in numbers of plants can vary substantially among sub-populations, values in the demography plots were often near the means of the three surrounding sub-populations, and usually within one standard deviation of the mean. The total number of plants included in this analysis represented roughly 10-11% of the total population, lending support to the interpretation that the newly established plots should have little bias relative to the larger population, and thus represent a robust demographic monitoring system for the future.

Our population matrix model incorporated demographic data from the 11 historic plots and the four new plots, as well as a long-running plot (since 1993) maintained by project collaborator Donald Drake. Together these plots provided demographic rates from 1983 through 2015, with the exception of a gap from 1987 to 1994 when the historic plots were not visited in consecutive years. The model also included a seed bank stage, estimated the effect of seed predation, and incorporated density-dependent seed set rates using prior findings of Stacey Forsyth and the PI's work on silversword reproductive ecology. Sensitivity and elasticity analysis using the resultant model indicated that, when considering all plots and years of data, survival of medium (5cm < rosette diameter < 20cm) and large (rosette diameter > 20cm) plants are the vital rates that contribute most strongly to positive population growth. As is commonly the case with long-lived plants, survival of seedlings (first year) and small plants (rosette diameter < 5cm) and rates of fecundity had small elasticities, indicating that they contribute relatively little to population growth rate on a relative or proportional scale. However, some of latter rates, like seedling recruitment and flowering rate, can fluctuate very strongly from year to year in the case of silverswords, which can make their actual influences more important.

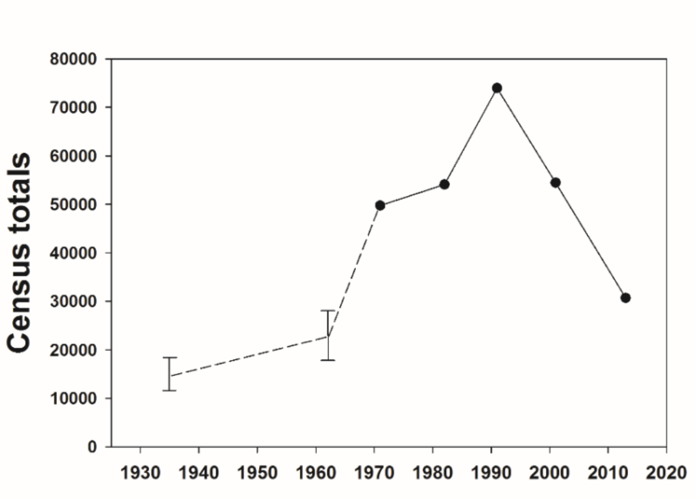

Figure 1. *Estimated Haleakala silversword population trend over time. Adjusted census totals for the entire population from 1971-2013 are shown, along with population size estimates for 1935 and 1962, with lower and upper bounds projected from counts on a single cinder cone.*

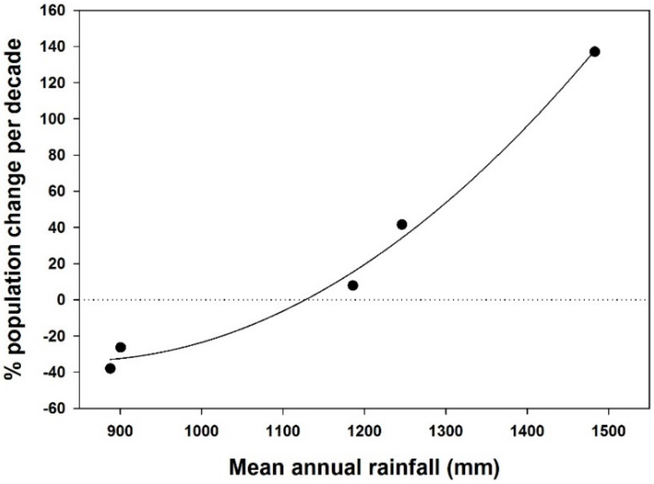

***Figure 2**. Relationships between decadal-scale population change and average annual rainfall during the inter-census periods (r^2 = 0.991, p = 0.009).*

Examination of spatial and temporal patterns in the asymptotic rate of growth, λ, supported prior interpretations that demographic rates have shifted over time, and differ between lower and higher elevation areas (Fig. 3). We used a cutoff of 2500m elevation to separate lower and upper plots, which is the approximate midpoint of the silversword elevational range. When considering annual values of λ and other vital rates, a shift to more detrimental demographic rates was suggested to have occurred around 1999, with the exception of strong growth in 2014 and 2015, which experienced wetter conditions. This shift is later than the one suggested from the decadal census data (Fig. 1), but this may have been influenced by the gap in demographic data from 1987 to 1994 (the gap actually extended to 1997 for lower elevation plots). Based on these spatial and temporal categories (lower/higher elevation, pre/post 1999), we calculated quasi-extinction probabilities over the next 100 years, using a threshold of 100 remaining individuals in the population. These analyses, each using 1 million stochastic matrix projections, predicted essentially zero chance of extinction over the next 100 years for upper elevation areas given demographic rates observed both pre- and post-1999, and zero chance of extinction for lower elevation areas given demographic rates observed before 1999. However, extinction probabilities rise dramatically in the latter portion of the coming century for lower elevation areas if they are assumed to continue experiencing the same demographic rates observed after 1999 (Fig. 4).

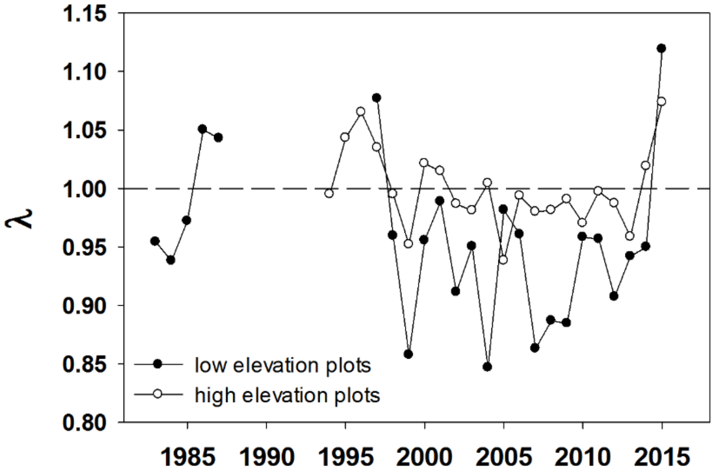

Figure 3. *Annual values of the asymptotic population growth rate, λ, from the matrix population model, calculated separately for lower and upper elevation plots. A value of 1 indicates a stable population.*

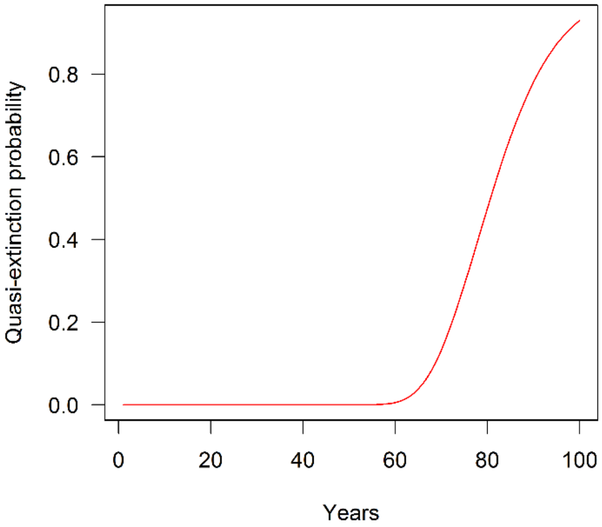

Figure 4. *Time to reach a quasi-extinction threshold of 100 remaining individuals given demographic rates observed in lower elevation plots after 1999.*

We attempted to correlate the vital rates from the demography model to the three climate variables that had the greatest availability of data coverage over the period of record: rainfall, air temperature, and the incidence of the TWI. We found that climate associations with the vital rates were often complex, and in some cases fairly weak. This was likely owing at least in part to the fact that despite this being an unusually long demographic data set, there were still only 20-22 years of data, which is a relatively small sample size with which to decipher potentially complicated climate relationships. In addition, it can be expected that some rates, like seedling recruitment, are likely to be much more responsive to weather and climate than other rates, like survival of large plants. Nevertheless, most of the vital rates were found to correlate with the climate variables to at least some degree, and some of the relationships were fairly strong. In general, in the low elevation plots, rates of survival and growth tended to be promoted by wetter conditions, while the effect of higher TWI incidence was often positive when rainfall was also high, but tended to be negative when rainfall was low. This suggests that sunny and wet conditions are favorable for growth and survival, while sunny and dry conditions are stressful. Higher air temperatures were also often found to be associated with lower survival and growth in the low elevation plots. In contrast, in the high elevation plots, higher air temperatures and higher TWI incidence tended to be correlated with higher survival and growth. The contrasting influences of temperature between lower and higher elevation plots was evident for several of the vital rates, and suggests that plants near the summit of Haleakala are currently more cold-temperature limited than plants in the lower part of the silversword range. The strongest of these climate associations may subsequently be used to refine the matrix model predictions, wherein projections could be made for different climate scenarios.

Climate station data

The climate stations operated with relatively few problems during the project period. Degradation of the leaf wetness sensors required their replacement at all stations, one of the AT/RH sensors was replaced because it began drawing excessive current (without impacting data collection), and one rain gauge failed and was replaced. Two of the data loggers experienced temporary stoppage, likely caused by extreme weather events, while a third stopped due to ruptured batteries. Despite these issues, data were successfully collected for 95.3% of the >1.4 million total sensor-hours at the six stations over the project period. The time series captured the expected drier than normal 2015-16 wet season resulting from El Nino conditions, and confirmed that despite this period, weather on upper Haleakala was considerably wetter from mid-2013 through mid-2016, particularly during the dry seasons, than the prior three years that the stations have been operating.

Drought tolerance experiment

The greenhouse experiment revealed that all three of the main factors of interest (seed source area, water treatment, and growth elevation) had significant effects on at least some morphological traits that often influence plant drought tolerance. One of the traits that responded most strongly to water treatment, indicating phenotypic plasticity, as well as to source elevation, indicating genetic differentiation, was the root mass fraction (RMF), or the proportion of plant biomass allocated to roots (Fig. 5). The total root length per unit shoot mass (RLSM) also responded significantly to water treatment. Several other traits, the leaf area ratio (LAR; total leaf area relative to total plant biomass), specific leaf area (SLA; leaf area relative to leaf mass), and water use efficiency (WUE; net photosynthetic gain per unit water transpired), responded significantly to growth elevation, also an indication of phenotypic plasticity. Other physiological traits, including net photosynthetic rate, transpiration, stomatal conductance, and the water potential and relative water content at the turgor loss point, exhibited less variability with respect to the treatment factors. Overall, when adjusting for seedling size, high elevation source plants exhibited trait values that should promote greater drought tolerance than low elevation source plants; plants subjected to the low water treatment exhibited trait values that should promote greater drought tolerance than high water treatment plants; and plants grown at high elevation exhibited trait differences that should promote greater drought tolerance than plants grown at low elevation.

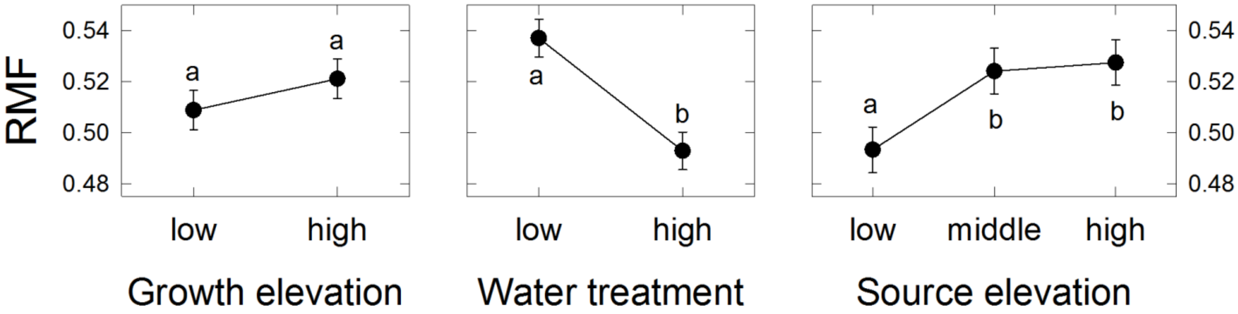

Figure 5. *Mean (±SE) root mass fraction (RMF), or the proportion of total plant biomass allocated to root tissue, for the different levels of the three main treatment factors imposed during seedling growth. Higher RMF implies greater ability to tolerate water limitation.*

During the experimental drought, plants in the higher elevation greenhouse died more quickly and had higher evapotranspiration than those in the lower greenhouse, which experienced cloudier conditions and lower evaporative demand. However, this effect acted mainly on plants that were originally grown in the lower greenhouse, while those grown in the higher greenhouse performed similarly at both elevations during the drought. The other treatment factors imposed during growth -- water treatment and source elevation -- had no significant effect on drought performance.

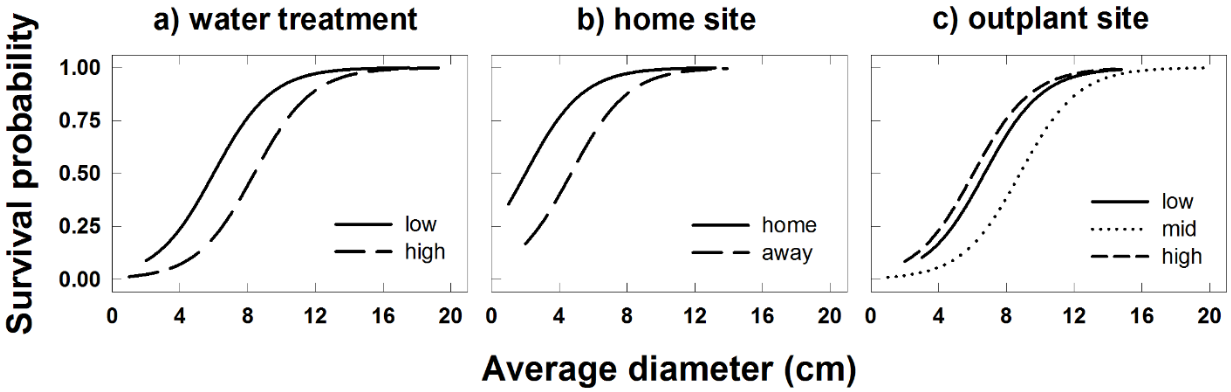

Figure 6. *Fitted survival curves of outplants as a function of plant size (rosette diameter). a) Effect of growth-stage water treatment, assessed at end of the second wet season after planting (23 months), b) Effect of planting at home site versus away from home site, assessed at end of first wet season after planting (11 months), c) Effect of outplant site elevation, assessed at end of the second wet season (23 months).*

The outplanting experiment served as an important comparison with the greenhouse drought experiment, because plants experiencing water shortage under field conditions may perform differently than those exposed to extreme drought conditions in pots in the greenhouse. However, the timing of the outplanting experiment coincided with wetter conditions than have been seen in recent years, especially during the two dry seasons that have passed since planting. Therefore, the outplants have not experienced substantially stressful conditions to date, and 69.4% of the plants were still alive at 23 months after planting. Despite this relatively high rate, several factors were found to influence patterns of survival in the outplant plots. Plant size was by far the most important factor, with small plants much more likely to perish than larger plants. After controlling for plant size, the strongest and most persistent effect has been the water treatment applied during growth, with plants in the low water group exhibiting higher survival rates than plants in the high water group (Fig. 6). This corresponds to the patterns of trait variation measured in the greenhouse experiment (e.g. Fig. 5), which predicted greater capacity to tolerate water stress among low water treatment plants. Another factor influencing survival was whether plants were planted at their home sites, i.e., near the source location of their seeds. Plants planted at their home site had higher survival during the first year after planting (Fig. 6), but this effect disappeared subsequently. Finally, survival was marginally significantly different among outplant sites, with survival lower at the mid elevation site compared to the other two (Fig. 6). Analysis of weather patterns during the outplanting experiment found that warmer air temperatures during the 30 days prior to each monitoring date was the best predictor, among weather variables considered, of the probability of plant mortality. However, this effect was quite weak.

C. FINDINGS/EVALUATION

a. FINDINGS AND CONCLUSIONS

The demographic data and analyses in this project indicate worrisome trends for the Haleakala silversword. Based on decadal censuses, the total population has declined by approximately 60% from a peak around 1990, with decadal-scale population changes strongly associated with rainfall averages. The upward shift in the frequency of the TWI that also occurred around 1990 serves as a compelling underlying causal mechanism for the deteriorating demographic rates, because this shift led to lower rainfall, higher solar radiation, and greater evaporative demand at upper elevations of Haleakala. Data from the network of demographic plots corroborate these trends, recording negative population growth in most years after 1999, with the exception of 2014 and 2015 which were wetter and showed strong seedling recruitment. It remains to be seen how this vulnerable life stage will fare over the next few years. Moreover, matrix model projections found that even considering these two favorable years, the lower elevation portion of the silversword range can be expected to continue declining and face high risk of extinction within the next 100 years, if demographic rates seen since 1999 persist. This is of concern because the vast majority of the silversword population (~90%) occurs in the lower part of the range. Somewhat surprisingly, climate associations with matrix model vital rates suggested that plants near the summit of Haleakala currently fare better under warmer and clearer conditions. However, it might be expected that as temperatures continue to rise, the beneficial effects of warmer temperatures will begin to reverse and eventually become detrimental, as they already appear to be at lower elevations.

Variation in traits often associated with ability to tolerate water stress were linked to some degree to the source location of seeds, and additionally arose via phenotypic plasticity. The greenhouse experiment suggested that under extreme drought conditions, these trait differences acquired during growth may have relatively weak effects on longevity, compared to differences in the magnitude of external climate stress (especially evaporative demand, but also temperature). However, under more moderate and perhaps realistic conditions of water stress experienced in the field, phenotypic traits may influence patterns of survival. Indeed, plants grown under a lower water treatment subsequently had higher survival rates in the outplanting experiment. Phenotypic plasticity may therefore enhance survival of plants in any given location, while at the same time contributing to differential survival across sites along environmental gradients. For example, plants growing at lower elevations and at wetter sites are predicted to develop trait values less tolerant to water stress based on our results, which may lead to higher mortality if conditions in these areas subsequently diverge further from the norm during stressful periods.

Variation in survival among outplant sites, due to differences in environmental conditions, was less than expected, but this result was likely influenced by the relatively benign conditions that prevailed during the outplanting experiment. For example, soil moisture fluctuated strongly between wet and dry seasons in the three years prior to the experiment, but because of consistent rainfall remained high and nearly constant even through the dry seasons in the most recent two years. Consequently, air temperature was the only weather variable that correlated with probability of outplant mortality, and this effect was weak. It is likely that at least some of these patterns would change under conditions of greater water stress, as often occurs during the dry season at Haleakala. Under such conditions, rainfall and/or soil moisture levels may better correlate with probability of mortality, and the pattern of survival across elevation might differ. For example, a group of seedlings planted in the same outplant plots in preliminary trials a year earlier exhibited a pattern of survival positively related to elevation, which more closely matches the pattern observed across the wild population. On balance, it appears likely that the elevational gradient in mortality in recent decades has been influenced by all three factors considered (genetic differentiation, phenotypic plasticity, differences in climatic stress), but that the latter two contribute most strongly.

b. LESSONS LEARNED

Aside from the relatively minor climate station equipment failures, the largest issue encountered was the weather conditions during the study. A key goal of the project was to test seedling performance under conditions of water stress, both in the greenhouse and in the field. While soil moisture status could be controlled in the greenhouse, atmospheric conditions were more humid than expected for the dry season, especially at the lower elevation greenhouse, which prevented a test of the combined effects of higher evaporative demand (VPD) and higher air temperatures. More importantly, wet conditions in the field prevented a good test of outplant survival under water-limited dry season conditions, at least to date. However, this factor is beyond control, so it is difficult to envision an alternate approach to mitigate its effects.

c. IMPLICATIONS AND RECOMMENDATIONS

Most of the Haleakala silversword population appears to be at risk if climate patterns over the past several decades continue into the future. Likewise, the favorable model projections for the upper elevation portion of the population are dependent on future demographic rates remaining similar to recent ones, and not gradually shifting, as temperature continues to rise, towards rates currently seen in the lower portion of the range. Of central importance to future population status and trends is the future pattern of precipitation on upper Haleakala. Unfortunately, different downscaled climate projections currently conflict on this topic, and include predictions of both wetter and drier conditions. Given this uncertainty, it seems prudent to plan for a warmer and drier scenario.

Future adaptation actions should focus on determining the most favorable habitats (including microhabitats) on Haleakala volcano for silversword survival, and directing outplanting and/or seed sowing efforts to these areas. While seed source location was tied to some phenotypic differentiation, this factor was not found to be important in either the greenhouse drought experiment or in the outplanting experiment. This suggests that genetic differences in drought tolerance are probably limited, and not likely to form the basis of an effective strategy for mitigating against potentially drier conditions. Likewise, phenotypic plasticity may provide some buffer against changing conditions, but to date has not been sufficient to prevent significant mortality and decline in the wild population. Nevertheless, our findings that a lower watering regime during growth appears to increase survival during at least the first few years after outplanting has important implications for future propagation and restoration activities.

The findings of the project have directly led to the next phase of silversword research and management at the park, in which additional outplanting trials are currently being implemented. These trials will establish outplanting plots across wider gradients in rainfall and elevation than are encompassed by the current silversword range, by including sites on the wetter north slope of the volcano and the eastern end of the crater. The experiment will therefore test how higher precipitation may counter the effects of warmer temperatures, and at the same time will re-establish silverswords in areas that supported them in the past but from which they have since been extirpated.

D. INFORMATION DISSEMINATION

a. OUTREACH

The project PI and intern both interacted regularly with park staff regarding project progress and findings. During the greenhouse study, project personnel and park staff interacted with hundreds of park visitors, as the two greenhouses were located next to park visitor centers. As part of his intern position, Jesse Felts also conducted multiple outreach events and public presentations to educate local school groups and teachers on the silversword study and climate change more generally. These included:

2/27/14 - Kula Elementary Science Night - 71 students & parents
2/28/14 - Native Hawaiian Plant Society presentation - approx. 30 attendees

3/20/14 - Presentation for Kupukupu 'Aina interns at summit greenhouse - 13 students
4/5/14 - Project Learning Tree presentation in Kihei - 15 teachers
4/22/14 - Presentation for STEM Teacher Workshop at HQ greenhouse - 31 teachers
5/1/14 - Climate Change presentation at Kihei Charter High - 34 students
8/9/14 & 8/30/14 - Presentations for Teacher Workshops at Haleakala HQ - 20 teachers

The project received media attention on a number of occasions, including several features in The Maui News, including a front page story of the 8/17/14 Sunday edition, coverage in the Honolulu Star Advertiser and the Ka Leo student newspaper at the University of Hawaii, and several mentions on local TV news broadcasts and on Hawaii Public Radio. The PI was also interviewed on HPR's morning talk show, The Conversation on 2/15/16.

b. SCIENCE OUTPUTS

Three papers were published during the study period:

Krushelnycky, P.D., L.L. Loope, T.W. Giambelluca, F. Starr, K. Starr, D.R. Drake, A.D. Taylor, and R.H. Robichaux. 2013. Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. Global Change Biol. 19: 911-922.

Krushelnycky, P.D. 2014. Evaluating the interacting influences of pollination, seed predation, invasive species and isolation on reproductive success in a threatened alpine plant. PLoS One 9(2): e88948.

Krushelnycky, P.D., F. Starr, K. Starr, R.J. Longman, A.G. Frazier, L.L. Loope, and T.W. Giambelluca. 2016. Change in trade wind inversion frequency implicated in the decline of an alpine plant. Climate Change Responses 3:1.

Two additional papers are in preparation, covering the population matrix model analysis, and the greenhouse and outplanting study.

Several presentations were made at scientific meetings by the PI and project intern:

Krushelnycky, P.D. 2013. The role of drought tolerance in Haleakala silversword viability. PI CSC/PICCC Science Symposium, July 15, 2013, Honolulu.

Krushelnycky, P.D., L.L. Loope, T.W. Giambelluca, F. Starr, K. Starr, D.R. Drake, A.D. Taylor, R.H. Robichaux, and J. Felts. 2014. Climate-associated population declines reverse recovery and threaten future of the iconic Haleakalā silversword. Island Biology Conference, July 7-11, 2014, Honolulu.

Felts, J., P.D., Krushelnycky, K. Asiu and M. Brown. 2014. Educating National Park visitors about climate change and its effects on the Haleakala ahinahina. Hawaii Conservation Conference, July 15-17, 2014, Honolulu.

Krushelnycky, P.D., J. Felts. 2015. Factors influencing seedling drought tolerance in the Haleakalā silversword. PI CSC/PICCC Science Symposium, February 26-27, 2015, Honolulu.

Krushelnycky, P.D., J. Felts. 2015. Factors influencing seedling drought tolerance and potential response to climate change in the Haleakalā silversword. Association for Tropical Biology and Conservation Conference, July 12-16, 2015, Honolulu.

Felts, J., and P.D. Krushelnycky. 2015. Factors influencing seedling drought tolerance and potential response to climate change in the Haleakalā silversword. Hawaii Conservation Conference, August 3-6, 2015, Hilo.

Two webinar presentations were made by the PI:

Krushelnycky, P.D. 2016. The role of climate in recent population declines of the Haleakala silversword. Climate Academy 2016, USFWS, National Conservation Training Center, February 10, 2016.

Krushelnycky, P.D. 2016. Effects of climate on the Haleakala silversword and research to improve future mititgation. Climate Change Webinar Series 2016, NPS Natural Resource Stewardship and Science, Climate Change Response Program, June 9, 2016.