FINAL REPORT

Remote Sensing Technology for Threatened and Endangered Plant Species Recovery

ESTCP Project RC-201203

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ACRONYMS AND ABBREVIATIONS

ACUB	Army Compatible Use Buffer
BO	Biological Opinion
CAO	Carnegie Airborne Observatory
CEMML	Center for Environmental Management of Military Lands
DEM	Digital Elevation Model
DoD	US Department of Defense
DOFAW	State of Hawaii Department of Forestry and Wildlife
GIS	Geographic Information System
GLM	General Linear Model
GPS	Global Positioning System
HETF	Hawaii Experimental Tropical Forest
HS	High Suitability
HSM	Habitat Suitability Model
IPIF	USDA Forest Service, Institute of Pacific Islands Forestry
LiDAR	Light Detecting and Ranging
LS	Low Suitability
PTA	Pohakuloa Training Area
PWW	Puu Waawaa
SERDP	Strategic Environmental Research and Development Program
SMMNRA	Santa Monica Mountains National Recreation Area
TA	Training Area
TER-S	Threatened, Endangered, and At-Risk Plant Species
USAF	US Air Force
VBG	Vandenberg Air Force Base
WV-2	WorldView-2

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EXECUTIVE SUMMARY

INTRODUCTION

For the more than 100,000 plant species worldwide thought to be at risk of extinction, a lack of suitable habitat is the major barrier to their recovery (Pitman and Jorgensen 2002, Godefroid et al. 2011, Maschinski and Haskins 2012). The two primary conservation actions for threatened, endangered, and at-risk plant species (TER-S) are to restore suitable habitat areas so that extant populations can expand and to reintroduce individuals to restored or protected areas. Reintroduction is an expensive, slow effort but is often essential when population sizes are very low or there are other barriers to dispersal among suitable habitats (Maschinski and Haskins 2012). The success rates of reintroduction projects are variable, and low success is often due to a lack of suitable habitat, the very cause of decline (Godefroid et al. 2011, Drayton and Primack 2012, IUCN 2013). This demonstration addresses a major challenge to reintroduction success - finding suitable habitats in fragmented and degraded landscapes.

Recent reviews of reintroduction studies indicate that habitat quality and microsite conditions of reintroduction projects are one of the key drivers of plant establishment, growth, survival, and population persistence (Bottin et al. 2007, Godefroid et al. 2011, Kaye 2011, Maschinski and Haskins 2012). In particular, microclimatic conditions can strongly influence early life stages of germination and establishment, which are the most critical life history phases for regeneration, i.e., the *regeneration niche* (Grubb 1977, Maschinski et al. 2012, Wendelberger and Maschinski 2016). For example, local topography can influence physical variables such as solar radiation, soil water retention, and temperature which alter where plants can regenerate and persist (Rovzar et al. 2017).

Many hotspots important for the conservation of at-risk plant species occur in dryland ecosystems (Dobson et al. 1997, Friday et al. 2015); however, reintroduction programs have had limited success in many dry ecosystems due to a low probability of establishment and high levels of plant mortality (e.g., Cordell et al. 2008, Lloyd et al. 2018). Often planting areas are arbitrarily or opportunistically selected without consideration of microclimatic gradients. Thus, identifying high quality microclimates for reintroduction can significantly improve plant survival and reproduction (Bottin et al. 2007, Godefroid et al. 2011, Drayton and Primack 2012, Guerrant 2012, Maschinski et al. 2012, Monks et al. 2012, IUCN 2013, Wendelberger and Maschinski 2016, Rovzar et al. 2017, Lloyd et al. 2018).

Overcoming barriers to plant establishment in dryland environments is especially critical for TER-S management on Department of Defense (DoD) installations. The top ten DoD installations with the greatest number of federally listed species occur in dryland ecosystems, and the top four are in Hawaii (Stein et al. 2008). The DoD spends over $10 million annually on environmental programs in Hawaii to protect TER-S and associated critical habitat (Michelle Mansker, pers. comm. 2011). Therefore, technology to increase the success of TER-S planting programs in dryland ecosystems in general, and Hawaiian dryland ecosystems in particular, can positively affect the outcome of TER-S management for the DoD. This technology also can enhance the DoD's training capability by improving the quality of protected areas and planning training activities in lower quality habitat.

In dryland ecosystems, topography can be an important landscape feature for reintroduction planning, and planting activities may have the greatest success in topographic depressions where soil and water accumulate and where plants are protected from desiccating winds. Our habitat suitability modeling (HSM) technology formally incorporates the importance of wind into topographic modeling to improve plant growth and survival, and use the information for landscape planning for the reintroduction and management of at-risk species. We developed the HSM technology to identify habitat suitability based on topography for TER-S reintroduction using high resolution airborne Light Detecting and Ranging (LiDAR) data, the leading edge technology for high resolution topographic and vegetation structure mapping (Lefsky et al. 2002, Turner et al. 2003, Goetz et al. 2007, Vierling et al. 2008, Asner et al. 2009, Bergen et al. 2009, Goetz et al. 2010, Fricker et al. 2015, Friday et al. 2015, Cordell et al. 2017).

We developed topographic models of habitat suitability for plant restoration on the Island of Hawaii in a 49,000 ha military training area (Pohakuloa Training Area, PTA) and a state forest reserve (Puu Waawaa, PWW), and in Southern California at Vandenberg Airforce Base (VBG) and the Santa Monica Mountains National Recreation Area (SMMNRA). We used LiDAR data from The Carnegie Airborne Observatory to produce a digital elevation model (DEM) for PTA. We then used the DEM to define areas of suitable topography for plant reintroduction by developing two criteria based on the landscape's capacity to reduce water stress. The criteria were combined to develop a mapped habitat suitability model (HSM) for outplanting with three suitability classes: no criteria met (Low Suitability - LS), one criterion met (Moderate Suitability), and two criteria met (High Suitability - HS). Our demonstration validated the utility of the HSM to guide reintroduction efforts at PTA and demonstrated the use of this technology for TER-S restoration planning at other DoD installations.

OBJECTIVES OF THE DEMONSTRATION

We used three tasks to demonstrate how our HSM technology can inform TER-S reintroduction programs to increase plant performance and survival across DoD installations.

1. Task 1 evaluated the potential of the HSM to improve success of TER-S reintroduction activities in the field. We experimentally planted TER-S into replicate LS and HS areas at PTA and PWW. We monitored survival and measures of plant and population performance to determine how plants respond differently to restoration in different suitability classes. We evaluated whether plants had greater survival and growth and reduced plant stress in HS, compared to LS, sites.
2. With Task 2, we developed methodology for generating HSMs from high resolution satellite data. Our HSM for PTA was derived from high resolution airborne LiDAR data, which is at the leading edge of technology available for digital elevation modeling, but the data are somewhat expensive and difficult to obtain. WorldView-2 (WV-2) satellite data are available globally and could be used to create HSM maps for sites that lack LiDAR. We used optical stereo measurements from the WV-2 satellite and compared its cost and performance to LiDAR.
3. In Task 3, we quantified the cost of implementing the technology as well as the cost savings that can result from using the technology. We developed materials for technology transfer including a software extension for ArcGIS.

TECHNOLOGY DESCRIPTION

The HSM technology identifies habitat suitability based on topography using DEMs made from high resolution airborne LiDAR data. The DEM is used to define areas of suitable topography for plant reintroduction by developing two criteria based on the landscape's capacity to reduce water stress (Fig. ES1). The criteria are that an area is protected from the prevailing wind by a topographic feature (leeward protection) and is in a topographic depression (descending topography). These areas are shown to be less stressful to plants and to have higher resource availability. The criteria are combined to develop a mapped HSM for outplanting with three suitability classes (Fig. ES2): no criteria met (Low Suitability - LS), one criterion met (Moderate Suitability), and two criteria met (High Suitability – HS).

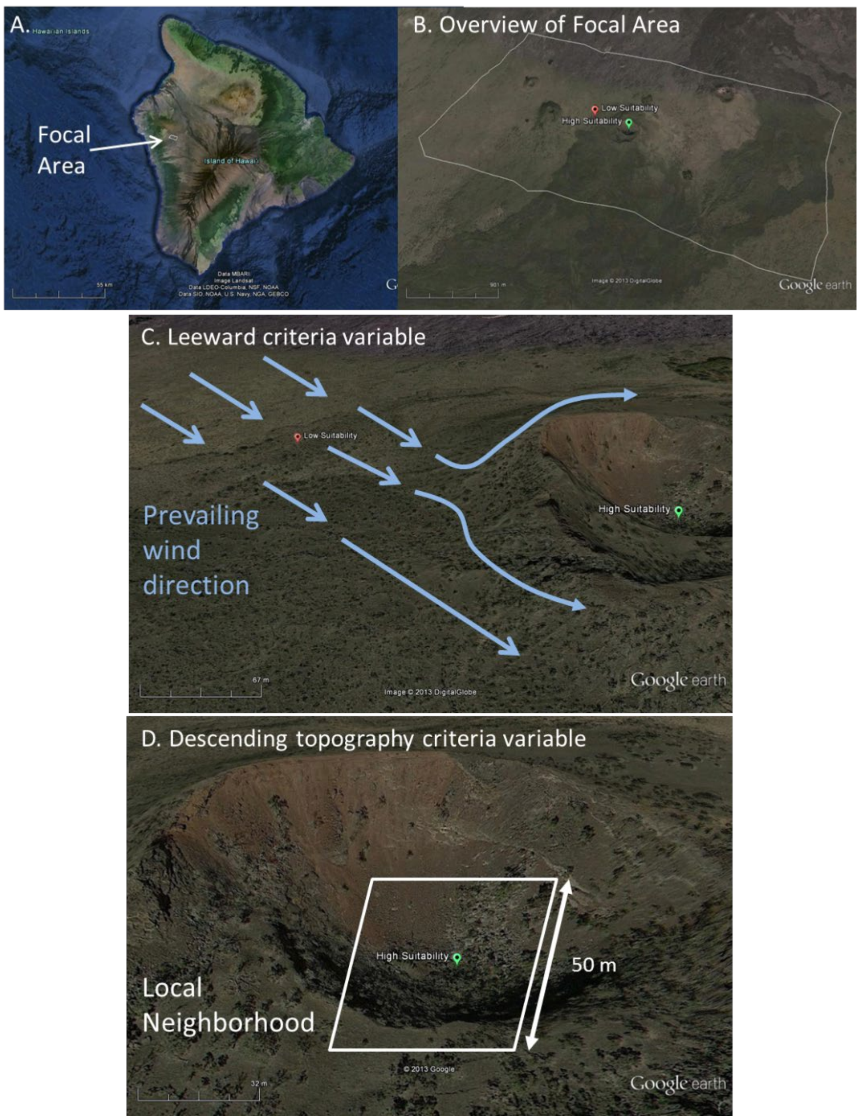

Figure ES1. Diagram of Suitability Criteria Variables.

Figures are shown at different extents to illustrate the local nature of the criteria variables: A) An overview of Hawaii Island showing the Focal Area selected to illustrate the variables; B) A regional view of hypothetical high and low suitability sites; C) A diagram of the Leeward criteria variable.

Blue arrows indicate a hypothetical prevailing wind direction and are drawn to illustrate how low suitability sites are more exposed to winds than high suitability sites (arrows are illustrations and do not represent actual wind patterns); D) A diagram of the Descending Topography criteria variable shows how a high suitability site is lower than the average elevation of other areas in its neighborhood. The neighborhood is drawn to approximate the scale of ca. 50 x 50 m used for analysis. Note that even though the high suitability site has an absolute elevation that is higher than the low suitability site, its elevation relative to its local neighborhood is low (i.e., it is in a localized depression).

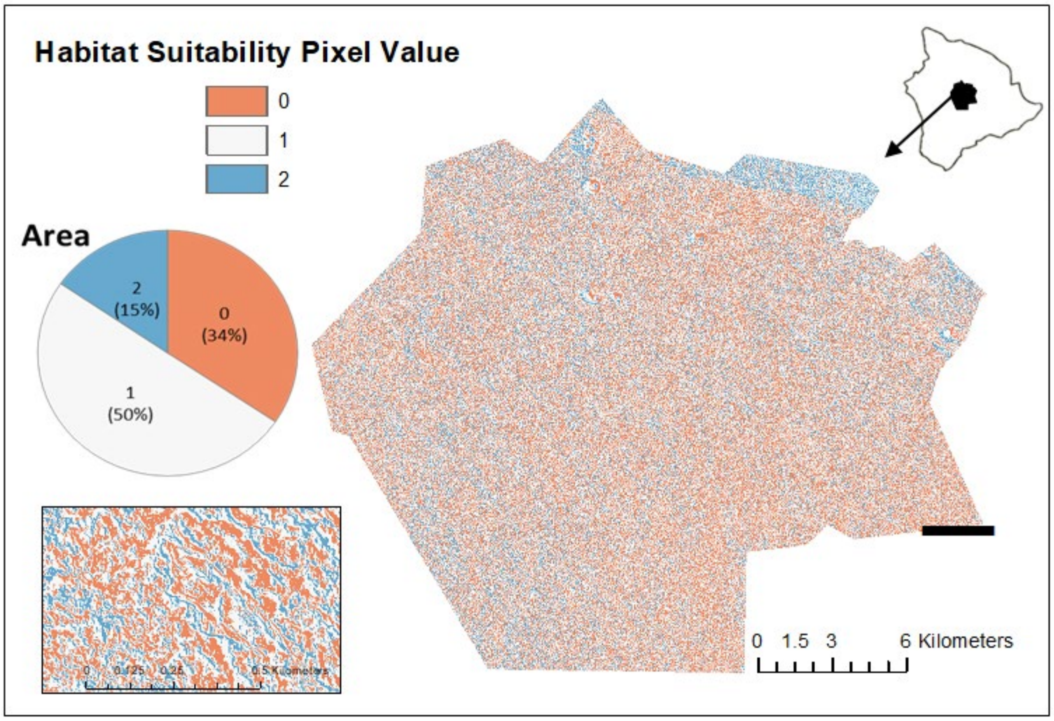

Figure ES2. Habitat Suitability Model Map for Pohakuloa Training Area (PTA), Hawaii.

PTA is located on Hawaii Island and is 49,000 ha in size (inset). We based habitat suitability classes on highly descending local topography and protection from prevailing winds to model areas with the optimal conditions for plant growth and survival. Pixel values are integers ranging from 0 (Low Suitability) to 2 (High Suitability). 35% of the landscape of PTA had pixel values = 0, 50% had pixel values = 1, and 15% had pixel values = 2.

PERFORMANCE ASSESSMENT

The demonstration included six performance objectives (Table E1):

PO1. Plant survival increases in HS habitats

The survival of planted individuals was compared between HS and LS plots at PTA and PWW. Due to a lack of a significant effect of habitat suitability on survival, this performance objective was not supported by the data during the timeframe of this demonstration project.

PO2. Plant performance increases in HS habitats

Measures of plant health, growth, stress, reproduction, and recruitment were compared between HS and LS plots at PTA and PWW. We found evidence for success of this performance objective at PTA when analyzing growth, health rating, and physiology/stress and at PWW when analyzing physiology/stress, but performance was not met at either site for recruitment and reproductive output during the study period.

PO3. Spatial correspondence of suitability classes

We compared elevation values from airborne LiDAR with WV-2 stereo satellite data at PTA, PWW, and VBG. Analysis showed strong and statistically significant agreement between the LiDAR and stereo-derived DEMs, indicating success of this performance objective.

PO4. Field measurements of weather and microclimate variables indicate greater suitability for plant growth in HS, compared to LS, plots

We measured weather and microclimate variables in the field that correspond with conditions important for plant growth at all four sites. Overall, we found reduced wind speeds in high suitability (HS) areas at all sites, increased leaf wetness in HS areas at all sites except PWW, and increased soil moisture during dry periods at sites in California but not Hawaii. These results indicate success for this performance objective at all sites except PWW.

PO5. Correspondence of existing TER-S with HS areas.

We tested whether existing populations of TER-S at VBG and PWW corresponded with our suitability classes, similar to our analysis of TER-S at PTA. This analysis allowed us to explore how current plant distributions track habitat suitability. Two species, *Chrysodracon hawaiiensis* and *Aplenium peruvianum var. insulare*, showed an association with HS areas at PWW. Neither species at VBG and eight species at PWW did not show an association with either habitat type. Taken together, these data do not show a strong association across species with either HS or LS areas. The data suggest that *C. hawaiiensis* and *A. peruviannum* may benefit the most from the HSM at PWW.

PO6. Ease of use

We evaluated the ability of trained professionals to use the modeling ArcGIS software extension that we developed, and to understand our written instructions for use. The actual response rates to survey questions indicated a high level of success for this performance objective.

Summary assessment

Our data indicated success for three of the six performance objectives for this demonstration (POs 3, 4, and 6), partial success for two performance objectives (PO 2 and 5), and no success for PO 1. WorldView-2 DEMs showed significant correlation with LiDAR DEMs (PO 3). Abiotic conditions indicated greater resource availability and reduced stress in HS areas at all sites, but less so at PWW (PO 4). Surveys of professional end users indicated that our GIS Toolbox was easy to use (PO 6). Planted individuals were less stressed and showed greater performance in HS areas at PTA, and less so at PWW; however measures of reproduction and recruitment were not altered by habitat suitability, indicating partial success for PO 2.

We also found partial success for PO5, in which two species were associated with HS areas but 11 others were not. Our data did not show higher survival in HS habitats during the timeframe of this study, but these results could change over a longer time period (PO1). Overall, we have produced a method for others to implement HSMs into landscape planning for TER-S conservation. Based on our findings in this demonstration, this method is likely to have the greatest impact in regions with fairly low annual precipitation around 300-600 mm, similar to PTA, VBG, and SMMNRA (but not PWW) and in areas with high wind speeds, similar to PTA and VBG.

Table E1. Performance Objectives and Results

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
Quantitative Performance Objectives				
PO1. Plant survival increases in HS habitats.	Increased outplant survival in HS plots	Survival – measured quarterly for all planted individuals for two years after outplanting	• Statistically significant increase in number of plants surviving in HS over LS areas. We will analyze survival for each quarterly census, and over all sampling periods using a repeated measures analysis.[2]	• Performance not met during the timeframe of the demonstration.
PO2. Plant performance increases in HS habitats.	• Increased growth • Increased health • Increased recruitment • Increased reproduction • Increased physiological performance / decreased stress	• Growth(height), biannually • Health (0 to 5), biannually • Recruitment (# new seedlings), annually • Reproductive output (# and size of fruits and # of seeds), annually • Physiological measurements,), biannually (maximum rates of photosynthesis and quantum yield) and plant functional traits (leaf nutrient content and specific leaf area)	• Statistically significant increase in growth in HS over LS areas.[2] • Statistically significant increase in health in HS over LS areas.[2] • Statistically significant increase in recruitment in HS over LS areas.[2] • Statistically significant increase in reproductive output in HS over LS areas.[2] • Statistically significant increase in physiological performance in HS over LS areas.[2]	• PTA: Performance met for growth, health rating, physiology/stress • PWW: Performance met for physiology/stress • Recruitment and reproductive output: performance not met during the timeframe of the demonstration.
PO3. Spatial correspondence of ground elevation estimates between LiDAR and WV-2 models.	Correspondence of elevation values from LiDAR and WV-2 models	Two Digital Elevation Models (DEMs), one derived from LiDAR and one from WV-2 data	• A statistically significant relationship between WV-2 elevation (Y) and LiDAR elevation (X).	• Performance met in both locations: • *Hawaii:* $r^2 = 0.998$, $P < 0.001$ • • *VBG:* $r^2 = 0.934$, • $P < 0.05$

Table E1. Performance Objectives and Results (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
PO4. Measurements of weather and microclimate variables indicate greater suitability for plant growth in HS areas.	• Weather conditions more suitable in HS plots • Microclimate for regeneration more suitable in HS plots • Plant stress reduced in HS plots	• Weather data – wind speed • Microclimate data – leaf wetness, soil moisture • Plant size	• Significantly lower wind speeds in HS compared to LS areas. • Significantly greater leaf wetness and soil moisture in HS compared to LS areas. • Significantly greater plant size in HS compared to LS areas.	• Wind: Performance met at at PWW, PTA, VBG, and SMMNRA. • Leaf wetness: Performance met at PTA, VBG, and SMNNRA but not PWW. • Soil moisture: Performance met at VBG and SMMNRA during dry period. • Plant size: Performance met at VBG but not SMMNRA.
PO5. Correspondence of existing TER-S with HS areas.	• Existing TER-S plants occur more frequently in HS areas.	• GPS locations of TER-S plants at VBG.	• Significant association of populations with HS areas. • More plants/km^2 in HS compared to LS areas.	• Performance met for *Chrysodracon hawaiiensis* and *Asplenium peruvianum var. insulare* at PWW. • Performance not met for 11 other species.
Qualitative Performance Objectives				
PO6. Ease of use	Ability of a trained professional to use the technology	Survey and feedback from professionals on usability of the technology and time required to use. Survey will use a Likert scale.	Success is defined as survey results that indicate more than 75% of respondents "Agree" or "Strongly Agree" with question 7 (The software is easy to use) and question 17 (I would recommend the software to a colleague).	Performance met: • 83% of respondents "Agree" or "Strongly Agree" with question 7 • 94% of respondents "Agree" or "Strongly Agree" with question 17

[1]Significance of statistical tests is defined as $P < 0.05$.

[2]A typical General Linear Model (GLM) included the following terms: Block (spatial location of plot), Species, Suitability (High/Low), Species x Suitability. A significant interaction term indicates that the response to habitat suitability varies among species. If this term is significant we examined the species-specific responses. When data were taken on more than one date or at more than one time of day, a repeated measures design was used and a term for Date or Time was added as well as the appropriate interaction terms.

COST ASSESSMENT

Imagery costs are the main area for cost comparison for our project, and we compared the costs of acquiring LiDAR and WV-2 imagery and processing each dataset into a DEM. The cost of WV-2 satellite imagery ranges from \$8,400 - \$17,400 per 300 km^2, approximately the size of PTA.

A reasonable cost would be $11,400 per 300 km^2 ($38/km^2). It should be noted that orders must be at least 100 km^2. We carefully considered whether stereo imagery from WorldView-2 would be a better option compared to LiDAR imagery from an airborne sensor and considered the following in our analysis:

1. Despite claims of the ease of acquisition, stereographic satellite imagery was surprisingly difficult to acquire due to cloud cover. We note that the Hawaii site in particular required tasking the satellite for almost one year before a useful pair of stereo images could be acquired. In regions where cloud cover is more substantial, this difficulty will increase.

2. The real cost of generating DEMs from stereographic satellite data is not small after considering the significant person-effort, expertise, and time that is required to produce elevation models from these data. This is in contrast to airborne LiDAR, where post-processing is much more mature and automated, requiring little to no human intervention after data collection to produce a georeferenced point cloud and elevation models.

3. Coastal regions of the United States are high priority areas for LiDAR DEM mapping due to issues related to resource management, erosion, sea level rise, etc. Many coastal areas already have freely available DEMs that would be suitable for use in the HSM. Many DoD installations already have LiDAR DEMs for construction and planning purposes. Therefore, the DEM data for many areas of interest already exist and can be available to the use for free or for a minimal cost.

4. The cost of new airborne LiDAR data acquisition has fallen significantly in the last few years. In-house costs for the production of a DEM from airborne LiDAR can range from $8-10 per km^2 (compared to $38 per km^2 for WV-2 image acquisition only). Contracted costs may be higher; however, if the DoD desired the capability to produce LiDAR DEMs it could acquire the ability to do it.

5. A major barrier to using WV-2 is the time and expertise required to generate a stereo DEM with a reasonable RMSE. We explored using third-party software to improve the RMSE between WorldView-2 and LiDAR elevation models. PhotoSat uses proprietary algorithms that are purported to produce elevation models with RMSE similar to airborne LiDAR. PhotoSat does not sell its proprietary stereo DEM algorithm, but rather processes individual requests on a fee-for-service basis. We requested a quote for the areas of Hawaii and California at issue here. Processing stereo satellite images for the Hawaii and Vandenberg installations would cost $99,000 and $60,000, respectively.

In our analysis of using WV-2 data for DEMs we concluded that the maps can be useful in the sense that they provide measurements that are similar to, but not as accurate as, airborne LiDAR. However, our opinion after having performed the DEM extraction and the cost analysis is that they are not a cost-effective way for DoD (or other users) to acquire high-resolution elevation data. Airborne or UAV-based LiDAR systems would provide a more cost-effective solution for the DoD.

IMPLEMENTATION ISSUES

Implementation of the HSM is straightforward and simple. During this demonstration, we developed a user-friendly GIS Toolbox that is available for others to use (http://www.cpp.edu/~ejquestad/HSMhome.shtml). We have developed guides to assist users with creating the HSM for a site of interest. Implementation will be based on whether a DEM is available for the site or is cost-effective to acquire. Typical LiDAR datasets that map elevation with pixel sizes of 5m or less are sufficient for mapping most topographic features. However, if very small features are of interest, then higher resolution data would be needed. Users in our workshop indicated a high level of interest in incorporating the HSM into future management plans, especially as LiDAR elevation data are becoming freely available for many regions. Our collaborators at PTA and PWW have already incorporated the HSM into their conservation plans for TER-S. The HSM is also easily combined with other data layers (roads, aspect, etc.) to facilitate selection of conservation areas.

Our demonstration results highlighted that the HSM was somewhat useful in designating high quality habitat at all sites, but it had the greatest impact in differentiating high quality and low quality sites in areas that were dry and windy, especially PTA and VBG. The HSM approach should be more effective in dry, windy sites than in wetter, less windy conditions. In addition, users should consider whether there may be species-specific responses to habitat suitability. We found that numerous measures of growth and physiology were improved in HS habitats across *all species*. At PTA, there was a significant main effect of Suitability across all species on four measures of leaf physiology; whereas only two species, *Haplostachys haplostachya* and *Stenogyne angustifolia*, showed increased growth and health in HS plots. At PWW, there was a significant main effect of Suitability across all species on six measures of leaf physiology; whereas three species, *Haplostachys haplostachya, Colubrina oppositifolia,* and *Stenogyne angustifolia*, showed lower water stress in HS plots and *Euphorbia olowaluana* had increased health ratings in HS plots. Thus, measures of physiology were improved in HS plots across all species, but certain species, especially *H. haplostachya* and *S. angustifolia*, showed more consistent positive responses to being planted in HS areas across both sites. Users should consider the potential responses of individual species when planning to incorporate habitat suitability into management and reintroduction plans.

In order to facilitate future outplanting projects for the native Hawaiian species that were studied, we performed an extensive interview survey of regional managers and native plant growers in order to determine the best techniques for propagating each species (seed, cuttings, etc.). All propagation protocols were documented in our Hawaiian Native Plant Propagation Resource, which is available online (Janas et al. 2015). We also developed a standard method for evaluating plants for outplanting based on a health status rating of one to five as follows: 1) no foliage but living stem; 2) foliage less than 25% and damaged by pest or disease; 3) 25-60% foliage, foliage showing signs of stress; 4) 60-90% foliage and health, showing no sign of decline; 5) greater than 90% foliage and extremely healthy with vigorous growth and no damage. Plants of health status class five were selected for outplanting, with a few plants of health status four included for species with fewer individuals.

We did not find differences in survival in HS sites during the time of this demonstration, which could deter some users from implementing the HSM. However, we found that *at times* resource availability and plant physiological functioning were higher in HS areas. In particular, the growth and leaf nutrient data showed higher resource acquisition across all species over the period of leaf and plant growth in HS, compared to LS, areas. These data illustrate that there are times when HS sites have better growing conditions and times when they do not, but over a longer period the benefit of HS conditions is apparent in improved physiological functioning and growth. It is expected that in some contexts this improved growth will also lead to greater survival, especially when survival and population persistence are examined over longer time periods.

Our conclusion is that if a site is dry and windy, the HSM is likely to add value to conservation planning for TER-S. For other sites, the HSM may still be useful but the decision to implement the HSM may be based on attributes of the species of interest and whether the DEM data are easily obtained. If so, then the HSM can be an additional consideration in the planning of conservation areas and reintroduction projects.

1.0 INTRODUCTION

1.1 BACKGROUND

For the more than 100,000 plant species worldwide thought to be at risk of extinction, a lack of suitable habitat is the major barrier to their recovery (Pitman and Jorgensen 2002, Godefroid et al. 2011, Maschinski and Haskins 2012). The two primary conservation actions for threatened, endangered, and at-risk plant species (TER-S) are to restore suitable habitat areas so that extant populations can expand and to reintroduce individuals to restored or protected areas. Reintroduction is an expensive, slow effort but is often essential when population sizes are very low or there are other barriers to dispersal among suitable habitats (Maschinski and Haskins 2012). The success rates of reintroduction projects are variable, and low success is often due to a lack of suitable habitat, the very cause of decline (Godefroid et al. 2011, Drayton and Primack 2012, IUCN 2013). Thus, a major challenge to reintroduction success is finding suitable habitats in fragmented and degraded landscapes.

Recent reviews of reintroduction studies indicate that habitat quality and microsite conditions of reintroduction projects are one of the key drivers of plant establishment, growth, survival, and population persistence (Bottin et al. 2007, Godefroid et al. 2011, Kaye 2011, Maschinski and Haskins 2012). In particular, microclimatic conditions can strongly influence early life stages of germination and establishment, which are the most critical life history phases for regeneration, i.e., the *regeneration niche* (Grubb 1977, Maschinski et al. 2012, Wendelberger and Maschinski 2016). For example, local topography can influence physical variables such as solar radiation, soil water retention, and temperature which alter where plants can regenerate and persist (Rovzar et al. 2017). Rare species may be rare because the conditions that support their regeneration niches are not widespread (Maschinski et al. 2012) or have been altered by land-use change.

Identifying the optimal conditions for regeneration and survival is especially important in dry or seasonal ecosystems, where water availability significantly limits plant growth (Guerrant 2012, Rovzar et al. 2017, Lloyd et al. 2018). Desiccation, one of the primary barriers to the successful establishment of reintroduced plants, is likely in these ecosystems (Helenurm 1998, Godefroid et al. 2011). In addition, over 40% of all at-risk plant species occur in dryland or rocky habitats where water-stress is a significant barrier to recovery (Kew Royal Botanic Gardens 2010).

Many hotspots important for the conservation of at-risk plant species occur in dryland ecosystems, including the dryland ecosystems where we work in Hawaii and California (Dobson et al. 1997, Friday et al. 2015); however, reintroduction programs have had limited success in many dry ecosystems due to a low probability of establishment and high levels of plant mortality (e.g., Cordell et al. 2008, Lloyd et al. 2018). Often planting areas are arbitrarily or opportunistically selected without consideration of microclimatic gradients. Thus, identifying high quality microclimates for reintroduction can significantly improve plant survival and reproduction (Bottin et al. 2007, Godefroid et al. 2011, Drayton and Primack 2012, Guerrant 2012, Maschinski et al. 2012, Monks et al. 2012, IUCN 2013, Wendelberger and Maschinski 2016, Rovzar et al. 2017, Lloyd et al. 2018).

Overcoming barriers to plant establishment in dryland environments is especially critical for TER-S management on Department of Defense (DoD) installations. The top ten DoD installations with the greatest number of federally listed species occur in dryland ecosystems, and the top four are in Hawaii (Table 1; Stein et al. 2008). The DoD spends over $10 million annually on environmental programs in Hawaii to protect TER-S and associated critical habitat (Michelle Mansker, pers. comm. 2011). Therefore, technology to increase the success of TER-S planting programs in dryland ecosystems in general, and Hawaiian dryland ecosystems in particular, can positively affect the outcome of TER-S management for the DoD. This technology also can enhance the DoD's training capability by improving the quality of protected areas and planning training activities in lower quality habitat.

Table 1. Top 10 DoD installations with the Greatest Number of Listed TER-S with Average Annual Rainfall.

TER-S data are reproduced from Boice (2010). All installations occur in relatively dry areas.

DoD Installation	Location	Approx # of TER-S	Approx # of TER-S plants	Average Annual Rainfall (mm)
Schofield Barracks Military Reservation	Honolulu, HI	47	34	737
Makua Military Reservation	Waialua, HI	39	27	762
Lualualei Naval Reservation	Waianae, HI	37	23	696
Pohakuloa Training Area	Hawaii Island, HI	17	15	358
Marine Corps Base Camp Pendleton	Oceanside, CA	17	3	304
San Clemente Island Range Complex	San Clemente Island, CA	10	5	302
Vandenberg Air Force Base	Lompoc, CA	10	3	403
Eglin Air Force Base	Valparaiso, FL	10	1	1103
Fort Lewis Military Reservation	Tacoma, WA	10	1	461
Avon Park Air Force Range	Avon Park, FL	10	2	1330

In dryland ecosystems, topography can be an important landscape feature for reintroduction planning, and planting activities may have the greatest success in topographic depressions where soil and water accumulate and where plants are protected from desiccating winds. There is strong evidence linking topographic lowlands with greater soil depth, organic matter, and water availability compared with uplands (e.g., Abrams et al. 1986, Knapp et al. 1993, Burke et al. 1999, Nippert et al. 2011), leading to greater plant heights and annual net primary productivity in lowlands, where soil conditions are more favorable for plant growth (Knapp et al. 1993, Nippert et al. 2011). Topography is associated with the distribution of plant populations and vegetation types (Slaton 2014, Takahashi and Murayama 2014, Ward et al. 2016). Topographic position controlled the survival of a wild population of *Dracocephalum austriacum*, an endangered plant species in subalpine ecosystems in France, and the growth of restored populations of *Stipa pulchra*, a perennial grass native to California (Nicole et al. 2011, Fitch 2017). Survival and growth of these species were higher on gentle slopes compared to steep slopes (Nicole et al. 2011, Fitch 2017). Microtopographic position can also positively affect native plant restoration in dry or windy habitats by protecting young plants from stressful conditions (Biederman and Whisenant 2011, Simmons et al. 2011). Our habitat suitability modeling (HSM) technology formally incorporates the importance of wind into topographic modeling to improve plant growth and survival, and use the information for landscape planning for the reintroduction and management of at-risk species.

We developed the HSM technology to identify habitat suitability based on topography for TER-S reintroduction using high resolution airborne Light Detecting and Ranging (LiDAR) data.

LiDAR is currently the leading edge technology for high resolution topographic and vegetation structure mapping, and has been applied to conservation research and planning in areas such as forest structure and biomass, water resource management, habitat associations of wildlife species, and forest restoration (Lefsky et al. 2002, Turner et al. 2003, Goetz et al. 2007, Vierling et al. 2008, Asner et al. 2009, Bergen et al. 2009, Goetz et al. 2010, Fricker et al. 2015, Friday et al. 2015, Cordell et al. 2017). Since the mid 1990's, data from airborne LiDAR sensors have been used to generate topographic models with very high spatial resolution (< 1m). We developed topographic models of habitat suitability for plant restoration in a 49,000 ha military training area on the Island of Hawaii (Pohakuloa Training Area, PTA). We used LiDAR data from The Carnegie Airborne Observatory to produce a digital elevation model (DEM) for PTA. We then used the DEM to define areas of suitable topography for plant reintroduction by developing two criteria based on the landscape's capacity to reduce water stress. The criteria were combined to develop a mapped habitat suitability model (HSM) for outplanting with three suitability classes: no criteria met (Low Suitability - LS), one criterion met (Moderate Suitability), and two criteria met (High Suitability - HS). Our demonstration validated the utility of the HSM to guide reintroduction efforts at PTA and demonstrated the use of this technology for TER-S restoration planning at other DoD installations.

1.1.1 Study Site Overview

PTA and PWW

PTA and Puu Waawaa (PWW) were selected as research sites for experimental work because our technology and methodology were described using high resolution airborne imagery and specific GPS locations of TER-S obtained for these locations from a previously DoD-SERDP funded project (RC-1645). We had already established field plots and infrastructure, such as fences and weather stations, at these sites. In addition we had land manager support at both sites for the demonstration. See Section 4.0 Site Descriptions for detailed information for each study site.

Vandenberg Airforce Base and Santa Monica Mountains National Recreation Area

We selected Vandenberg Airforce Base (VBG) as an additional site for field verification of the HSM due to its many similarities to PTA and PWW. It occurs in a dryland area (mean annual precipitation = 403mm), has a low-stature coastal scrub vegetation, and has significant variation in topography. Due to a long approval process for fieldwork at VBG, we also added the Santa Monica Mountains National Recreation Area (SMMNRA) as a California coastal site for field verification of the HSM. Its topography and plant community is similar to VBG, access and permitting was easily obtained, and LiDAR DEM data were available. See Section 4.0 Site Descriptions for detailed information for each study site.

1.2 OBJECTIVE OF THE DEMONSTRATION

We used three tasks to demonstrate how our HSM technology can inform TER-S reintroduction programs to increase plant performance and survival across DoD installations.

1. Task 1 evaluated the potential of the HSM to improve success of TER-S reintroduction activities in the field. We experimentally planted TER-S into replicate LS and HS areas at PTA and an adjacent site in Hawaii (Puu Waawaa). We monitored survival and measures of plant and population performance to determine how plants respond differently to restoration in different suitability classes. We evaluated whether plants had greater survival and growth and reduced plant stress in HS, compared to LS, sites.

2. With Task 2, we developed methodology for generating HSMs from high resolution satellite data. Our HSM for PTA was derived from high resolution airborne LiDAR data, which is at the leading edge of technology available for digital elevation modeling, but the data are somewhat expensive and difficult to obtain. WV-2 satellite data are available globally and could be used to create HSM maps for sites that lack LiDAR. We used optical measurements from the WV-2 satellite and compared its cost and performance to LiDAR.

3. In Task 3, we quantified the cost of implementing the technology as well as the cost savings that can result from using the technology. We developed materials for technology transfer including a software extension.

1.3 REGULATORY DRIVERS

In 2003, the U.S. Fish and Wildlife Service issued a Biological Opinion (BO) for PTA and adjacent areas in response to a formal Section 7 consultation with the U.S. Army. In 2008 the Army reinitiated formal Section 7 consultation to address issues that arose following the 2003 BO. The two BOs stipulate specific management actions to be implemented by the Army to ensure the continued non-jeopardy status of the federally listed species found at PTA. Technology developed in this demonstration will assist with meeting the objectives of the BO as well as support conservation planning efforts at PWW.

2.0 TECHNOLOGY/METHODOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

Our habitat suitability model (HSM) is based on the understanding that individual plants directly interact with a defined space in the landscape and larger regional processes influence that defined space. A plant's root system occupies a volume of soil where it can uptake water and nutrients; a plant's aboveground structures occur in a volume of space where the plant performs photosynthesis, interacts with pollinators and seed dispersers, etc. The volume that a plant occupies is clearly defined; however, the region of the landscape that influences that volume may be much larger. For example, soil substrate type may vary at the scale of kilometers due to geologic processes, a larger area may create precipitation runoff into the plant's territory when it rains, and a larger area may provide habitat for herbivores, pollinators and dispersers. Thus, phenomena across many spatial extents can influence the growth, survival, and reproduction of an individual plant (Wiens 1989, Levin 1992).

In addition, the conditions important for plant growth may vary across plant life history stages. Plant physiological adaptations can differ across life stages, and seedlings often experience more physiological stress than adult plants (e.g., Ishida et al. 2005, Mahall et al. 2009). Our HSM methodology is focused on the establishment life history phase, which is the most relevant to restoration and reintroduction. Microclimatic conditions significantly influence early life stages of germination and establishment, which are the most critical life history phases for regeneration, i.e., the *regeneration niche* (Grubb 1977, Maschinski et al. 2012, Wendelberger and Maschinski 2016). Desiccation is a significant barrier to the successful establishment of reintroduced plants across all ecosystems, from arid to mesic environments (Helenurm 1998, Godefroid et al. 2011), and local topographic features can reduce this stress.

We hypothesize that our model reduces desiccation stress by protecting seedlings from wind (Leeward variable) and by increasing soil resources during establishment (Descending Topography variable). Our data from the Pohakuloa Training Area (PTA) indicated better growing conditions for plants in high suitability areas and improved survival of planted individuals. Thus, the model designated suitable habitat for the *establishment* of early life stages (seedlings, saplings, etc.) at this site. We hypothesize that these conditions are important for establishment across sites because the size of reintroduced plants is similar; therefore, we expect the model to be directly transferrable to modeling habitat suitability for early life stages at other sites.

2.1.1 Initial Study area

We developed a topographic habitat suitability model (HSM) for the Pohakuloa Training Area (PTA) in Hawaii (Fig. 1). Initial development and testing of the model occurred under DoD's Strategic Environmental Research and Development Program (SERDP, RC-1645) from 2008-2011 (Table 2). PTA covers over 49,000 ha of a subalpine region between three volcanoes on the Island of Hawaii (1300-2600 m elevation). Mean annual precipitation is low (< 400 mm) and soils are poorly developed due to recent deposition of substrates from volcanic sources (Rhodes and Lockwood 1995, Shaw 1997). Approximately 50% of federally listed endangered plant species in the US occur in Hawaii, and 25% of these species are found in dryland forest or shrubland ecosystems (Loope 1998, Gillespie et al. 2011). Fifteen federally-listed TER-S occur at PTA, and several of these species only exist in the wild at PTA (Shaw 1997).

Table 2. Timeline of Initial HSM Development and Testing.

	2008	2009	2010	2011
LiDAR data acquisition				
HSM development				
Field testing				

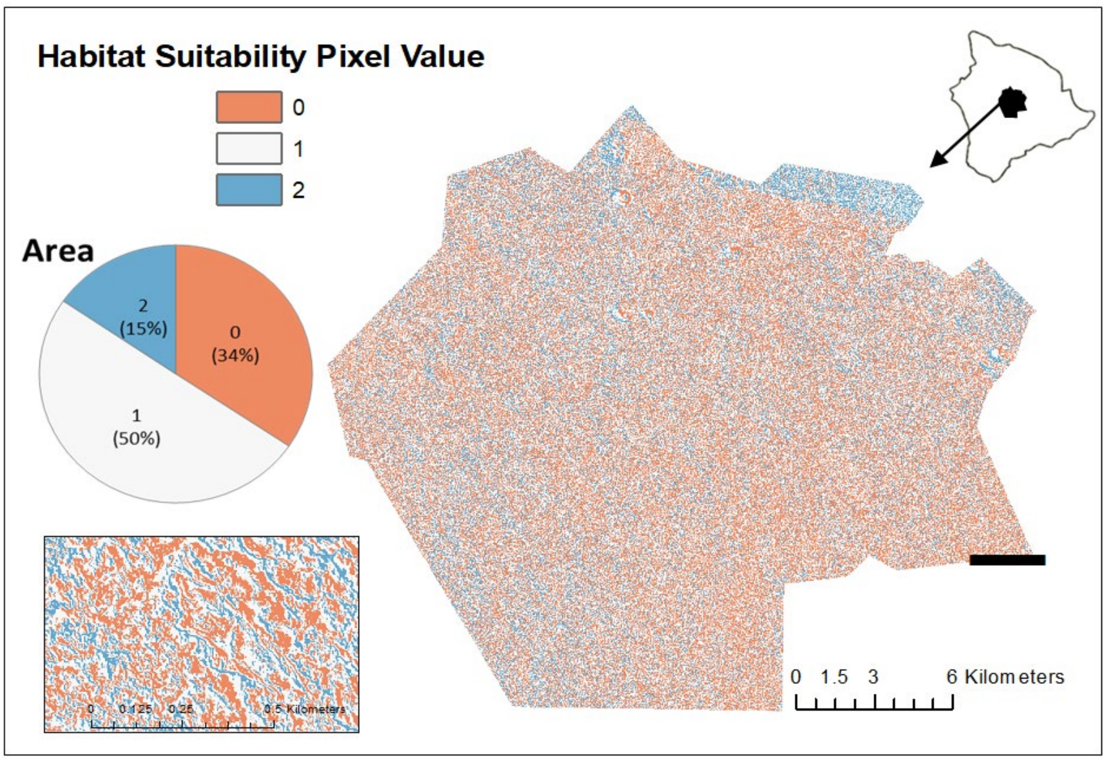

Figure 1. Habitat Suitability Model Map for Pohakuloa Training Area (PTA), Hawaii.

PTA is located on Hawaii Island and is 49,000 ha in size (inset). We based habitat suitability classes on highly descending local topography and protection from prevailing winds to model areas with the optimal conditions for plant growth and survival. Pixel values are integers ranging from 0 (Low Suitability) to 2 (High Suitability). 35% of the landscape of PTA had pixel values = 0, 50% had pixel values = 1, and 15% had pixel values = 2.

2.1.2 High resolution surface cover mapping

The Carnegie Airborne Observatory (CAO) Beta system was used to map PTA on 7 January 2008 (Asner et al. 2007). The CAO-Beta instrument package included a small-footprint, high-power Light Detection and Ranging (LiDAR) scanner that mapped the position and elevation of the ground surface and vegetation. The LiDAR sub-system was configured to record the locations of up to four reflecting surfaces for every emitted laser pulse at 1.1 m laser spot spacing. Horizontal and vertical accuracy of the LiDAR system were provided by Asner et al. (2007), and is on the order of 15 cm. To quantify ground elevation, LiDAR ranging measurements were processed to identify laser pulses that penetrated vegetation and reached the ground surface. These points were then used to model the elevation of the ground (DEM) at 2.2-m spot sampling distance.

2.1.3 Topographic suitability modeling

Our HSM is based on two modeling criteria: leeward position and descending topography. Leeward position designates the degree that an area of the landscape is protected from the prevailing winds (Fig. 2C). It is modeled using long-term records of monthly diurnal wind direction from Remote Automatic Weather Stations at PTA (National Interagency Fire Center; www.nifc.gov) to quantify exposure to prevailing winds. The prevailing wind direction at PTA was 67.5 degrees. We used shaded relief modeling to calculate the degree of exposure of each pixel in the DEM to prevailing wind patterns. Shaded relief is typically used to simulate the appearance of natural light on a DEM from a user defined azimuth and elevation above the horizon. Computing shaded relief models for sunlight requires knowing the direction of the sun, and the elevation above the horizon of the sun. Using shaded relief to model wind patterns requires the input of the same parameters. We used the direction of prevailing winds as the direction parameter and a low elevation (6 degrees) for the elevation parameter. Low elevation values approximate the wind blowing over the ground surface, and 6 degrees was our best estimate of this parameter. When applied to the azimuth of wind direction, the resultant image has pixels with brightness values ranging continuously from 0 to 1, low brightness in areas that are protected from prevailing winds and high brightness in areas that are directly exposed. Values less than 0.05 were classified as suitable.

Descending topography describes an area that is lower than the average elevation of areas in its local neighborhood (e.g., in a depression), whereas ascending topography describes an area that is higher (e.g., on top of a ridge). We distinguished descending and ascending topography by subtracting DEM values from the mean within the local neighborhood of a focal pixel (Fig. 2D). We set the neighborhood size to a ca. 50 m window (23 x 23 pixels) centered on each focal pixel. This window size was selected to reflect the area in which a plant's root system is hypothesized to capture water and nutrients, based on the stature of the plants in this study (i.e., < 1 m tall; immature life stages). This area could be expanded or reduced for plant species that have more extensive or more localized root systems, respectively. It could also be expanded for more mature life stages with larger root systems. If elevation within a given pixel is greater than the window's mean, the focal location has a positive value and is ascending. A location has a negative value and is descending if the focal pixel is less than the mean. Negative values were classified as suitable.

We created binary raster layers on the basis of each criterion with a score of 1 if the condition was true and a score of 0 if false. The binary criteria layers were combined to develop a map of our HSM with three suitability classes (Fig. 1): no criteria met (pixel value = 0; Low Suitability-LS), one criterion met (pixel value = 1; Moderate Suitability), and both criteria met (pixel value = 2;

High Suitability-HS). Field observations confirmed that areas coded as high suitability corresponded with leeward topographic depressions and areas with low suitability corresponded with ridges and areas with high wind exposure.

Fig. 2

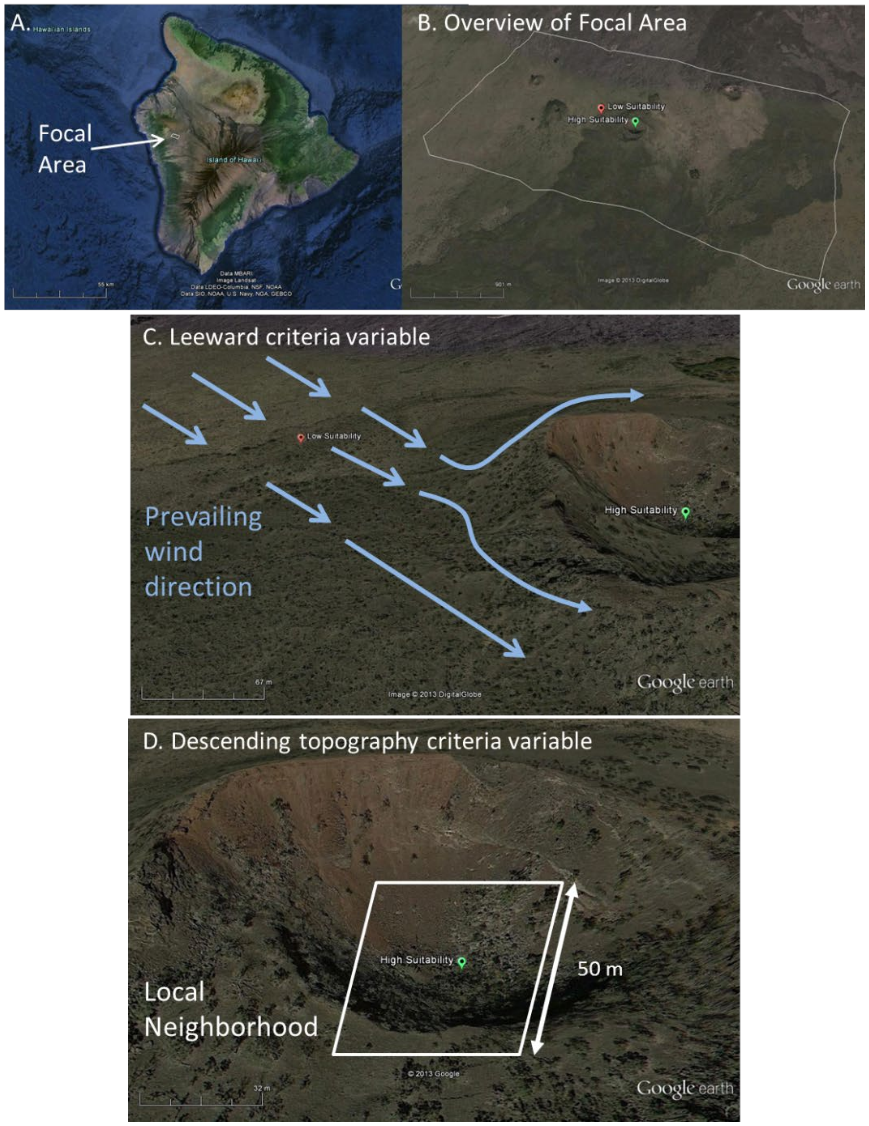

Figure 2. Diagram of Suitability Criteria Variables.

Figures are shown at different extents to illustrate the local nature of the criteria variables: A) An overview of Hawaii Island showing the Focal Area selected to illustrate the variables; B) A regional view of hypothetical high and low suitability sites; C) A diagram of the Leeward criteria variable. Blue arrows indicate a hypothetical prevailing wind direction and are drawn to illustrate how low suitability sites are more exposed to winds than high suitability sites (arrows are illustrations and do not represent actual wind patterns); D) A diagram of the Descending Topography criteria variable shows how a high suitability site is lower than the average elevation of other areas in its neighborhood. The neighborhood is drawn to approximate the scale of ca. 50 x 50 m used for analysis. Note that even though the high suitability site has an absolute elevation that is higher than the low suitability site, its elevation relative to its local neighborhood is low (i.e., it is in a localized depression).

2.1.4 Image segmentation

During this demonstration project we produced an algorithm that enables an end user to filter the HSM to identify areas with a high local density of highly suitable and moderately suitable areas, corresponding to both criteria satisfied and one criterion satisfied, respectively. The algorithm works by considering the local density of suitable areas, and requires two inputs: (1) the area in which local density should be calculated. This is defined by a filter that is centered on each pixel of the two input variables used to produce the HSM (e.g., a 9 × 9 pixel filter corresponds to 19.8 × 19.8 m, and a 23 × 23 pixel window corresponds to a 50.6 × 50.6 m. Filter shapes can be rectangular, circular, annulus, wedge, irregular, or user-defined. (2) As the filter is passed over each input variable image, the algorithm evaluates the percentage, p, of pixels within the window that satisfy the suitability criterion for that variable, where p can be defined by a user. By specifying a threshold on p, users can filter the HSM to retain only those areas that have a local density of suitable areas $\geq p$. In the example below, we considered window sizes of 9 × 9 and 23 × 23, and we set $p = 0.75$. Thus, for a position to be classified as suitable, at least 75% of the pixels within the window centered on the focal position needed to satisfy the suitability criterion for a given input variable. Although users can determine what values of window size and p would be appropriate to a given application, window size could be determined based on practical needs or conservation objectives.

The strength of this algorithm is that it allows one to focus only on those regions with a high-density of suitable areas that are ‘hot spots’ for restoration or conservation effort. An example for Pohakuloa Training Area illustrates the filtering algorithm. We ran the algorithm on an 11 km^2 area as a test case and produced the suitability index at the native resolution (Fig. 3). We compared this to the suitability index after filtering in a 9 × 9 and 23 × 23 pixel window with $p = 0.75$ in both cases. In the unfiltered scenario, 12.95% of the landscape is highly suitable and 49.2% is suitable, with the remainder unsuitable. With a 9 × 9 window and $p = 0.75$ these numbers drop to 0.98% highly suitable and 33.17% suitable. In a 23 × 23 window with $p = 0.75$, these numbers drop further to 0.21% highly suitable and 18.76% suitable. Clearly, choosing the window size and threshold for inclusion will strongly impact the selectivity of the filter.

2.1.5 Stereographic digital elevation models

In the demonstration, we generated digital elevation models using stereographic pairs of high-resolution WV-2 satellite observations. The pixel size of WV-2 data ranges from less than 0.52 m in panchromatic channels to less than 2.07 m in multispectral channels, and is comparable to the 2.2-m pixel size of our LiDAR dataset. Two images of our study areas were acquired from different view perspectives. Because the location and orientation of the satellite was known precisely at the time each acquisition is made, we could compute a ray that travels from the satellite sensor to a given fixed location on the ground. When this is done using two or more images, one can use algebra to find the location where the two rays intersect, and hence determine the elevation of the given object on the ground. Although this process has traditionally been done manually, semi-automated processing is now standard in readily available remote sensing software (e.g., ENVI). We used ENVI’s DEM extraction tool to generate digital elevation models from WV-2 satellite data (Fig. 4).

We evaluated the accuracy of these models by comparison to a LiDAR DEM generated for the same areas using airborne lidar. As needed, we fine-tuned the DEM extraction so that the DEMs generated from satellite data were as accurate as possible. Habitat suitability models can be derived from these DEMs and validated in the field.

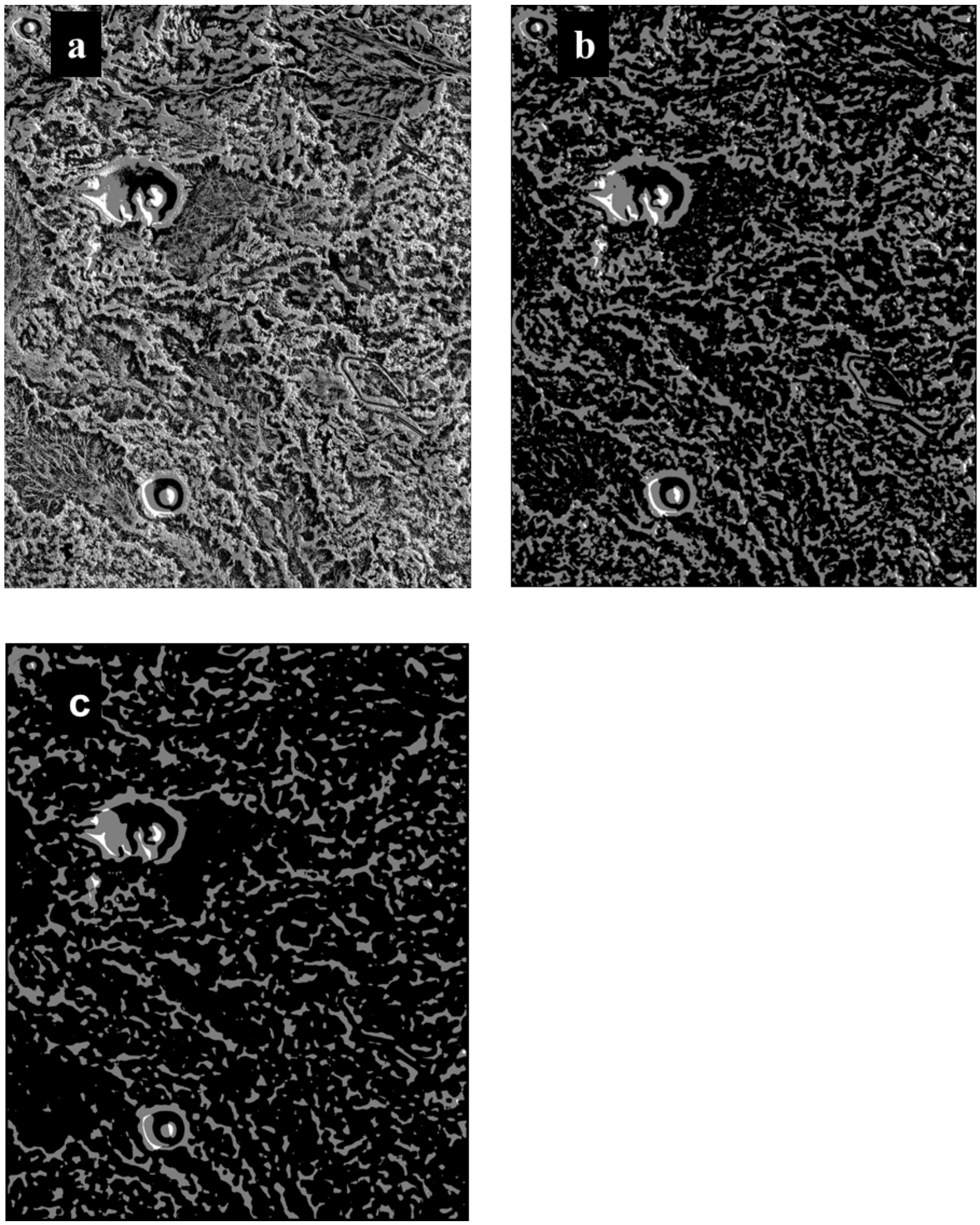

Figure 3. HSM for an 11 km2 Subset of PTA

a) without filtering (i.e. all values retained, regardless of local density); b) after filtering in a 9 × 9 pixel m window (i.e. approximately 20 × 20 m) with p = 75; after filtering in a 23 × 23 pixel m window (i.e. approximately 50 × 50 m) with p = 75c) Black = not suitable, grey = suitable, white = highly suitable.

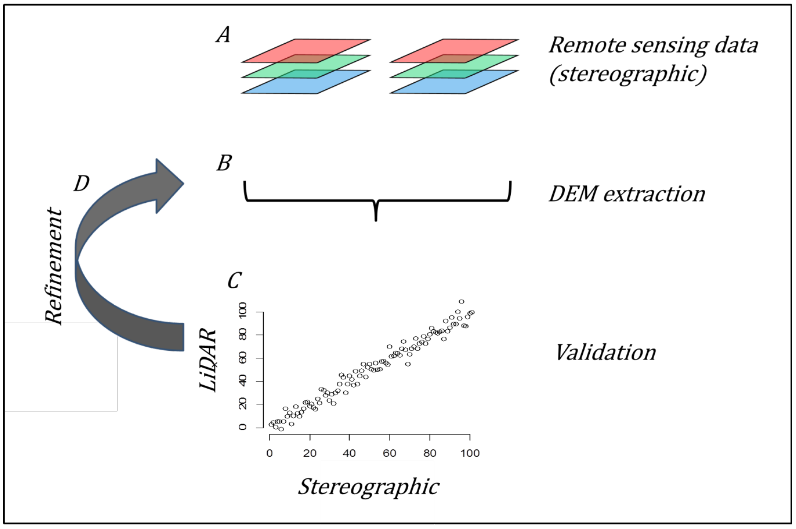

Figure 4. Workflow Diagram.

Data processing steps include A) stereographic satellite data acquisition; B) DEM extraction; C) validation with LiDAR DEM; D) refinement of DEM if necessary.

2.1.6 Expected applications of the technology

The HSM can immediately assist TER-S outplanting efforts at PTA by guiding planting to high suitability areas of the landscape where growth and survival should be greater. We expect this guided restoration approach to **reduce the costs of outplanting programs through increased survival rates.** The data processing techniques we develop for generating DEMs from satellite data could allow HSMs to be created for any site of interest in the future. Thus, **the technology we develop can be used to generate HSMs for TER-S recovery for sites anywhere in the world,** including DoD installations in dry environments (S. California, Southwestern states, etc.). We expect an additional benefit to be **improved training capabilities by protecting high quality habitat** and focusing training activities in low-quality habitat areas that are not valued for conservation for other reasons.

2.2 TECHNOLOGY/METHODOLOGY DEVELOPMENT

Before this demonstration, the HSM was extensively tested with field surveys, a field experiment, and longterm datasets collected at PTA (Questad et al. 2014). In summary, this prior work found that when comparing high suitability (HS) with low suitability (LS) areas, high suitability habitats had 1) more favorable microclimate conditions important for plant regeneration and growth (Fig. 5), 2) plants that showed greater growth and resource-capture through measured functional traits (Table 3; Fig. 6), and 3) greater survival of planted *D. viscosa* seedlings (Fig. 7). We also found that six of the existing TER-S plant species were significantly associated with HS habitats (Table 4; Fig. 8). These results supported the demonstration of how to use the HSM to improve restoration success by guiding planting activities to areas of the landscape with favorable microclimates that reduce plant stress and increase survival.

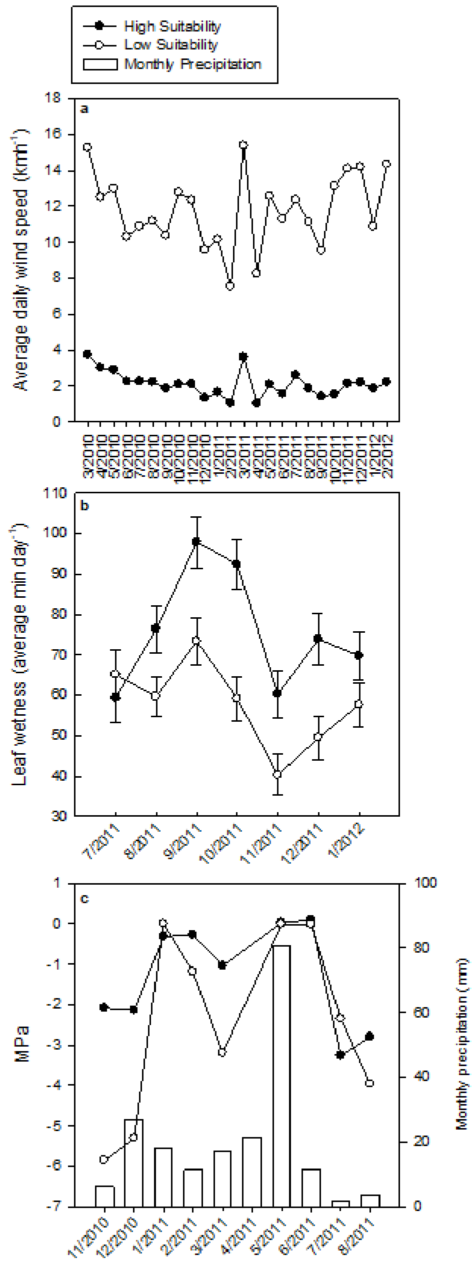

Figure 5. Microclimate Conditions in High and Low Suitability Areas.

(a) *Average daily wind speeds were much higher and more variable in the Low Suitability, compared to the High Suitability, plot. In both plots average wind speeds were highest in May and November and lowest in February.* ***(b)*** *The average number of minutes per day with measurable leaf wetness was higher in High Suitability relative to Low Suitability plots. Error bars show 1SE. Leaf wetness differences between the suitability classes were greatest in October during the onset of winter rains and the least in July during the dry season, where leaf wetness was almost identical between the classes. Leaf wetness was highest in the early morning and evening hours with almost negligible leaf wetness measured in both sites between the hours of 0800-1400.* ***(c)*** *Soil water potential (MPa) was generally higher in the High Suitability, compared to the Low Suitability, plot. Each point is a mean of three permanent sampling locations. More negative values indicate drier soil conditions. Bars show total monthly precipitation measured at the site. Figure adapted from Questad et al. 2014.*

Table 3. Plant Functional Trait General Linear Model Results.

Test statistic (F) and significance (P) are reported for general linear models of plant functional traits that included the following factors: Block DF = 4; Species DF = 4; Suitability Class DF = 1; Suitability Class x Species DF = 4. Table adapted from Questad et al. 2014.

Plant Trait[a]	Block		Species		Suitability Class		Suitability Class x Species		
	F	P	F	P	F	P	F	P	R^2
Plant Height	7.67	***	8.05	*	3.02	0.157	10.19	***	0.654
ln (SLA)	1.01	0.404	63.50	***	0.00	0.977	0.95	0.435	0.519
Leaf N	4.72	***	13.60	*	11.31[b]	*	5.17	***	0.634
Leaf P	11.45	***	174.99	***	178.71[b]	***	0.09	0.986	0.359
Leaf C	8.17	***	120.97	***	0.05	0.828	2.40	0.051	0.844

[a]Error DF was 231 for height, 260 for SLA, and 229 for Leaf N, P, and C. Significance codes: *** ≤ 0.001; **< 0.01; * <0.05

[b]The significant Suitability Class effect for leaf N and P indicates higher nutrient content in High Suitability, compared with Low Suitability, plots.

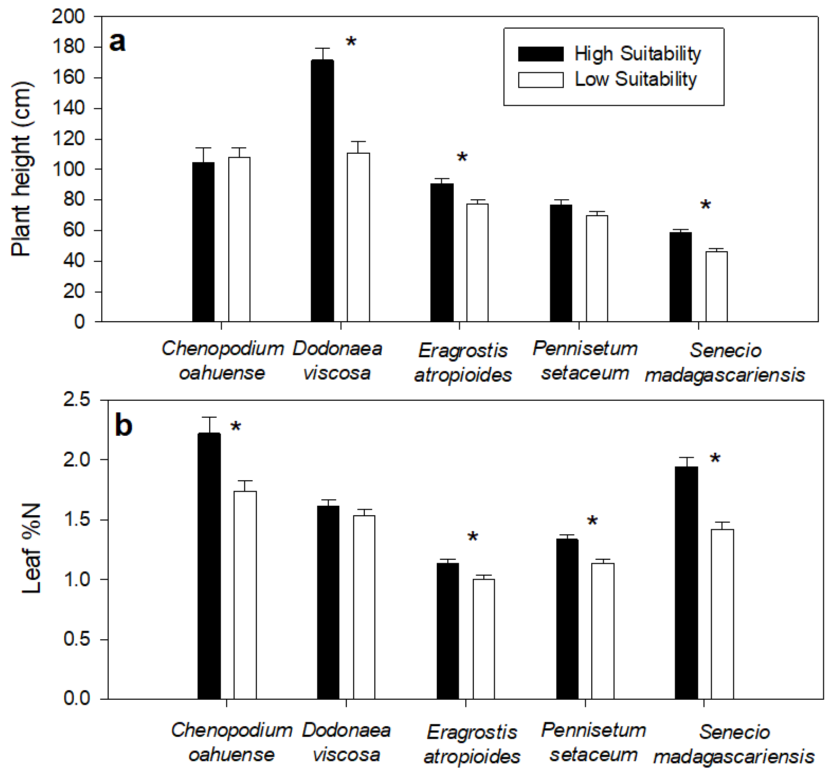

Figure 6. Plant Functional Traits of Dominant Species Among Suitability Classes.

*Species are native shrubs C. oahuense and D. viscosa, native grass E. atropioides, invasive grass P. setaceum, and invasive forb S. madagascariensis. Plant height (a) and leaf N (b) varied among species and among suitability classes. * indicates significant differences among suitability classes tested within each species (t-test, P < 0.001). Figure adapted from Questad et al. 2014.*

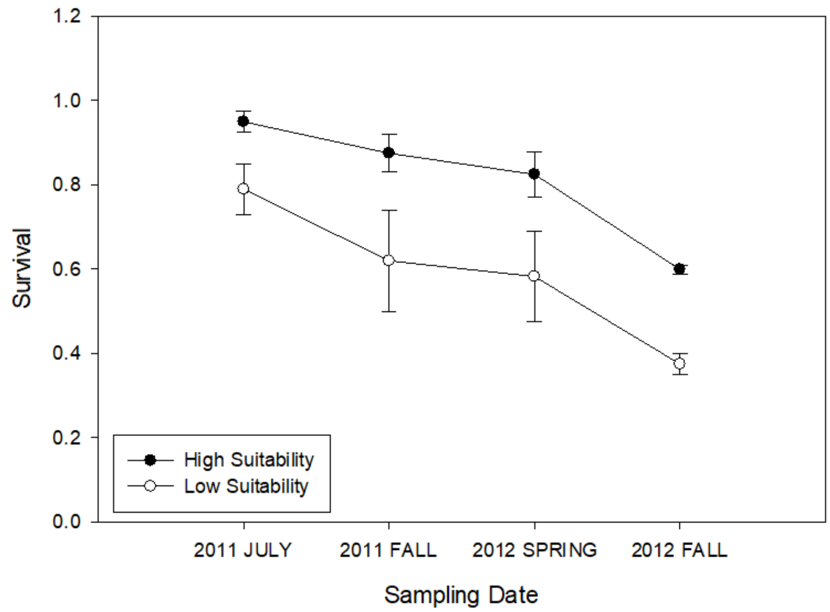

Figure 7. Survival of Dodonaea Viscosa Seedlings.

Twenty individual seedlings were planted in April 2011 in three high suitability and three low suitability plots. The mean proportion of surviving planted D. viscosa was significantly higher in HS plots, compared to LS plots on all sampling dates: July 2011 (one-tailed t-test, t = 2.43, P = 0.025), Fall 2011 (one-tailed t-test, t = 2.03, P = 0.044), and Spring 2012 (one-tailed t-test, t = 2.01, P = 0.042).

Table 4. Results of Habitat Suitability Analysis for Existing At-risk Species.

Results include the mean suitability class value across all known plant points and the 95% confidence interval (CI) of the mean suitability class values of 10,000 simulated populations. Table adapted from Questad et al. 2014.

Species[b]	Number of individuals	Mean Suitability Value of Known Plants	95% CI of Mean Suitability Values from Simulated Populations	Direction of Habitat Association[a]
Haplostachys haplostachya	11373	0.9719	0.7542 – 0.7759	Higher*
Hedyotis coriacea	175	0.7257	0.6743 – 0.8457	No Association
Neraudia ovata	41	0.2927	0.5122 – 0.8537	Lower*
Portulaca sclerocarpa	65	0.7231	0.5846 – 0.8615	No Association
Silene hawaiiensis[b]	2730	0.8048	0.7498 – 0.7938	Higher*
Silene lanceolata	14607	0.9393	0.7406 – 0.7594	Higher*
Solanum incompletum	154	1.0260	0.6558 – 0.8377	Higher*
Spermolepis hawaiiensis	5367	0.7593	0.7339 – 0.7650	No Association
Stenogyne angustifolia	2533	1.1283	0.7165 – 0.7619	Higher*
Tetramolopium arenarium	871	0.5465	0.6349 – 0.7118	Lower*
Zanthoxylum hawaiiense	619	0.7868	0.6801 – 0.7738	Higher*

[a] Asterisks indicate a statistically significant association of the species with either higher or lower classes. Six species showed an association with higher valued classes, and two species showed an association with lower valued classes. Three species did not show an association.

[b] All species are listed by the US Fish and Wildlife Service as Endangered except *Silene hawaiiensis*, which is listed as Threatened.

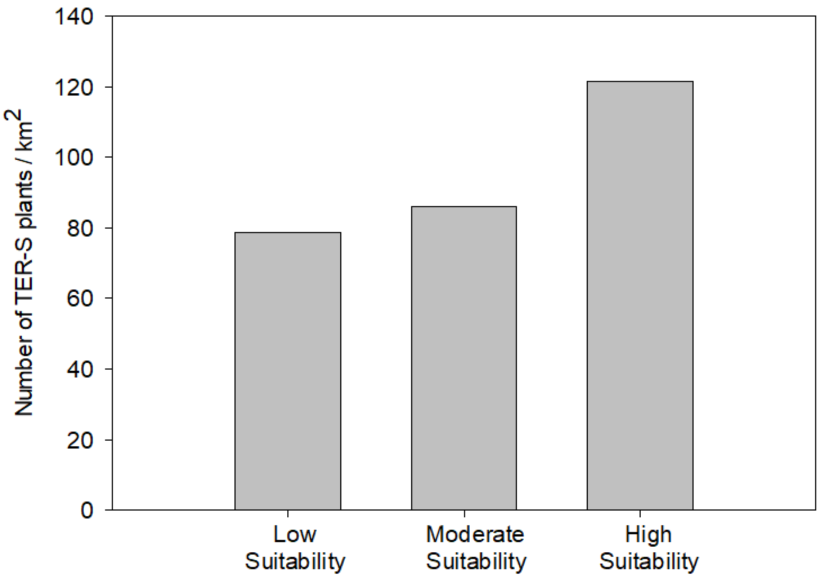

Figure 8. Density of TER-S Plants in Each Topographic Suitability Class.

Data are total number of federally-listed threatened and endangered plants recorded at PTA divided by total area of each class at PTA. Low Suitability pixel values = 0, Moderate Suitability pixel values = 1, High Suitability pixel values = 2. Figure adapted from Questad et al. 2014.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

The HSM can re-define the way DoD installations manage their TER-S programs by providing a set of quantitatively based and spatially explicit tools to ensure effective and compliant land-use management for TER-S recovery. This work is not only relevant in Hawaii as it applies to all DoD installations located in dryland environments. The current survival rate of TER-S outplants at PTA is highly variable among species and sites (15 - 73%, K. Kawakami unpublished data). Outplanting sites at PTA are arbitrarily selected and had a median suitability pixel value of one, indicating moderate, but not high, habitat suitability. Using the HSM to select outplanting sites in high suitability areas should improve plant survival and performance. Additional advantages of the HSM include reduced costs of TER-S outplanting programs through increased survival rates and decreased travel time for monitoring. More importantly, targeted natural resource management can improve training capabilities by protecting high quality habitat and focusing training activities in low quality habitat. Extending this analysis to areas surrounding DoD installations can further enhance compatible use and offsite mitigation opportunities (e.g., the ACUB project).

The initial cost of imagery and modeling may be a limitation of the technology. Recently, the ability to acquire a DEM from airborne LiDAR has become very affordable compared to alternative sources of data, such as stereo satellite imagery. In addition, many regions have LiDAR DEMs freely available (e.g., coastal California, numerous DoD installations) making the technology cost effective and fast to implement.

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3.0 PERFORMANCE OBJECTIVES

Table 5. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
Quantitative Performance Objectives				
PO1. Plant survival increases in HS habitats.	Increased outplant survival in HS plots	Survival – measured quarterly for all planted individuals for two years after outplanting	• Statistically significant increase in number of plants surviving in HS over LS areas. We will analyze survival for each quarterly census, and over all sampling periods using a repeated measures analysis.[2]	• Performance not met during the timeframe of the demonstration.
PO2. Plant performance increases in HS habitats.	• Increased growth • Increased health • Increased recruitment • Increased reproduction • Increased physiological performance / decreased stress	• Growth(height), biannually • Health (0 to 5), biannually • Recruitment (# new seedlings), annually • Reproductive output (# and size of fruits and # of seeds), annually • Physiological measurements,), biannually (maximum rates of photosynthesis and quantum yield) and plant functional traits (leaf nutrient content and specific leaf area)	• Statistically significant increase in growth in HS over LS areas.[2] • Statistically significant increase in health in HS over LS areas.[2] • Statistically significant increase in recruitment in HS over LS areas.[2] • Statistically significant increase in reproductive output in HS over LS areas.[2] • Statistically significant increase in physiological performance in HS over LS areas.[2]	• PTA: Performance met for growth, health rating, physiology/stress • PWW: Performance met for physiology/stress • Recruitment and reproductive output: performance not met during the timeframe of the demonstration.
PO3. Spatial correspondence of ground elevation estimates between LiDAR and WV-2 models.	Correspondence of elevation values from LiDAR and WV-2 models	Two Digital Elevation Models (DEMs), one derived from LiDAR and one from WV-2 data	• A statistically significant relationship between WV-2 elevation (Y) and LiDAR elevation (X).	• Performance met in both locations: • *Hawaii:* $r^2 = 0.998$, $P < 0.001$ • • *VBG:* $r^2 = 0.934$, • $P < 0.05$

Table 5. Performance Objectives (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
PO4. Measurements of weather and microclimate variables indicate greater suitability for plant growth in HS areas.	• Weather conditions more suitable in HS plots • Microclimate for regeneration more suitable in HS plots • Plant stress reduced in HS plots	• Weather data – wind speed • Microclimate data – leaf wetness, soil moisture • Plant size	• Significantly lower wind speeds in HS compared to LS areas. • Significantly greater leaf wetness and soil moisture in HS compared to LS areas. • Significantly greater plant size in HS compared to LS areas.	• Wind: Performance met at at PWW, PTA, VBG, and SMMNRA. • Leaf wetness: Performance met at PTA, VBG, and SMNNRA but not PWW. • Soil moisture: Performance met at VBG and SMMNRA during dry period. • Plant size: Performance met at VBG but not SMMNRA.
PO5. Correspondence of existing TER-S with HS areas.	• Existing TER-S plants occur more frequently in HS areas.	• GPS locations of TER-S plants at VBG.	• Significant association of populations with HS areas. • More plants/km^2 in HS compared to LS areas.	• Performance met for *Chrysodracon hawaiiensis* and *Asplenium peruvianum var. insulare* at PWW. • • Performance not met for 11 other species.
Qualitative Performance Objectives				
PO6. Ease of use	Ability of a trained professional to use the technology	Survey and feedback from professionals on usability of the technology and time required to use. Survey will use a Likert scale.	Success is defined as survey results that indicate more than 75% of respondents "Agree" or "Strongly Agree" with question 7 (The software is easy to use) and question 17 (I would recommend the software to a colleague).	Performance met: • 83% of respondents "Agree" or "Strongly Agree" with question 7 • 94% of respondents "Agree" or "Strongly Agree" with question 17

[1]Significance of statistical tests is defined as $P < 0.05$.

[2]A typical General Linear Model (GLM) included the following terms: Block (spatial location of plot), Species, Suitability (High/Low), Species x Suitability. A significant interaction term indicates that the response to habitat suitability varies among species. If this term is significant we examined the species-specific responses. When data were taken on more than one date or at more than one time of day, a repeated measures design was used and a term for Date or Time was added as well as the appropriate interaction terms.

3.1 DESCRIPTION OF PERFORMANCE OBJECTIVES

PO1. Plant survival increases in HS habitats

Relevance of PO – Increasing the survival, reproduction, and recruitment of planted individuals through guided planting in HS areas is the ultimate goal of the project. Increased survival benefits reintroduction programs and will reduce costs of sustaining populations of TER-S. As such, we expect to detect an increase in plant survival in HS, compared to LS, areas. However, the degree to which survival increases in HS sites may vary among plant species. Some species may be more sensitive to microclimatic conditions, and may show a larger difference in survival between HS and LS sites. Other species may tolerate a larger range of conditions or have greater plasticity. These species may show a smaller difference in survival among HS and LS sites. Therefore, we will analyze survival differences across all species and also within species to account for species-specific responses.

Description of metric – The metric for survival is the proportion of individual plants surviving per species per plot. Mean survival can be calculated for HS (n=5 per site) and LS (n=5 per site). We will analyze the data separately for each site, PTA and PWW. A typical General Linear Model (GLM) to analyze the data will include a random Block factor (to account for the paired design of the experiment), a fixed Suitability factor (HS or LS), a random Species factor, a Suitability x Species interaction term (to account for different responses to suitability among species), and a repeated measures Time factor (to account for multiple measurements over time). We can also include a Time x Suitability interaction term to examine whether survival responds to habitat suitability at some times and not others.

Data requirements – We collected quarterly measurements of survival for two years following outplanting.

Criteria for success – Success was determined by a statistically significant increase in the proportion of plants surviving in HS over LS areas. This was determined by either a p-value less than 0.05 for the Site term (with species showing higher, not lower, survival in HS sites) or by a p-value less than 0.05 for the interaction term whereby some species show higher survival in HS sites. In the latter case, success was achieved for some species, but not others. We analyzed survival over all sampling periods using the repeated measures design described in the "Description of metric" section above. Due to a lack of a significant effect of habitat suitability on survival, this performance objective was not supported by the data during the timeframe of this demonstration project.

PO2. Plant performance increases in HS habitats

Relevance of PO – We monitored outplants for two years from planting. In this time period, we expected to be able to observe significant differences in survival among sites. However, some plants may remain alive, but may be significantly stressed. These plants may be on trajectory towards death that will take longer than two years to observe. As a result, we measured indicators of plant performance and growth to better understand the overall health of individual plants.

These data also help us assess the viability of the plant populations by determining the level of reproduction and recruitment in each site. We expected to detect an increase in plant performance indicators in HS, compared to LS, areas. Like survival, the degree to which performance increases in HS sites may vary among plant species. Therefore, we analyzed performance differences across all species and also within species to account for species-specific responses.

Description of metric – The metrics for plant performance include metrics measured at the level of individual plants: growth, health, physiological performance, reproduction; and population-level metrics: recruitment and reproduction. The data were analyzed using the model described above in "PO1. Description of metric".

Data requirements – We collected biannual measurements of all indicators for two years following outplanting. Growth was measured as a change in plant height over time since outplanting. Health was recorded as a scaled variable from 1 to 5 where 0 indicated a dead plant and 5 indicated a plant that is visually in good health. We analyzed physiological performance with several physiological measurements and plant functional trait measurements. Physiological measurements included the maximum rate of photosynthesis and quantum yield of at least three individuals per species per plot. We measured the plant functional traits of leaf nutrient content (%N, %P, $\delta^{13}C$) and specific leaf area for at least three individuals per species per plot. Population-level recruitment of each species was measured as the number of unplanted seedlings, and reproductive output will be measured as the number of seeds.

Criteria for success – Success was determined by a statistically significant increase in a performance metric in HS over LS areas. This was determined as described above in "PO1. Criteria for success". We analyze the performance metric data for each census separately using the model in the "PO1. Description of metric" section above. We found evidence for success of this performance objective at PTA when analyzing growth, health rating, and physiology/stress and at PWW when analyzing physiology/stress, but performance was not met at either site for recruitment and reproductive output during the study period.

PO3. Spatial correspondence of ground elevation estimates between LiDAR and WV-2 models.

Relevance of PO – All calculations from a DEM are sensitive to inaccuracies in vertical elevation measurements; therefore, it is important to verify that elevation measured by satellite imagery is similar to elevation measured with LiDAR. We expected there to be correspondence between the two DEM's based on the results of previous studies, but think it is important to confirm the correspondence for our study areas and datasets. A recent study (Hobi and Ginzler 2012) compared elevation estimates from airborne LiDAR to WorldView-2 (WV-2). In herbaceous and grassland vegetation, comparisons to several thousand ground control points indicated that the mean absolute deviation was 0.29 m for airborne LiDAR and 0.67 m for WV-2. The RMSE was 0.53 m for airborne LiDAR and 3.92 m for WV-2. This indicated that accuracies are similar between LiDAR and WV-2, but that precision of the relationship is greater for airborne LiDAR than for WV-2.

It is also possible that the presence of tree canopies may introduce error in elevation estimates from WV-2 data. In grassland or shrubland ecosystems like most of the ecosystems we are working with in HI and CA, trees are isolated or absent, so that it is straightforward to determine ground elevation beneath individual trees. However, in systems with dense tree cover where it is not possible to observe the ground from above, WV-2 may be unlikely to estimate ground elevation beneath the vegetation canopy, introducing error into the ground elevation estimates. With our data, we will be able to examine the correspondence of elevation estimates for grassland, shrubland, savanna-type woodland, and forest communities. The analysis among different communities will help us understand how broadly we can apply the HSM to different community types.

Description of metric – We sampled the same locations (points) from two DEMs, one generated from LiDAR and one from WV-2 data. We used correlation analysis to determine if there was a significantly positive correlation between the elevation values from the two DEMs ($P < 0.05$). We performed this analysis for a target area in Hawaii and a target area at VBG.

Data requirements – Elevation data from digital elevation models derived from either LiDAR or WV-2 data. We used randomly generated points (10,000 per analysis) to sample the same areas from each dataset.

Criteria for success – Success was defined as a statistically significant correlation between WV-2 elevation (Y) and LiDAR elevation (X) with a p-value less than 0.05. Analysis in both target areas indicated strong and statistically significant agreement between the LiDAR and stereo-derived DEMs, indicating success of this performance objective.

PO4. Measurements of weather and microclimate variables indicate greater suitability for plant growth in HS areas.

Relevance of PO – We measured weather and microclimate variables in the field that correspond with conditions important for plant growth in order to validate our initial HSM from LiDAR at PTA. These data were important for understanding how HS sites differ from LS sites in conditions that are important for plant regeneration. Like PTA, we expected measures of water stress to plants (wind speed, leaf wetness, and soil moisture) and measures of plant size to be important verification measures of habitat suitability for restoration.

Description of metric – We collected microclimate data from all sites: PTA, PWW, SMMNRA, and VBG. Data collected included wind speed, leaf wetness, soil moisture, and plant size. All data measured were compared between high and low suitability classes graphically or with a GLM as described above. Significance was determined as $P < 0.05$.

Data requirements – We used weather stations to measure wind speed, gust speed, air temperature, rainfall, and relative humidity in one pair (high and low suitability) of plots at each site ($n = 6$). These data were recorded at least every 30 minutes, 24 hours a day. Leaf wetness and soil moisture were recorded every 15-30 minutes, 24 hours a day by Decagon sensors in each plot at all sites. We recorded measures of plant size twice in plots at VBG and once in plots at SMMNRA.

Criteria for success – Success was defined as an observable or statistically significant differences ($P < 0.05$) between HS and LS areas that indicate more favorable conditions for plant growth in HS sites. HS sites should have greater leaf wetness, soil moisture, and plant biomass; and lower wind speeds. We found reduced wind speeds in HS areas at all sites, increased leaf wetness in HS areas at all sites except PWW, and increased soil moisture during dry periods at sites in California but not Hawaii. These results indicate success for this performance objective at all sites except PWW.

PO5. Correspondence of existing TER-S with HS areas.

Relevance of PO – One goal of this project is to better understand how broadly the HSM can be applied across species. We may find that most species respond favorably to HS areas during regeneration. We also may find that some species respond more favorably than others. Because little is known about the natural history or resource requirements of many TER-S, it is currently difficult to predict which species are the most likely to respond. We tested whether existing populations of TER-S at VBG and PWW corresponded with our suitability classes, similar to our analysis of TER-S at PTA (Table 4). This analysis allowed us to explore how current plant distributions track habitat suitability.

However, we do not yet know how well the current distributions of mature TER-S will identify the species that will benefit from the HSM. We have proposed that our HSM is appropriate for plants that are in the regeneration phase. During this phase, microclimatic conditions are important for survival and growth. Adult phases may not rely as heavily on small changes to these conditions because they are able to tolerate a wider range of conditions. Because of this issue, we expect that some species may respond to the HSM as juveniles but not as adults. In addition, these plant populations have been disturbed by decades of military training, wildfires, grazing, and invasive plant species. It is very possible that the existing plant populations were excluded from certain areas in the past by one of these disturbances, so they do not occur in their optimal habitats. Because of this issue, it is possible that the patterns of species occurrence in the field that we observe now may not represent true habitat associations of these species, but they are the best data we have available to us. As a result, we view this analysis as information that enriches the use of the HSM at a given site, but does not necessarily determine whether or not it will be useful for a given species.

Description of metric – We analyzed the habitat suitability of locations of existing TER-S plant populations at VBG and PWW, similar to our analysis at PTA (Table 4, Fig. 8). We tested for statistical associations of each species with our suitability classes with randomization tests ($P < 0.05$).

Data requirements – A shapefile of GPS locations of the known locations of individuals. These data were available from the staff at VBG and PWW.

Criteria for success – Success was defined as a greater number of plants in HS, compared to LS, areas. Two species, *Chrysodracon hawaiiensis* and *Aplenium peruvianum var. insulare*, showed an association with HS areas at PWW. Neither species at VBG and eight species at PWW did not show an association with either habitat type. Taken together, these data do not show a strong association across species with either HS or LS areas. The data suggest that *C. hawaiiensis* and *A. peruviannum* may benefit the most from the HSM at PWW.

PO6. Ease of use

Relevance of PO – The GIS Toolbox that we developed will help other land managers to apply the HSM technology to their sites. This software should be easy for professionals to use and should make producing a HSM for a site a relatively straightforward process. We evaluated the ability of trained professionals to use the modeling software extension that we developed, and to understand our written instructions for use.

Description of metric – We distributed test versions of the software to at least 10 users and evaluated its ease of use with their feedback and a survey based on a Likert scale (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree). We also asked open-ended questions to stimulate written suggestions for improvements.

Data requirements – Answers to survey questions from at least 10 users.

Criteria for success – Success was defined as survey results that indicate more than 75% of respondents "Agree" or "Strongly Agree" with question 7 (The software is easy to use) and question 17 (I would recommend the software to a colleague). Question 17 is one of the most effective measures of user satisfaction with a product (Reichheld 2006). The actual response rates were 83% (15/18) for question 7 and 94% (16/17) for question 17 indicating a high level of success for this performance objective (Table 17).

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4.0 SITE DESCRIPTIONS

4.1 SITE LOCATION AND HISTORY

PTA

PTA is located in the north central portion of the Island of Hawaii and is the single largest U.S.

Army holding in the state of Hawaii at 53,340 ha (131,805 ac) of ceded, leased, and fee simple lands (Fig. 9). There are 22 live-fire and 4 non live-fire ranges, 23 training areas, a centrally located impact area, 1 airfield, and 113 surveyed field artillery and mortar firing points. Twenty-seven ranges and artillery firing points in training areas surround the impact area and are oriented so 28 munitions are fired into the impact area, with the exception of two ranges that direct fire away from the impact area (U.S. Army Garrison Hawaii 2010). The installation provides resources for active and reserve component units. Training area (TA 22) comprises 8,373 ha (20,690 ac) and contains 63 km (39 mi) of bordering and interior roads and trails. The training area is used for maneuver training. Ground-training use is low and largely limited to infrequent helicopter insertions, most of which support land management activities. Live fire does not occur at firing points in TA 22. To protect the biological resources in TA 22 and to support mission, some 16 km (10 mi) of fire break/roads will be constructed (US Army Garrison Hawaii 2010). These firebreak roads will be available for military use as maneuver lanes.

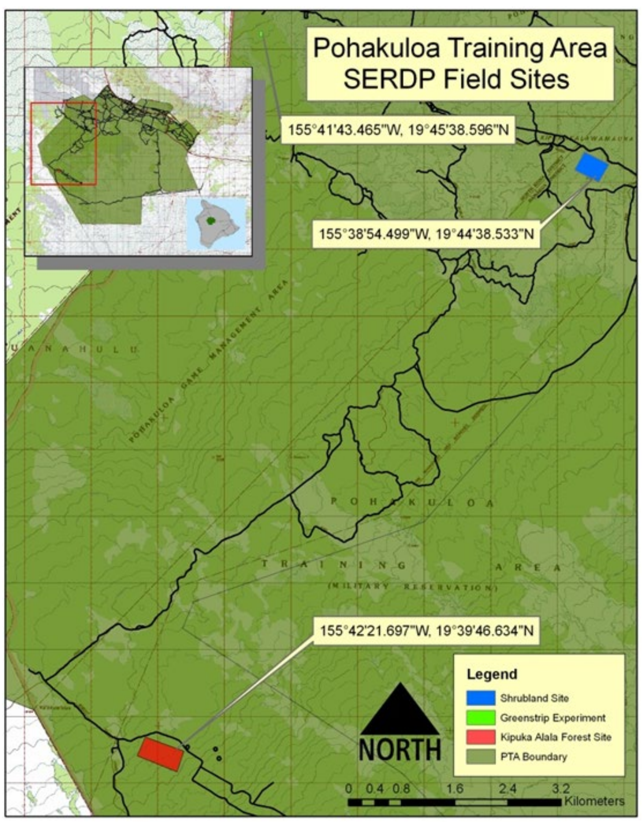


Figure 9. PTA Site Map.

Specifically, the PTA demonstration sites are located in TA 22 and in the conservation unit Kipuka Kālawamauna, a known habitat for the TER-S honohono (*Haplostachys haplostachya*) and creeping mint (*Stenogyne angustifolia* var. *angustifolia*). The fenced in unit Kipuka Kālawamauna where we will conduct our studies includes about 24 percent of the Kīpuka Kālawamauna and is the location of populations of the federally listed fragile fern (*Asplenium peruvianum* var. *fragile*), kio‘ele (*Kadua coriacea*), honohono (*Haplostachys* haplostachya), lance-leaf catchfly (*Silene lanceolata*), Mauna Kea pamakani (*Tetramolopium arenarium* var. *arenarium*), and a‘e (*Zanthoxylum hawaiiense*). Only foot access is permitted, and no live fire or pyrotechnics are allowed. The presence of federally listed species has resulted in training restrictions for TA 22 and other areas (e.g., no off-road driving, restricted driving to existing roads on cinder cones, restriction of fire-prone munitions based on the Burning Index, no vehicles inside the Kīpuka ‘Alalā or Kīpuka Kālawamauna fence units without prior approval, training units must clean all vehicles at wash rack facilities, etc.). All sites have year round road access.

PWW

PWW is located on the North Kona coast on the Island of Hawaii. This 38,885 acre (15,743 ha) unit lies on the northern flank of Hualalai volcano, extending from sea level to within 1 mile (1.6 km) of the mountain summit (Fig. 10). It is primarily managed by the State of Hawaii Division of Forestry and Wildlife (DOFAW) with an overlay of the entire area as the Hawaii Experimental Tropical Forest (HETF) managed by the USDA Forest Service, Institute of Pacific Islands Forestry (IPIF). At least 40 rare plant taxa have been reported from the area. Of these, 17 are Federally-listed TER-S. The PWW demonstration sites are in a fenced conservation unit with year round road access and where no recreational or cultural activities are performed.

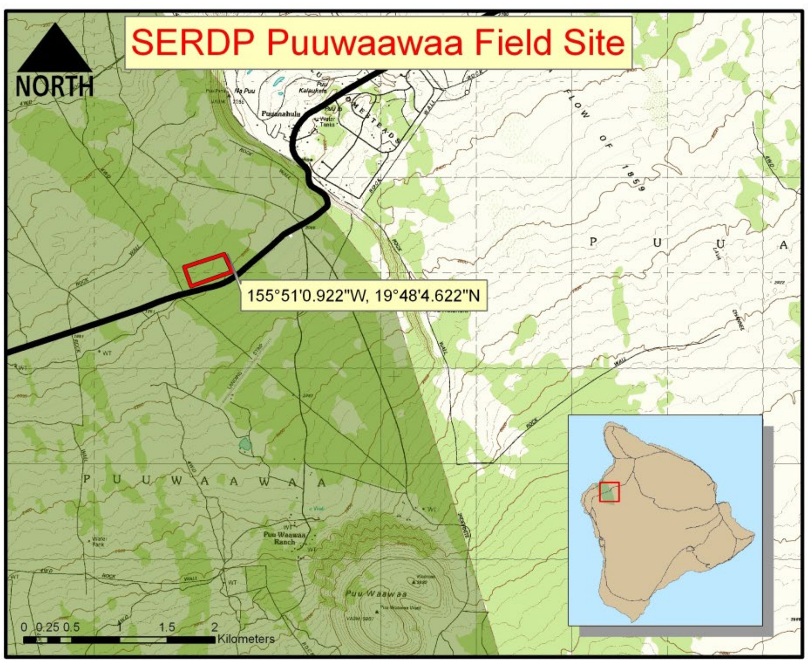


Figure 10. PWW Site Map.

VBG

VBG covers 155 square miles (99,579 acres) in south-central coastal California along the Santa Barbara County coastline (Fig. 11). The nature of Vandenberg AFB operations requires that a large area of the base be maintained as undeveloped open space to fulfill security and safety needs. As a result, approximately 67 percent of Vandenberg AFB is maintained in an undeveloped state where no training activities occur (USAF 2005). More than 850 plant species occur at VBG. Four of these are Federally-listed TER-S (USAF 2011): Beach layia (*Layia carnosa*), Gambel’s watercress (*Rorippa gambellii*), Lompoc yerba santa (*Eriodictyon capitatum*), and Gaviota tarplant (*Deinandra increscens* ssp. *villosa*). The Vandenberg Monkeyflower (*Mimulus fremontii* var. *vandenbergensis*) is a candidate species for listing (USAF 2011). Plots for the demonstration will be established after completion of the HSM for VBG. We will locate the plots in coordination with the VBG botanist and biologists to make sure they are accessible and do not interfere with VBG operations.

Figure 11. Location of VBG. Reproduced from (USAF 2011).

SMMNRA

SMMNRA consists of 239 square miles (153,250 acres) of land owned by the National Park Service, the California State Park System, and additional local parks, reserves, and conservation easements. The park is located in the Santa Monica Mountains west of Los Angeles, in both Los Angeles and Ventura Counties (Fig. 12). Open to the public for recreation, with over 500 miles of hiking trails and multiple campgrounds, the park was visited by over 900,000 people in 2016 alone (NPS 2017). Approximately 90 percent of the area is still undeveloped and the park is known to harbor approximately 1000 species of plants. Three of these are federally endangered (NPS 2005): Salt marsh bird's-beak (*Cordylanthus maritimus* ssp. *maritimus*), Lyon's pentachaeta (*Pentachaeta lyonii*), and Braunton's milk-vetch (*Astragalus brauntonii*).

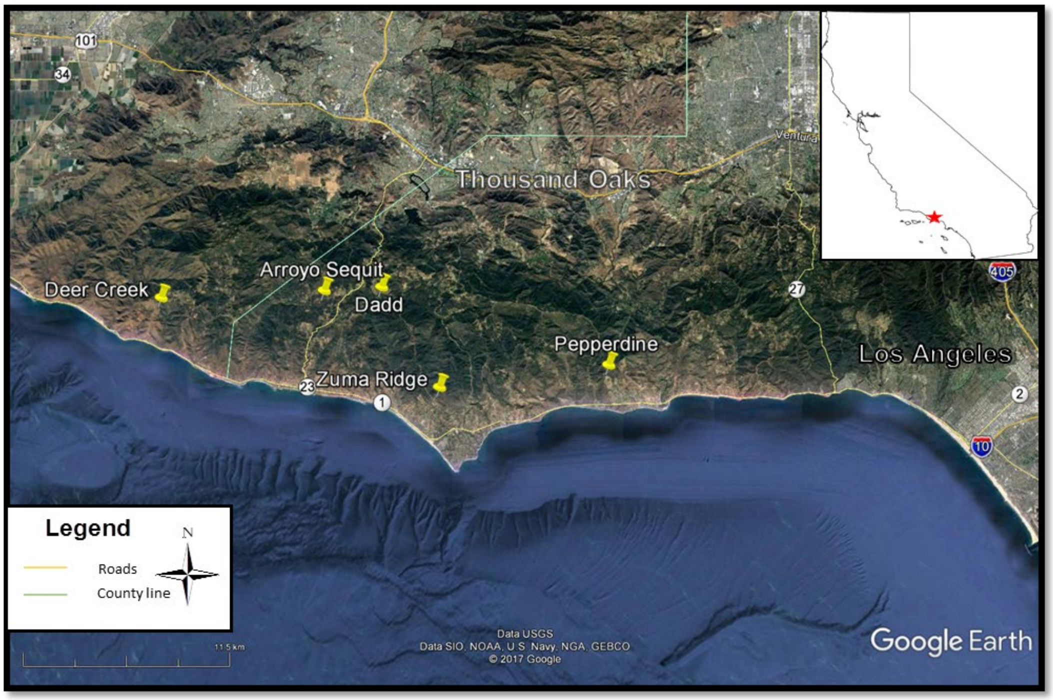


Figure 12. Location of SMMNRA.

4.2 SITE CHARACTERISTICS

Pohakuloa Training Area (PTA): PTA is located on the Big Island of Hawaii and encompasses 53,750 ha in the saddle between Mauna Loa and Mauna Kea volcanoes. It is managed by the Department of Defense and is the Army's largest training area in the Pacific. The climate is classified as cool tropical, or, upper montane to alpine, as elevation at PTA ranges from 1,300 - 2,700 meters (mean = 1883 m). Annual precipitation varies from year-to year, but is typically < 250 mm and varies more than 5 fold on a strong gradient from the windward to leeward side of the island (Giambelluca et al. 1986). Highest monthly precipitation generally occurs in winter months from November to February, and driest months are in June and July. The annual mean temperature is about 16°C. with little monthly flux but high diurnal fluctuation. Most of PTA is composed of relatively young substrate from Mauna Loa; however, there are highly developed soils on the older Mauna Kea substrates that consist of soil, cinder, or ash deposits.

Vegetative cover varies from barren lava to dense shrub and forest ecosystems but is collectively classified as Subalpine Dryland (Bern 1995). The vegetation found in a given area is largely a function of the age of the lava flow on which it grows. Because of PTA's position largely above the inversion layer, its rainfall is considerably lower than the rain forest zone at lower elevations. PTA is biologically rich encompassing 24 vegetation communities and substrates from at least 13 volcanic eruptions. PTA contains 19 federally listed species (15 of which are plants); 2 candidate species, 21 species of concern (species at risk); and numerous rare plants, animals, and invertebrates. Two areas on PTA are within the Palila Critical Habitat. There are a number of areas that are designated as sensitive on the installation including our study site (US Army Garrison Hawaii 2010)

Pu`u Wa`awa`a (PWW): The land division or ahupuaʻa of Pu`u Wa`awa`a encompasses 14,383 ha on the northern flank of Hualālai volcano on the western or leeward side of the Island of Hawaii extending from sea level to within 1.6 km of the mountain summit, approximately 1920 m elevation. The term "ahupuaʻa" pertains to a traditional Hawaiian land designation similar in concept to a watershed. Lavas of Hualalai are primarily Holocene in age, but some deposits date to late Pleistocene (Moore and Clague 1991). The study site is on a 3-10k year old lava flow at approximately 600 m elevation with a mean annual temperature around 20°C and receives approximately 60 cm annual precipitation. Native plant communities in this zone are among the most diverse in Hawaii, containing many rare and endangered species. These woodlands have been greatly damaged by fire and feral animals during the past 150 years. Lama (*Diospyros sandwicensis*) and ʻōhiʻa (*Metrosideros polymorpha*) are the dominant tree species and occur in both mixed and pure stands. Other less common trees include alaheʻe (*Psydrax odoratum*), wiliwili (*Erythrina sandwicensis*), ʻohe makai (*Reynoldsia sandwicensis*), and kauila (*Colubrina oppositifolia*). The rare lama and lama/kauila plant communities are restricted to this zone at Puʻu Waʻawaʻa.

Vandenberg Air Force Base (VBG): Vandenberg AFB covers 40,298 ha in south-central coastal California, an area characterized by a series of prominent mountains, mesas, canyons, and valleys with various drainage systems that flow to the Pacific Ocean. The topography is varied, including hills, mountains, terraces, floodplains, mesas, canyons, and rocky headlands. VBG is a geologically complex area that includes the transition zone between the southern Coast Ranges and western Transverse Ranges geomorphic provinces of California (a transition zone between central and southern California). The base contains diverse biological resources of considerable significance due to its location in the transitional geographic zone between central and southern coastal California, unique geological and soil characteristics, remote location, restricted access, and limited development (USAF 2011). A variety of plant communities occur on VBG including scrublands (coastal sage scrub, chaparral, and dune scrub types), forests and woodlands (willow-riparian, coast live oak, and Bishop pine types), and herblands (salt marsh, freshwater marsh and grasslands) (Coulombe and Cooper 1976, Coulombe and Mahrdt 1976, Schmalzer et al. 1988, USAF 2011). These habitats include more than 850 plant species, 53 species of mammals, 315 species of birds, 18 species of reptiles, and 10 species of amphibians (USAF 2003). A number of these species are federally threatened, endangered, or otherwise listed as special-status species. Human induced disturbances (e.g., cattle grazing, groundwater withdrawal, agriculture, and recreation) and the introduction of invasive plants (e.g., pampas grass [*Cortaderia* spp.], perennial veldt grass [*Ehrharta calycina*], European beachgrass [*Ammophila arenaria*], iceplant [*Carpobrotus* spp.].) have resulted in the degradation of these habitats (USAF 2003).

Santa Monica Mountains National Recreation Area (SMMNRA):

The SMMNRA covers 153,075 acres in Southern California. The Santa Monica Mountains are found along the coast and, together with the northern Channel Islands, are a part of the Transverse Ranges. The topography ranges from rugged mountain areas to coastal areas and valleys with an abundance of creeks and springs found in the range (NPS 2005). The park contains an abundance of plant communities, including herblands (coastal dunes, marshes, and grasslands), woodlands (oak and riparian woodlands), scrublands (coastal sage and chaparral), and developed habitats (agricultural and suburban areas) (Swenson and Franklin 2000, NPS 2005). Approximately 1000 species of plants are known to occur in the SMMNRA, as well as 35 species of reptiles and amphibians, 400 species of birds, and 50 species of mammals (NPS 2005). Of these species, 23 plants and animals are listed federally as threatened, endangered, or as special-status species. Human induced disturbances (e.g. fire, agriculture, urbanization, and recreation) and the introduction of approximately 275 exotic plant species have resulted in type conversion and degradation of many habitats in the SMMNRA (NPS 2005).

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

Our demonstration validated the utility of the HSM to guide outplanting efforts at PTA and PWW and demonstrated the use of this technology for TER-S restoration planning at other DoD installations. The demonstration included three tasks. In Task 1, we used an outplanting experiment to evaluate the potential of habitat suitability mapping to improve TER-S outplanting activities at PTA and PWW. In Task 2, we acquired satellite data for PTA and VBG and compared the satellite-derived DEMs with LiDAR DEMs. In Task 2, we also made HSMs for VBG and SMMNRA and performed field measurements to examine the performance of the HSM at all sites. In Task 3, we used information gathered from Tasks 1 and 2 to determine costs of implementing outplanting programs based on the HSM and cost benefits of using HSMs to guide outplanting programs. In Task 3 we also developed written materials and a toolbox for ArcMap that will make the HSM technology available to new users.

5.2 BASELINE CHARACTERIZATION AND PREPARATION

Initial site preparation included the removal of all non-native plants from all research plots and a 5-meter buffer surrounding the research plots. Non-native plants were trimmed using a weed trimmer and then sprayed with an herbicide (Round-Up) following re-growth. After the herbicide treatment was effective, the non-native plants were then manually removed with hand tools. Round-Up is short lived and at least 90 days was given prior to outplanting to allow the herbicide to dissipate so as not to negatively impact the outplants. Drip irrigation linked to large capacity tanks were established in every research plot so that each outplant had its own drip line. Holes were made for each outplant that was approximately 25 cm wide x 25 cm deep. A 1/2 gallon volume of a mixture of 3 parts Sunshine Commercial Potting Media and 1 part back volcanic cinder was added to each outplant hole at outplanting and each plant was given the same volume of water during the establishment period. Plants were initially watered in for 15min using 1gal/hour emitters equaling 32oz per watering. The first week consisted of watering everyday followed by 2 weeks of every other day watering and the final week watering occurred every 3rd day. When watering occurred, all plots were watered at PTA or PWW.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY AND METHODOLOGY COMPONENTS

The demonstration project was divided into three Tasks. Task 1 was completed at PTA and PWW only. Task 2 was completed at all sites. Task 3 related to technology transfer and cost assessment.

5.3.1 Task 1

Evaluated the potential of habitat suitability mapping to improve TER-S outplanting activities at PTA and PWW using field experiments.

This task employed field experiments to test whether the success of TER-S reintroduction activities was greater in HS, compared to LS, sites. We employed the following steps:

5.3.1.1 Identified pairs of HS and LS sampling plots with the HSM.

We used our HSM for PTA to identify five pairs of HS and LS sites at PTA. Each site was 8 m x 45 m, and was located in open *Dodonaea* shrubland habitat on the same volcanic substrate (Fig. 13). We selected this site size because it reflects a reasonably large contiguous area that met the high suitability criteria and is fenced to exclude ungulate herbivores. The combination of downward sloped areas on leeward facing sides yielded long but narrow results.

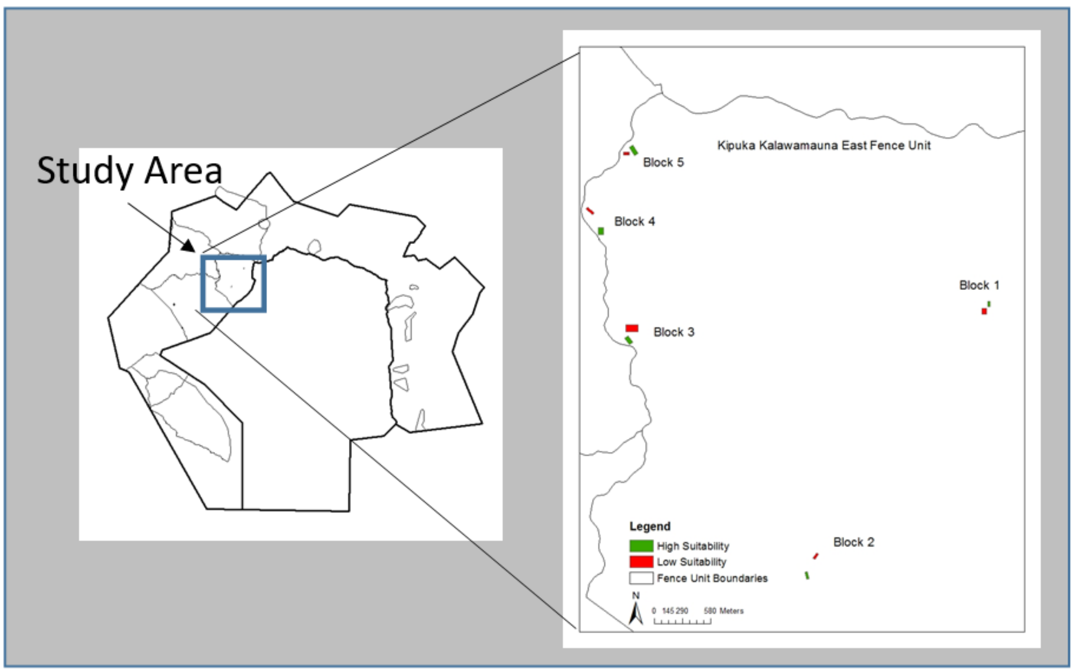


Figure 13. Study Plot Locations at PTA.

We used airborne LiDAR data from the CAO to create the HSM for PWW, and we used the HSM to identify plots at that site. Plots were selected in two units that had been fenced to exclude ungulates and where outplanting projects occur.

5.3.1.2 Delineated plots in the field.

Ten paired 8-m by 45-m HS and LS plots were delineated at PTA (Fig. 13). Ten paired HS and LS plots were also delineated at PWW (Fig. 14). Plots were various sizes at PWW due to the difficulty in finding large contiguous areas of the same dimensions of LS habitat. In some cases, plots were divided into subplots in order to accommodate the large number of outplants planted.

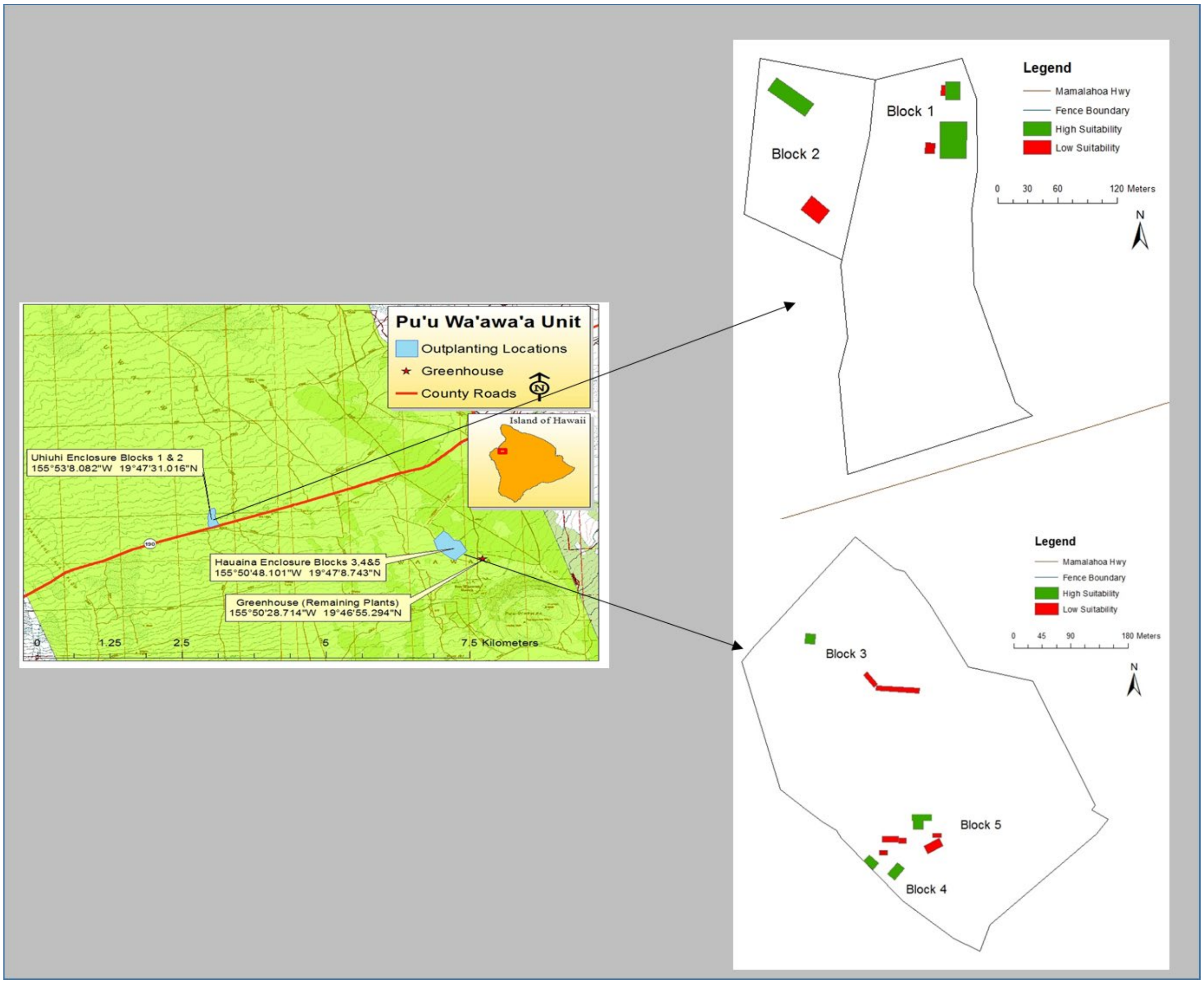


Figure 14. Study Plot Locations at PWW.

5.3.1.3 Experimental outplanting of TER-S and common native species in all plots.

We used our paired plots as experimental units, comparing the outcome of restoration between HS and LS plots (Fig. 15). LS serves as an appropriate control at PTA because this class is currently used most often for outplanting, due to its prevalence in the landscape. We grew outplants of selected TER-S using seed collected by CEMML staff at PTA and seed we collect ourselves from PTA and PWW. These outplants will be planted into the replicated HS and LS areas at both sites.

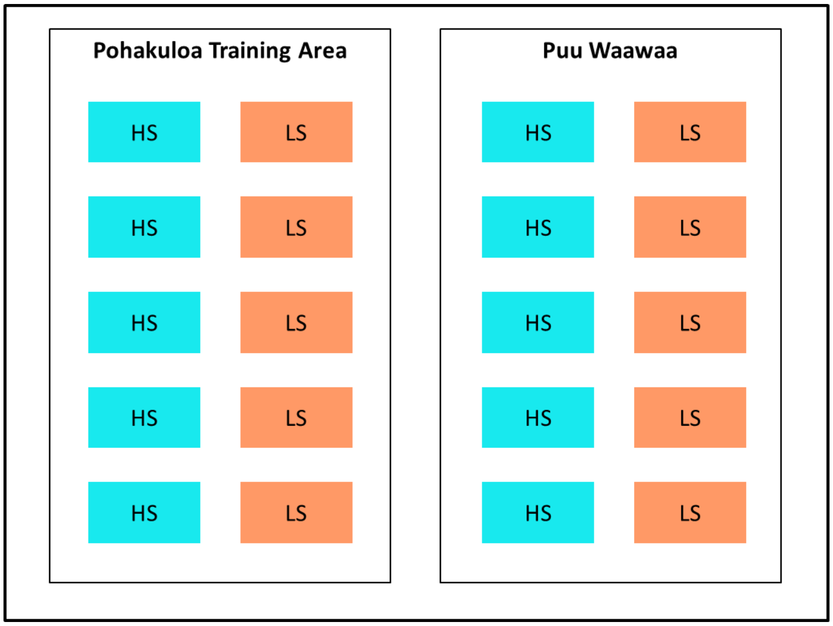


Figure 15. Schematic of Experimental Design.

Planting occurred in five pairs of high suitability (HS) and low suitability (LS) plots at each site. Plot pairs were located opportunistically throughout the study areas using the HSM to guide placement, and were not in a grid.

5.3.1.4 Monitoring of planted individuals.

We recorded common measures of plant reintroduction success, including measures of survival (PO 1), reproduction, and recruitment (PO 2; Monks et al. 2012). In addition, we measured plant physiological performance, which allowed us to determine whether plants were more stressed in LS plots even if plant mortality did not occur within the demonstration timeframe (PO 2). We monitored these measures of success for over two years after outplanting.

5.3.2 Task 2

Developed HSM technology from satellite data sources for DoD installations in dry areas of Hawaii and California. In order for our modeling technology to have a wide application to other DoD users, we examined additional sources of data for developing DEMs and HSMs. Airborne measurements from the CAO are unique and not available to other installations; however, satellite data sources, such as WorldView-2 (WV-2), now exist that equal or surpass the spatial detail of airborne LiDAR (i.e. pixel sizes << 1 m).

5.3.2.1 Acquired stereographic WV-2 satellite imagery for PTA and VBG.

We were able to acquire imagery for VBG at no cost to the project through federal government sources. We purchased imagery directly from DigitalGlobe for PTA.

5.3.2.2 Created DEMs from imagery for each site.

We generated DEMs using ENVI's DEM extraction tool. The method works by solving a system of equations that characterize a hypothetical vector drawn from the satellite sensor to a fixed location on the ground at two angles. By setting these vectors equal to each other, one can solve for elevation. Repeating this process a very large number of times using semi-automated processing generates spatially detailed elevation measurements that can be processed to generate a DEM. We evaluated the accuracy of the DEM by comparison to a DEM generated from airborne LiDAR using the CAO. As needed, we augmented and improved the DEM extraction to produce a DEM with the highest accuracy possible from the data (Fig. 4d).

5.3.2.3 Acquired additional data needed for HSM for each site.

We acquired long-term measurements of prevailing wind direction at all four sites. These data were available from weather stations at or near each study site. We were also able to acquire LiDAR DEMs for all sites either directly from the installation or from other sources.

5.3.2.4 Developed HSM for each site.

We followed our same protocol to generate HSMs from the LiDAR DEMs for PWW, VBG, and SMMNRA (Section 2.1).

5.3.2.5 Tested HSM models.

We compared the correspondence of the DEMs derived from WV- 2 data with the DEMs derived from LiDAR data at PTA and VBG (PO 3).

5.3.2.6 Field sampling of resource variables and microclimatic conditions in plots.

We collected data of environmental variables in our HS and LS outplanting plots at PTA and PWW. We also delineated five pairs of HS and LS plots at VBG and five pairs of plots at SMMNRA and measured the same environmental variables to examine microclimatic and resource conditions of high and low suitability areas (PO 4).

5.3.2.7 Correspondence of TER-S with suitability classes.

We analyzed the correspondence of TER-S with the HSM for plant populations at PWW and VBG (PO 5).

5.3.3 Task 3

Transfer technology to DoD users. Our overall goal was to provide DoD and other conservation users with an HSM tool that is easy to use and cost-effective to implement.

5.3.3.1 Developed software extension.

We developed a user-friendly toolbox for ArcMap that can be distributed to other users, making the technology simple and quick to deploy. We also developed a written manual to accompany the software.

5.3.3.2 Solicited feedback from users.

We asked our existing DoD collaborators and other conservation professionals to evaluate the toolbox and provide feedback. Feedback was in the form of written comments and a survey using a Likert scale (PO 6).

5.3.3.3 Written instructions for field validation.

We wrote a manual that includes methods for validating the model and suggestions for using the model to guide an outplanting program.

5.3.3.4 Distributed HSM maps to users at PTA, PWW, and VBG.

The HSM maps that were developed as part of our demonstration can be used immediately by users at these sites, and we will supply supplementary material to these users if requested, such as GPS points and GIS layers. Maps have already been distributed to staff at PTA and PWW for use in their ongoing outplanting programs and conservation planning.

5.4 FIELD TESTING

5.4.1 Task 1. Experimental Outplanting

5.4.1.1 Build Greenhouse

We constructed a greenhouse for plant propagation at the PWW site in order to eliminate any strain by this project on the greenhouse activities already planned at PTA (Fig. 16). In addition, this greenhouse now serves as a second propagation site for TER-S plants and is currently in use by numerous resource managers in the region for propagating plants for restoration projects. IPIF has an agreement with the State of Hawaii Department of Land and Natural Resources who owns and manages PWW as part of the Hawaii Experimental Tropical Forest, and there is support for this project among these partners. IPIF will maintain this greenhouse for at least 15 years and will contribute approximately $135,000 in cost sharing to maintenance costs over this time. The agreement between IPIF and the State of Hawaii is included in Appendix C.

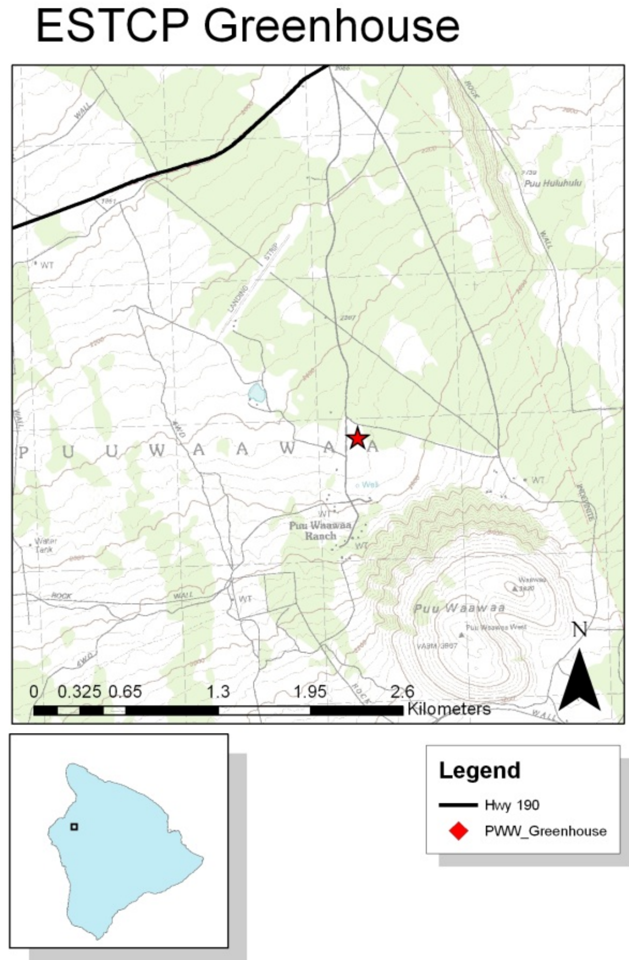


Figure 16. Greenhouse Location Map.

5.4.1.2 Collect seed of TER-S and common native species

We propagated 12 species for our outplanting experiment, selected based on availability of seed or cuttings, ability to grow, and based on their association with HS and LS areas at PTA (Table 4). We chose two species that showed No Association with suitability classes (*Portulaca sclerocarpa* and *Spermolepis hawaiiensis*), one species that showed an association with Lower Suitability sites (*Neraudia ovata*), and four species that showed an association with Higher Suitability sites (*Haplostachys haplostachya*, *Silene hawaiiensis*, *Silene lanceolata*, and *Stenogyne angustifolia*; see Table 4). We also included five additional TER-S and state-listed native species (*Mezonevron kavaiensis*, *Colubrina oppositifolia*, *Nothocestrum breviflorum*, *Dracaena konaensis*, and *Euphorbia olowaluana*). These species are all locally rare and likely will become eventual TER-S candidates. These additional species were recommended to us by land managers as species of concern. We will work with PTA CEMML and DOFAW staff to coordinate the collection of TER-S seed and cuttings from PTA and PWW. When possible, we used materials that were in existing collections. We maintained a database of information for all seeds collected, including date of collection, source, field location, and status of individual.

5.4.1.3 Propagate outplants

We performed an extensive interview survey of regional managers and native plant growers in order to determine the best techniques for propagating each species (seed, cuttings, etc.). All propagation protocols were documented in our Hawaiian Native Plant Propagation Resource (Janas et al. 2015). Plants were grown for at least six months before outplanting.

We grew plants with a variety of life-history traits for outplanting, in order to test how different species respond to the HSM. Species included large woody shrubs *Stenogyne angustifolia, Haplostachys haplostachya,* and *Neraudia ovata*; small, shorter-lived woody shrubs *Silene lanceolata* and *Silene hawaiiensis*; and trees found at PTA (*Euphorbia olowaluana*) and PWW (*Mezonevron* kavaiensis, *Nothocestrum breviflorum, Colubrina oppositifolia* and *Dracaena konaensis*). We planted seedlings and also added seeds of *Spermolepis hawaiiensis*, an annual, herbaceous species. We also planted a low-growing succulent *Portulaca sclerocarpa.*

5.4.1.4 Plant outplants into experimental plots

We aimed to plant 30 individuals of each species in each plot; however, the number for each species differed due to the total number of available plants after propagation (Table 6). Extra plants were planted in HS plots and were also monitored regularly. Plants for outplanting were selected based on their health status (see "Health rating" in section 5.6.2 for descriptions of health classes). Plants in health class five were identified for outplanting. In a few cases, for species with limited numbers, plants in health class four were also used. Plants were distributed evenly across plots based on health status, size, and founder in order to have the same plant types represented equally in all plots. Planting occurred in April-May 2014 at PWW and October – December 2014 at PTA.

Table 6. Number of Seedlings Planted in Each Plot at PTA and PWW.

Species	Number planted per plot at PTA	Number planted per plot at PWW	Life form
Colubrina oppositifolia		30	Tree
Dracaena konaensis		30	Tree
Euphorbia olowaluana	35		Tree
Haplostachys haplostachya	55	30	Large shrub
Mezonevron kavaiensis		20	Tree
Neraudia ovata		27	Large shrub
Nothocestrum breviflorum		5	Tree
Portulaca sclerocarpa	40	30	Succulent
Silene hawaiiensis	32		Small shrub
Silene lanceolata		35	Small shrub
Spermolepis hawaiiensis	5 seedlings; 28 seeded areas	5 seedlings; 35 seeded areas	
Stenogyne angustifolia	55	55	Large shrub

5.4.1.5 Monitor plants and environmental variables

Survival of outplants was monitored from September 2014 – March 2017 at PWW. Plants were surveyed nine times during this time period. Survival was monitored from February 2015 – February 2017 at PTA. Plants were surveyed eight times during this time period. We recorded more extensive data on plant size and health approximately every other sampling time for a total of five times at each site. We will continue to monitor the survival of outplants once per year through 2019 at the expense of IPIF.

5.4.2 Task 2. Field verification of new HSMs

5.4.2.1 Develop HSM from WV-2 imagery (Section 5.3.2).

5.4.2.2 Identify pairs of HS and LS sampling plots with HSM at VBG and SMMNRA.

We used our LiDAR-based HSMs for SMMNRA and VBG to identify five pairs of HS and LS plots at each site. We used the plots identified for outplanting (Task 1, Section 5.3.1) at PWW and PTA.

5.4.2.3 Delineate plots in the field.

Plots at SMMNRA and VBG were delineated using a tablet PC equipped with GPS and our HSM for each site.

5.4.2.4 Field sampling of resource variables and microclimatic conditions in plots.

We collected environmental data in all plots delineated at PTA, PWW, SMMNRA, and VBG using environmental sensor arrays (Section 5.5.2). At SMMNRA and VBG, we took additional measures of plant size in a subset of the plots. Measurements were taken in 2014 at VBG and 2017 at both sites.

5.4.3 Task 3. Technology transfer

We developed a toolbox for ArcMap and distributed it to users during a formal workshop held at IPIF on March 24, 2017. Workshop participants provided written comments. Prior versions of the toolbox were tested by students in Dr. Questad's graduate geospatial course in May 2016 in order to identify bugs and refine the final version of the toolbox. Future workshops are planned to increase the awareness and use of the toolbox (e.g., at the 2018 California Native Plant Society meeting).

5.5 SAMPLING PROTOCOL

5.5.1 Task 1

5.5.1.1 PO1. Plant survival increases in HS habitats

The survival of each individual plant was monitored every 3-6 months from the time of outplanting through the end of the project. Survival will be monitored annually through 2019.

5.5.1.2 PO2. Plant performance increases in HS habitats

Performance was measured as growth, recruitment, reproduction, and increased physiological performance / decreased stress.

a. Growth was measured as the change in plant size since the time of outplanting and was measured biannually for the first two years after outplanting and annually thereafter.
b. Health was determined on a scale of 0 to 5 where dead plants receive a 0 and visually healthy individuals receive a score of 5. Health was measured biannually for the first two years after outplanting and annually thereafter.
c. Recruitment was measured as the number of new seedlings in a plot. Recruitment surveys were made at PWW in March 2015, November 2015, September 2016, and March 2017; at PTA in January 2016, June 2016, and March 2017.
d. Reproduction was measured annually as the reproductive output of each plant. Measures included the number and size of fruits, number of seeds per fruit, and total number of seeds produced per plant. The number of fruiting and flowering individuals was also recorded.
e. Physiological measurements were made on at least three individuals/ species/ plot. Target species were selected based on their abundance and ability to be measured with standard methods (i.e., leaves were large enough to fill the LICOR chamber). Measurements were taken at PWW in March 2015, November 2015, July 2016, and March 2017; and at PTA in November 2015, July 2016, and March 2017. Measurements included the following:
    1. CO_2 uptake rate (A), stomatal conductance (g_s), transpiration (E), and maximum quantum yield of photosystem II (F_V/F_M) measured with nondestructive technology (i.e., LICOR 6400, fluorometer). Measurements were taken at PWW in March 2015, November 2015, and March 2017; and at PTA in November 2015, and March 2017.
    2. Specific leaf area – Area was measured at PTA in November 2015 and March 2017 and for PWW in March 2015, September 2015, and August 2016 with a LI3000 leaf area meter. Leaves were dried for at least 48 h and weighed.
    3. Leaf nutrient content - %N, %P, $\delta^{13}C$. The same leaves used for specific leaf area were also utilized for nutrient content so as to reduce the need to collect additional plant material. Leaves used for nutrient analysis were collected at PTA in November 2015 and March 2017 and for PWW in March 2015 and September 2015 (to have a wet and dry period represented for each site). Leaves were dried and sent to the University of Hawaii, Hilo Analytical Laboratory.

5.5.2 Task 2

5.5.2.1 PO3. Spatial correspondence of suitability classes

We used simulations of 10,000 random points to compare elevation values from the DEM derived from LiDAR with the DEM derived from satellite data for VBG, PTA, and PWW.

5.5.2.2 PO4. Field measurements of weather and microclimate variables indicate greater suitability for plant growth in HS, compared to LS, plots

Data collected from our PTA, PWW, SMMNRA, and VBG field plots (Section 5.4.2.4) included:

a. Wind speed, gust speed, air temperature, rainfall, relative humidity, and dew point. These data were be recorded every 30-60 minutes, 24 hours a day by weather stations placed in one pair (high and low suitability) of plots at each site (eight plots total).

b. Leaf wetness was recorded every 15-30 minutes, 24 hours a day by Decagon sensors in each plot at PTA, PWW, SMMNRA, and VBG (40 plots total). We recorded soil moisture with Decagon sensors at the same frequency (15-30 minutes, 24 hours a day) at PTA, PWW, SMMNRA, and VBG (40 plots total).

c. We recorded measures of plant size (height) in a subset of plots at SMMNRA and VBG.

5.5.2.3 PO5. Correspondence of existing TER-S with HS areas.

We obtained a GIS shapefile of the GPS locations of known individual plants of four TER-S at VBG: Beach layia (Layia carnosa), Gaviota tarplant (Deinandra increscens ssp. villosa), Lompoc yerba santa (Eriodictyon capitatum), and Vandenberg monkey flower (Mimulus fremontii vandenbergensis). Locations of E. capitatum and M. fremontii vandenbergensis fell within the area of our HSM and were able to be statistically analyzed. We obtained a GIS shapefile of the known locations of individual plants of 11 species at PWW that we were also able to analyze (see Table x for list of species).

We quantified associations between the locations of each species and habitat suitability using a spatial-point-pattern simulation. We did this by first extracting the values of the HSM at the locations of each species, and computing the mean value of habitat suitability for each species. We then generated a null distribution by randomizing the locations of each species 1000 times. At each iteration, we computed the mean value for each species at the randomized locations. We compared the true value to the distribution of simulated values over all 1000 randomizations, and asked whether the true value was statistically different from the null distribution. This analysis allowed us to formally test the hypothesis that associations for a given population are significantly associated with topographic features that influence habitat suitability.

Table 7. Summary of Field Samples.

	Unit of measure	Approximate # samples per census	Census frequency
Task 1			
Plant survival	Plant	5000[a]	Every 3-6 months
Plant growth	Plant	5000[a]	Biannually
Plant health	Plant	5000[a]	Biannually
Recruitment	Plot	80[b]	Annually
Reproduction	Plant	2400[a]	Annually
Physiological performance	Leaf	240[c]	Biannually when possible
Task 2			
Weather data	Plot	8[d]	Every 30-60 min.
Leaf wetness	Plot	40[e]	Every 15-30 minutes
Soil moisture	Plot	40[e]	Every 15-30 minutes
Plant biomass	Plot	20[f]	Annually

[a]250 individuals / plot x 10 plots x 2 sites = 5000; [b]4 species / plot x 10 plots x 2 sites = 80; [c]3 individuals x 4 species / plot x 10 plots x 2 sites = 240; [d]2 plots / site x 4 sites = 8; [e]10 plots / site x 4 sites = 40; [f]10 plots / site x 2 sites = 20

5.5.3 Calibration of Equipment

Decagon 10HS soil moisture sensors were calibrated using an equation based on soil specific dielectric permittivity counts plotted against volumetric water content to account for variation in electrical conductivity within soils. Licor 6400 leaf-level gas exchange calibration was conducted before each field use following manufacturer guidelines http://www.licor.com/env/pdf/photosynthesis/Fluoro.pdf. The LI3100 leaf area meter was calibrated as instructed by the manufacturer: ftp://ftp.licor.com/perm/env/LI-3100/Manual/LI-3100%20 Manual.pdf.

5.5.4 Quality Assurance Sampling

N/A

5.5.5 Sample Documentation

Field logbooks contain site location, date, activity, personnel present, and personnel taking measurements/transcribing. Hard copy data sheets will be transferred to an electric format and then retained for the duration of the project. Data will be error checked and archived.

5.6 SAMPLING RESULTS

5.6.1 PO1. Plant survival increases in HS habitats

The HSM can reduce costs of outplanting if outplant survival increases when planting efforts are guided to high suitability areas, thereby reducing the planting effort required to produce a given number of surviving individuals. Thus, outplant survival should be statistically significantly greater in HS, compared to LS, plots. However, the degree to which survival increases in HS sites may vary among plant species. Some species may be more sensitive to microclimatic conditions, and may show a larger difference in survival between HS and LS sites. Other species may tolerate a larger range of conditions or have greater plasticity. These species may show a smaller difference in survival among HS and LS sites. Therefore, we analyzed survival differences across all species and also within species to account for species-specific responses.

The metric for survival is the proportion of individual plants surviving per species per plot. Mean survival can be calculated for HS (n=5 per site) and LS (n=5 per site). We analyze the data separately for each site, PTA and PWW. Statistical models included a random Block factor (to account for the paired design of the experiment), a fixed Suitability factor (HS or LS), a fixed Species factor, a Suitability x Species interaction term (to account for different responses to suitability among species), and a repeated measures Date factor (to account for multiple measurements over sampling dates). All statistical analyses were performed in the R computer language and all mixed models were fit using the lme4 package (Bates et al. 2015) version 1.1-12 (Bates et al. 2015, R Core Team 2015).

Success was determined by a statistically significant increase in the proportion of plants surviving in HS over LS areas. This was determined by either a p-value less than 0.05 for the Suitability factor (with species showing higher, not lower, survival in HS sites) or by a p-value less than 0.05 for the interaction term whereby some species show higher survival in HS sites. In the latter case, depending on the reason for the interaction success could be achieved for some species, but not others.

We analyzed survival over all sampling periods using a repeated measures design. We began with a model with all terms, all two-way interaction terms, and the three-way interaction term and chose the most parsimonious model based on AIC scores of models with successively fewer terms. The most parsimonious model for PWW included the Date, Species, Suitability, and Date:Species terms. The most parsimonious model for PTA included these terms as well as the Species:Suitability interaction term. Survival declined over time as expected (significant Date terms) and varied among species (significant Species terms; Table 8; Fig. 17). The significant Species:Suitability interaction term occurred in the PTA analysis because the differences in survival among species varied with habitat suitability (Fig. 18); however, there were no significant effects of Suitability on survival within each species ($P > 0.05$).

Table 8. GLM Results of Analysis of Survival.

F statistics and df are shown for analysis of variance with type III SS with Satterthwaite approximation for df.

	PWW		**PTA**	
Factor	**F**	**df**	**F**	**df**
Date	154.33***	8, 720	116.49***	7, 347
Species	40.84***	8, 720	95.62***	4, 347
Suitability	2.42	1, 4	0.003	1, 4
Date:Species	4.46***	64, 720	7.37***	28, 347
Species: Suitability	N/A	N/A	5.87***	4, 347

***P < 0.001; **P < 0.01; *P < 0.05; + P = 0.07

When analyzing survival from the last census date only, there were significant differences in survival among species at PTA ($F_{36,29}$ = 28.87; P < 0.001) and PWW ($F_{10,84}$ = 4.82; P < 0.001). There was a significant effect of Suitability at PWW ($F_{1,84}$ = 4.57; P < 0.05) but not at PTA (P > 0.45). There were no significant effects of the Suitability:Species interaction term at either site (P > 0.45). At PWW, survival among species ranged from 27% to 70%. At PTA, survival among species ranged from 11% to 79%. Averaged over all species, survival at PWW was 7% higher in LS plots. It was exactly the same (47%) in HS and LS plots at PTA. Thus, differences in survival among species were much greater than the effect of habitat quality on survival.

Spermolepis hawaiiensis, a short-lived annual species, was difficult to monitor with quarterly monitoring events. It appears to complete its lifecycle quickly and was not often observed actively growing. We chose an opportune time on March 9, 2015 when individuals were observed in all plots at PWW to complete an exhaustive count of individuals present. Thirty-two individuals were found across all HS plots and 38 individuals were found across all LS plots. There was not a statistically significant difference in number of individuals between HS and LS plots or between areas that were seeded or planted with seedlings (P > 0.40).

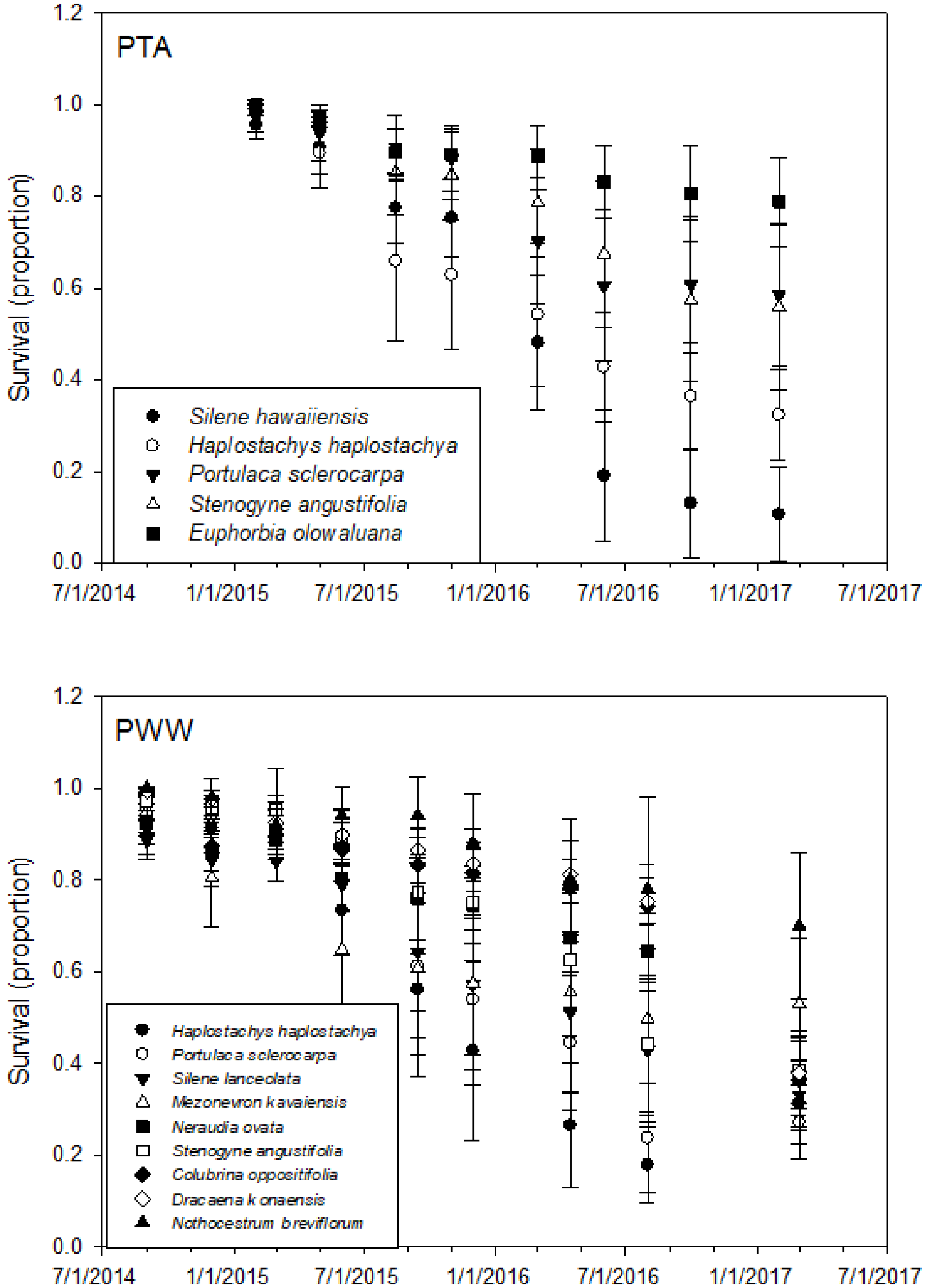


Figure 17. Survival at PTA and PWW by Species and Date.

Bars represent means and error bars show 2SE.

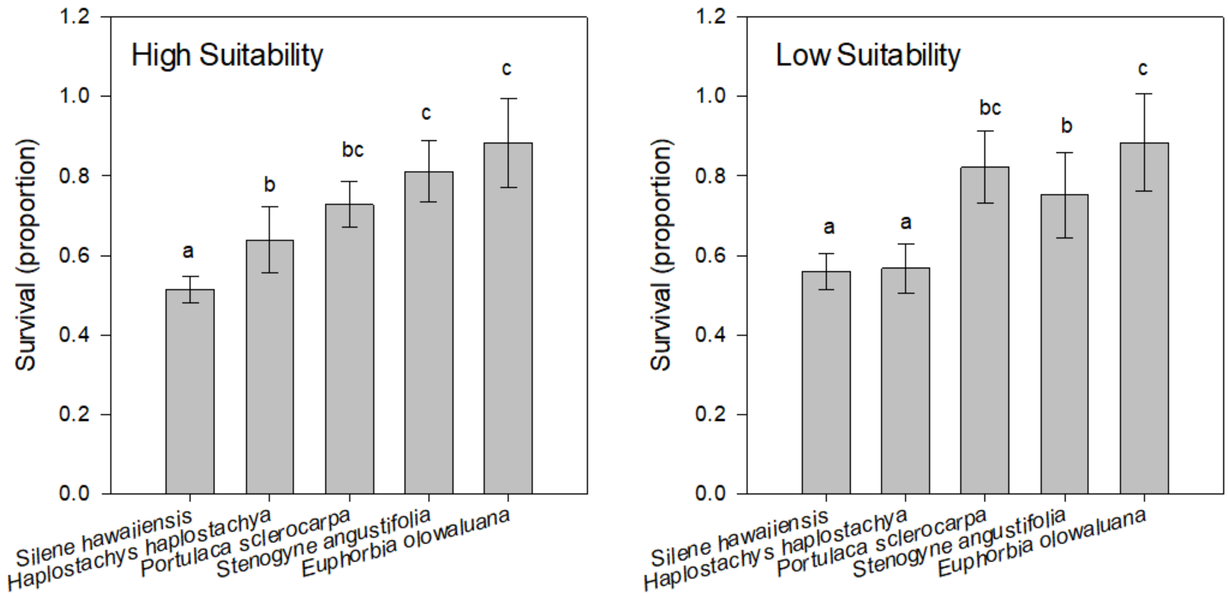


Figure 18. Survival at PTA by Species and Habitat Suitability.

The difference in survival rates among species varied among HS and LS plots. Bars represent means and error bars show 2SE. Letters indicate significant differences with Tukey HSD (P < 0.05).

5.6.2 PO2. Plant performance increases in HS habitats

We expected to see greater overall plant performance in HS, compared to LS, plots. Performance was measured as indicator variables of growth, health, recruitment, reproduction, and increased physiological performance / decreased stress.

We used a GLM to analyze measures of performance with Suitability and Species as fixed factors, a Block random factor and a Date term for measures taken repeatedly in the same manner. Appropriate interaction terms were included in each model. For many physiological variables, the numbers of samples differed from one date to the next based on the limitations of instrumentation and weather. Therefore, these datasets were analyzed separately for each sampling date due to the unbalanced nature of the sampling designs.

Success is determined by a statistically significant increase in performance measures in HS over LS areas. This is determined by either a p-value less than 0.05 for the Suitability factor (with species showing higher, not lower, performance in HS sites) or by a p-value less than 0.05 for the interaction term whereby some species show higher performance in HS sites. In the latter case, success may be achieved for some species, but not others. We analyzed data for PWW and PTA separately and qualitatively compared results among the sites.

Growth

Growth of all plants at PTA and six species at PWW was measured as the proportional change in height compared to the initial height at outplanting ($(height_t - height_0)/height_0$). To account for significant lateral growth and branching of larger vines and shrubs, growth of three species at PWW (*H. haplostachya*, *P. sclerocarpa*, and *S. angustifolia*) was measured as plant volume calculated as a spheroid. There were no effects of habitat suitability on measures of growth at PWW, but there were at PTA (Table 9). At PTA, growth was higher (or less negative) in HS plots on the final two sampling dates, indicating a stronger effect of habitat suitability over time. Growth was significantly greater (or less negative) in HS plots for *H. haplostachya* and *S. angulstifolia* (Fig. 19), but not for other species. Thus, **habitat suitability increased growth for these two species at PTA, and the benefit of HS areas on growth became more pronounced over time.**

Table 9. GLM Results of Analysis of Growth.

Growth of all plants at PTA and six species at PWW was measured as the proportional change in height compared to the initial height at outplanting. To account for significant lateral growth and branching, growth of three species as PWW was measured as plant volume calculated as a spheroid.

	PWW				PTA	
	Volume – 3 species		Height – 6 species		Height – All 5 Species	
	F	df	F	df	F	df
Date	224.21***	4, 133307	641.87***	4, 642	74.46***	4, 5751
Species	215.36***	2, 1201	134.53***	5, 1285	185.43***	4, 2580
Suitability	0.14	1, 5	0.03	1, 4	0.86	1, 4
Date:Species	217.44***	8, 137391	79.42***	20, 4122	94.45***	16, 5720
Date:Suitability	0.26	4, 159138	0.90	4, 4119	6.47***	4, 5678
Species:Suitability	0.23	2, 770	0.96	5, 1266	3.39**	4, 2268

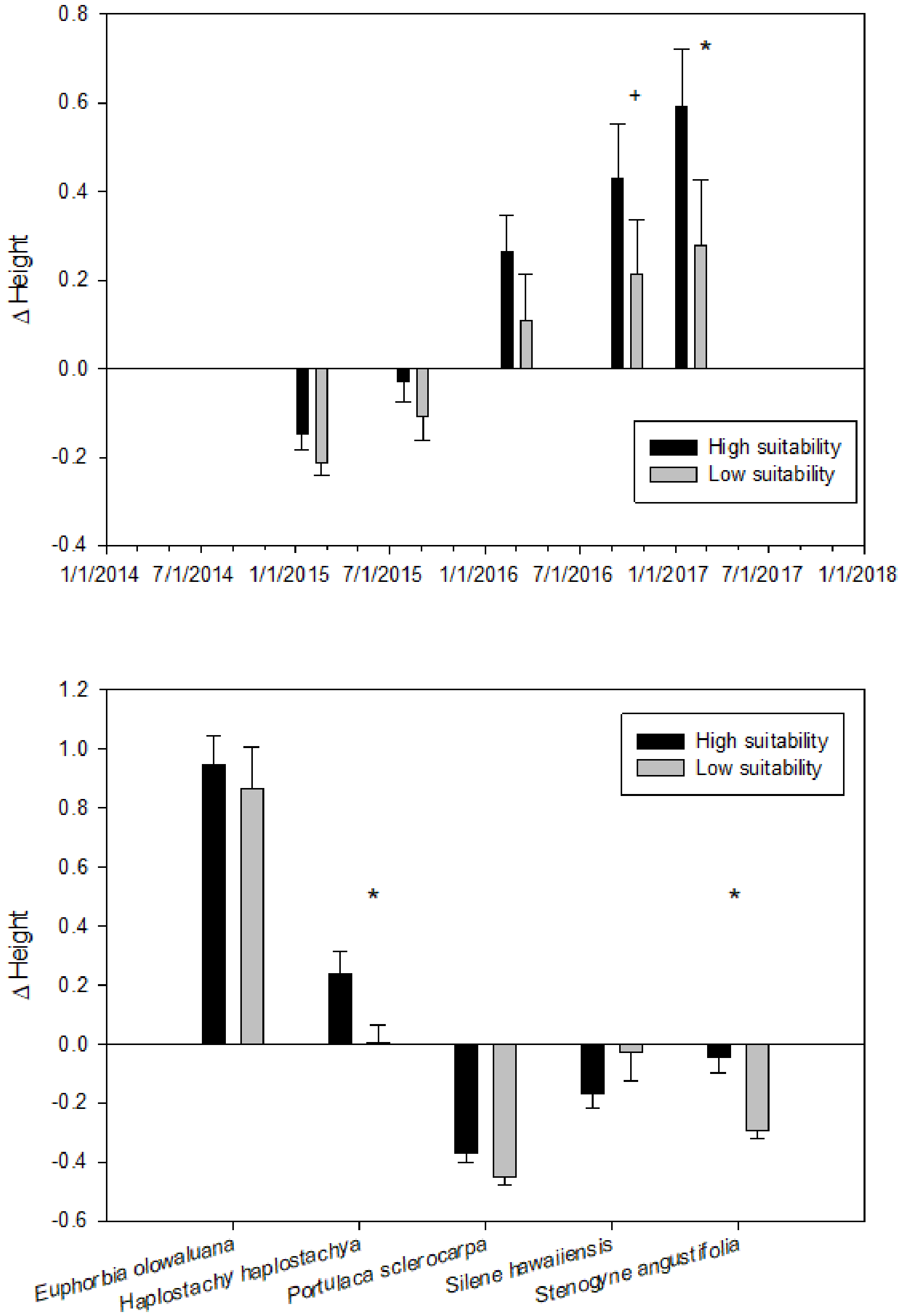


Figure 19. Growth at PTA.

*Growth is measured as the proportional change in height compared to the initial height at outplanting. Significant differences between HS and LS are noted with * (P < 0.05).*

Health rating

The health status of living plants was determined with a rating of one to five as follows: 1) no foliage but living stem; 2) foliage less than 25% and damaged by pest or disease; 3) 25-60% foliage, foliage showing signs of stress; 4) 60-90% foliage and health, showing no sign of decline; 5) greater than 90% foliage and extremely healthy with vigorous growth and no damage.

Health status at both sites varied over time and among species (Table 10). At PWW, health status of plants was higher in LS plots on two sampling dates (Table 10 significant Date:Suitability term; Fig. 20), but there was not difference on other dates. At PTA, health status was greater in HS for *E. olowaluana*, *H. haplostachya*, and *S. angustifolia* but not for *P. sclerocarpa* or *S. hawaiiensis* (Table 10 significant Species:Suitability term; Fig. 21). Health status was higher in HS plots on all sampling dates except October 2016 (Table 10 significant Date:Suitability term; Fig. 21). Therefore, **we found support for higher health status of three species at PTA in HS plots and no support for higher health status in HS plots at PWW.**

Table 10. GLM Results of Analysis of Health Rating.

Plants were given a categorical health rating of 1-5.

	PWW		PTA	
	F	df	F	df
Date	283.25***	4, 5887	260.75***	4, 4875
Species	54.32***	8, 1844	42.23***	4, 1400
Suitability	3.89	1, 8.6	1.60	1, 4
Date:Species	28.38***	32, 5876	16.09***	16, 4761
Date:Suitability	8.45***	4, 5832	8.14***	4, 4655
Species:Suitability	1.30	8, 1627	8.01***	4, 1186

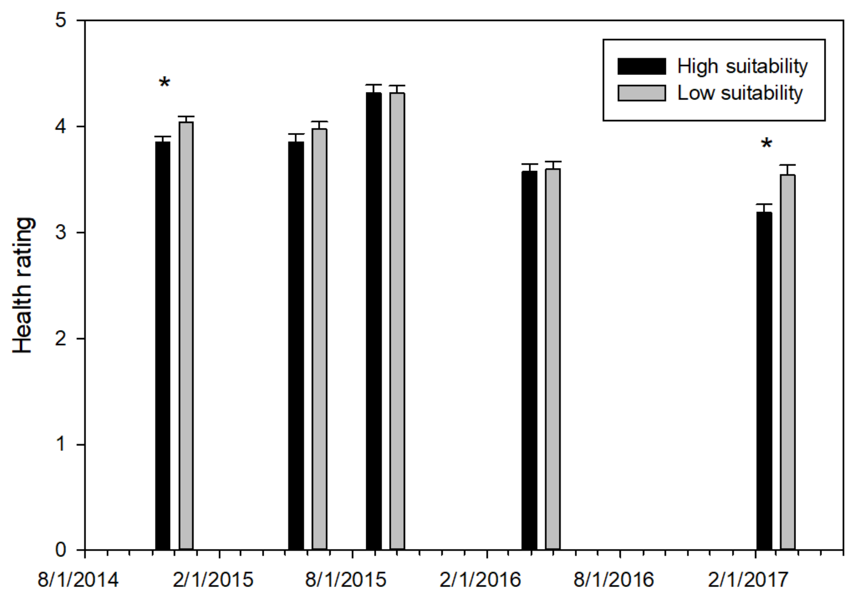


Figure 20. Health Rating of Plants at PWW.

*Significant differences between HS and LS are noted with * (P < 0.05).*

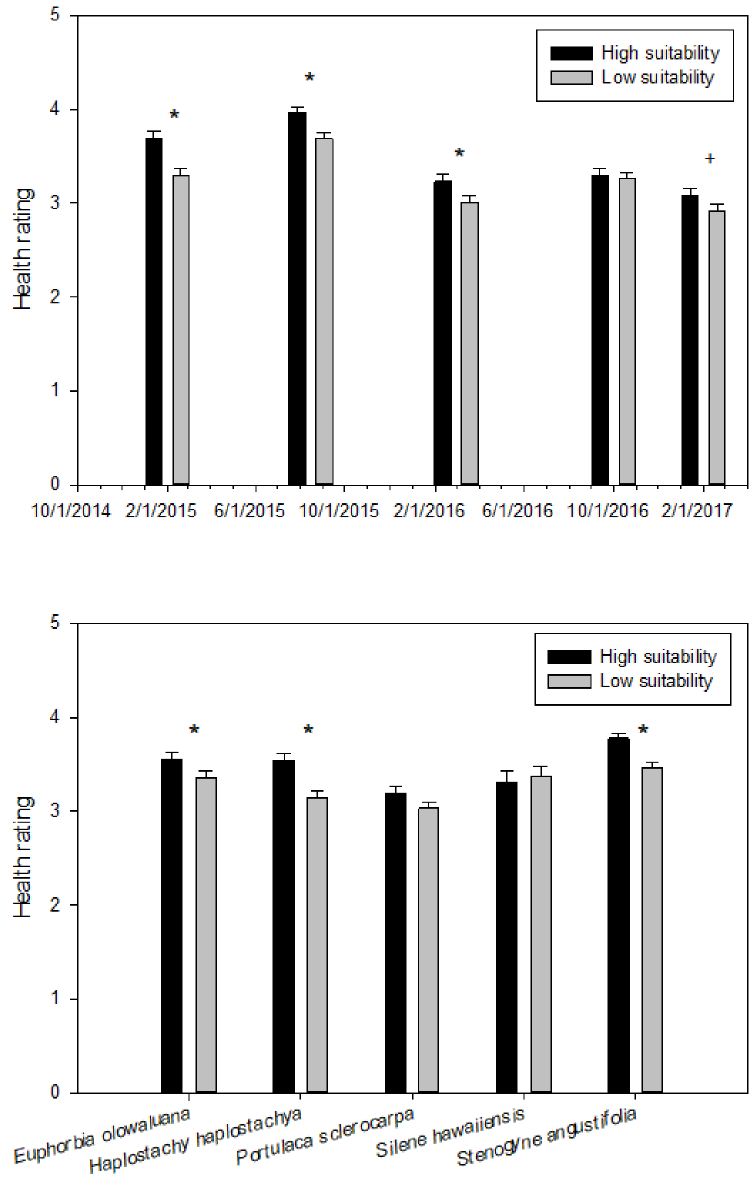


Figure 21. Health Rating of Plants at PTA.

*Significant differences between HS and LS are noted with * (P < 0.05) and + (P = 0.06).*

Physiology/stress

Overall, outplants exhibited less stress and greater physiological function in HS plots, compared to LS plots (Tables 11-13; Figs. 22-26). At PWW, all measures of leaf physiology indicated less stress in HS plots in March 2017 (Tables 11,12; Figs. 22 - 24; F_V/F_M, A, g_s, E, and Ψ). In March 2015, g_s was higher in HS, but no other measures were significantly affected by habitat suitability in March 2015 or during July or October measurements (Fig. 23). July and October represent drier times of year when plants are less physiologically active, whereas growing conditions were more favorable in March during a wetter period. Thus, the effect of habitat suitability class was more evident when plants were more physiologically active.

Leaf water potential (Ψ) measured in March 2017 was significantly more negative (drier) in mid-day compared to predawn, in LS compared to HS, and the response to habitat suitability varied among species (significant Suitability:Species interaction term; Table 12; Fig. 24). The predawn measures indicate the greatest water status the plant is able to achieve while its stomata are closed. These measures showed that plants in HS plots were less water stressed than in LS plots for *C. oppositifolia, H. haplostachya,* and *S. angustifolia*. *N. ovata* had the highest water status overall and did not show a difference between HS and LS. Leaves of plants at PWW had higher %P and more negative $\delta^{13}C$ in HS plots suggesting that plants in HS have access to greater resource availability (Table 13; Figs. 25 - 27). Overall eight of 17 measurements were consistent with significantly greater plant performance in HS plots at PWW. The Suitability:Species interaction term was significant for only one measurement (Ψ), further suggesting that for other measures all species had a similar response to conditions in the HS plots.

Plants at PTA exhibited more stress than plants at PWW and had overall lower physiological performance as would be expected in a drier, colder environment. At PTA, measures of F_V/F_M and A were significantly higher in HS plots during the March 2017 measurements, but other measures of leaf physiology did not vary with habitat suitability (Tables 11, 12; Figs. 22, 23). Leaves of plants at PTA had higher %N, and %P in HS plots suggesting that plants in HS have access to greater resource availability (Table 13; Figs. 25, 26). Overall 5 of 14 measurements were consistent with significantly greater plant performance in HS plots at PTA. The Suitability:Species interaction term was significant for only one measurement (F_V/F_M in July 2016), further suggesting that for other measures all species had a similar response to conditions in the HS plots.

Overall, there were large differences in physiological performance among species for most measures and a significant effect of habitat suitability for fewer measures of plant performance. However, all analyses showed either no effect of habitat suitability or a positive effect of HS on plant performance. There was never a case where LS plants performed better. These results illustrate that the effect of habitat suitability on performance and growth is dynamic over time. At times there is a difference among plot types, while at other times they are the same. However, leaf nutrient data show the effect of habitat suitability integrated over the lifespan of the leaf. These data showed that plants in HS had access to greater resource availability and were less stressed. **Taken together, the plant physiology results strongly support greater performance and lower plant stress in HS environments.**

Table 11. GLM Results of Analysis of Physiology Data.

F statistics and df are shown for analysis of variance with type III SS with Satterthwaite approximation for df.

	Suitability		Species		Suitability:Species	
	F	df	F	df	F	df
PWW						
F_V/F_M – July 2016	0.04	1, 172	3.22*	4, 173	0.28	4, 172
F_V/F_M – March 2017	5.63*	1, 126	7.96***	3, 126	0.35	3, 126
A - March 2015	0.55	1, 188	55.61***	4, 188	0.61	4, 188
g_s- March 2015	5.68*	1, 188	30.00***	4, 188	0.61	4, 188
E - March 2015	0.34	1, 186	38.22***	4, 186	0.40	4, 186
A - Oct 2015	0.15	1, 176	16.78***	4, 176	0.31	4, 176
g_s - Oct 2015	0.004	1, 176	17.70***	4, 176	0.23	4, 176
E - Oct 2015	0.26	1, 174	23.78***	4, 174	0.29	4, 174
A – March 2017	5.80*	1, 15	2.48	2, 15	0.29	1, 15
g_s – March 2017	6.98*	1, 15	1.41	2, 15	0.08	1, 15
E – March 2017	6.97*	1, 15	2.14	2, 15	0.01	1, 15
PTA						
F_V/F_M – July 2016	0.66	1, 6	6.043**	2, 106	2.99+	2, 106
F_V/F_M – March 2017	4.30*	1, 96	14.18***	2, 93	0.70	2, 93
A – Nov 2015	0.0001	1, 106	5.88**	2, 106	1.62	2, 106
g_s – Nov 2015	0.02	1, 107	8.59***	2, 107	2.33	2, 107
E - Nov 2015	0.0007	1, 104	9.45***	2, 104	2.13	2, 104
A – March 2017	16.05*	1, 48	24.90***	2, 46	0.70	2, 46
g_s – March 2017	1.73	1, 40	2.48	2, 39	1.57	2, 39
E - March 2017	0.97	1, 39	0.84	2, 38	0.93	2, 38

***P < 0.001; **P < 0.01; *P < 0.05; +P = 0.05

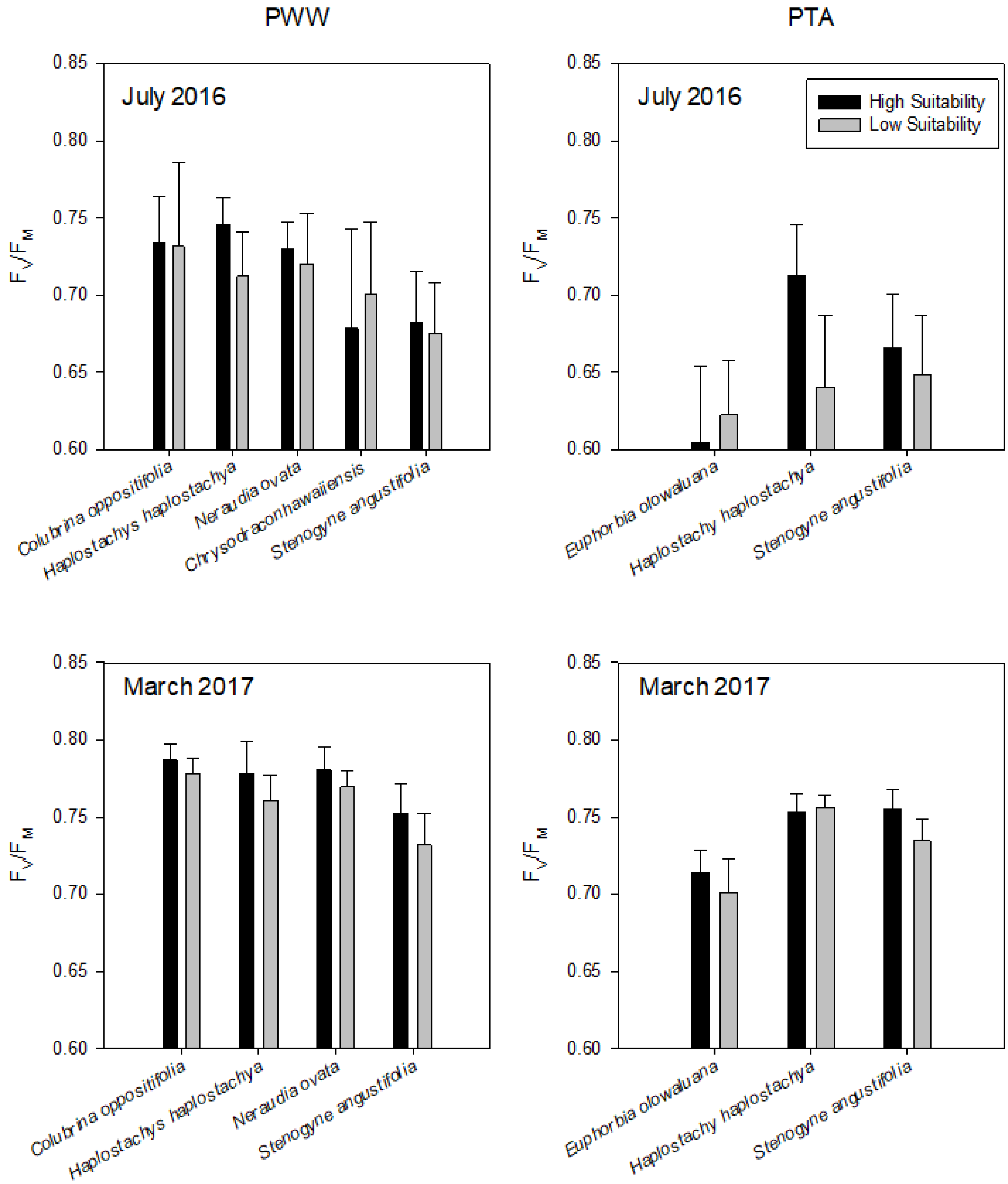


Figure 22. Mid-day Maximum Quantum Yield (FV/FM).

Measurements were taken in July 2016 and March 2017. Bars represent means and error bars show 2SE. FV/FM was greater in HS compared to LS plots at both sites and across all species measured in March 2017, but not in July 2016.

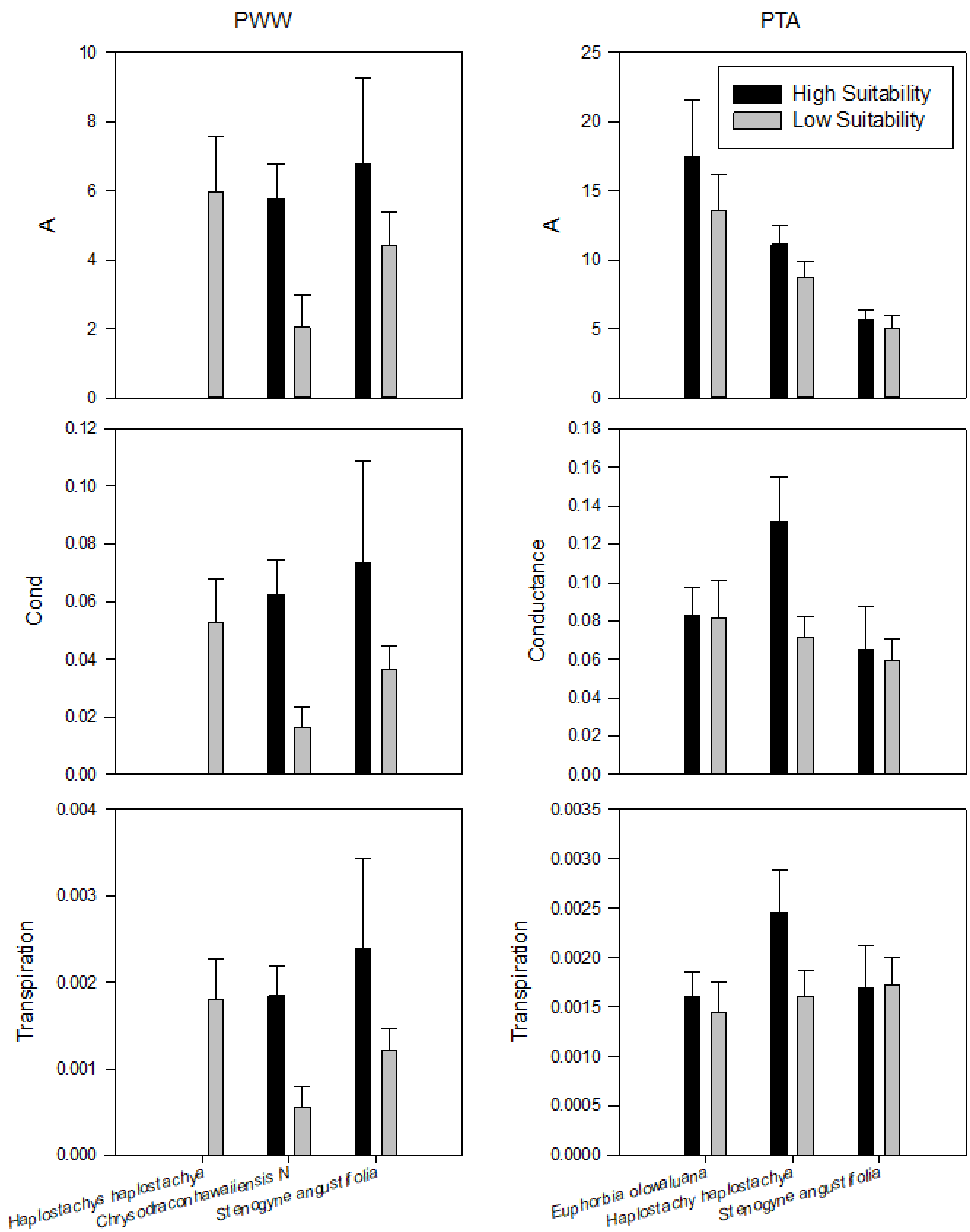


Figure 23. Mid-day Leaf Physiology Measurements (A, Cond, Transpiration).

Measurements were taken in March 2017 at the end of the study. Bars represent means and error bars show 2SE. A was greater in HS compared to LS plots at both sites and across all species measured in March 2017. At PTA, g_s was greater in HS compared to LS plots across all species in March 2015 and 2017; E was greater in HS plots in March 2017 only.

Table 12. GLM Results of Analysis of Leaf Water Potential Data.

A Time factor and the Time: Suitability interaction term were added to the model for data from PWW to account for measurements that were taken pre-dawn or mid-day. F statistics and df are shown for analysis of variance with type III SS with Satterthwaite approximation for df.

Site	Time		Suitability		Species		Suitability: Species		Suitability: Time	
	F	df	F	df	F	df	F	df	F	df
PWW	31.43***	1, 211	6.86**	1, 210	24.71***	3, 210	4.90**	1, 209	3.39	1, 209
PTA			0.18	1, 103	2.22	2, 103	0.30	2, 103		

***P < 0.001; **P < 0.01; *P < 0.05

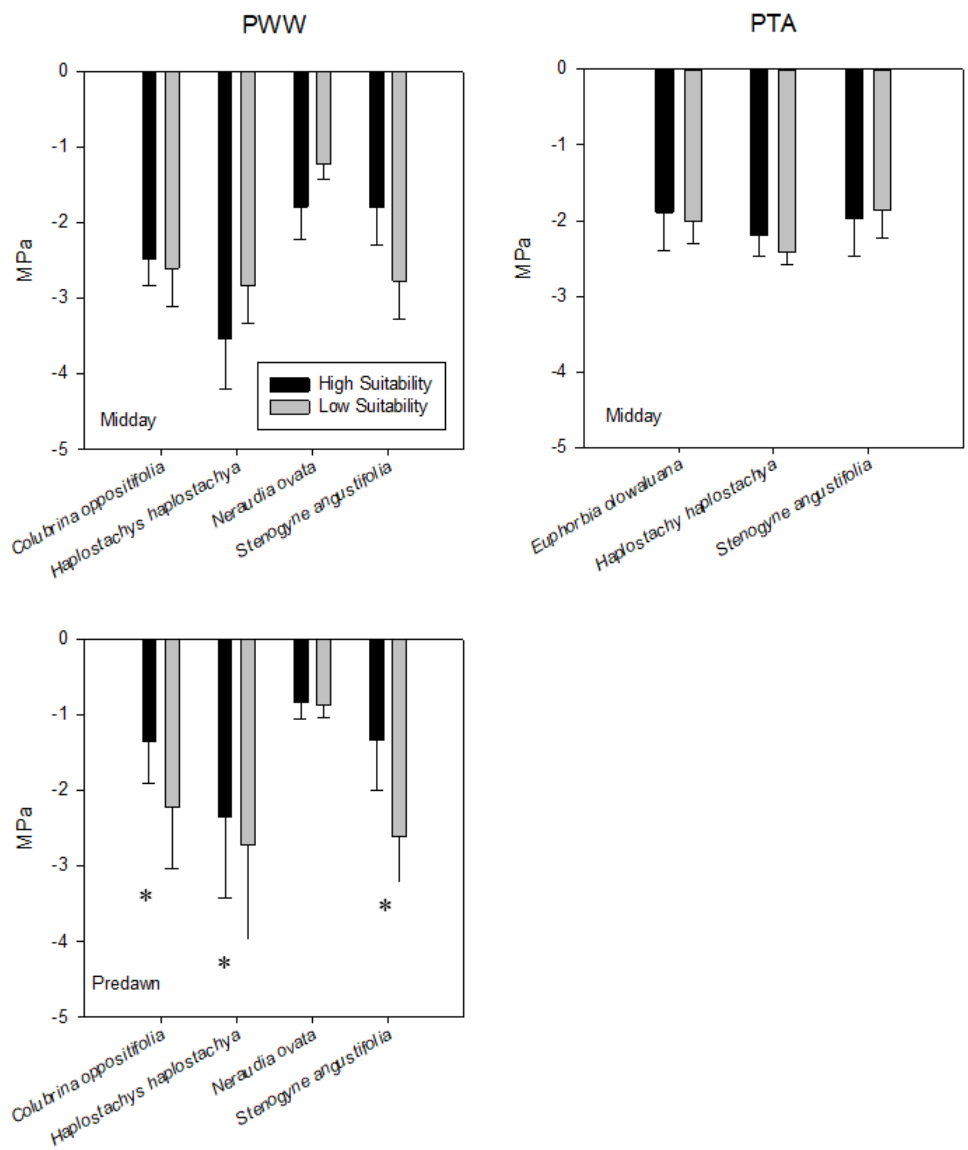


Figure 24. Leaf Water Potential (MPa).

*Measurements were taken in March 2017 at the end of the study. Bars represent means and error bars show 2SE. Predawn measurements were made at PWW; midday measurements were made at both sites. Significant differences between HS and LS are noted with * (P < 0.05).*

Table 13. GLM Results of Analysis of LMA and Leaf Nutrient Data.

A Date factor, the Date: Suitability, and the Species: Date interaction terms were added to the models to account for samples collected on two dates, one during a dry period and one during a wet period. F statistics and df are shown for analysis of variance with type III SS with Satterthwaite approximation for df.

	Date		Suitability		Species		Suitability: Species		Suitability: Date		Species: Date	
	F	df	F	df	F	df	F	df	F	df	F	df
PWW												
LMA	36.10***	1, 377	0.19	1, 377	212.52***	4, 376	0.96	4, 377	0.58	1, 377	11.44***	4, 376
%N	27.72***	1, 79	2.55	1, 79	37.43***	4, 79	0.49	4, 79	1.30	1, 79	0.92	4, 79
%P	25.26***	1, 79	15.56***	1, 79	30.69***	4, 79	1.56		0.0001	1, 79	9.45***	4, 79
%C	1.37	1, 83	0.0001	1, 83	67.18***	4, 83	1.13	4, 83	1.33	1, 83	1.11	4, 83
$\delta^{13}C$	53.09***	1, 79	8.18**	1, 79	85.65***	4, 79	0.73	4, 79	1.61	1, 79	0.31	4, 79
PTA												
LMA	53.97***	1, 219	1.29	1, 220	8.60***	2, 220	1.71	2, 220	0.83	1, 219	1.94	2, 219
%N	15.74***	1, 46	7.49**	1, 46	3.62*	2, 46	2.75	2, 46	0.10	1, 46	0.11	2, 46
%P	34.60***	1, 46	4.59*	1, 46	15.23***	2, 46	0.80	2, 46	1.86	1, 46	0.05	2, 46
%C	1.12	1, 46	1.31	1, 46	54.49***	2, 46	0.48	2, 46	0.36	1, 46	0.73	2, 46
$\delta^{13}C$	0.2	1, 50	0.3	1, 50	3390.6***	2, 50	0.3	2, 50	0.001	1, 50	0.5	2, 50

***P < 0.001; **P < 0.01; *P < 0.05

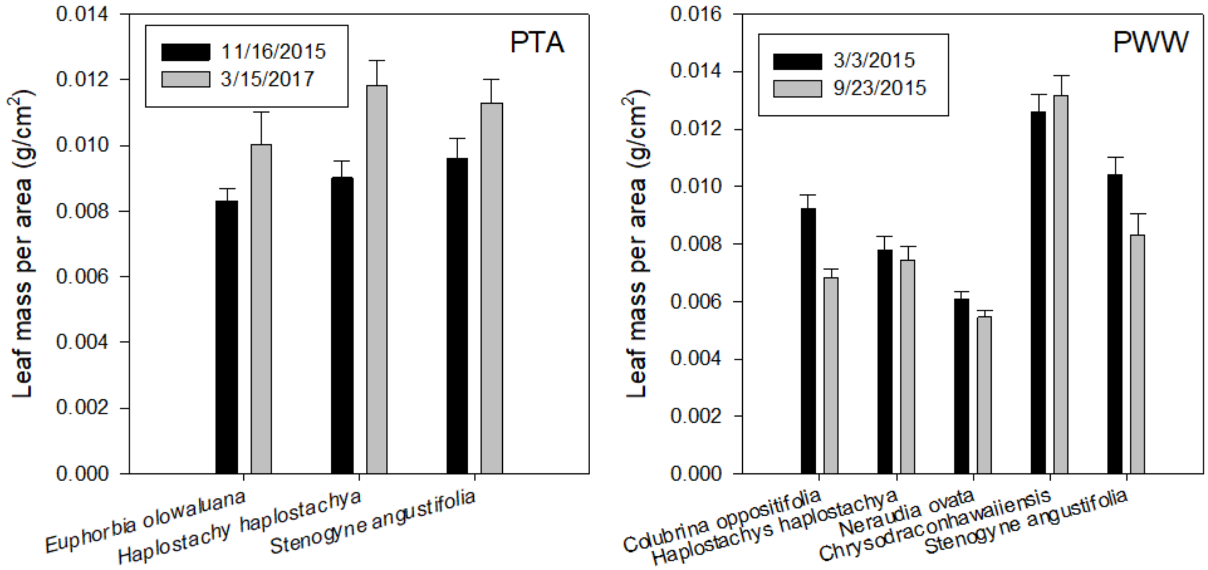


Figure 25. Leaf Mass Per Area (LMA).

Measurements were taken at two times at each site, one time following a dry period and one time following a wet period. Bars represent means and error bars show 2SE. There was no effect of habitat suitability on LMA.

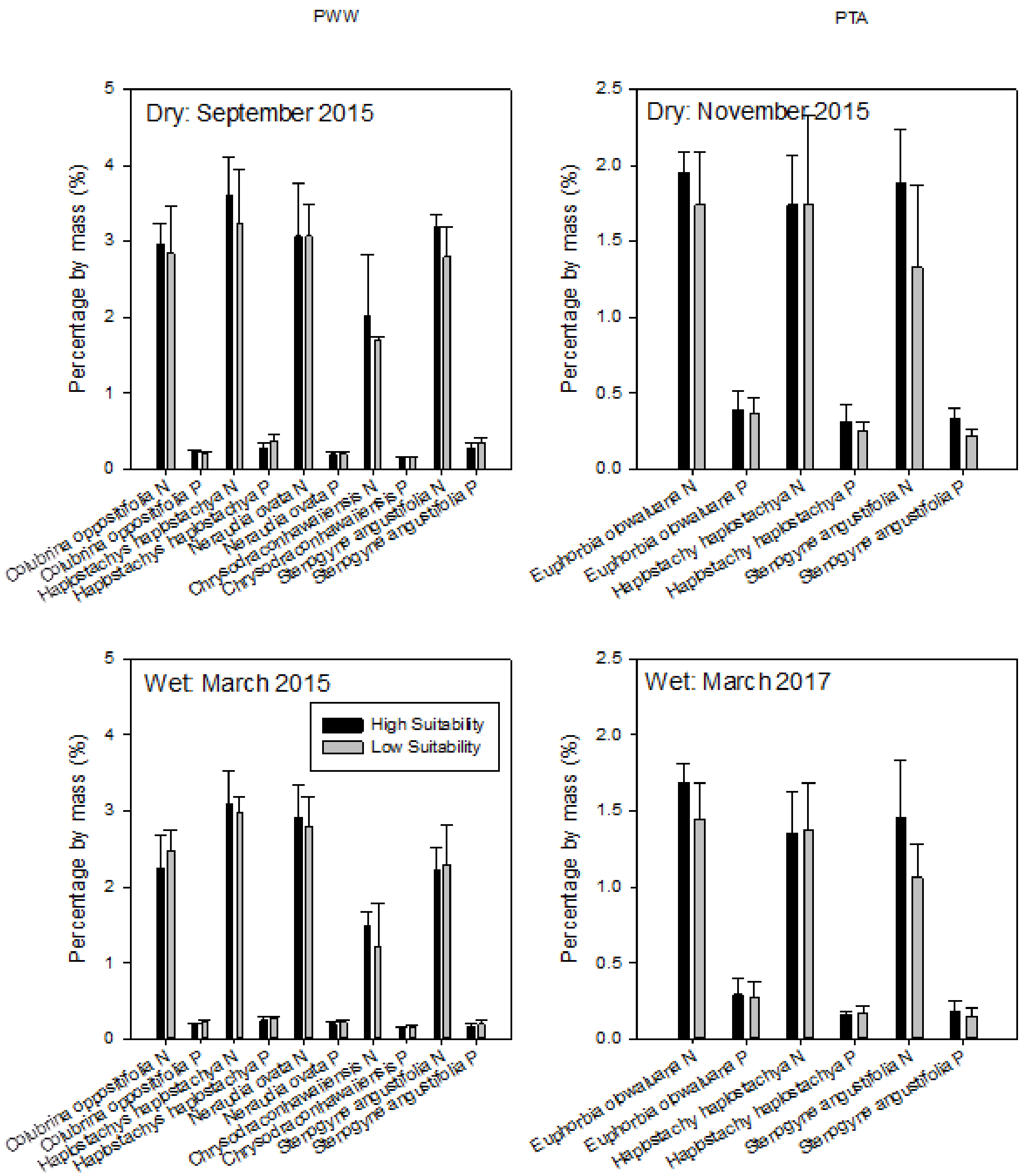


Figure 26. Leaf %N and %P. Measurements Were Taken at Two Times at Each Site, One Time Following a Dry Period and One Time Following a Wet Period.

Bars represent means and error bars show 2SE. There was no effect of habitat suitability on %N at PWW. HS plants had greater %P across all species at both sites when compared to LS plants. At PTA, HS plants had greater %N.

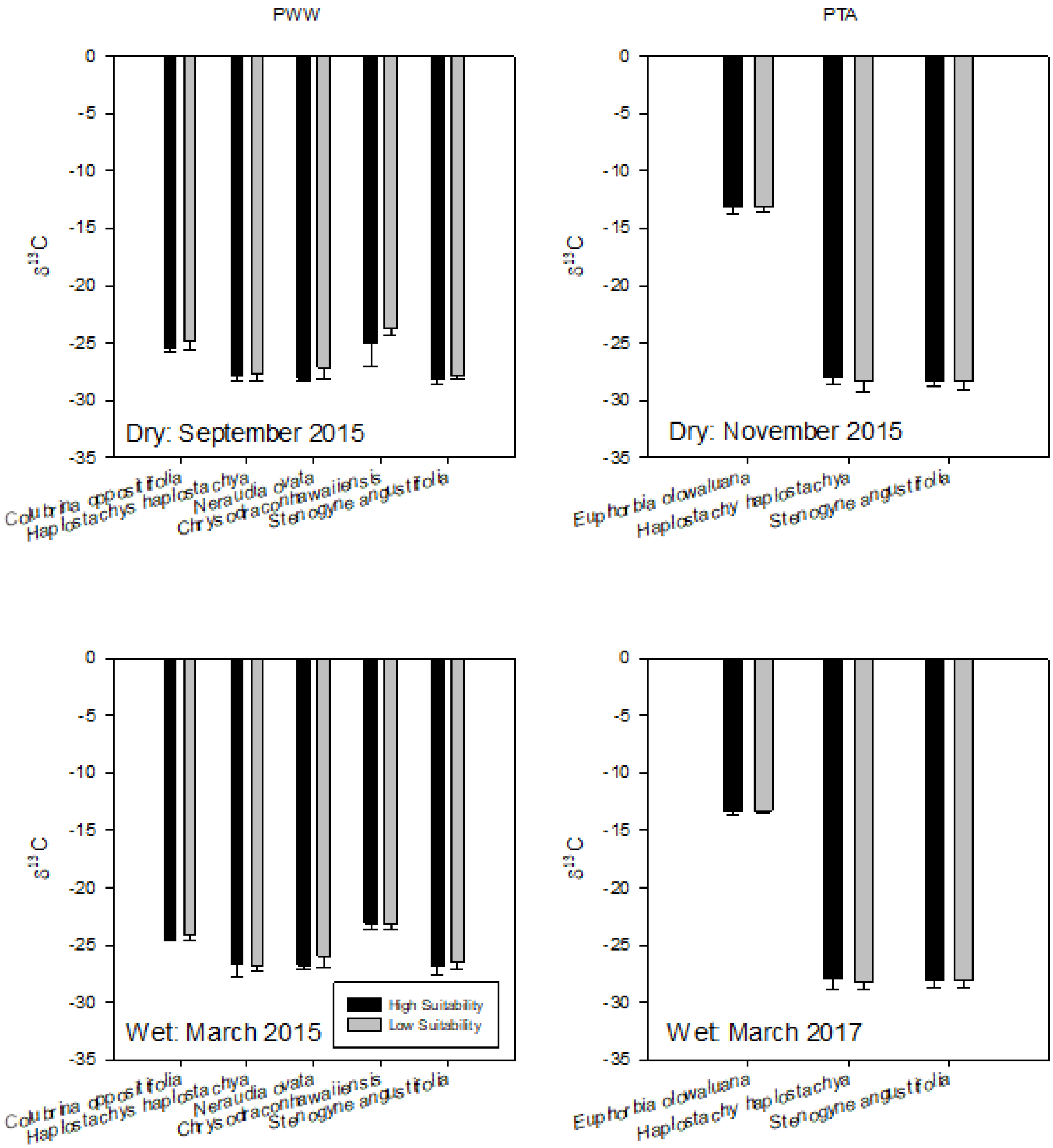


Figure 27. **Leaf δ13C. Measurements Were Taken at Two Times at Each Site, One Time Following a Dry Period and One Time Following a Wet Period.**

Bars represent means and error bars show 2SE. At PWW, HS plants had more negative $\delta^{13}C$.

Reproduction

Surveys of reproductive output (seed number per individual) were made; however, most species reproduce throughout the year so these data provide only a snapshot of seed production. At PWW the number of seeds of *P. sclerocarpa* was greater in LS, compared to HS, plots. No other species showed a difference in seed production among suitability classes (Table 14).

Table 14. GLM Results of Analysis of Seed Production for Species at PWW and PTA.

A Date factor and the Date: Suitability interaction term were added to the models for PWW to account for surveys conducted in 2015 and 2016. C. oppositifolia was setting seed during the 2016 survey only. H. haplostachya seeds were counted on 15 December 2015. F statistics and df are shown for analysis of variance with type III SS with Satterthwaite approximation for df.

Species	Date		Suitability		Date: Suitability	
	F	df	F	df	F	df
PWW						
Colubrina oppositifolia	N/A	N/A	1.84	1, 38	N/A	N/A
Haplostachys haplostachya	56.35***	1, 72	0.22	1, 72	0.07	1, 72
Portulaca sclerocarpa	22.91***	1, 77	6.48*	1, 77	2.11	1, 77
Silene lanceolata	0.44	1, 742	3.82	1, 742	0.68	1, 742
Stenogyne angustifolia	24.59***	1, 66	1.54	1, 66	0.04	1, 66
PTA						
Haplostachys haplostachya	N/A	N/A	0.63	1, 34	N/A	N/A

***P < 0.001; **P < 0.01; *P < 0.05

Recruitment

Recruitment of most species was low or did not occur during the time of study, but is expected to increase over time as the surviving outplants become reproductive. At PTA, there was one recruit of *E. olowaluana* found in a HS plot January 12, 2016. No recruits were found from surveys on June 30, 2016 or March 2017. At PWW, recruits of *H. haplostachya*, *P. sclerocarpa*, and *S. lanceolata* were found (Table 15). There were enough recruits of *S. lanceolata* to statistically analyze; however, there were not significant effects of the factors Year, Suitability, or Year: Suitability on recruitment ($P > 0.40$). These recruitment data should be viewed as preliminary as recruitment dynamics are likely to change as the outplants mature.

Table 15. Total Number of Recruits Summed Across HS and LS Plots at PWW.

	High Suitability	Low Suitability
H. haplostachya		
2016	0	7
2017	5	11
P. sclerocarpa		
2016	0	3
2017	0	1
S. lanceolata		
2015	100	36
2016	0	87
2017	53	161

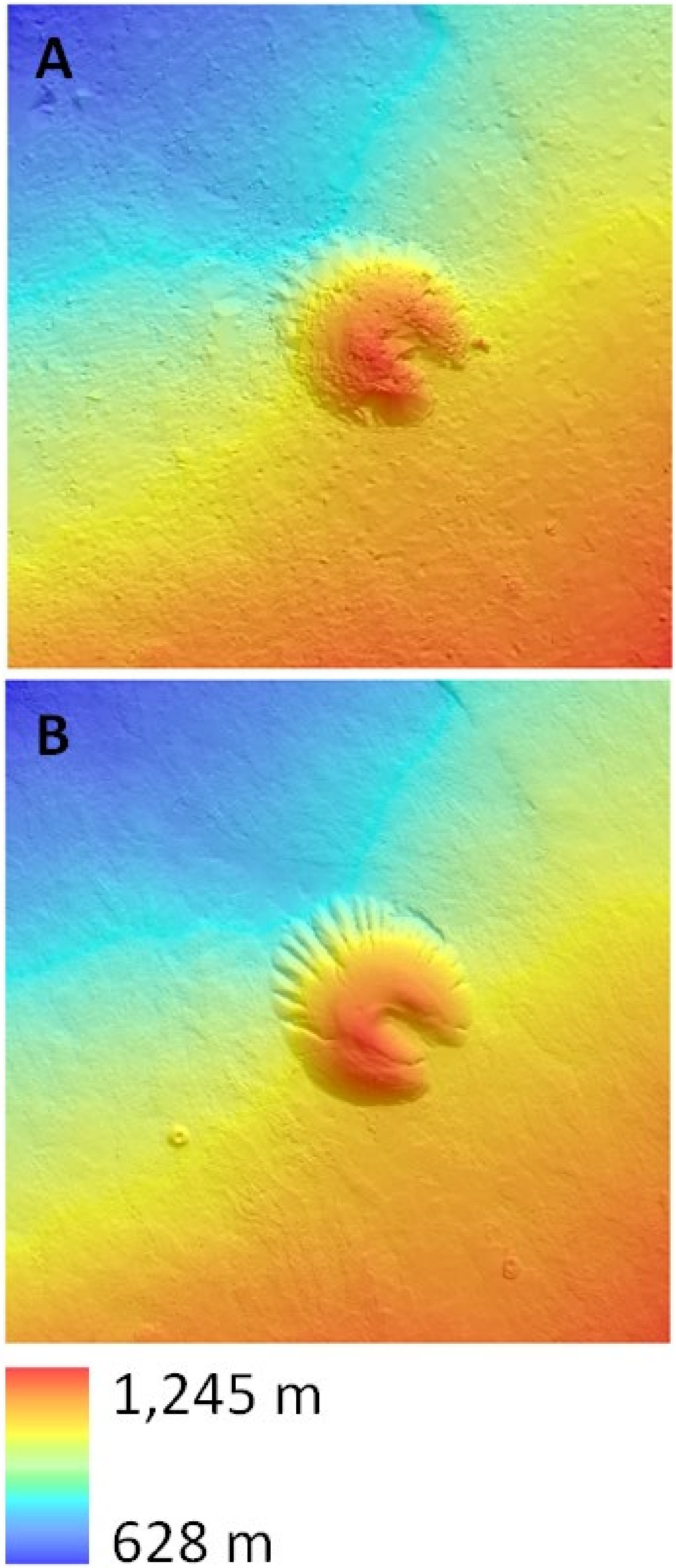
5.6.3 PO3. Spatial correspondence of suitability classes

We developed our original DEM and HSM with high-precision, high-accuracy airborne LiDAR data. DEMs derived from satellite data should have reasonable correspondence with our original models. We used correlation analysis to examine the strength of the relationship between the elevation values. Success was defined as a statistically significant relationship between the satellite elevation values and LiDAR elevation values ($P < 0.05$).

We produced digital elevation models (DEMs) from WorldView-2 satellite data for Hawaii Island and Vandenberg Air Force Base. We have also compared these DEMs with the LiDAR DEM for each region. Fig. 28A shows a sample DEM for a 25 km^2 area near Kailua-Kona, HI, which contains PWW. The stereo DEM has a spatial resolution of 0.5 m. Fig. 28B shows a DEM for the same area acquired using airborne LiDAR by the Carnegie Airborne Observatory (CAO). The LiDAR DEM has a spatial resolution of 1.5 m. We generated a random sample of 10,000 pixels within the DEMs shown in Fig. 28 and then quantified the relationship between corresponding elevation values using linear regression (Fig. 29). The relationship is: WorldView DEM (m) = -7.19 + 1.01 × LiDAR DEM (m), $r^2 = 0.998$, $P < 0.001$, RMSE = 6.42 m. Analysis at VAFB indicated strong agreement between the LiDAR and stereo-derived DEMs (Fig. 30). The relationship is: WorldView DEM (m) = 5.76 + 0.96 × LiDAR DEM (m), $r^2 = 0.934$, $P < 0.001$, RMSE = 15.3 m (Fig. 30). The slope relating the two data sources is very close to 1.00 for both datasets (the 1:1 line is indicated in red in Fig. 29), which indicates excellent average agreement between the stereographic and LiDAR DEMs.

However, there are two important caveats to this interpretation. First, the intercept indicates a 7.19 m offset between the data sources in Hawaii and a 5.76 m offset for VBG. We consider this to be a trivial problem, because the offset can be easily corrected (e.g., by adding 7.19 m to every pixel within the stereographic DEM). Second, and more importantly, the RMSE is 6.42 m for the Hawaii data and 15.3 m for the VBG data. This indicates that although the two data sources are in tight correspondence *on average*, there are localized departures that introduce uncertainty into the WorldView DEM. This uncertainty is apparent when visually by comparing panels A and B of Fig. 28, in which some features are better resolved in the LiDAR DEM.

Figure 28. DEMs for Lowland Hawaii, Including PWW from A) WorldView-2 Data and B) LiDAR Data.



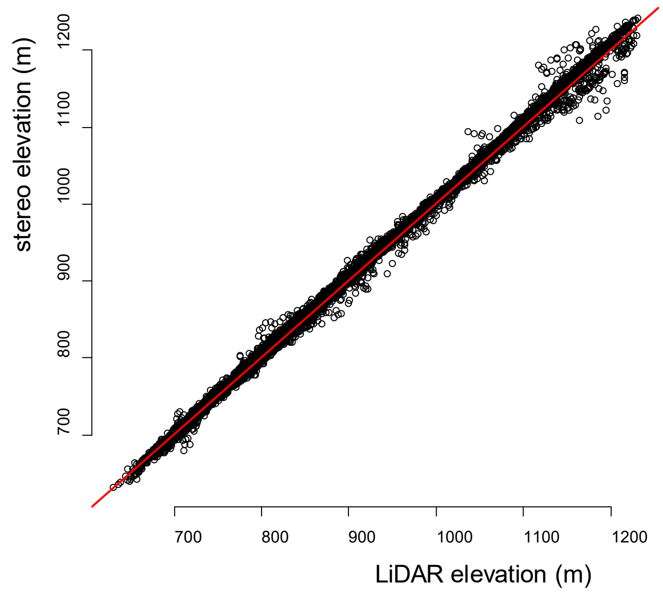


Figure 29. Relationship Between LiDAR DEM and a Stereo DEM Generated from WorldView-2 Data Across Sites in Hawaii.

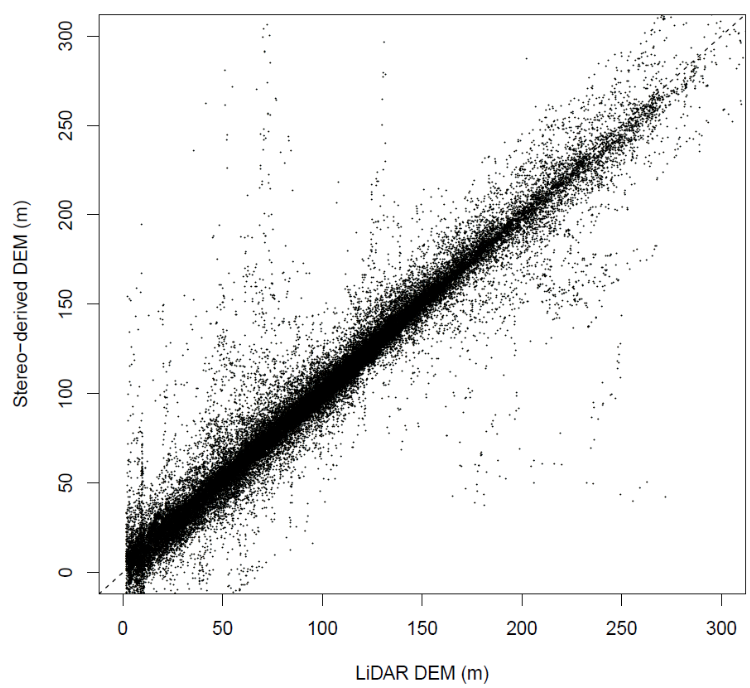


Figure 30. Relationship Between LiDAR DEM and a Stereo DEM Generated from WorldView-2 Data from VBG.

5.6.4 PO4. Field measurements of weather and microclimate variables indicate greater suitability for plant growth in HS, compared to LS, plots

We measured weather and microclimate variables in the field that correspond with conditions important for plant growth in order to validate our initial HSM from LiDAR at PTA. We continued these measurements at PTA. In addition, we performed this field validation for the PWW, VBG, and SMMNRA HSMs. Like PTA, we expected measures of evaporative demands on plants (wind speed, leaf wetness, and soil moisture) and measures of plant biomass to be important verification measures of habitat suitability for restoration. All data measured were compared between high and low suitability classes either graphically for large abiotic datasets or with an appropriate GLM. Significance was determined as $P < 0.05$.

Wind speed was measured in one HS and one LS pair of plots at each site, and was lower in LS plots (Fig. 31). Wind speeds were particularly high at PTA and VBG, and there was therefore a greater difference between HS and LS speeds. However, the trend at all sites was higher wind speed in LS, compared to HS, plots. We include detailed wind speed and direction diagrams in Appendix B. Soil moisture and leaf wetness were measured in all five pairs of plots at each site; however, a subset of plots were selected for calculating averages across HS and LS sensors (see Appendix B for complete data description). Leaf wetness was higher in HS plots at PTA, VBG, and SMNNRA, but was similar in HS and LS at PWW (Fig. 32). The difference between HS and LS plots was greatest at PTA and VBG, which is likely due to the much higher wind speeds at these sites that increase evaporation in LS areas.

Soil moisture was very variable among plots and across sites (Fig. 33; Appendix B). At sites in Hawaii, soil moisture did not differ greatly between HS and LS plots. At sites in California, average soil moisture was higher in HS than LS plots during a very dry period from May – November 2016; suggesting that HS plots may have been somewhat less stressful during this time period. However, the range of values was greater across HS plots at SMMNRA; whereas, the range was greater across LS plots at VBG (dotted lines). This difference may occur due to the differing soil substrates at each site or differences in solar exposure that may affect soil moisture. Plant size was measured as height at VBG and SMMNRA. Plants were taller in HS plots at VBG on both sampling dates, but height did not differ among suitability classes at SMMNRA (Table 16; Fig. 34).

Overall, **we found reduced wind speeds in HS areas at all sites, increased leaf wetness in HS areas at all sites except PWW, and increased soil moisture during dry periods at sites in California but not Hawaii.** Together, these data support the use of the HSM to reduce stress and increase resource availability to plants.

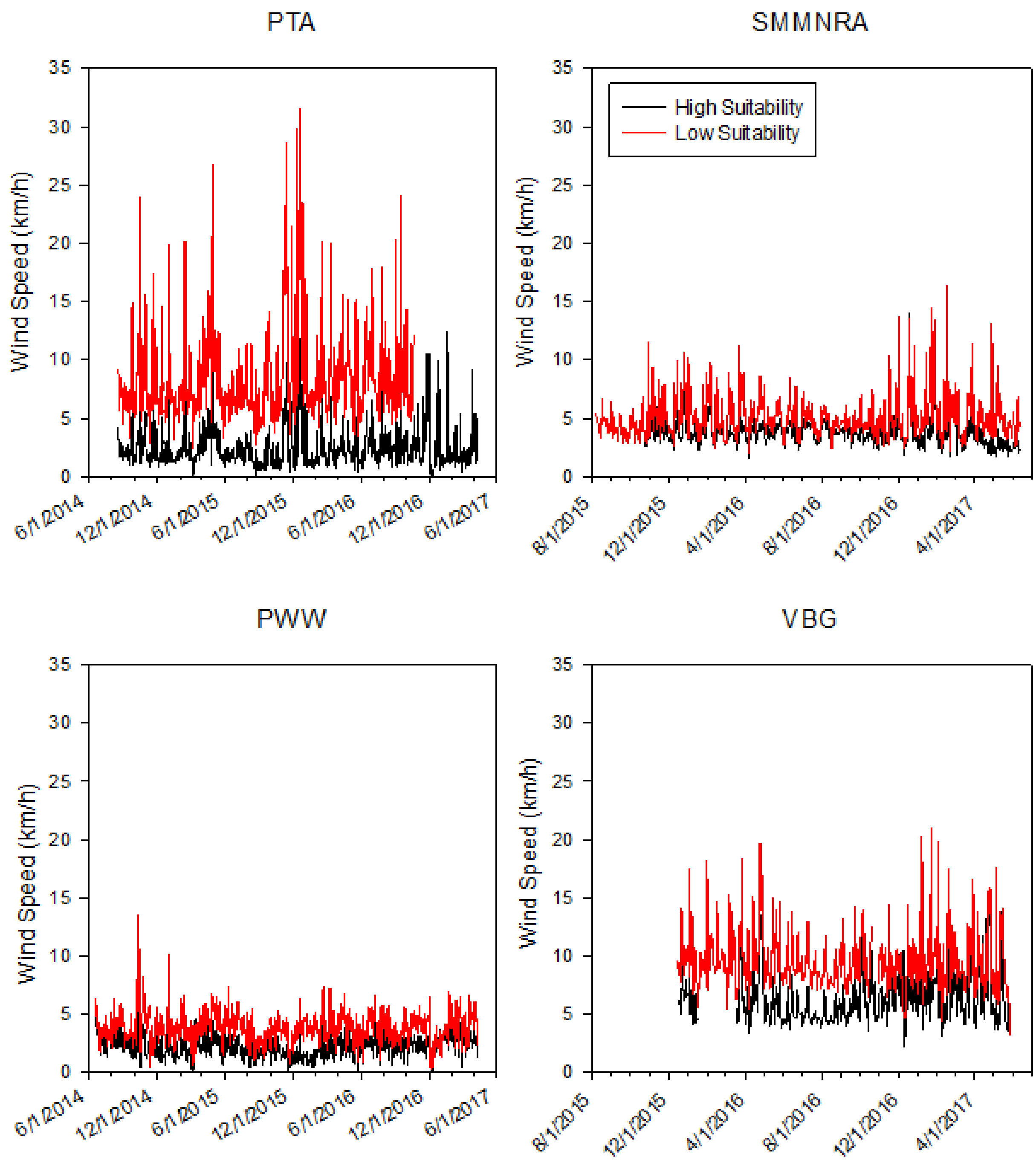


Figure 31. Average Daily Wind Speed at Each Site.

Solid lines show daily averages from one anemometer.

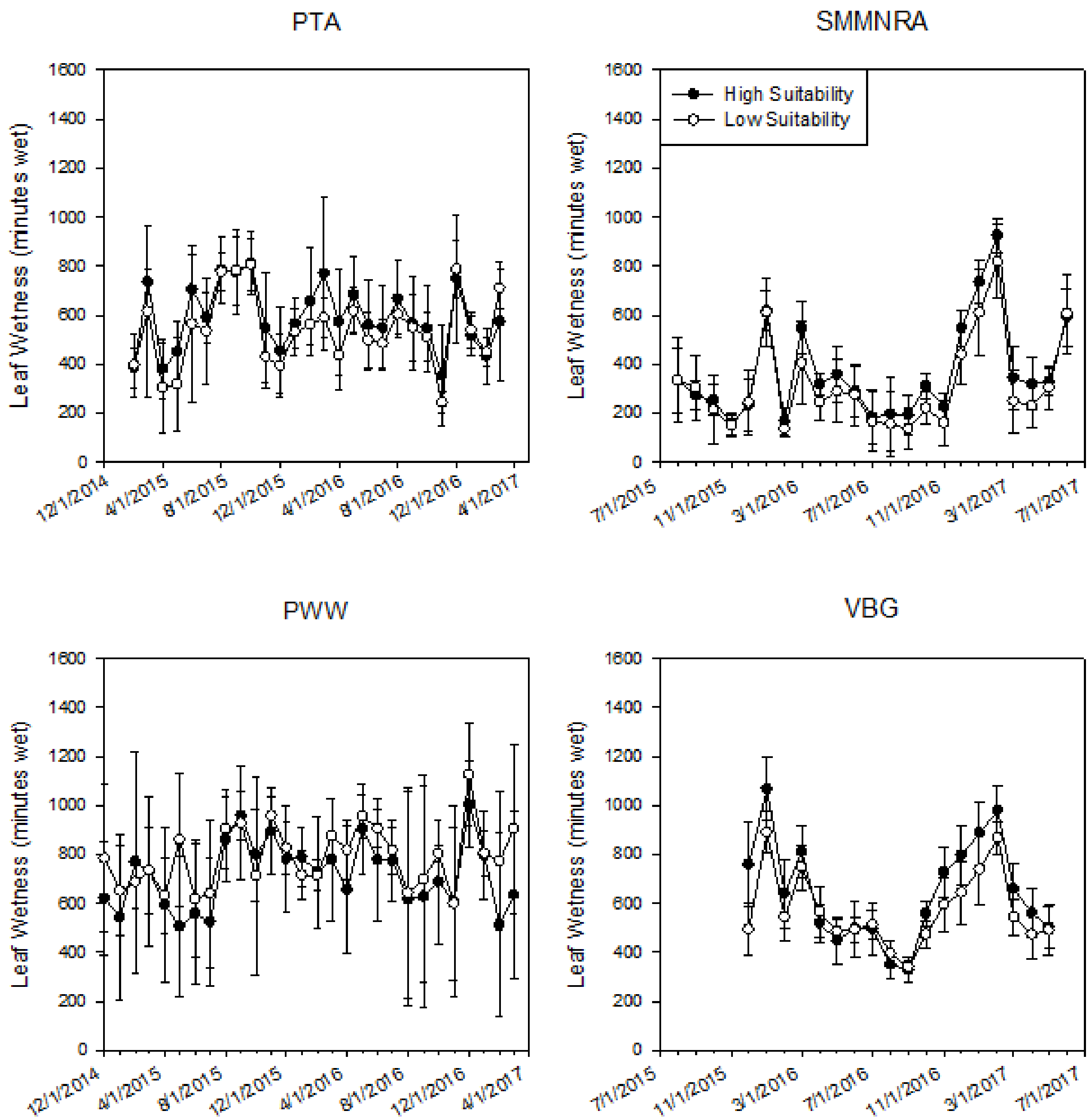


Figure 32. Average Daily Leaf Wetness at Each Site.

Data were summed for each day and then averaged for each month. Symbols show averages across plots. Bars show the standard deviation across plots. See Appendix B for detailed data within each site.

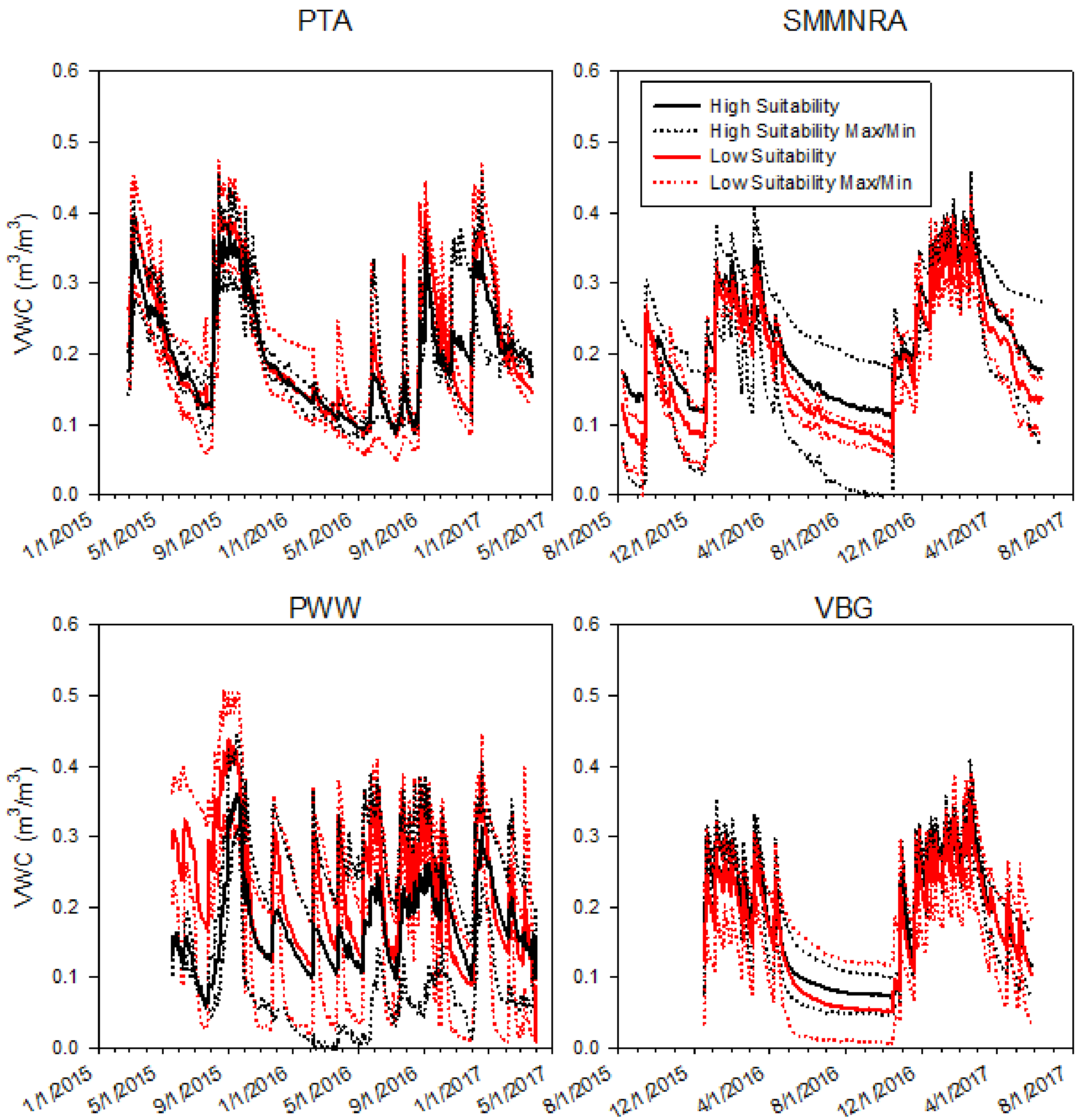


Figure 33. Average Daily Soil Moisture at Each Site.

Solid lines show data averaged across plots. Dotted lines show the minimum and maximum value across plots for each day. See Appendix B for detailed data within each site.

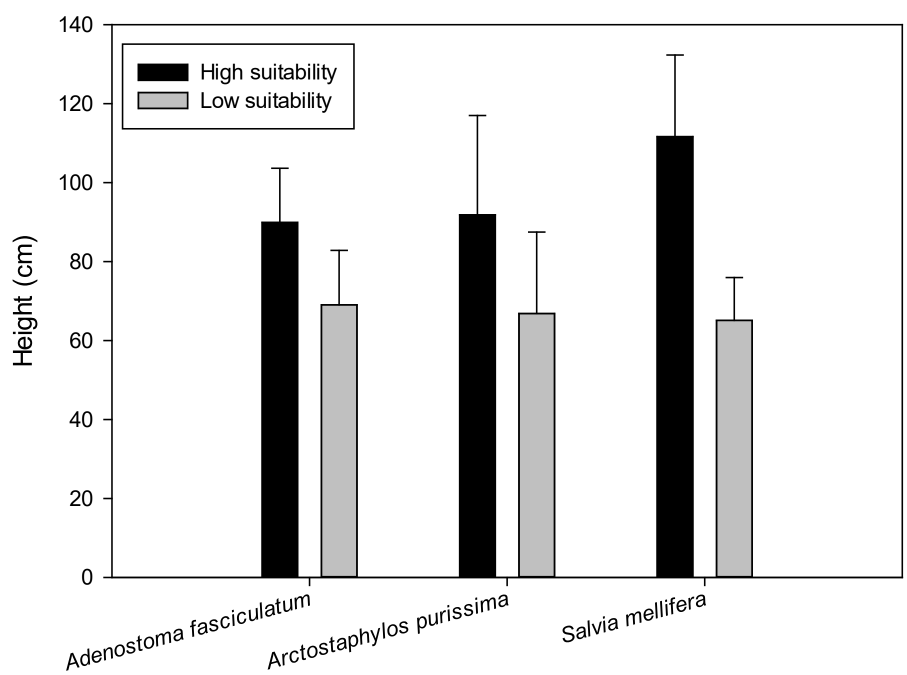
Table 16. GLM Results of Analysis of Plant Size at VBG and SMMNRA.

	Species		Suitability		Species: Suitability	
	F	**df**	**F**	**df**	**F**	**df**
VBG						
2014	0.42	2, 72	169.80***	1, 73	2.42	2, 73
2017	5.35**	2, 96	37.98***	1, 96	1.69	2, 96
SMMNRA						
2017	23.84***	3, 32	1.67	1, 32	0.48	3, 32

***P < 0.001; **P < 0.01; *P < 0.05

Figure 34. Plant Height at VBG.

Data are from the 2017 survey. Height was significant greater in high suitability plots for all species. Bars show means and error bars show 2SE.



5.6.5 PO5. Correspondence of existing TER-S with HS areas.

We used randomization tests to evaluate how the location of existing TER-S plants correspond with our HSM for two TER-S at VBG and 11 TER-S at PWW. The randomization tests evaluated whether the observed locations of individuals from each population were different from a null distribution of 1,000 simulated populations. At each iteration of the simulation, we extracted the topographic suitability index value from the location of each simulated individual (LS = 0, Moderate Suitability = 1, HS = 2). We compared the mean suitability class value across all known plant locations with the distribution of mean values from the simulated populations. If the mean of known plants falls outside the 95% confidence interval, there is an association of the species with either higher or lower suitability sites. This analysis allowed us to determine if a species was associated with higher or lower class values. Two species, *Chrysodracon hawaiiensis* and *Aplenium peruvianum var. insulare*, showed an association with HS areas at PWW (Table 16). One species, *Solanum incompletum*, showed an association with LS areas (Table 17). Neither species at VBG and eight species at PWW did not show an association with either habitat type. Taken together, these data do not show a strong association across species with either HS or LS areas. However, these landscapes are disturbed by prior fires, ranching, and recreational uses. Therefore, some species may have been locally extirpated from their most suitable habitats. Performance was met for *C. hawaiiensis* and *A. peruvianum* at PWW, suggesting that the HSM could be useful for managing these species.

Table 17. Habitat Suitability Analysis for Existing At-risk Species at VBG and PWW.

Results include the mean suitability class value across all known plant points and the 95% confidence interval (CI) of the mean suitability class values of 10,000 simulated populations.

Species[b]	Site	Number of individuals	Mean Suitability Value of Known Plants	95% CI of Mean Suitability Values from Simulated Populations	Direction of Habitat Association[a]
Eriodictyon capitatum	VBG	21	0.580	0.333 – 0.857	No Association
Diplacus vandenbergensis	VBG	42	0.635	0.427 – 0.786	No Association
Asplenium peruvianum var. insulare	PWW	64	1.906	0.875 – 1.234	Higher*
Mezoneuron kavaiense	PWW	48	1.208	0.874 – 1.271	No Association
Chrysodracon hawaiiensis	PWW	277	1.273	0.975 – 1.135	Higher*
Nothocestrum breviflorum	PWW	156	1.160	0.942 – 1.173	No Association
Colubrina oppositifolia	PWW	739	1.0555	1.004 – 1.107	No Association
Hibiscus brackenridgei ssp.brackenridgei	PWW	65	0.938	0.877 – 1.231	No Association
Silene lanceolata	PWW	88	1.037	0.870 – 1.124	No Association
Solanum incompletum	PWW	13	0.538	0.692 – 1.385	Lower*
Stenogyne angustifolia	PWW	92	0.977	0.908 – 1.195	No Association
Zanthoxylum dipetalum var. tomentosum	PWW	13	1.077	0.692 – 1.385	No Association
Zanthoxylum hawaiiense	PWW	219	0.990	0.965 – 1.156	No Association

[a] Asterisks indicate a statistically significant association of the species with either higher or lower classes ($P < 0.05$). Two species showed an association with higher valued classes, and one species showed an association with lower valued classes. Ten species did not show an association.

[b]All species are listed by the US Fish and Wildlife Service as Endangered.

5.6.6 PO6. Ease of use

We evaluated the ability of trained professionals to use the HSM GIS Toolbox at a workshop at IPIF on March 24, 2017. We distributed test versions of the software to 18 conservation professionals and recorded their written feedback and scores on a survey based on a Likert scale (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree). Success was defined as survey results that indicate more than 75% of respondents “Agree” or “Strongly Agree” with question 7 (The software is easy to use) and question 17 (I would recommend the software to a colleague). Question 17 is one of the most effective measures of user satisfaction with a product (Reichheld 2006). **The actual response rates were 83% (15/18) for question 7 and 94% (16/17) for question 17 indicating a high level of success for this performance objective (Table 18).**

Table 18. Answers to Survey Questions from Conservation Professionals.

Survey Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree	Total
1. The toolbox can help me make better decisions about at-risk species management.				13	5	18
2. The toolbox can help me identify field sites for plant reintroduction and/or restoration.				13	5	18
3. The toolbox can help me be more effective in my job.			7	8	3	18
4. The toolbox is useful.				13	5	18
5. The toolbox makes landscape planning easier to achieve.			3	12	3	18
6. The toolbox meets my needs.			11	7		18
7. The toolbox is easy to use.			3	8	7	18
8. The toolbox uses the fewest steps possible to accomplish what I want to do with it.			4	12	2	18
9. I don't notice any inconsistencies as I use it.			8	5	3	16
10. I can recover from mistakes quickly and easily.			7	7	2	16
11. I can use it successfully every time.		1	9	5	1	16
12. I learned to use it quickly.		1	3	11	3	18
13. I easily remember how to use it.		1	2	12	3	18
14. It is easy to learn to use it.		1	1	9	6	17
15. I am satisfied with the software toolbox.			2	12	4	18
16. It works the way I want it to work.			3	11	4	18
17. I would recommend the toolbox to a colleague.			1	10	6	17

6.0 PERFORMANCE ASSESSMENT

A detailed discussion of our results is in section 5.6. Here we present an outline of the overall conclusions of the performance assessment.

6.1 PO1. PLANT SURVIVAL INCREASES IN HS HABITATS

Success was determined by a statistically significant increase in the proportion of plants surviving in HS over LS areas. This was determined with GLMs containing Date, Species, and Suitability fixed factors. Success was defined by either a p-value less than 0.05 for the Suitability factor (with species showing higher, not lower, survival in HS sites) or by a p-value less than 0.05 for the interaction term whereby some species show higher survival in HS sites. We analyzed survival over all sampling periods using a repeated measures design. We began with a model with all terms, all two-way interaction terms, and the three-way interaction term and chose the most parsimonious model based on AIC scores of models with successively fewer terms. The most parsimonious model for PWW included the Date, Species, Suitability, and Date:Species terms. The most parsimonious model for PTA included these terms as well as the Species:Suitability interaction term (Table 8; Fig. 17). This significant Species:Suitability interaction term occurred in the PTA analysis because the differences in survival among species varied with habitat suitability (Fig. 18); however, there were no significant effects of Suitability on survival within each species ($P > 0.05$). Differences in survival among species were much greater than any effect of habitat quality on survival. **Due to a lack of a significant effect of habitat suitability on survival, this performance objective was not supported by the data during the timeframe of this demonstration project.**

6.2 PO2. PLANT PERFORMANCE INCREASES IN HS HABITATS

We expected to see greater overall plant performance in HS, compared to LS, plots. Performance was measured as indicator variables of growth, health, recruitment, reproduction, and increased physiological performance / decreased stress. We used a GLM to analyze measures of performance with Suitability and Species as fixed factors, a Block random factor and a Date term for measures taken repeatedly in the same manner. Appropriate interaction terms were included in each model. For many physiological variables, the numbers of samples differed from one date to the next based on the limitations of instrumentation and weather. Therefore, these datasets were analyzed separately for each sampling date due to the unbalanced nature of the sampling designs. We analyzed data for PWW and PTA separately and qualitatively compared results among the sites. Success was determined in a manner similar to PO1.

We found evidence for success of this performance objective at PTA when analyzing growth, health rating, and physiology/stress and at PWW when analyzing physiology/stress, but performance was not met at either site for recruitment and reproductive output during the study period (Table 19). At PTA, plants grew larger, had higher health rating, and had higher physiological function in HS plots. The physiology data, in particular, are very comprehensive and illustrated the largest difference across all species among HS and LS areas. These data also showed higher functioning in HS plots for plants at PWW, but no other measures of performance were affected by habitat suitability at PWW. **Therefore, there is some evidence for success of this performance objective at PWW and stronger evidence at PTA.**

Table 19. Summary of Plant Performance Results.

Measure of performance	PTA	PWW
Growth	Yes	No
Health rating	Yes	No
Physiology/stress	Yes	Yes
Reproduction	No	No
Recruitment	No	No

Growth

There were no effects of habitat suitability on measures of growth at PWW, but there were at PTA (Table 9). At PTA, growth was higher (or less negative) in HS plots on the final two sampling dates, indicating a stronger effect of habitat suitability over time. Growth was significantly greater (or less negative) in HS plots for *H. haplostachya* and *S. angulstifolia* (Fig. 19), but not for other species. Thus, **habitat suitability increased growth for these two species at PTA, and the benefit of HS areas on growth became more pronounced over time.**

Health rating

At PWW, health status of plants was higher in LS plots on two sampling dates (Table 10 significant Date:Suitability term; Fig. 20), but there was not difference on other dates. At PTA, health status was greater in HS for *E. olowaluana*, *H. haplostachya*, and *S. angustifolia* but not for *P. sclerocarpa* or *S. hawaiiensis* (Table 10 significant Species:Suitability term; Fig. 21). Health status was higher in HS plots on all sampling dates except October 2016 (Table 10 significant Date:Suitability term; Fig. 21). Therefore, **we found support for higher health status of species at PTA in HS plots and no support for higher health status in HS plots at PWW.**

Physiology/stress

Overall, outplants exhibited less stress and greater physiological function in HS plots, compared to LS plots (Table x, Figs x). Eight of 17 measurements were consistent with significantly greater plant performance in HS plots at PWW. The Suitability:Species interaction term was significant for only one measurement (Ψ), further suggesting that for other measures all species had a similar response to conditions in the HS plots. Five of 14 measurements were consistent with significantly greater plant performance in HS plots at PTA. The Suitability:Species interaction term was significant for only one measurement (F_V/F_M in July 2016), further suggesting that for other measures all species had a similar response to conditions in the HS plots. All analyses showed either no effect of habitat suitability or a positive effect of HS on plant performance. There was never a case where LS plants performed better. These results illustrate that the effect of habitat suitability on performance and growth is dynamic over time. At times there is a difference among plot types, while at other times they are the same. However, leaf nutrient data show the effect of habitat suitability integrated over the lifespan of the leaf. These data showed that plants in HS at both sites had access to greater resource availability and were less stressed. **Taken together, the plant physiology results strongly support greater performance and lower plant stress in HS environments at both sites.**

Reproduction

At PWW the number of seeds of *P. sclerocarpa* was greater in LS, compared to HS, plots. No other species showed a difference in seed production among suitability classes (Table 14).

Recruitment

Recruitment of most species was low or did not occur during the time of study, and there were no effects of habitat suitability on recruitment at either site. These recruitment data should be viewed as preliminary as recruitment dynamics are likely to change as the outplants mature.

6.3 PO3. SPATIAL CORRESPONDENCE OF SUITABILITY CLASSES

We used correlation analysis to examine the strength of the relationship between the elevation values from DEMs produced from WorldView-2 satellite data and airborne LiDAR data. Success was defined as a statistically significant relationship between the satellite elevation values and LiDAR elevation values ($P < 0.05$). In Hawaii the relationship is: WorldView-2 DEM (m) = -7.19 + 1.01 × LiDAR DEM (m), $r^2 = 0.998$, $P < 0.001$, RMSE = 6.42 m (Fig. 29). At VBG, the relationship is: WorldView-2 DEM (m) = 5.76 + 0.96 × LiDAR DEM (m), $r^2 = 0.934$, $P < 0.001$, RMSE = 15.3 m (Fig. 30). **Analysis in both regions indicated strong and statistically significant agreement between the LiDAR and stereo-derived DEMs, indicating success of this performance objective.**

6.4 PO4. FIELD MEASUREMENTS OF WEATHER AND MICROCLIMATE VARIABLES INDICATE GREATER SUITABILITY FOR PLANT GROWTH IN HS, COMPARED TO LS, PLOTS

At all four sites, we measured weather and microclimate variables that correspond with conditions important for plant growth. We expected measures of evaporative demands on plants (wind speed, leaf wetness, and soil moisture) and measures of plant size to be important verification measures of habitat suitability for restoration. All data measured were compared between high and low suitability classes either graphically for large abiotic datasets or with an appropriate GLM. Significance was determined as $P < 0.05$.

- Wind speed - The trend at all sites was higher wind speed in LS, compared to HS, plots. This difference was greatest at the two sites with the highest wind speeds (PTA and VBG).

- Leaf wetness was higher in HS plots at PTA, VBG, and SMNNRA, but was similar in HS and LS at PWW (Fig. 32). The difference between HS and LS plots was greatest at PTA and VBG, which is likely due to the much higher wind speeds at these sites that increase evaporation in LS areas.

- At sites in Hawaii, soil moisture did not differ greatly between HS and LS plots. At sites in California, average soil moisture was higher in HS than LS plots during a very dry period from May – November 2016; suggesting that HS plots may have been somewhat less stressful during this time period.

Overall, we found reduced wind speeds in HS areas at all sites, increased leaf wetness in HS areas at all sites except PWW, and increased soil moisture during dry periods at sites in California but not Hawaii. **These results indicate success for this performance objective at all sites except PWW.**

6.5 PO5. CORRESPONDENCE OF EXISTING TER-S WITH HS AREAS.

We used randomization tests to evaluate how the location of existing TER-S plants correspond with our HSM for two TER-S at VBG and 11 TER-S at PWW. The randomization tests evaluated whether the observed locations of individuals from each population were different from a null distribution of 1,000 simulated populations. At each iteration of the simulation, we extracted the topographic suitability index value from the location of each simulated individual (LS = 0, Moderate Suitability = 1, HS = 2). We compared the mean suitability class value across all known plant locations with the distribution of mean values from the simulated populations. Success was determined if the mean of known plants fell outside the 95% confidence interval, indicating that there was an association of the species with either higher or lower suitability sites. This analysis allowed us to determine if a species is associated with higher or lower class values. Two species, Chrysodracon hawaiiensis and Aplenium peruvianum var. insulare, showed an association with HS areas at PWW (Table 16). One species, Solanum incompletum, showed an association with LS areas (Table 16). Neither of the two species at VBG and eight species at PWW did not show an association with either habitat type. Taken together, these data do not show a strong association across species with either HS or LS areas. **The data across species did not support success for this performance objective. However, a history of disturbance at these sites may reduce the ability of plants to occupy suitable habitat areas. Performance was met for C. hawaiiensis and A. peruvianum at PWW, suggesting that the HSM could assist management of these species.**

6.6 PO6. EASE OF USE

We evaluated the ability of trained professionals to use the HSM GIS Toolbox at a workshop at IPIF on March 24, 2017. We distributed test versions of the software to 18 conservation professionals and recorded their written feedback and scores on a survey based on a Likert scale (Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree). Success was defined as survey results that indicate more than 75% of respondents “Agree” or “Strongly Agree” with question 7 (The software is easy to use) and question 17 (I would recommend the software to a colleague). **The actual response rates were 83% (15/18) for question 7 and 94% (16/17) for question 17 indicating a high level of success for this performance objective (Table 17).**

Summary assessment

Our data indicated success for three of the six performance objectives for this demonstration (POs 3, 4, and 6), partial success for two performance objectives (PO 2 and 5), and no success for PO 1. WorldView-2 DEMs showed significant correlation with LiDAR DEMs (PO 3). Abiotic conditions indicated greater resource availability and reduced stress in HS areas at all sites, but less so at PWW (PO 4). Surveys of professional end users indicated that our GIS Toolbox was easy to use (PO 6). Planted individuals were less stressed and showed greater performance in HS areas at PTA, and less so at PWW; however measures of reproduction and recruitment were not altered by habitat suitability, indicating partial success for PO 2.

We also found partial success for PO5, in which two species were associated with HS areas but 11 others were not. Our data did not show higher survival in HS habitats during the timeframe of this study, but these results could change over a longer time period (PO1). Overall, we have produced a method for others to implement HSMs into landscape planning for TER-S conservation. Based on our findings in this demonstration, this method is likely to have the greatest impact in regions with fairly low annual precipitation around 300-600 mm, similar to PTA, VBG, and SMMNRA (but not PWW) and in areas with high wind speeds, similar to PTA and VBG.

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7.0 COST ASSESSMENT

7.1 COST MODEL

A cost assessment was completed to help us determine the cost of outplanting endangered species. Total expenditures for the project were evaluated by categorizing the labor costs and material expenditures into three broad categories: establishment; maintenance and monitoring, and; research (Table 20). Establishment activities accounted for more than half of the labor hours (Figs. 35-37) and research material expenditures were higher than establishment material expenditures (Table 20). The total cost (including labor hours and expenditures) for outplanting 5000 plants is $76.52 per plant (Table 20). If the research component is removed the total cost per plant is reduced to $63.94 per plant.

Table 20. Cost Model

Reintroduction Costs				
Category	**Material Expenditures**	**Labor hours**	**Total cost***	**Cost per outplant****
Establishment	$37,504	4408	$209,416	$41.88
Maintenance and Monitoring	$0	2828	$110,292	$22.06
Research	$43,166	506	$62,900	$12.58
Total	$80,670	7742	$382,608	$76.52
Imagery Costs				
		Cost per 300 km^2		
WorldView-2 imagery costs***	Archive: $28-38/km^2 New Task: $48-58/ km^2	$8,400 – $11,400 $14,400 – $17,400		

*Labor cost = $39/hour

***cost based on 5000 outplants*

*Cost data from Landinfo (2017): http://www.landinfo.com/satellite-imagery-pricing.html

Establishment

Establishment costs include materials required for plant propagation and site preparation, and labor required for seed collection, plant propagation, and site preparation. Labor costs included greenhouse construction, plant collection, propagation, greenhouse setup, monitoring plants in the greenhouse, plot setup, plot clearing, plant transport, and outplanting (Figs. 35-37).

Maintenance and monitoring

Maintenance and monitoring costs include labor required for ongoing plant monitoring and plot maintenance. Labor categories included watering, census (monitoring), plot maintenance, plant setup, and imaging.

Research

Research costs were required to install weather stations and environmental sensors as well as maintain these sensors, download data, and collect detailed measurements from plants in the field. Labor categories included electronics, biomass, reproduction census, photosynthesis, seed counts, recruitment, and specific leaf area.

Imagery costs

Updated imagery cost data were obtained from Landinfo (2017). Costs include acquiring stereo data from the WorldView-2 satellite. Costs are lower if data already exist in the archive. Costs do not include labor required to produce the DEM (see Section 7.3 for detailed discussion).

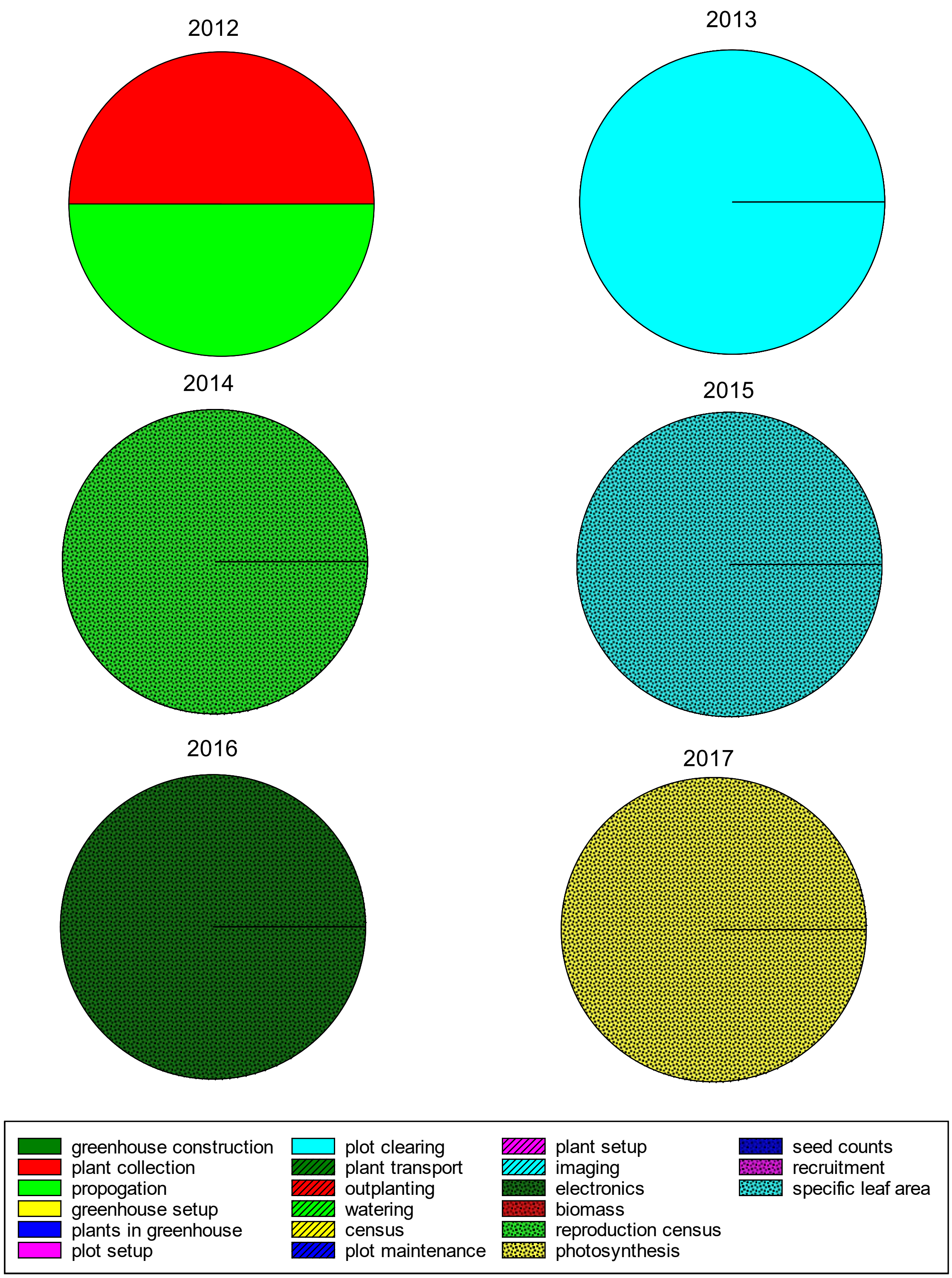

Figure 35. Costs of Establishment, Maintenance and Monitoring, and Research Detailed by Task.

Establishment tasks have no pattern, maintenance and monitoring tasks have lined pattern, and research tasks have dotted pattern.

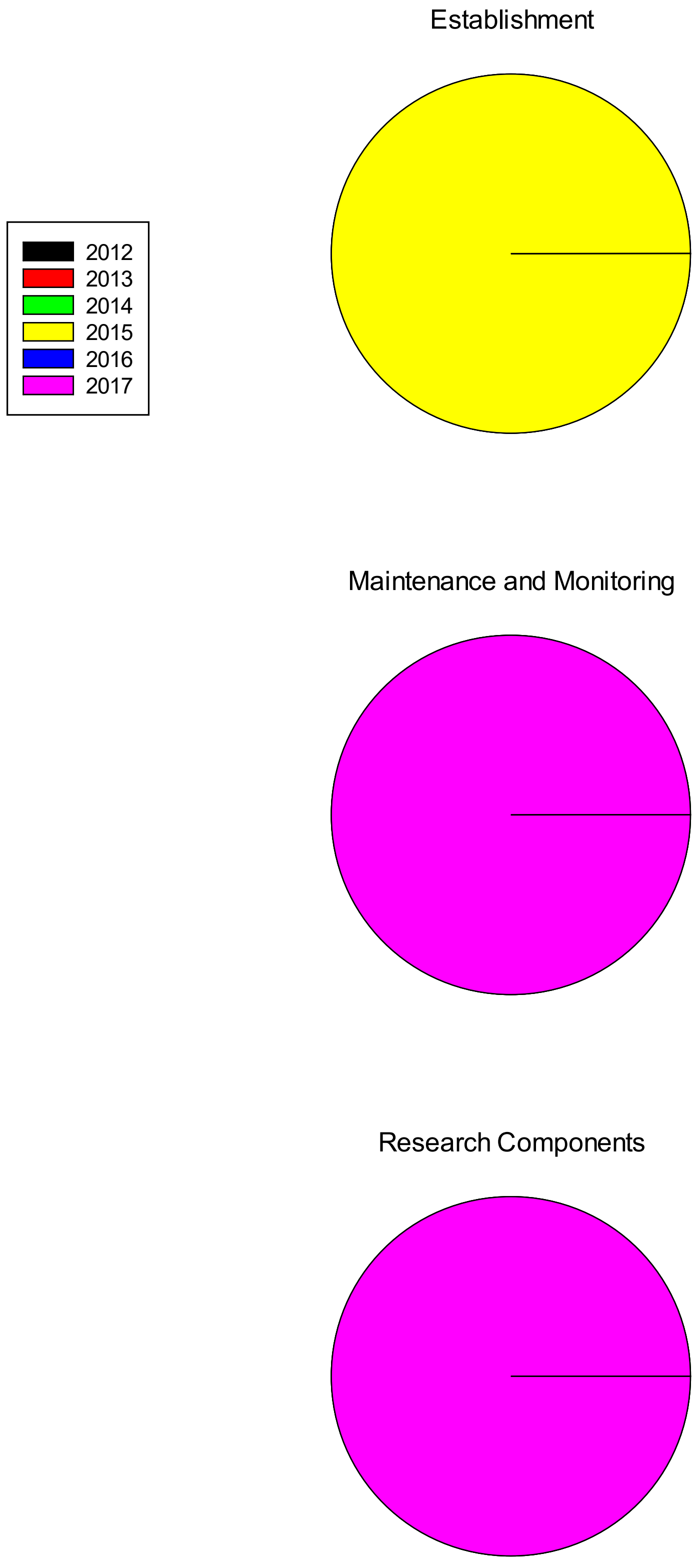

Figure 36. Outplanting Costs by Category and Year.

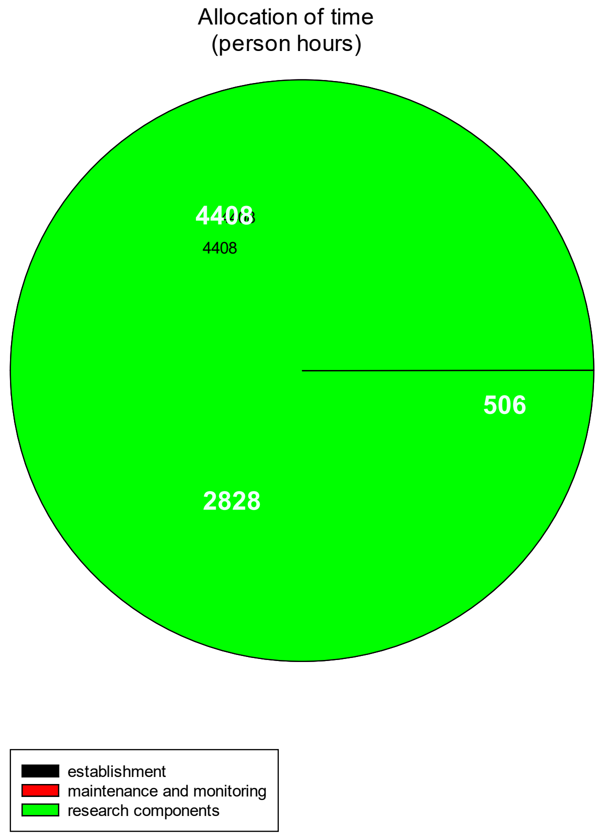

Figure 37. Total Allocation of Hours by Outplanting Category.

7.2 COST DRIVERS

Cost drivers will be determined by an organization's operating costs for the reintroduction program as well as cost of acquiring a DEM for the area of interest. Costs for reintroduction will be borne by the organization with or without the use of the HSM. Therefore, we report our costs here to assist with a program's planning, but do not analyze them in relation to another option. We assume an organization would be planning a reintroduction project with or without the HSM.

Our costs are comprehensive and include all of our expenditures for establishment, maintenance and monitoring, and research ($76.52 per plant; $382,608 for 5,000 plants). Most programs would require the establishment and maintenance and monitoring costs ($63.94 per plant; 319,708 for 5,000 plants). Economies of scale are likely to be modest because any cost reduction would be offset by the increased labor required for propagation, monitoring, and maintaining larger areas in the field (e.g., weeding, etc.).

Imagery costs are the second major driver and the main area for comparison for our project. The cost of WorldView-2 satellite imagery ranges from $8,400 - $17,400 per 300 km^2, approximately the size of PTA. A reasonable cost would be $11,400 per 300 km^2 ($38/km^2). It should be noted that orders must be at least 100 km^2.

7.3 COST ANALYSIS AND COMPARISON

The main consideration for cost analysis is the cost of acquiring a high resolution DEM to be used to create the HSM. The costs will include both the acquisition of imagery and also the time and expertise needed to convert the raw imagery into a DEM. We carefully considered whether stereo imagery from WorldView-2 would be a better option compared to LiDAR imagery from an airborne sensor and considered the following in our analysis:

1. Despite claims of the ease of acquisition, stereographic satellite imagery was surprisingly difficult to acquire due to cloud cover. We note that the Hawaii site in particular required tasking the satellite for almost one year before a useful pair of stereo images could be acquired. In regions where cloud cover is more substantial, this difficulty will increase.
2. The real cost of generating DEMs from stereographic satellite data is not small after considering the significant person-effort, expertise, and time that is required to produce elevation models from these data. This is in contrast to airborne LiDAR, where post-processing is much more mature and automated, requiring little to no human intervention after data collection to produce a georeferenced point cloud and elevation models.
3. Coastal regions of the United States are high priority areas for LiDAR DEM mapping due to issues related to resource management, erosion, sea level rise, etc. Many coastal areas already have freely available DEMs that would be suitable for use in the HSM. Many DoD installations already have LiDAR DEMs for construction and planning purposes. Therefore, the DEM data for many areas of interest already exist and can be available to the use for free or for a minimal cost.
4. The cost of new airborne LiDAR data acquisition has fallen significantly in the last few years. In-house costs for the production of a DEM from airborne LiDAR can range from \$8-10 per km^2 (compared to \$38 per km^2 for WorldView-2 image acquisition only). Contracted costs may be higher; however, if the DoD desired the capability to produce LiDAR DEMs it could acquire the ability to do it.
5. A major barrier to using WorldView-2 is the time and expertise required to generate a stereo DEM with a reasonable RMSE. We explored using third-party software to improve the RMSE between WorldView-2 and LiDAR elevation models. PhotoSat uses proprietary algorithms that are purported to produce elevation models with RMSE similar to airborne LiDAR. According to the company website, "*PhotoSat has invented a new satellite elevation mapping process based on oil and gas seismic processing technology. Our geophysical process generates topographic grids with over 4 times the accuracy of conventional photogrammetric maps derived from the same stereo satellite photos."* The firm claims to be *"the only company in the world that has demonstrated the capacity to produce satellite topographic mapping with better than 30cm elevation accuracy, as measured by thousands of accurate ground survey points and by direct comparison to highly accurate LiDAR surveys."* PhotoSat does not sell its proprietary stereo DEM algorithm, but rather processes individual requests on a fee-for-service basis. We requested a quote for the areas of Hawaii and California at issue here. Processing stereo satellite images for the Hawaii and Vandenberg installations would cost \$99,000 and \$60,000, respectively.

In our analysis of using WorldView-2 data for DEMs we concluded that the maps can be useful in the sense that they provide measurements that are similar to, but not as accurate as, airborne LiDAR. However, our opinion after having performed the DEM extraction and the cost analysis is that they are not a cost-effective way for DoD (or other users) to acquire high-resolution elevation data. Airborne or UAV-based LiDAR systems would provide a more cost-effective solution for the DoD.

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8.0 IMPLEMENTATION ISSUES

Implementation of the HSM is straightforward and simple. During this demonstration, we developed a user-friendly GIS Toolbox that is available for others to use (http://www.cpp.edu/~ejquestad/HSMhome.shtml). We have developed guides to assist users with creating the HSM for a site of interest. The Toolbox was made as an extension for ArcGIS for ease of use and to avoid cybersecurity issues that would occur with a stand-alone software program. ArcGIS is used widely as a preferred mapping platform across DoD, federal, state, and private users. Our Toolbox is added into the existing ArcMap program and uses the ArcMap Spatial Analyst functions to produce habitat suitability maps. In this respect, the Toolbox acts like a regular data file, not a program. It contains specific commands that are executed by the ArcMap program. In this way security concerns with downloading and using the Toolbox file are minimized because it is not independently executable.

Implementation will be based on whether a DEM with sufficient spatial resolution is available for the site or is cost-effective to acquire. Typical LiDAR datasets that map elevation with pixel sizes of 5m or less are sufficient for mapping most topographic features. However, if very small features are of interest, then higher resolution data would be needed. Users in our workshop indicated a high level of interest in incorporating the HSM into future management plans, especially as LiDAR elevation data are becoming freely available for many regions. Our collaborators at PTA and PWW have already incorporated the HSM into their conservation plans for TER-S. The HSM is also easily combined with other data layers (roads, aspect, etc.) to facilitate selection of conservation areas.

One aspect users will consider is whether the HSM will be useful overall for their outplanting program. Our demonstration results highlighted that the HSM was somewhat useful in designating high quality habitat at all sites, but it had the greatest impact in differentiating high quality and low-quality sites in areas that were dry and windy, especially PTA and VBG. The HSM approach should be more effective in dry, windy sites than in wetter, less windy conditions.

In addition, users should consider whether there may be species-specific responses to habitat suitability. We found that numerous measures of growth and physiology were improved in HS habitats across *all species*. At PTA, there was a significant main effect of Suitability across all species on F_V/F_M, A, %N, and %P; whereas only two species, *Haplostachys haplostachya* and *Stenogyne angustifolia*, showed increased growth and health in HS plots. At PWW, there was a significant main effect of Suitability across all species on F_V/F_M, g_s, A, E, %P, and $\delta^{13}C$; whereas three species, *Haplostachys haplostachya, Colubrina oppositifolia,* and *Stenogyne angustifolia*, showed lower water stress in HS plots and *Euphorbia olowaluana* had increased health ratings in HS plots. Thus, measures of physiology were improved in HS plot across all species, but certain species, especially *H. haplostachya* and *S. angustifolia*, showed more consistent positive responses to being planted in HS areas across both sites. Users should consider the potential responses of individual species when planning to incorporate habitat suitability into management and reintroduction plans.

In order to facilitate future outplanting projects for the native Hawaiian species that were studied, we performed an extensive interview survey of regional managers and native plant growers in order to determine the best techniques for propagating each species (seed, cuttings, etc.). All propagation protocols were documented in our Hawaiian Native Plant Propagation Resource, which is available online (Janas et al. 2015). We also developed a standard method for evaluating plants for outplanting based on a health status rating of one to five as follows: 1) no foliage but living stem; 2) foliage less than 25% and damaged by pest or disease; 3) 25-60% foliage, foliage showing signs of stress; 4) 60-90% foliage and health, showing no sign of decline; 5) greater than 90% foliage and extremely healthy with vigorous growth and no damage. Plants of health status class five were selected for outplanting, with a few plants of health status four included for species with fewer individuals.

We did not find differences in survival in HS sites during the time of this demonstration, which could deter some users from implementing the HSM. However, we found that *at times* resource availability and plant physiological functioning was higher in HS areas. In particular, the growth and leaf nutrient data showed higher resource acquisition across all species over the period of leaf and plant growth in HS, compared to LS, areas. These data illustrate that there are times when HS sites have better growing conditions and times when they do not, but over a longer period the benefit of HS conditions is apparent in improved physiological functioning and growth. It is expected that in some contexts this improved growth will also lead to greater survival, especially when survival and population persistence are examined over longer time periods.

Our conclusion is that if a site is dry and windy, the HSM is likely to add value to conservation planning for TER-S. For other sites, the HSM may still be useful but the decision to implement the HSM may be based on attributes of the species of interest and whether the DEM data are easily obtained. If so, then the HSM can be an additional consideration in the planning of conservation areas and reintroduction projects.

9.0 REFERENCES

Abrams, M. D., A. K. Knapp, and L. C. Hulbert. 1986. A 10-Year Record of Aboveground Biomass in a Kansas Tallgrass Prairie - Effects of Fire and Topographic Position. American Journal of Botany **73**:1509-1515.

Asner, G. P., S. R. Levick, T. Kennedy-Bowdoin, D. E. Knapp, R. Emerson, J. Jacobson, M. S. Colgan, and R. E. Martin. 2009. Large-scale impacts of herbivores on the structural diversity of African savannas. Proceedings of the National Academy of Sciences of the United States of America **106**:4947-4952.

Bates, D., M. Machler, B. M. Bolker, and S. C. Walker. 2015. Fitting linear mixed-effects models using lme4. Journal of Statistical Software **67**:1-48.

Bergen, K. M., S. J. Goetz, R. O. Dubayah, G. M. Henebry, C. T. Hunsaker, M. L. Imhoff, R. F. Nelson, G. G. Parker, and V. C. Radeloff. 2009. Remote sensing of vegetation 3-D structure for biodiversity and habitat: Review and implications for lidar and radar spaceborne missions. Journal of Geophysical Research-Biogeosciences **114**.

Bern, C. M. 1995. Land Condition-Trend Analysis Summary of Vegetation Monitoring, Pohakuloa Training Area, Hawaii, 1893-1993. Center for Ecological Management of Military Lands, Department of Forest Sciences, Colorado State University, Fort Collins, CO.

Biederman, L. A. and S. G. Whisenant. 2011. Using Mounds to Create Microtopography Alters Plant Community Development Early in Restoration. Restoration Ecology **19**:53-61.

Bottin, L., S. Le Cadre, A. Quilichini, P. Bardin, J. Moret, and N. Machon. 2007. Re-establishment trials in endangered plants: A review and the example of Arenaria grandiflora, a species on the brink of extinction in the Parisian region (France). Ecoscience **14**:410-419.

Burke, I. C., W. K. Lauenroth, R. Riggle, P. Brannen, B. Madigan, and S. Beard. 1999. Spatial variability of soil properties in the shortgrass steppe: The relative importance of topography, grazing, microsite, and plant species in controlling spatial patterns. Ecosystems **2**:422-438.

Cordell, S., M. McClellan, Y. Y. Carter, and L. J. Hadway. 2008. Towards restoration of Hawaiian tropical dry forests: the Kaupulehu outplanting programme. Pacific Conservation Biology **14**:279-284.

Cordell, S., E. J. Questad, G. P. Asner, K. Kinney, J. Thaxton, A. Uowolo, S. Brooks, and M. W. Chynoweth. 2017. Remote sensing for restoration planning: how the big picture can inform stakeholders. Restoration Ecology **25**:S147-S154.

Coulombe, H. N. and C. F. Cooper. 1976. Ecological assessment of Vandenberg Air Force Base, California., Air Force Civil Engineering Center, Tyndall Air Force Base, Florida.

Coulombe, H. N. and C. R. Mahrdt. 1976. Ecological assessment of Vandenberg Air Force Base, California., Air Force Civil Engineering Center, Tyndall Air Force Base, Florida.

Dobson, A. P., J. P. Rodriguez, W. M. Roberts, and D. S. Wilcove. 1997. Geographic distribution of endangered species in the United States. Science **275**:550-553.

Drayton, B. and R. B. Primack. 2012. Success rates for reintroduction of eight perennial plant species after 15 years. Restoration Ecology **20**:299-303.

Fitch, R. L. 2017. The effects of nitrogen, water, and topography on the distribution of *Stipa pulchra*. M.S. California State Polytechnic University, Pomona, Pomona, CA.

Fricker, G. A., J. A. Wolf, S. S. Saatchi, and T. W. Gillespie. 2015. Predicting spatial variations of tree species richness in tropical forests from high-resolution remote sensing. Ecological Applications **25**:1776-1789.

Friday, J. B., S. Cordell, C. P. Giardina, F. Inman-Narahari, N. Koch, J. Leary, C. M. Litton, and C. Trauernicht. 2015. Future directions for forest restoration in Hawaii. New Forests **46**:733-746.

Giambelluca, T. W., M. A. Nullet, and T. A. Schroeder. 1986. Rainfall atlas of Hawaii. State of Hawaii, Department of Land and Natural Resources, Division of Water and Land Development, Honolulu, Hawaii.

Gillespie, T. W., G. Keppel, S. Pau, J. P. Price, T. Jaffre, J. Y. Meyer, and K. O'Neill. 2011. Floristic Composition and Natural History Characteristics of Dry Forests in the Pacific. Pacific Science **65**:127-141.

Godefroid, S., C. Piazza, G. Rossi, S. Buord, A. D. Stevens, R. Aguraiuja, C. Cowell, C. W. Weekley, G. Vogg, J. M. Iriondo, I. Johnson, B. Dixon, D. Gordon, S. Magnanon, B. Valentin, K. Bjureke, R. Koopman, M. Vicens, M. Virevaire, and T. Vanderborght. 2011. How successful are plant species reintroductions? Biological Conservation **144**:672-682.

Goetz, S., D. Steinberg, R. Dubayah, and B. Blair. 2007. Laser remote sensing of canopy habitat heterogeneity as a predictor of bird species richness in an eastern temperate forest, USA. Remote Sensing of Environment **108**:254-263.

Goetz, S. J., D. Steinberg, M. G. Betts, R. T. Holmes, P. J. Doran, R. Dubayah, and M. Hofton. 2010. Lidar remote sensing variables predict breeding habitat of a Neotropical migrant bird. Ecology **91**:1569-1576.

Grubb, P. J. 1977. The maintenance of species-richness in plant communities: the importance of the regeneration niche. Biological Review **52**:107-145.

Guerrant, E. O., Jr. . 2012. Characterizing two decades of rare plant reintroductions.*in* J. Maschinski and K. E. Haskins, editors. Plant reintroduction in a changing climate: promises and perils. Island Press, Washington, DC.

Helenurm, K. 1998. Outplanting and differential source population success in *Lupinus guadalupensis*. Conservation Biology **12**:118-127.

Hobi, M. L. and C. Ginzler. 2012. Accuracy Assessment of Digital Surface Models Based on WorldView-2 and ADS80 Stereo Remote Sensing Data. Sensors **12**:6347-6368.

Ishida, A., K. Yazaki, and A. L. Hoe. 2005. Ontogenetic transition of leaf physiology and anatomy from seedlings to mature trees of a rain forest pioneer tree, Macaranga gigantea. Tree Physiology **25**:513-522.

IUCN. 2013. IUCN Guidelines for reintroductions and other conservation translocations. IUCN, Gland and Cambridge.

Janas, D., A. Uowolo, S. Brooks, and K. Hinds. 2015. Hawaiian native plant propagation resource. *Accessed* November 2, 2015. http://www.cpp.edu/~ejquestad/hawaiipropguide/home.html

Kaye, T. N. 2011. Toward successful reintroductions: the combined importance of species traits, site quality, and restoration technique. Proceedings of the CNPS Conservation Conference:99-106.

Kew Royal Botanic Gardens. 2010. Plants under pressure a global assessment. The first report of the IUCN Sampled Red List Index for Plants.

Knapp, A. K., J. T. Fahnestock, S. P. Hamburg, L. B. Statland, T. R. Seastedt, and D. S. Schimel. 1993. Landscape Patterns in Soil Plant Water Relations and Primary Production in Tallgrass Prairie. Ecology **74**:549-560.

Lefsky, M. A., W. B. Cohen, G. G. Parker, and D. J. Harding. 2002. Lidar remote sensing for ecosystem studies. Bioscience **52**:19-30.

Levin, S. A. 1992. The problem of pattern and scale in ecology. Ecology **73**:1943-1967.

Lloyd, K., V. Fay, and L. Easton. 2018. Experimental translocations of the threatened New Zealand plants *Carex inopinata* Cook (Cyperaceae) and *Simplicia laxa* Kirk (Poaceae). New Zealand Journal of Ecology **42**:214-221.

Loope, L. L. 1998. Hawaii and the Pacific Islands. Status and Trends of the Nation's Biological Resources **2**:747-774.

Mahall, B. E., C. M. Tyler, E. S. Cole, and C. Mata. 2009. A Comparative Study of Oak (Quercus, Fagaceae) Seedling Physiology during Summer Drought in Southern California. American Journal of Botany **96**:751-761.

Maschinski, J., D. A. Falk, S. J. Wright, J. Possley, J. Roncal, and K. S. Wendelberger. 2012. Optimal locations for plant reintroductions in a changing world.*in* J. Maschinski and K. E. Haskins, editors. Plant reintroduction in a changing climate: promises and perils. Island Press, Washington, DC.

Maschinski, J. and K. E. Haskins. 2012. Plant reintroduction in a changing climate: promises and perils. Island Press, Washington, DC.

Monks, L., D. Coates, T. Bell, and M. Bowles. 2012. Determining success criteria for reintroductions of threatened long-lived plants.*in* J. Maschinski and K. E. Haskins, editors. Plant reintroduction in a changing climate. Island Press, Washington, DC.

Nicole, F., J. P. Dahlgren, A. Vivat, I. Till-Bottraud, and J. Ehrlen. 2011. Interdependent effects of habitat quality and climate on population growth of an endangered plant. Journal of Ecology **99**:1211-1218.

Nippert, J. B., T. W. Ocheltree, A. M. Skibbe, L. C. Kangas, J. M. Ham, K. B. S. Arnold, and N. A. Brunsell. 2011. Linking plant growth responses across topographic gradients in tallgrass prairie. Oecologia **166**:1131-1142.

NPS. 2005. Final environmental impact statement for a fire management plan at SMMNRA.

NPS. 2017. NPS annual recreation visits report.

Pitman, N. and P. M. Jorgensen. 2002. Estimating the size of the world's threatened flora. Science **298**:989.

Questad, E. J., J. R. Kellner, K. Kinney, S. Cordell, G. P. Asner, J. Thaxton, J. Diep, A. Uowolo, S. Brooks, N. Inman-Narahari, S. A. Evans, and B. Tucker. 2014. Mapping habitat suitability for at-risk plant species and its implications for restoration and reintroduction. Ecological Applications **24**:385-395.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reichheld, F. 2006. The ultimate question: driving good profits and true growth. Harvard Business School Publishing Corporation, Boston, MA.

Rhodes, J. M. and J. P. Lockwood. 1995. Mauna Loa revealed: structure, composition, history, and hazards. American Geophysical Union, Washington, DC.

Rovzar, C., T. W. Gillespie, M. K. Shirman, A. F. Hubel, and K. Kawelo. 2017. Management implications for the reintroduction of the endangered Hawaiian state flower *Hibiscus brackenridgei*. Restoration Ecology **26**:516-524.

Schmalzer, P. A., D. E. Hickson, and C. R. Hinkle. 1988. Vegetation studies on Vandenberg Air Force Base, California.

Shaw, R. B. 1997. Rare plants of Pohakuloa Training Area, Hawaii. Fort Collins, CO.

Simmons, M. E., X. B. Wu, and S. G. Whisenant. 2011. Plant and soil responses to created microtopography and soil treatments in bottomland hardwood forest restoration. Restoration Ecology **19**:136-146.

Slaton, M. R. 2014. The roles of disturbance, topography, and climate in determining the leading and rear edges of population range limits. Journal of Biogeography **42**:255-266.

Stein, B. A., C. Scott, and N. Benton. 2008. Federal lands and endangered species: The role of military and other federal lands in sustaining biodiversity. Bioscience **58**:339-347.

Swenson, J. J. and J. Franklin. 2000. The effects of future urban development on habitat fragmentation in the Santa Monica Mountains. Landscape Ecology **15**:713-730.

Takahashi, K. and Y. Murayama. 2014. Effects of topographic and edaphic conditions on alpine plant species distribution along a slope gradient on Mount Norikura, central Japan. Ecological Research **29**:832-833.

Turner, W., S. Spector, N. Gardiner, M. Fladeland, E. Sterling, and M. Steininger. 2003. Remote sensing for biodiversity science and conservation. Trends in Ecology & Evolution **18**:306-314.

U.S. Army Garrison Hawaii. 2010. Pōhakuloa Integrated Natural Resources Management Plan. Center for Environmental Management of Military Lands, Colorado State University, Fort Collins, Colorado

USAF. 2003. Final Draft Integrated Natural Resources Management Plan. Vandenberg Air Force Base, California. Plan Period 2003-2008.

USAF. 2005. Vandenberg Air Force Base General Plan.

USAF. 2011. Threatened and Endangered species management plan.

Vierling, K. T., L. A. Vierling, W. A. Gould, S. Martinuzzi, and R. M. Clawges. 2008. Lidar: shedding new light on habitat characterization and modeling. Frontiers in Ecology and the Environment **6**:90-98.

Ward, R. D., N. G. Burnside, C. B. Joyce, and K. Sepp. 2016. Importance of microtopography in determining plant community distribution in Baltic coastal wetlands. Journal of Coastal Research **32**:1062-1070.

Wendelberger, K. S. and J. Maschinski. 2016. Assessing microsite and regeneration niche preferences through experimental reintroduction of the rare plant *Tephrosia angustissima* var. *corallicola*. Plant Ecology **217**:155-167.

Wiens, J. A. 1989. Spatial scaling in ecology. Functional Ecology **3**:385-397.

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APPENDIX A POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Erin Questad	Biological Sciences Department California State Polytechnic University, Pomona 3801 West Temple Ave Pomona, CA 91768	Phone: (909) 869-4206 Fax: (909) 869-4078 ejquestad@csupomona.edu; equestad@gmail.com	PI
Susan Cordell	Institute of Pacific Islands Forestry Pacific Southwest Research Station USDA Forest Service 60 Nowelo St. Hilo, HI 96720	Phone: (808) 854-2628 Fax: (808) 933-8120 scordell01@fs.fed.us	Co-PI, Hawaii
Jim Kellner	Department of Geographical Sciences University of Maryland, College Park 2181 Lefrak Hall College Park, MD 20742	Phone: (301) 405 3144 Fax: (301) 314-9299 jkellner@umd.edu	Co-PI, Remote Sensing
Sam Brooks	Institute of Pacific Islands Forestry Pacific Southwest Research Station USDA Forest Service 60 Nowelo St. Hilo, HI 96720	Phone: (808) 933-8121 EXT168 Fax: (808) 933-8120 sebrooks@fs.fed.us	Ecologist, Hawaii
Peter Peshut	Natural Resources Office Pohakuloa Training Area P.O. Box 4607 Hilo, HI 96721	Phone (808) 969-1966 Fax (808) 969-9482 Peter.Peshut@us.army.mil	Assist with coordination of activities at PTA
Elliott Parsons	Three Mountain Alliance 71-1645 Mamalahoa Highway, #8 Kailua Kona, HI 96740	Phone: (808) 333-0084 Fax: (808) 325-3610 eparsons@hawaii.edu	Assist with coordination activities at PWW
Luanne Lum	Vandenberg Air Force Base 1028 Iceland Avenue Vandenberg AFB, CA 93437	Phone: (805) 606-5299 luanne.lum@us.af.mil	Assist with coordination of activities at VBG

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APPENDIX B ADDITIONAL DATA

Fig. B1. Soil moisture for pairs of plots at VBG. Averages were calculated with data from Pipeline, Powerline A, and Powerline B. Linda Vista was excluded because its soils were extremely dry compared to other sites, and the soil composition interfered with the sensors creating a lot of abnormal data. Lake Canyon was excluded due to its very different topography and substrate compared to other sites.

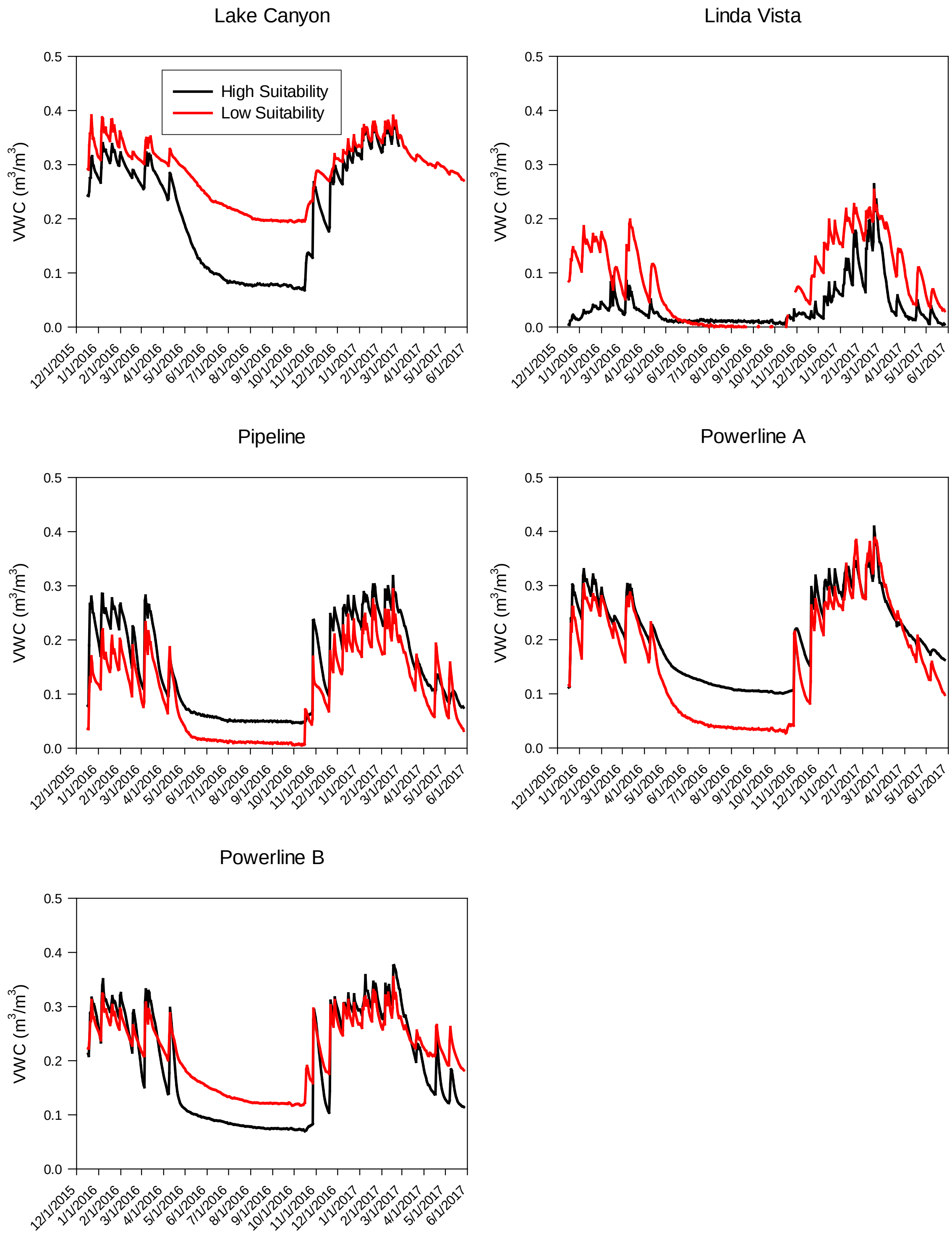


Fig. B2. Soil moisture of paired plots at SMMNRA. All plots were used to calculate averages. Data from Arroyo Sequit were used after October 2016 due to a broken sensor prior to that time.

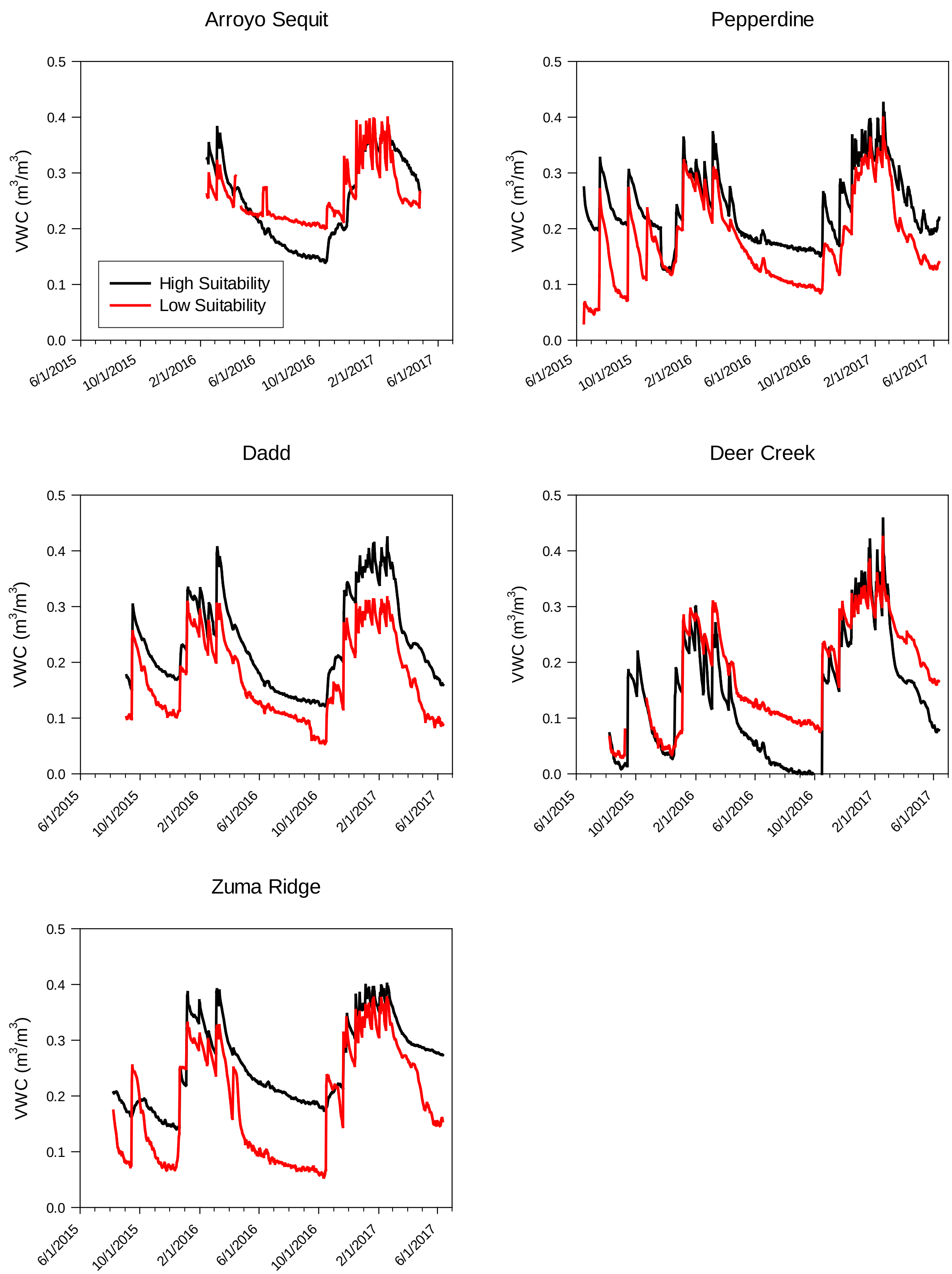


Fig. B3. Soil moisture of paired plots at PTA. Plots 220 and 222 were excluded from average calculations due to a lack of soil in plot 222 (high suitability) which made it difficult to collect accurate soil moisture data.

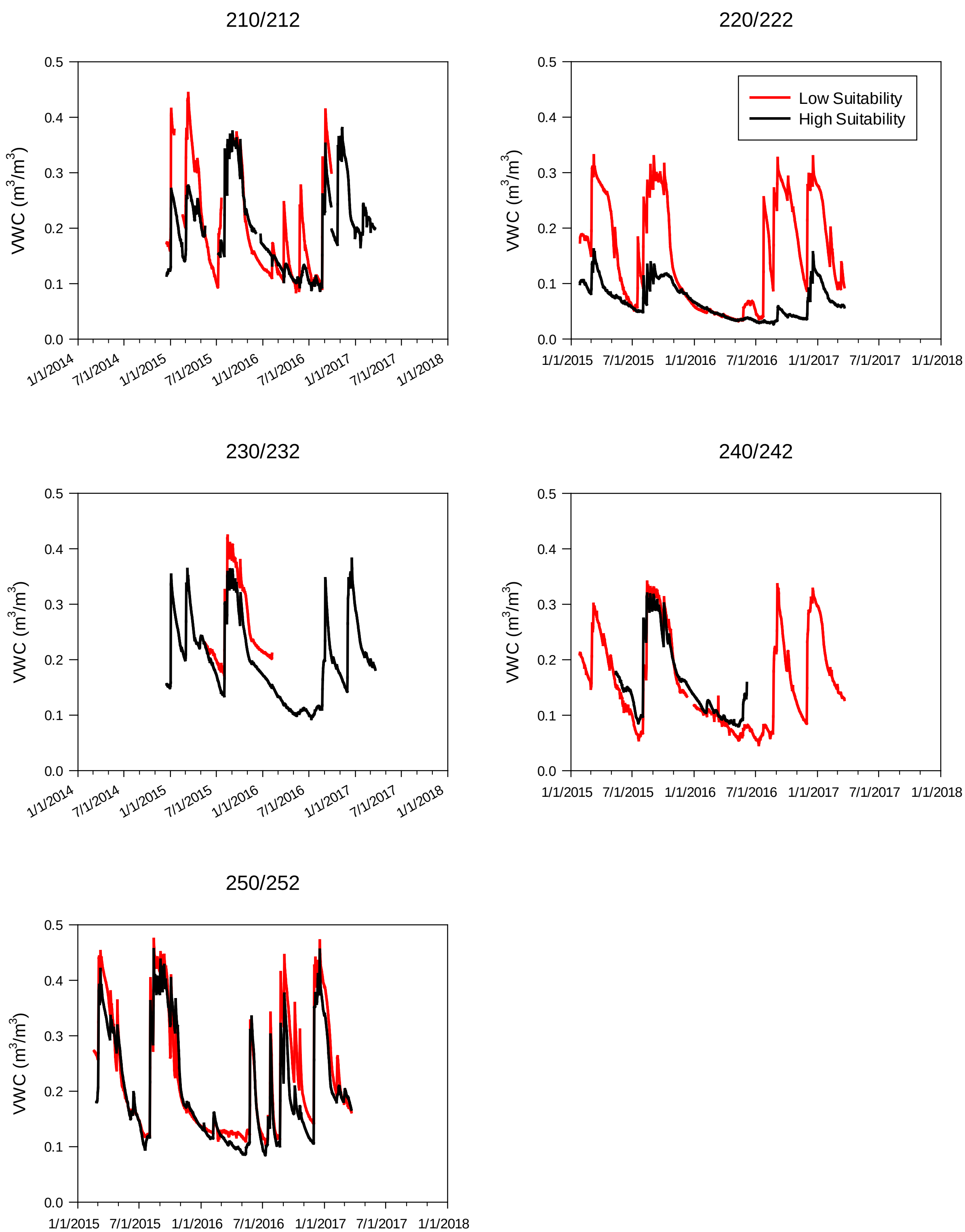


Fig. B4. Soil moisture for pairs of plots at PWW. Data from plots 110/112 and 140/142 were excluded due to errors in measurement due to lack of soil. Data from plots 150/152 were included after August 2015 due to a sensor malfunction before that time.

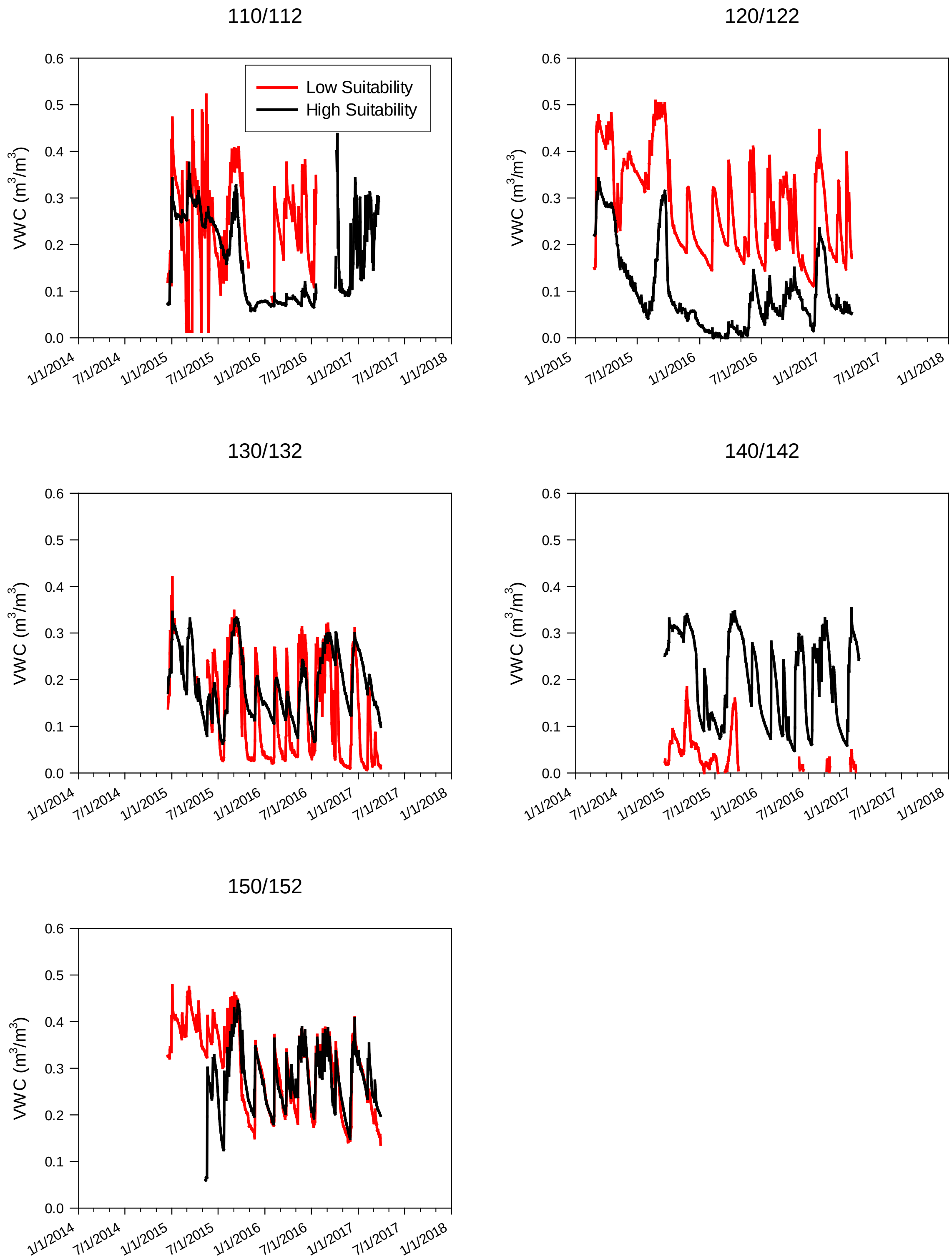


Fig. B5. Leaf wetness for pairs of plots at PTA.

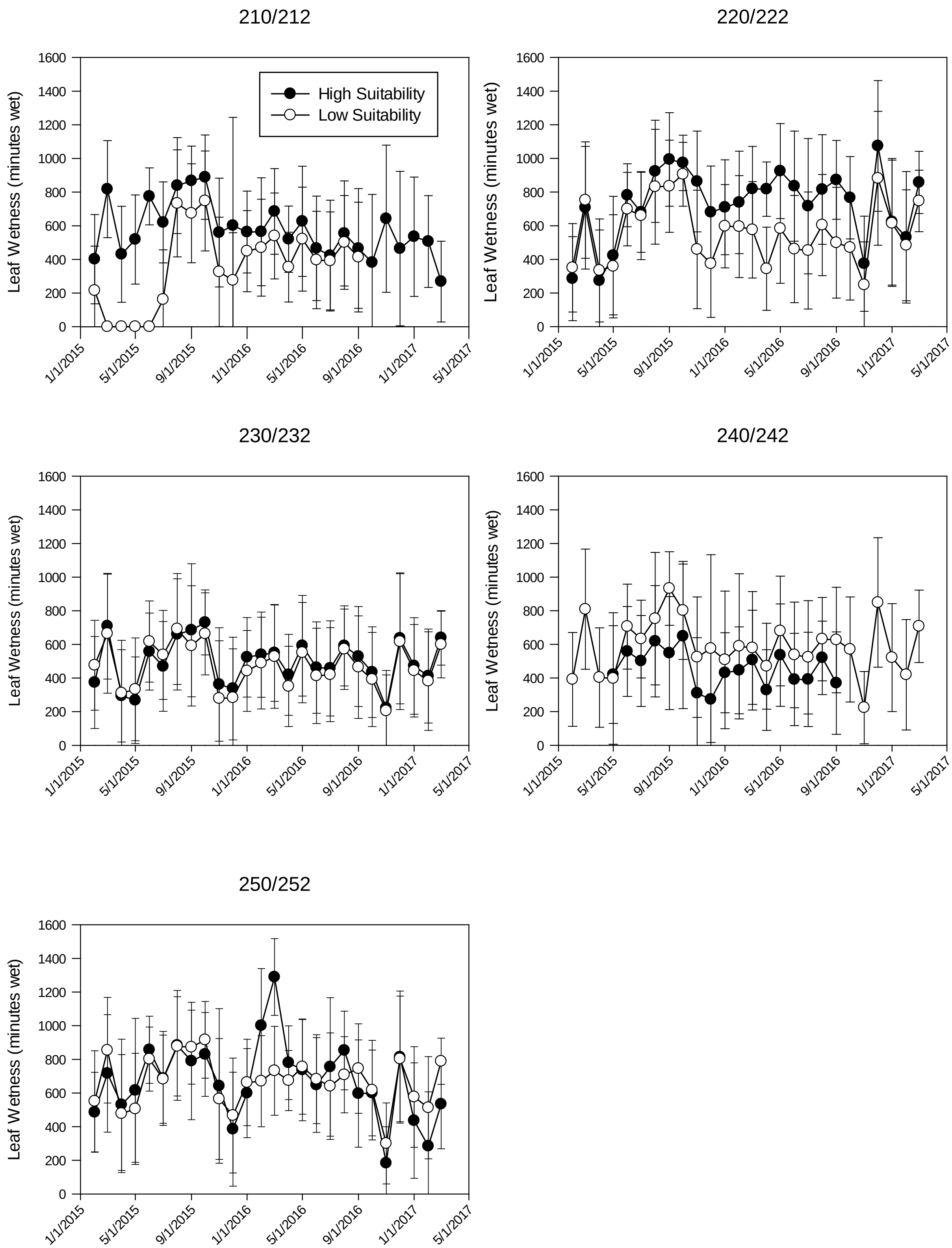


Fig. B6. Leaf wetness for pairs of plots at PWW.

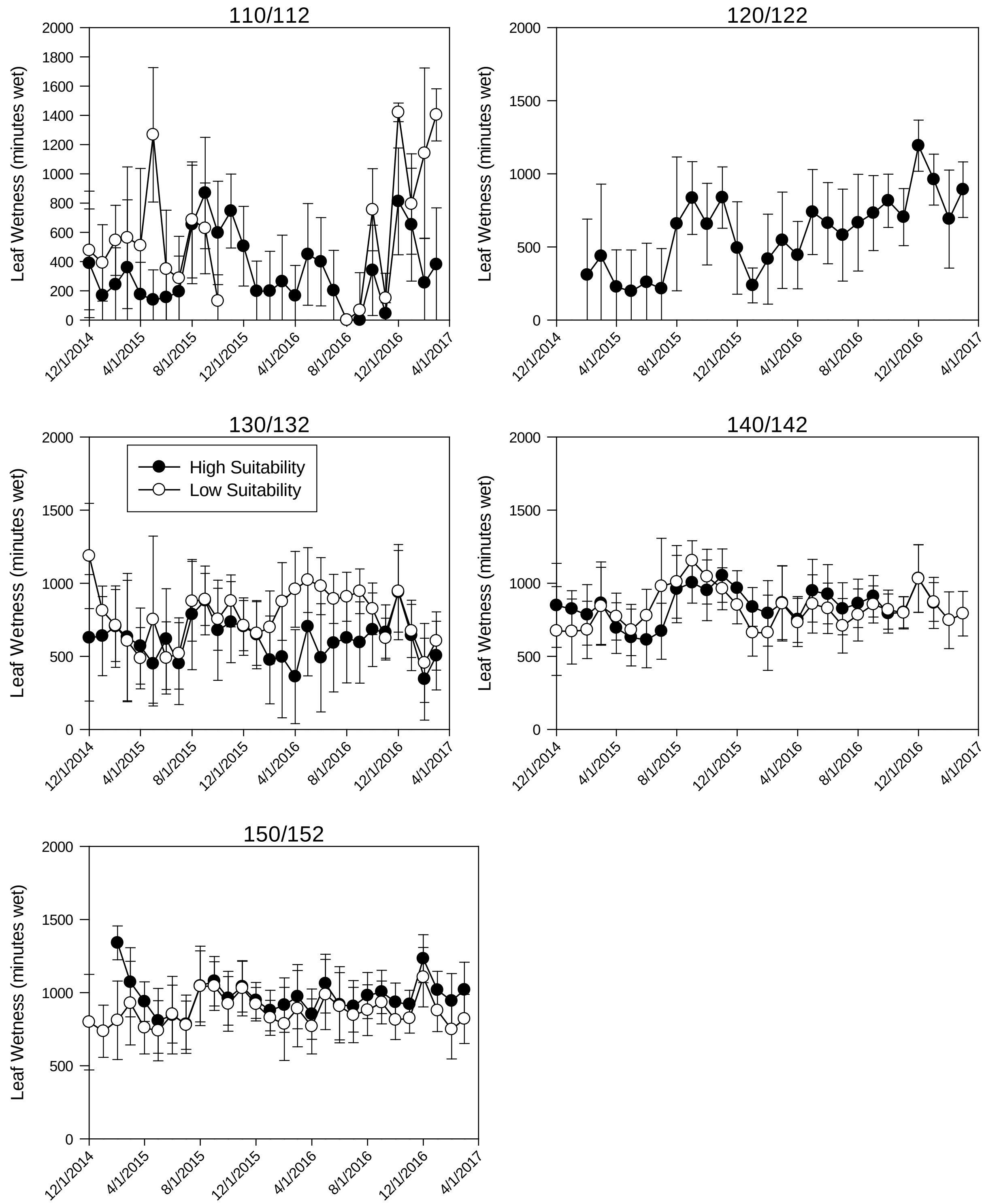


Fig. B7. Leaf wetness for pairs of plots at SMMNRA.

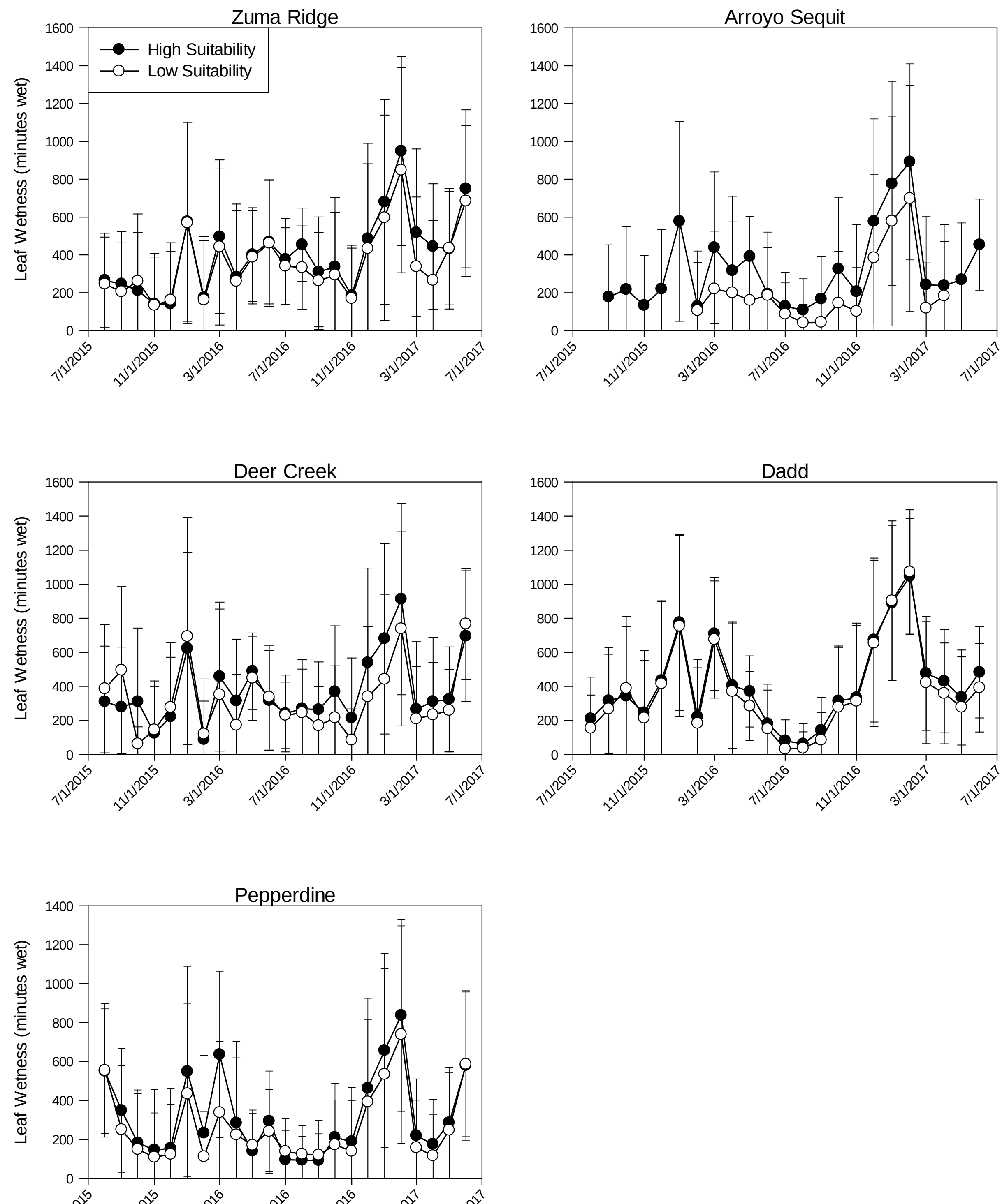


Fig. B8. Leaf wetness for pairs of plots at VBG.

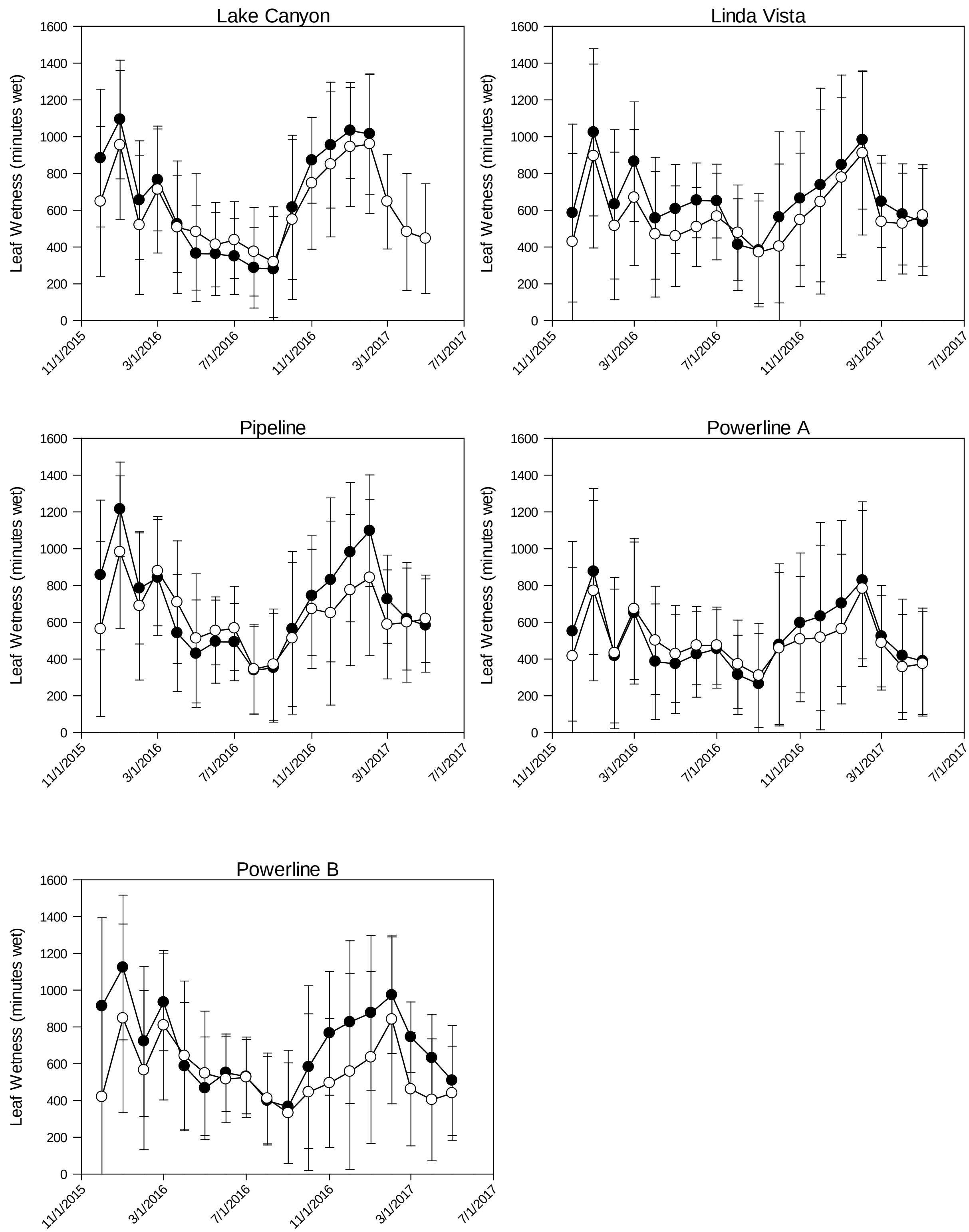


Fig. B9. Radar plot showing wind speed and direction in HS and LS at PTA.

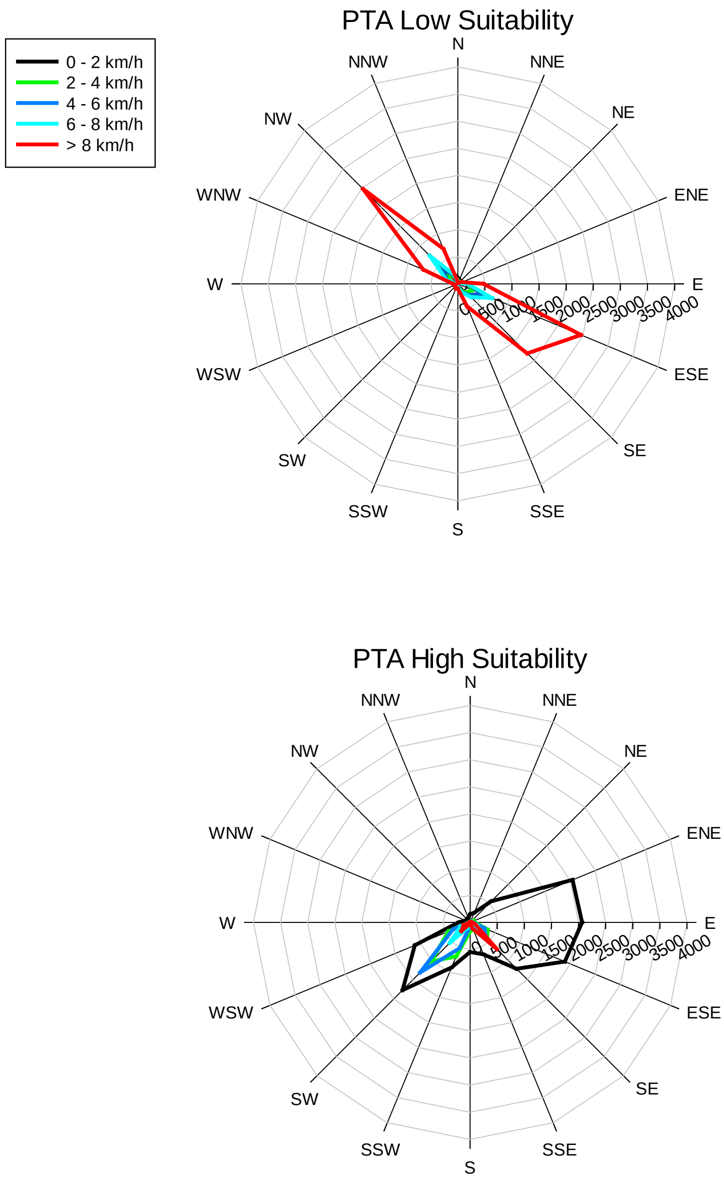


Fig. B10. Radar plot showing wind speed and direction in HS and LS at PWW.

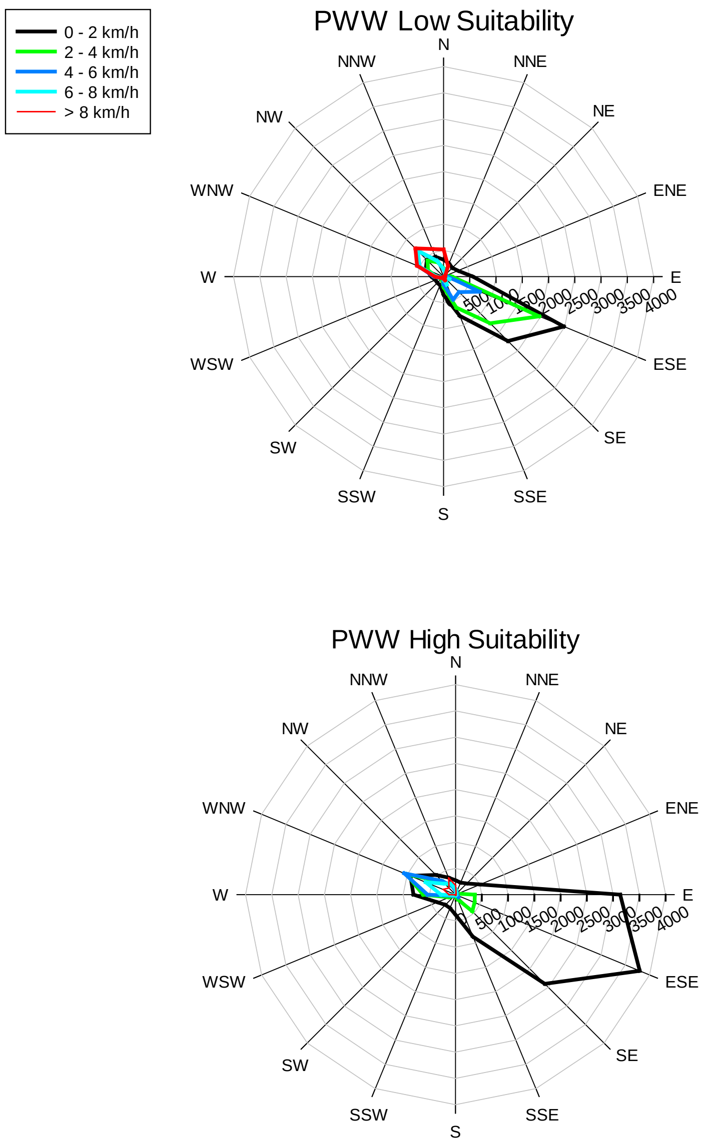


Fig. B11. Radar plot showing wind speed and direction in HS and LS at SMMNRA.

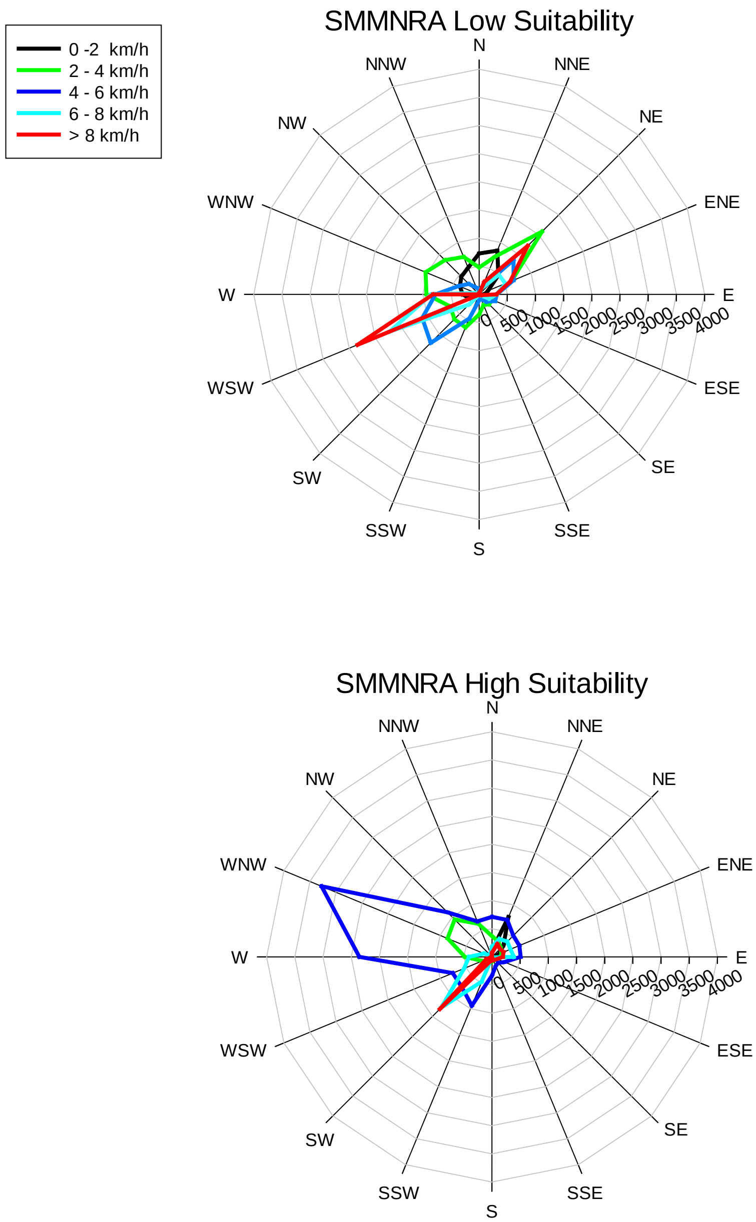
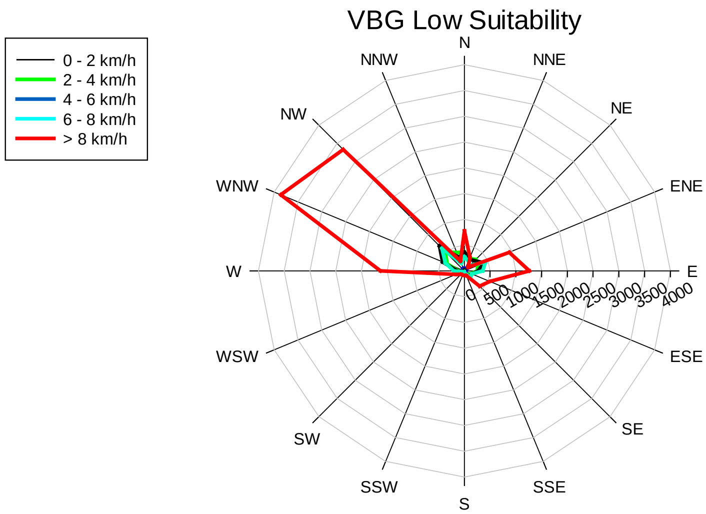
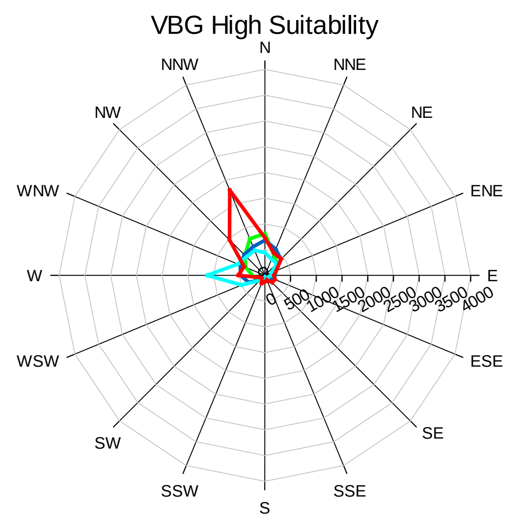


Fig. B12. Radar plot showing wind speed and direction in HS and LS at VBG.





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APPENDIX C AGREEMENTS

United States Department of the Interior

FISH AND WILDLIFE SERVICE

911 NE 11th Avenue
Portland, Oregon 97232-4181

IN REPLY REFER TO:
AES/Recovery

Dear Permittee:

Enclosed is your U.S. Fish and Wildlife Service recovery permit issued under section 10(a)(1)(A) of the Endangered Species Act (ESA), 16 U.S.C. 1531 *et seq.*, and its implementing regulations.

Please refer to the permit number in all correspondence and reports concerning permit activities. Engagement in any activity pursuant to this permit constitutes understanding and acceptance of the Special Terms and Conditions attached to your permit.

By accepting this permit and conducting activities authorized by it, you are agreeing to adhere to the attached terms and conditions. Failure to meet permit terms and conditions could result in ESA section 9 take violations, or suspension/revocation of this permit.

Please be aware that some species named in your recovery permit may also be listed under various State Endangered Species Acts or otherwise be of special concern to the States. As such, activities affecting those species may not be conducted without first obtaining the appropriate State permits. Possession of a federal permit does not render State authorization unnecessary.

If you have any questions regarding this matter, please contact Colleen Henson, Fish and Wildlife Biologist, at 503-231-6283. Thank you.

Sincerely,

Endangered Species Program Manager

Enclosures

United States Department of the Interior

FISH AND WILDLIFE SERVICE
911 NE 11th Avenue
Portland, Oregon 97232-4181

In Reply Refer to:
FWS/R1/AES/TE-77991A-0

LIST OF AUTHORIZED INDIVIDUALS
TE-77991A-0

Individuals authorized to independently conduct seed collection and take cuttings pursuant to this permit:

Susan Cordell, Elliot W. R. Parsons, Erin J. Questad and Amanda L. Uowolo.

Individuals authorized to independently conduct plant propagation pursuant to this permit:

Samuel Brooks, Susan Cordell, Howard Kaulana Hinds, David Janas, Elliot W. R. Parsons, Erin J. Questad and Amanda L. Uowolo.

Individuals authorized to independently outplant pursuant to this permit:

Samuel Brooks, Susan Cordell, Howard Kaulana Hinds, David Janas, Elliot W. R. Parsons, Erin J. Questad and Amanda L. Uowolo.

Supervised individuals may conduct specified activities pursuant to this permit only under the direct, on-site supervision of the independently authorized individuals named above. All individuals must be familiarized with appropriate procedures for collecting and handling, propagating, and outplanting the plant species named in this permit.

Supervised individuals will need to participate in at least four seed collection trips and four outplanting trips and have at least 6 months of plant propagation experience with the species named in this permit, before consideration for addition to the List of Authorized Individuals.

OCT 24 2012

Date

Endangered Species Program Manager

This List is valid only if dated on or after the permit issuance date.

DEPARTMENT OF THE INTERIOR
U.S. FISH AND WILDLIFE SERVICE

FEDERAL FISH AND WILDLIFE PERMIT

2. AUTHORITY-STATUTES
16 USC 1539(a)
16 USC 1533(d)

REGULATIONS
50 CFR 17.62
50 CFR 17.72

50 CFR 13

1. PERMITTEE

SUSAN CORDELL
dba USDA FOREST SERVICE
60 NOWELO STREET
HILO, HI 96720
U.S.A.

3. NUMBER
TE77991A-0

4. RENEWABLE	5. MAY COPY
[X] YES	[ ] YES
[ ] NO	[X] NO

6. EFFECTIVE	7. EXPIRES
10/24/2012	10/23/2016

8. NAME AND TITLE OF PRINCIPAL OFFICER *(If #1 is a business)*

9. TYPE OF PERMIT
NATIVE ENDANGERED & THREATENED SP. RECOVERY - E & T PLANTS

10. LOCATION WHERE AUTHORIZED ACTIVITY MAY BE CONDUCTED
ON LANDS SPECIFIED WITHIN THE ATTACHED SPECIAL TERMS AND CONDITIONS

11. CONDITIONS AND AUTHORIZATIONS:

A. GENERAL CONDITIONS SET OUT IN SUBPART D OF 50 CFR 13, AND SPECIFIC CONDITIONS CONTAINED IN FEDERAL REGULATIONS CITED IN BLOCK #2 ABOVE, ARE HEREBY MADE A PART OF THIS PERMIT. ALL ACTIVITIES AUTHORIZED HEREIN MUST BE CARRIED OUT IN ACCORD WITH AND FOR THE PURPOSES DESCRIBED IN THE APPLICATION SUBMITTED. CONTINUED VALIDITY, OR RENEWAL, OF THIS PERMIT IS SUBJECT TO COMPLETE AND TIMELY COMPLIANCE WITH ALL APPLICABLE CONDITIONS, INCLUDING THE FILING OF ALL REQUIRED INFORMATION AND REPORTS.

B. THE VALIDITY OF THIS PERMIT IS ALSO CONDITIONED UPON STRICT OBSERVANCE OF ALL APPLICABLE FOREIGN, STATE, LOCAL, TRIBAL, OR OTHER FEDERAL LAW.

C. VALID FOR USE BY PERMITTEE NAMED ABOVE.

D. Further conditions of authorization are contained in the attached Special Terms and Conditions.

[X] ADDITIONAL CONDITIONS AND AUTHORIZATIONS ALSO APPLY

12. REPORTING REQUIREMENTS
ANNUAL REPORT DUE: 01/31

ISSUED BY	TITLE	DATE
[signature]	ENDANGERED SPECIES PROGRAM MANAGER	10/24/2012

SPECIAL TERMS AND CONDITIONS
Susan Cordell

1. Acceptance of this permit serves as evidence that the permittee understands and agrees to abide by the "General Conditions for Native Endangered and Threatened Species Plant Permits," 50 CFR Part 13 (general permit regulations), 50 CFR 17.62 (endangered plants), and/or 50 CFR 17.72 (threatened plants), as applicable (copies attached). In addition, the permittee must have all other applicable Federal and State permits prior to the commencement of activities authorized by this permit.

2. The permittee is authorized to remove and reduce to possession *Colubrina oppositifolia* (kauila), *Haplostachys haplostachya* (honohono), *Pleomele hawaiiensis* (halapepe), *Portulaca sclerocarpa* (ihi makole), *Silene hawaiiensis* (Sherff's catchfly), *Silene lanceolata* (lanceolate catchfly), *Spermolepis hawaiiensis* (Hawaiian spermolepis), *Stenogyne angustifolia* (narrowleaf stenogyne), and *Zanthoxylum hawaiiense* (ae), for the purpose of biological and ecological research, as specified in the permittee's June 15, 2012, permit request, in accordance with the Special Terms and Conditions stated below.

3. Permitted activities are restricted to the following geographic areas in the State of Hawaii:

   Pohakuloa Training Area, Island of Hawaii.
   Puu Waawaa Forest Reserve, Island of Hawaii.

4. Authorized Individuals:

   Only individuals on the attached List of Authorized Individuals (List) are authorized to conduct activities pursuant to this permit. The List, printed on U.S. Fish and Wildlife Service (Service) letterhead, may identify special conditions or circumstances under which individuals are authorized to conduct permitted activities and must be retained with these Special Terms and Conditions. Each named individual shall be responsible for compliance with the Special Terms and Conditions of this permit.

   To request a change to the List, the permittee shall submit a written request to the Recovery Permit Coordinator at the Service's Pacific Islands Fish and Wildlife Office (PIFWO), 300 Ala Moana Boulevard, Room 3-122, Honolulu, Hawaii 96850 (telephone: 808-792-9400; fax: 808-792-9581). Two copies of the request shall be submitted at least 30 days prior to the requested effective date. The request shall be signed and dated by the permittee and include:

   a. The name of each individual to be appended to the List, if any;

   b. The title of their current position and employer's name for each individual;

   c. The resume/qualifications statement of each individual to be appended to the List, plus specific information on previous professional experience working with the species affected by the permit request. This information should include: the approximate number of hours of focused activity with each species in occupied habitat; approximate numbers of each species the applicant has worked with at each site (*e.g.*, how many plants at a specific site(s)); names, dates, and location of areas surveyed; and experience with similar species;

d. The names and phone numbers of a minimum of two references for each individual to be appended to the List; and

e. The names of any individuals to be deleted from the List.

Note: This procedure is for changes to the List only. For requests to renew/amend this permit, a complete application must be submitted to the Endangered Species Program Manager at the Service's Pacific Regional Office (PRO), Ecological Services, 911 NE 11th Avenue, Portland, Oregon 97232-4181. Applications may be obtained at www.fws.gov/forms/3-200-55.pdf.

5. The permittee is authorized to remove/reduce to possession specified parts (seeds) from no more than 10 individuals of each species per subpopulation and no more than 40 individuals within the geographic boundaries specified above and the time limits specified in the permit, take cuttings of *Stenogyne angustifolia*, and collect 3 leaves from mature outplants of all species for nutrient analysis, provided that the following conditions are met:

a. For seeds to be collected from a species' subpopulation, the number of individuals in the subpopulation must be at least 15 individuals.

b. No more than 10 percent of the seed from an individual plant may be collected.

c. No more than 800 seeds shall be collected for any one species.

d. If the plant is on a steep slope with roots exposed, the plant shall not be approached and no samples shall be collected.

e. No plants shall be climbed to obtain seed samples.

f. All propagation material collected shall be cultivated following the Hawaii Rare Plant Restoration Group's (HRPRG) "Phytosanitation Standards and Guidelines" located at http://www.hear.org/hrprg.

g. Outplants in the field shall be monitored for survival and physiological performance a minimum of 5 years after outplanting and provided supplemental water if climatic conditions are extreme.

h. The permittee is allowed to collect up to 3 cuttings (leaves and/or small stems) from 5 to 10 *Stenogyne angustifolia*. Cuttings shall be taken from plants in different subpopulations. Additionally, the permittee is allowed to collect up to three leaves (approximately 5 grams dry weight) from each out plant at maturity for all species. If leaves are big, only sufficient material will be taken for 5 grams dry weight. All cuttings collected from *Stenogyne angustifolia* and all leaf collections from mature outplants shall be conducted by appropriate Listed Authorized Individuals for the specific task. Permittee(s) shall follow the Hawaii Rare Plant Restoration Group (HRPRG), "Protocols for Collecting and Handling Native Hawaiian Plants" and "Revised Draft Policy-Collection of Endangered Plants" located at http://www.hear.org/hrprg/.

6. No wild plants are anticipated to be accidentally damaged or destroyed while conducting activities pursuant to this permit. In the event that a *Colubrina oppositifolia, Haplostachys haplostachya, Pleomele hawaiiensis, Portulaca sclerocarpa, Silene hawaiiensis, Silene lanceolata, Spermolepis hawaiiensis, Stenogyne angustifolia,* or *Zanthoxylum hawaiiense* plant is accidentally damaged or destroyed, the permittee shall:

   a. Immediately cease the activity that resulted in the damaged or destroyed plant until reauthorized by the PRO, which may, after analysis of the circumstances of the damage or destruction, revoke or amend this permit.

   b. Immediately notify the PRO (telephone: 503-231-6131; fax: 503-231-6243) and the PIFWO (telephone: 808-792-9400; fax 808-792-9580) by telephone or facsimile. Such notification must be followed up in writing to both the PRO and PIFWO within 3 working days at which time the permittee must provide a report of the circumstances that led to the damage or destruction; the date, time, and precise location of the damaged or destroyed specimen; disposition of the damaged specimen or suggested disposition of the dead specimen (see Special Term and Condition 7 below); and a description of the changes in activity protocols that will be implemented to reduce the likelihood of such damage or destruction from reoccurring, if appropriate. The incident should also be discussed in the annual report that is subsequently submitted to the Recovery Permit Coordinator at the PIFWO and the PRO.

   c. Preserve any dead specimens in accordance with standard museum practices. Before expiration of the permit, all specimens shall be properly labeled and deposited with the designated depository listed below. The permittee shall supply the depository with a copy of this permit to validate that the specimens were taken pursuant to this permit.

7. Designated Depository:

   a. The Bernice Pauahi Bishop Museum (Bishop Museum), Botany Collection Manager, 1252 Bernice Street, Honolulu, Hawaii 96817 (telephone: 808-848-4177).

   b. If the Bishop Museum does not wish to accession the specimens, the permittee shall contact the Service's Division of Law Enforcement (LE) in Honolulu, Hawaii (telephone: 808-861-8525) for further guidance.

c. If Service LE does not wish to accession the specimens, the permittee shall contact the PIFWO.

d. All depository specimens are to be reported in the annual report.

8. Precautions must be taken to prevent accidental ignition of a wildfire (*e.g.*, prohibit smoking); the introduction of alien weeds by boots and equipment; trampling of plant life; and unnecessary creation of trails that might enhance feral animal access or growth of alien species.

9. The plant species covered by this permit shall be outplanted and monitored. If any plants grown from seed are held back or there are progeny from these plants, these plants shall not be sold, donated, or transferred without written authorization from the Service. This Special Term and Condition applies until the authorized disposal of the subject species and their progeny is complete regardless of the expiration date of this permit. Genetic material may not be used for the unauthorized replication of the species or for other genetic experimentation other than that which is expressly authorized pursuant to the Special Terms and Conditions of this permit.

10. All reports, publications, or other documents that include information gathered under the authority of this permit (*e.g.*, reports prepared by consulting firms for their clients) shall reference this permit. Copies of such documents shall be provided to the PIFWO and PRO immediately upon their completion. Draft documents, raw/field notes, and other information resulting from work conducted under the authority of this permit shall be submitted to the Service upon request.

11. Annual Reports:

a. An annual report of activities shall be submitted to the Recovery Permit Coordinator at the PIFWO and PRO by January 31 following each year that this permit is in effect. The report shall be in the following format:

i. An introduction addressing reasons and objectives for removing and reducing to possession the species, as appropriate;

ii. A methodology section addressing data collection, analysis procedures and personnel working on the project;

iii. A results section that provides the data collected, including information on any other federally listed species detected while conducting activities authorized under this permit; and

iv. A brief discussion of significant research results and a conclusion section that specifically provides, at a minimum, recommendations for potential recovery of the species.

b. The report shall include, but not be limited to, the following information: HRPRG's "Rare Plant Background Information Form" and "Rare Plant Field Data Form" which are located at http:/www.hear.org/hrprg. Additionally, the following information must be provided:

i. The amount and type of specimens collected from each plant and the disposition of the collected specimens;

ii. The source of each propagule and maps indicating where the material was collected;

iii. Photos of the population(s) and habitat from which material was collected;

iv. Success or failure of propagation attempts;

v. Outplanting and transplanting locations; and

vi. Success or failure of outplanting attempts.

c. Copies of any other Federal and/or State permits required to perform permitted activities shall be submitted with the annual report.

d. Submission of Annual Reports:

i. One copy of an annual report (electronic format preferred) is required to be submitted to the Recovery Permit Coordinator at the PIFWO and the PRO each calendar year. Annual reports may be submitted electronically to the following email addresses:
PIFWO: FW1PIE-RecPermitAnnRpt@fws.gov
PRO: permitsR1ES@fws.gov.
Add the following subject line to the email: Annual report for recovery permit number TE-77991A-0.

ii. All email file attachments combined are limited to 25 megabytes in size. If electronic files exceed this size limitation, please copy them onto a DVD or CD (preferred submission) or send them as a printed document(s).

e. If no activities occurred over the course of a year, indication of such shall be submitted as an annual report.

12. Failure to comply with the reporting requirements may result in non-renewal or suspension/revocation of this permit.

OCT 24 2012
Date

Endangered Species Program Manager

United States Department of the Interior

FISH AND WILDLIFE SERVICE
911 NE 11th Avenue
Portland, Oregon 97232-4181

Revised August 2011

GENERAL CONDITIONS FOR NATIVE ENDANGERED AND THREATENED PLANT SPECIES PERMITS

1. All sections of Title 50 Code of Federal Regulations Part 13 (50 CFR 13) are conditions of the permit.

2. All applicable foreign, State, local, tribal, or other Federal laws, including trespass laws, and other laws requiring permits, must be observed.

3. The permittee must carry a copy of the permit while conducting authorized activities.

4. The permit number must be legibly printed on all documents and advertisements involving activities conducted under a permit.

5. Living plants must be prepared and shipped so as to minimize the risk of damage to the plants and to comply with U.S. Department of Agriculture/Animal & Plant Health Inspection Service regulations.

6. The container in which authorized plants are shipped must be plainly marked with the names and addresses of shipper and consignee, and with an accurate description of contents. An identification tag or label containing the following information must accompany the plant and its container during the course of any activity authorized by this permit: (a) the scientific name; (b) the words "artificially propagated" or wild", whichever is applicable; and (c) the U.S. Fish and Wildlife Service (Service) permit number.

7. Permits authorizing the sale of artificially propagated plants must be used only for the enhancement of propagation or survival of the species listed in the permit. With each sale, the permittee is encouraged to provide recipients with educational information about the species, including its range and status in the wild, as well as directions for adequate care of the specimens.

8. Unless otherwise specified on the permit, the required annual report must include the following information for each species authorized under the permit.

   For **wild plants**: a complete report of activities conducted under authority of the permit.

   For **artificially propagated plants**: (a) number of specimens held at present; (b) number of specimens produced at the permittee's facility during the year; (c) number of specimens purchased or otherwise acquired by the permittee during the year, including the complete name and address of the person from whom the specimens were acquired; and (d) number of specimens sold in interstate commerce during the year and names and addresses of buyers.

9. At the discretion of the Service, a Service employee may inspect the facilities or accompany the permittee during any activity conducted pursuant to this permit. The permittee shall allow Service personnel complete and immediate access to any materials and information generated as a result of this permit. Any refusal, obstruction, or hindrance of Service participation in such work shall be grounds for suspension or revocation of this permit in accordance with 50 CFR 13.27 or 50 CFR 13.28, respectively.

THE FOLLOWING CONDITIONS APPLY UNTIL AUTHORIZED DISPOSAL OF THE PLANTS (LIVE OR DEAD), AND THEIR PROGENY, REGARDLESS OF THE EXPIRATION DATE OF THE PERMIT:

10. Unless otherwise authorized on the face of the permit, the authorized plant may NOT be sold, donated, or transferred without written authorization from the Service.

11. Any dead authorized plant shall be preserved according to standard museum practices and held for scientific purposes whenever practical.

PERMIT FOR THREATENED AND ENDANGERED PLANT SPECIES
Department of Land and Natural Resources
Division of Forestry and Wildlife
1151 Punchbowl Street, Room 325
Honolulu, Hawaii 96813
(808) 587-0165, Fax (808) 587-0160

Permit No. **P-177**
Date of Issue: **July 15, 2012**
Expiration Date: **July 14, 2013**

The Board of Land and Natural Resources hereby grants permission under the authority of Hawaii Administrative Rules §13-104, §13-107, and §13-124, Hawaii Revised Statutes §195D and all other applicable laws, to the person(s) listed below.

Persons in violation of the terms and conditions of this permit and /or related or appropriate laws may be subject to criminal and or administrative penalty under Hawaii Revised Statutes 195D-8, §195D-9, §195D-27, §183-4, §183-5, § 183-18, §183-21, §183C-7, §171-6.4 §171-31.6, Hawaii Administrative Rules §13-104-3, §13-107-8, or as otherwise provided by law.

Susan Cordell
USDA Forest Service
60 Nowelo Street
Hilo, Hawaii 96720

Phone: 808-854-2628
Email: Scordell01@fs.fed.us

To collect, possess, propagate, transfer, and outplant for the purpose of research, the following **endangered** plant life:

Colubrina oppositifolia
Haplostachys haplostachya
Pleomele hawaiiensis
Portulaca sclerocarpa
Silene hawaiiensis
Silene lanceolata

Spermolepis hawaiiensis
Stenogyne angustifolia
Zanthoxylum hawaiiense

To create 3 to 5 paired Class 3 and Class 0 test plots (with a total of 6-10 plots) in Puu waawaa to perform experimental outplantings of selected T&E species. These plots will be use to test if topographic models derived from airborne Light Detecting and Ranging (LiDAR) data can accurately predict habitat suitability for T&E species in dry habitats. These models may provide information on how to increase plant performance and survival of T&E outplanting programs.

A greenhouse will be constructed for plant propagation at Puu waawaa. Seven species will be outplanted at PTA and 2 species at Puu waawaa. Outplanting may occur in 2013 in fenced areas and monitoring of plants will occur for at least 10 years after planting. Environmental conditions will also be monitored. The permit holder(s) will work with Puu waawaa and DOFAW staff on propagating plants using the best technique for each species and use locally-collected materials.

Subject to the following conditions:

I. GENERAL CONDITIONS

A. This permit authorizes the permit holder(s) to conduct described activities at Puu waawaa.
B. Activities conducted in DOFAW's Natural Area Reserves System (NARS) require a Special Use Permit. Activities conducted on other lands under the jurisdiction of DOFAW/DLNR, will require access permits.
C. The permit holder(s) must obtain approval from other landowners on lands where activities are planned, including other divisions of the DLNR, private landowners, tenants, and County, State, and Federal agencies prior to conducting activities on lands under their jurisdiction.
D. This permit is not transferable or assignable. A signed copy must be carried by permit holder(s) while engaging in activities authorized by this permit. Each permit holder is individually responsible and accountable for his or her actions under this permit.
E. This permit does not authorize activities with any other plant species except those stated. Permission to collect additional plant material must be obtained from district DOFAW offices.
F. Appropriate DOFAW district office must be notified in advance of proposed fieldwork, for a access permit, to coordinate collections, plant propagation needs, district requests, and approval of additional field personnel other than the listed associates for state reintroduction projects and/or their island cooperators.
G. Primary repositories are cooperating rare plant nurseries for live storage. Lyon micropropagation laboratory (for tissue culture) and seed storage facilities (for seed storage) are secondary depositories for these propagules.
H. This permit does not in any way make the Board of Land and Natural Resources of the State of Hawaii liable for any claims of personal injury or property damage to the permit holder(s) or his or her party which may occur while engaged in activities permitted under this permit;

further, the permit holder(s) agrees to hold the State harmless against any claims of personal injury, death or property damage resulting from the activities of the permit holder(s).

I. This permit shall become valid upon completion of the following:

1. **All persons who are actively involved in activities authorized by this permit have read this permit in its entirety and acknowledge understanding & agreement to abide by its conditions by signing this permit.**
2. **The signed permit is returned to DOFAW. Upon approval by the DOFAW Administration, a copy of the signed permit will be returned to the principal investigator.**

J. The permit holder(s) will provide copies of all publications/reports of any study resulting from the activities of this permit to DOFAW. The permit holder(s) will also provide or make available for inspection any raw data that is obtained under this permit when requested by the Division.

K. Any person violating any of the conditions stipulated under this permit will be subject to the penalty provision provided by law. Further, any infractions of this permit may be cause for revocation of this permit and/or denial of future permit requests.

L. This permit is issued for one year. This permit can be renewed at the end of this period. Please submit plans for the coming year and the need for permit renewal or extension before expiration of present permit.

II. SPECIAL CONDITIONS

A. The purpose of this permit is collection, possession, propagation, transferring and outplanting of rare Hawaiian plants for a research project.

B. Propagules resulting from this permit can be accessed for conservation programs focusing on plant restoration and outplanting programs.

C. When collecting, highest priority should be given to plants that have secure outplantings sites, are needed by district DOFAW nurseries or their cooperators, or are needed to complete genetic representation in *ex situ* collections.

D. Collection of viable seed is the preferred propagation material, whenever possible, rather than cuttings of T&E species. The permit holder(s) will keep records of date of seed or propagule collection and estimates of the number of seeds or propagule collected. This information will be provided to DOFAW in the annual report with an inventory of green house plants resulting from present and past collection permits.

E. Permit holder(s) is strictly prohibited from collecting whole plants unless under specific DOFAW request.

F. In advance of entry, permit holder(s) will notify the Puu waawaa Coordinator and District DOFAW of communication contacts in the field (cell phone/radio) and notify authorities of specific collection dates and times.

G. The permit holder(s) will adhere to methods that are in accordance with established procedures as published by the Hawaii Rare Plant Restoration Group (HRPRG) for collection of Threatened and Endangered species. Completion of HRPRG Rare Plant Monitoring Forms is required for all collections.

H. New/rare species or species thought to be extinct may be collected under this permit provided the above conditions are followed. For new populations or new species, completion of the HRPRG Rare Plant Monitoring forms is required.

I. Yearly reports with collection information are required and will be in electronic form. If a new population is discovered, GPS information will be supplied when possible.

The undersigned have read, understood, and hereby agree to abide by the conditions as stated above.

Principal Investigators:

Susan Cordell — 7/23/2012
Susan Cordell, Principal Investigator — (Date)

7/10/2012
Erin Questad, Principal Investigator — (Date)

James R. Kellner — 7/18/2012
James R. Kellner, Principal Investigator — (Date)

Associates:

Amanda Uowolo

Sam Brooks

Kealoha Kinney

David Janas

State of Hawaii
Department of Land and Natural Resources
Division of Forestry and Wildlife
1151 Punchbowl Street Room 325
Honolulu, Hawaii 96813

License No. P-177

Date of Issue: July 15, 2012

Expiration Date: July 14, 2013

Kaulana Hinds

APPROVED: ______________________ Date 7/27/12

PAUL CONRY, Administrator,
Hawaii Division of Forestry and Wildlife

USDA United States Department of Agriculture | Forest Service | Pacific Southwest Research Station | Institute of Pacific Islands Forestry
60 Nowelo Street
Hilo, HI 96720
(808) 933-8121 Fax: (808) 933-8120

File Code: 1560
Date: 22 January 2013

The purpose of this letter is to formalize in writing the agreement between the State of Hawaii, Division of Forestry and Wildlife (DOFAW) and the USDA Forest Service, Institute of Pacific Islands Forestry (IPIF) for construction, access, and use of the greenhouse facility at Pu'u Wa'a Wa'a Forest Reserve in the Hawaii Tropical Experimental Forest. DOFAW is the land manager where the greenhouse facility will be located. This collaboration is facilitated by our Cooperative Agreement in support of the Hawaii Experimental Tropical Forest and its associated 65 year lease.

The cost of the greenhouse structure, supplies, and its construction will be paid by IPIF. The greenhouse will be constructed on an existing concrete foundation on State lands. The greenhouse facility is intended for the propagation and care of threatened and endangered plant species (TER-S) of Pu'u Wa'a Wa'a and the dryland forest, and will be shared with DOFAW and other potential users for propagation and research needs. From 2013-2018 priority will be given to house the plants that will be utilized for the IPIF Environmental Security Technology Certification Program (ESTCP) demonstration project. In future years, the facility will be available to meet local needs, including use by the US Forest Service, DOFAW and other partners.

For the duration of the ESTCP project, 2013-2018, the DOFAW and the IPIF agree that -

- Priority will be given to house the plants that will be utilized for the ESTCP demonstration project.
- Maintenance expenses and the water utility cost will be paid by IPIF.
- The DOFAW Quonset Hut water meter will be used to supply water to the greenhouse. The water meter will be kept in DOFAW's name with a c/o IPIF for billing.
- Any repair/replacement of the above ground pipe from the meter to the greenhouse would be covered by IPIF.
- All pests will be monitored and controlled following appropriate regulations by IPIF.
- IPIF will arrange for access to the greenhouse through coordination between the IPIF HETF Coordinator (Melissa Dean) and the Pu'u Wa'a Wa'a site coordinator (Elliott Parsons).
- The IPIF point of contact for greenhouse space, maintenance, and the utility bill will be Samuel Brooks, Ecologist at: sebrooks@fs.fed.us and (808) 854-2668.

This agreement may be amended as necessary to meet the needs of DOFAW and IPIF.

Paul Scowcroft
Acting Director
Institute of Pacific Islands Forestry
Pacific Southwest Research Station
USDA Forest Service
60 Nowelo Street
Hilo, HI 96720

Steve Bergfeld
Acting Forestry and Wildlife Manager
Division of Forestry and Wildlife
Department of Land and Natural Resources
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