EXECUTIVE SUMMARY

Remote Sensing Technology for Threatened and Endangered Plant Species Recovery

ESTCP Project RC-201203

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1.0 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 is 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. The habitat

suitability modeling (HSM) technology formally incorporates the importance of wind into topographic modeling to improve plant growth and survival, and to use the information for landscape planning for the reintroduction and management of at-risk species. The research team 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).

The research team 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). LiDAR data from The Carnegie Airborne Observatory was used to produce a digital elevation model (DEM) for PTA. The DEM was then used 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 HSM for outplanting with three suitability classes: no criteria met (Low Suitability [LS)], one criterion met (Moderate Suitability [MS]), and two criteria met (High Suitability (HS)). The 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.

2.0 OBJECTIVES OF THE DEMONSTRATION

Three tasks were used to demonstrate how the 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. TER-S was experimentally planted into replicate LS and HS areas at PTA and PWW. Survival and measures of plant and population performance were monitored to determine how plants respond differently to restoration in different suitability classes. Plants were evaluated as to whether they had greater survival and growth and reduced plant stress in HS, compared to LS, sites.
2. With Task 2, methodology was developed for generating HSMs from high resolution satellite data. The 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. Optical stereo measurements were used from the WV-2 satellite and compared its cost and performance to LiDAR.
3. In Task 3, the research team quantified the cost of implementing the HSM technology as well as the cost savings that can result from using the HSM technology. Materials were developed for technology transfer including a software extension for ArcGIS.

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3.0 TECHNOLOGY DESCRIPTION

The HSM technology identifies habitat suitability based on topography using Digital Elevation Models (DEM) 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 [MS]), and two criteria met (High Suitability [HS]).

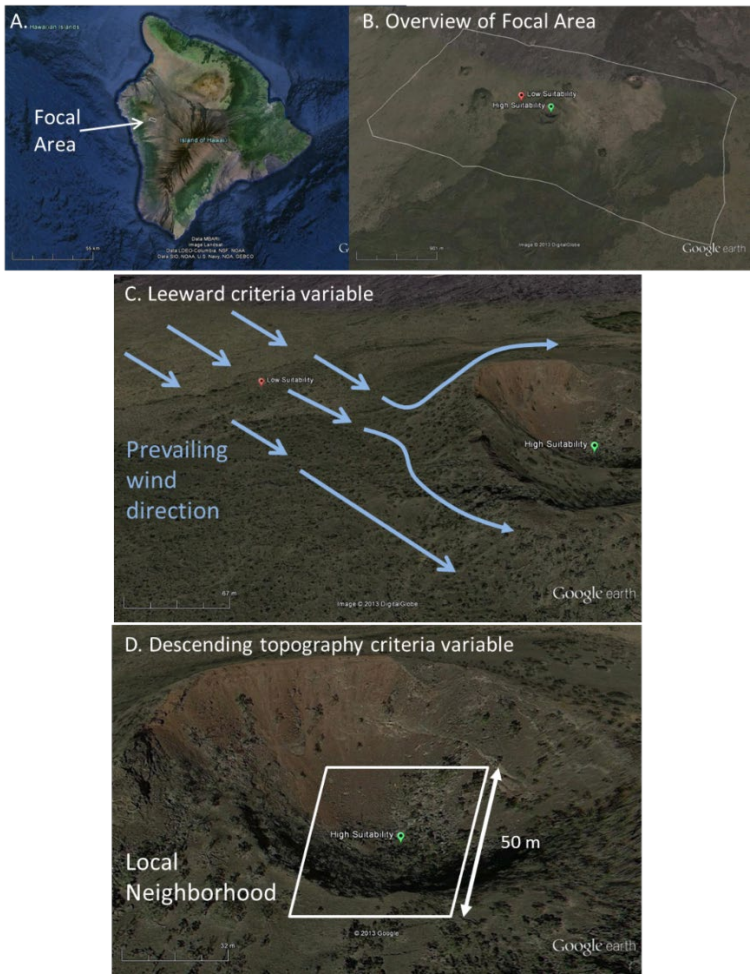

Figure ES1. Diagram of Suitability Criteria Variables.

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).

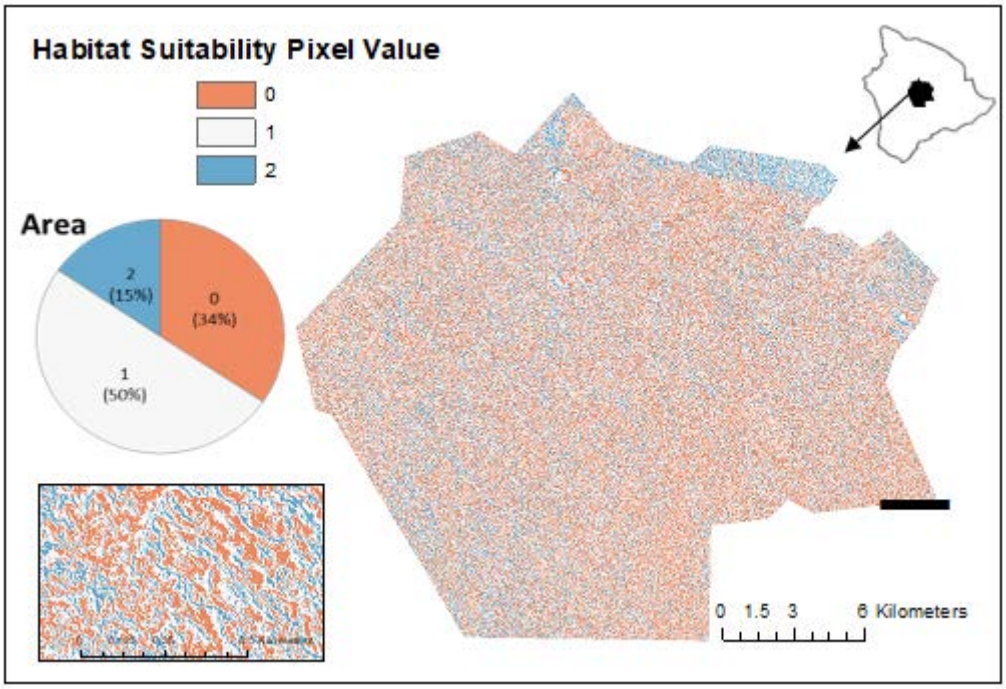

Figure ES2. Habitat Suitability Model Map for Pohakuloa Training Area (PTA), Hawaii.

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.

4.0 PERFORMANCE ASSESSMENT

The demonstration included six performance objectives (PO) (Table E1):

4.1 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.

4.2 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 either recruitment or reproductive output during the study period.

4.3 PO3. SPATIAL CORRESPONDENCE OF SUITABILITY CLASSES

Elevation values from airborne LiDAR were compared 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.

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

The research team measured weather and microclimate variables in the field that correspond with conditions important for plant growth at all four sites. Overall, the research team 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.

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

The research team tested whether existing populations of TER-S at VBG and PWW corresponded with the suitability classes, similar to the analysis of TER-S at PTA. This analysis allowed the research team 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 nor eight species at PWW showed 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.

4.6 PO6. EASE OF USE

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

4.7 SUMMARY ASSESSMENT

The data indicated success for three of the six performance objectives for this demonstration (POs 3, 4, and 6), partial success for two performance objectives (POs 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 the 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. Partial success was found for PO5, in which two species were associated with HS areas but 11 others were not. The 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 (PO 1). Overall, the research team has produced a method for others to implement HSMs into landscape planning for TER-S conservation. Based on the 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 /	• 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	• 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]	• 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.

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
	decreased stress	rates of photosynthesis and quantum yield) and plant functional traits (leaf nutrient content and specific leaf area)	• Statistically significant increase in physiological performance in HS over LS areas.[2]	

Table E1. Performance Objectives and Results (Continued)

Performance Objective	Metric	Data Requirements	Success Criteria[1]	Results
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: r2* = 0.998, *P* < 0.001 • *VBG: r2* = 0.934, *P* < 0.05
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 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/km2 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.

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5.0 COST ASSESSMENT

Imagery costs are the main area for cost comparison for the project, and the research team 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. The research team 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 the analysis:

1. Despite claims of the ease of acquisition, stereographic satellite imagery was surprisingly difficult to acquire due to cloud cover. It is noted 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 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 Root Mean Square Error (RMSE). The use of third-party software was explored 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. A quote was requested 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 the analysis of using WV-2 data for DEMs it was 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, the opinion of the research team 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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6.0 IMPLEMENTATION ISSUES

Implementation of the HSM is straightforward and simple. During this demonstration, a user-friendly GIS Toolbox was developed that is available for others to use (http://www.cpp.edu/~ejquestad/HSMhome.shtml). Guides were developed 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 the 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. The 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.

The 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. Numerous measures of growth and physiology were found to be 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, the research team performed an extensive interview survey of regional managers and native plant growers in order to determine the best techniques for propagating each species (e.g., seed, cuttings). All propagation protocols were documented in the Hawaiian Native Plant Propagation Resource, which is available online (Janas et al. 2015). A standard method was developed 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.

No differences were found in survival in HS sites during the time of this demonstration, which could deter some users from implementing the HSM. However, it was 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.

In conclusion, 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.