Department of Defense
Legacy Resource Management Program

LEGACY PROJECT NUMBER 11-320

Direct Seeding for Restoration of Coastal Wetlands in Hawai‘i

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November 2012

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TABLE OF CONTENTS

LIST OF FIGURES

1.0 EXECUTIVE SUMMARY

This technical report represents one of the final deliverables for the 2011 Legacy Resource Management Program project number 11-320 (Cooperative agreement **W9132T-11-2-0037**), titled *Developing coastal wetland restoration techniques to enhance coastal habitats at Ahua Reef, Hickam Air Force Base, Hawai‘i*. This project was developed and completed by SWCA Environmental Consultants (SWCA) to investigate species-specific techniques for seeding and outplanting Hawaiian coastal wetland plant species following different invasive species control strategies and subsequent management activities (i.e., weeding and supplemental watering). The experimental restoration project was carried out at Āhua Reef on Joint Base Pearl Harbor-Hickam (JBPHH), formerly Hickam Air Force Base, O‘ahu.

Outplanting is the most commonly used technique to increase native species cover in wetlands. Seeding may offer a simpler and more affordable restoration method than outplanting in wetlands, particularly for large-scale restoration projects. However, seeding in wetlands using standard seeding techniques can be problematic due to issues with proper germination conditions. Globally, very few field-based seeding studies have been published on seeding in wetlands. In Hawai‘i, there have been no studies investigating the results of seeding in wetlands. Although a few managers and biologists have attempted seeding in Hawaiian wetlands, information observed from these studies is limited.

The purpose of this report is to briefly describe the lessons learned during the seeding portion of SWCA's experiment at Āhua Reef and summarize the scant information that exists on seeding in Hawaiian wetlands. While it is difficult to provide a comprehensive guide to seeding in coastal wetlands (as originally intended), this report offers recommendations for Department of Defense managers considering using seeding to restore coastal wetlands in Hawai‘i.

Based on the results observed during this study, as well as information gathered from other seeding efforts, broadcast seeding or using seed + tackifier slurries should not be used as the primary means of revegetation in coastal wetlands. The largest unknowns with this method are the germination and establishment rates because seeds are either washed away by tides and fluctuating water levels, are buried too deep to allow light for germination, or are lacking other germination requirements. Outplanting seedlings is more likely to result in higher cover of native species. However, experimenting with small-scale seeding efforts can be implemented to augment outplanting or other restoration techniques. Finally, new techniques for seeding (such as Submerseed®) could be investigated to complement labor intensive, yet effective, outplanting efforts.

2.0 INTRODUCTION

In August 2011, SWCA Environmental Consultants (SWCA) was awarded funding through the Department of Defense (DoD) Legacy Program to conduct an experimental restoration project at Āhua Reef on Joint Base Pearl Harbor-Hickam (JBPHH), formerly Hickam Air Force Base, Oʻahu. The project is titled *Developing coastal wetland restoration techniques to enhance coastal habitats at Ahua Reef, Hickam Air Force Base, Hawaiʻi* (Legacy project number 11-320). The objective of this project was to investigate species-specific techniques for seeding and outplanting Hawaiian coastal wetland plant species following different invasive species control strategies (i.e., herbiciding and manual removal) and subsequent management activities (i.e., weeding and supplemental watering) at Āhua Reef.

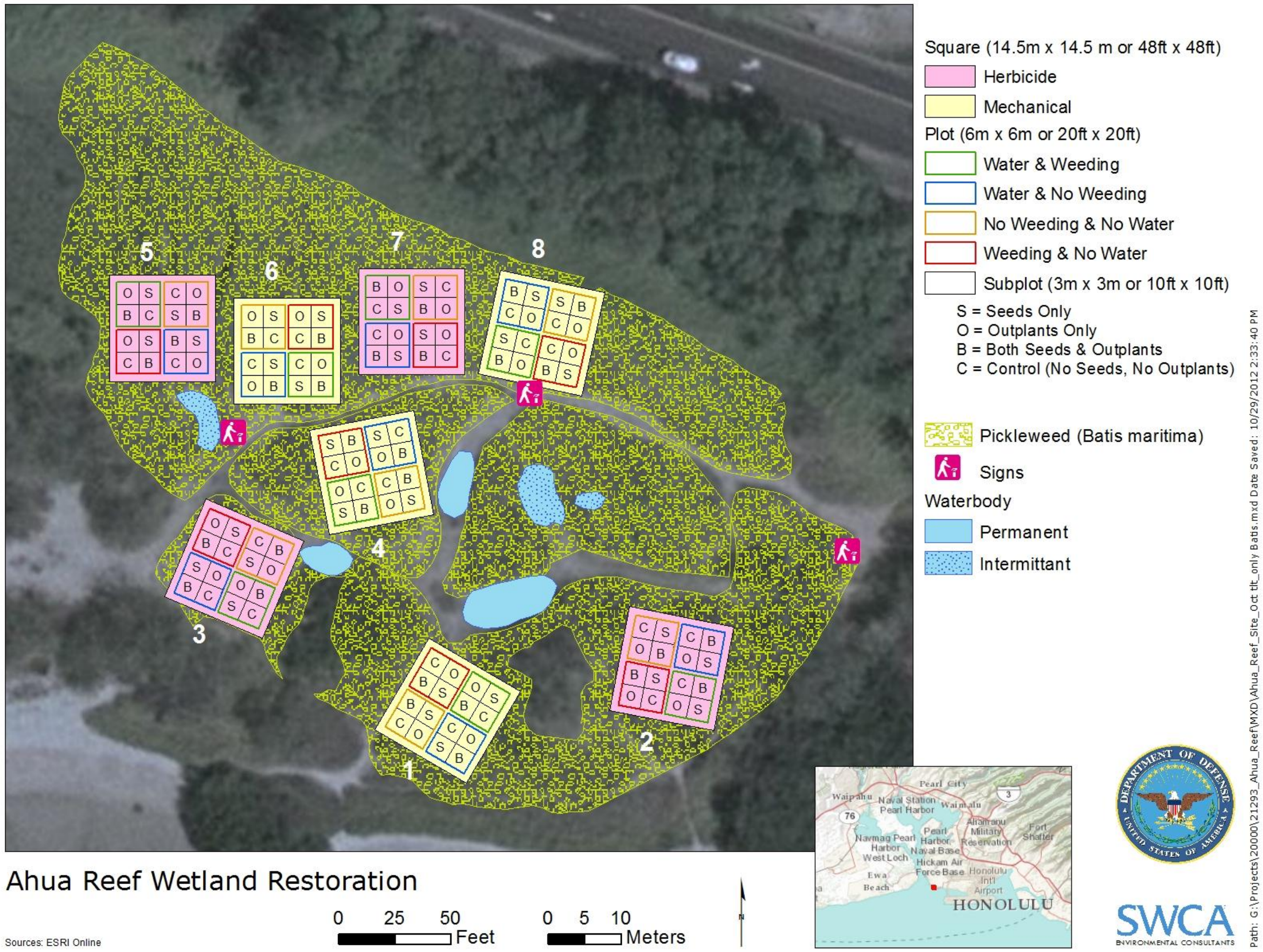
An important component of the project was evaluating the effectiveness of seeding native Hawaiian wetland species. Although restoring wetlands by outplanting nursery-raised seedlings is a widely accepted and often effective method, it is labor intensive and expensive. The time, money, and labor involved in large-scale outplanting efforts can often become cost prohibitive. Additionally, seedlings are often less able to survive more stressful conditions than seeds (Doust 2006, Brooks et al. 2009).

A simpler and more affordable restoration method is seeding, either by broadcasting seeds on the surface or directly sowing seeds beneath the soil surface. However, seeding in wetlands using standard seeding techniques can be problematic for several reasons. First, broadcasted seeds often float in saturated areas preventing soil contact and establishment. Broadcasted seeds can also be washed away during high tide events or displaced by receding water after inundation pulses. Furthermore, drilling or sowing can be ineffective because small wetland seeds often require light for germination (Tilley and Hoag 2006).

Globally, very few field-based seeding studies have been conducted in wetlands. Some in-depth studies have been conducted in greenhouses (Tilley and Hoag 2006) or controlled outdoor tanks (Tilley 2006). SWCA did not find any published studies on seeding in wetlands in Hawaiʻi and results from seeding efforts are mostly anecdotal. The few wetland seeding studies conducted on the U.S. mainland and internationally likely have limited applicability to Hawaiʻi because of the unique assemblage of coastal Hawaiian wetland plant species (Cuddihy and Stone 1990). For example, *Rhizophora mangle* (red mangrove) and *Batis maritima* (pickleweed) are considered very useful species for the restoration of wetlands in many places in the Pacific and elsewhere; However, these species are invasive in Hawaiʻi.

The purpose of this report is to briefly describe the lessons learned during the seeding portion of the experimental restoration project at Āhua Reef, as well as summarize information obtained from other seeding efforts in Hawaiʻi. It is intended to provide recommendations for DoD managers considering using seeding for restoration of coastal wetlands in Hawaiʻi.

Figure 1. Experimental Design at Āhua Reef, Joint Base Pearl Harbor-Hickam, O‘ahu.



3.0 METHODS

3.1 SWCA Seeding Study

Joint Base Pearl Harbor-Hickam (JBPHH) encompasses 11,207 hectares (27,694 acres) on the coastal plain along O'ahu's south shore. Āhua Reef is a 1.6 hectare (4 acre) wetland and an adjacent expanse of mud and reef flat at JBPHH, immediately west of Honolulu International Airport. This wetland is largely degraded with the majority of area being invaded by non-native species, such as *Rhizophora mangle* (red mangrove), *Batis maritima* (pickleweed), and *Prosopis pallida* (kiawe) (Figure 1).

For several years, the managers of Āhua Reef have been working closely with the community and various volunteer groups (e.g., Boy Scouts) to restore native plants to the site by organizing periodic weeding and outplanting events; however, these managers were seeking site-specific information on the most effective methods to control invasive vegetation and restore Hawaiian wetland plants. Because the managers are faced with the challenge of implementing and maintaining the wetland with minimal resources, they were particularly interested in techniques that would minimize future intensive management.

SWCA adopted a randomized block design to investigate the effect of two invasive species removal methods (herbicide versus mechanical removal), weeding and supplemental water on the growth and survival of outplantings and seeds of five native wetland species. The experiment design used in the project is described in detail in the DoD's Legacy Report No. 11-320 "*Developing Coastal Wetland Restoration Techniques to Enhance Coastal Habitats at Ahua Reef, Hickam Air Force Base, O'ahu, Hawai'i.*" Only aspects related to seeding are discussed here.

Seeds were only applied to the 3 m x 3 m (10 ft x 10 ft) subplots that were randomly assigned the following treatments: seeds only (S) or outplants + seeds (B) (Figures 1 and 2). Due to seed availability, only three indigenous sedge species were seeded at the site. These include: *Cyperus javanicus* ('ahu 'awa), *Cyperus polystachyos,* and *Fimbristylis cymosa* (mau'u 'aki'aki). Prior to seeding, three 1 m^2 (11 ft^2) rectangles were demarcated in each of the "seed only" (S) and "outplant + seeds" (B) subplots (Figure 3). A total of 192 seed rectangles (8 subplots x 3 species x 8 squares) were established throughout the site (Figure 1).

TripleTac® tackifier is an organic biodegradable substance which is commonly used in hydroseeding and hydromulching to bind the seeds to the soil or mulch and keep them from washing or blowing away. It easily dissolves in cold water to form slimy slurry. For slopes of 1:1, the label recommends using a concentration of 60 pounds of tackifier per acre (6.7 g/m^2). Our goal was to keep the seeds from being washed out of the subplots during high tide; therefore, we used this highest recommended concentration of TripleTac®. We also used the recommended dilution rate from the label (18,926 L/acre or 4.7 L/m^2). Given that there were eight subplots in each square, for each square, a tackifier solution was prepared for each species using 53.9 g of TripleTac® tackifier and 37.4 L of water. The slurry was well agitated in a container.

Based on the seeding rates used by Orville Baldos while hydroseeding *F. cymosa* (O. Baldos, PhD student, pers. comm.), SWCA weighed out the amount of seed material per species that was estimated to contain 1,000 seeds. A seed + tackifier solution was prepared for each rectangle, which contained roughly 1,000 seeds of one of the sedge species, 6.7 g (0.015 lbs) of tackifier and

4.7 L of water. The seed + tackifier solution was well stirred and poured into the demarked seed rectangles by hand (Figures 4 and 5). This method was used instead of broadcast seeding to minimize seed loss due to wind or high tide events (Tilley and Hoag 2006).

All seeding occurred on February 23, 2012 to allow for the maximum time before a high tide event. To assist establishment, each rectangle was watered 2 times per week with a hose for the first three weeks after seeding. Supplemental watering of the seeding rectangles was discontinued the following week due to an extreme rain event that caused flooding throughout the site. All seeds were obtained from Hui Kū Maoli Ola Native Plant Nursery.

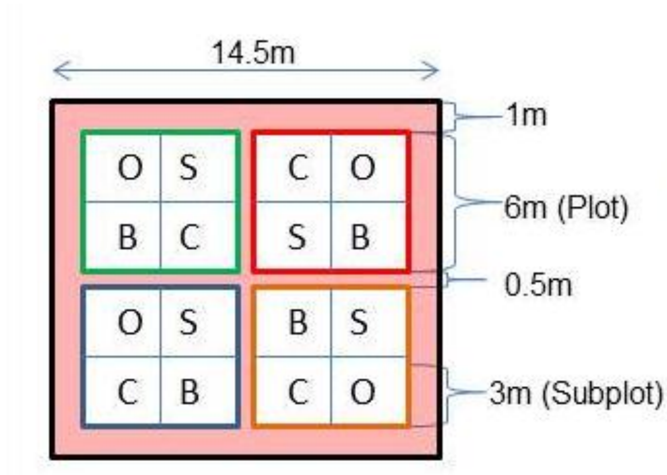


Figure 2. Dimensions of an experimental square at Āhua Reef.

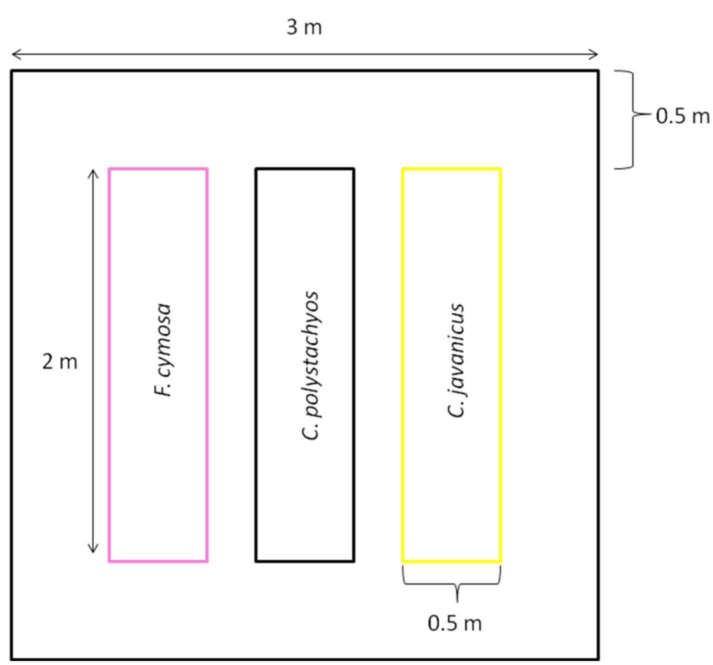


Figure 3. Example of seeding configuration within seed only and outplants + seeds subplots.

Figure 4. Preparing seed + tackifier solution on site prior to seeding.

Figure 5. Manually pouring seed + tackifier solution in seeding rectangles.

Within each seeding rectangle, three 900 cm^2 (139.5 in^2) squares were systematically placed to record seedling germination as a result of seeding. Observations of the squares were conducted weekly between March and May 2012.

3.2 Gathering Unpublished Information

Emails and phone calls were made to individuals and groups involved or potentially involved with wetland restoration projects in Hawaiʻi. This includes individuals at the U.S. Fish and Wildlife Service, Hawaiʻi Department of Land and Natural Resources, U.S. Natural Resources Conservation Service, University of Hawaiʻi, Hawaiʻi Rare Plant Restoration Group, and members of the Hawaiʻi Wetland Joint Venture (comprised of over 15 federal, state and local partners). The following questions were asked:

- Have you tried seeding as an alternative to planting in Hawaiian wetlands?
- If so, what method did you use (broadcasting, tackifier slurry, sowing) and what were the results?
- Do you think seeding of native wetland plant species is a useful technique in Hawaiʻi? Why or why not?

This questionnaire was conducted to obtain unpublished and undocumented, but valuable information about wetland seeding efforts in Hawaiʻi.

4.0 RESULTS

4.1 SWCA Seeding Study

No seedlings germinated in the squares monitored as a result pouring the seed + tackifier solution. Some *Cyperus* seeds did germinate outside of the monitoring squares (Figure 6), although this was very limited.

Figure 6. *Cyperus* sp. within one of the seedling rectangles roughly one month after seeding.

4.2 Other Unpublished Hawaiian Wetland Seeding Studies

Only five individuals responded that they have attempted seeding in Hawaiian wetlands. Because we distributed questions to a wide audience, this suggests that very little is being done with seeding in Hawaiian wetlands. Furthermore, information provided by individuals is largely observational and it is not always certain that observed germination is a direct result of seeding.

The Hawaiian Islands Land Trust seeded at two palustrine wetland refuges on Maui, including 11 hectares (27 acres) in Waiheʻe and 2.5 hectares (6 acres) in Nuʻu in Kaupō. They hand casted *Cyperus javanicus* and *Bolboschoenus maritimus* (kaluhā) either as single seeds or as seed bunches, usually after allowing the seeds to dry for some period of time. Seeds were hand casted in the wet season (from November to March in Hawaiʻi) and germination of both species was observed a month or two after casting seeds (S. Fisher, Director of Conservation, Hawaiian Islands Land Trust, pers. comm.).

Another method used by the Hawaiian Islands Land Trust involved hand placing mud balls of potting soil packed with *Cyperus javanicus* seeds. In Mr. Fisher's opinion, mud balls are more effective and economical than seeding because higher germination was observed. Mud balls can be used for less prolific species with low seed availability, and if bird predation is an issue (S. Fisher, Director of Conservation, Hawaiian Islands Land Trust, pers. comm.).

At ʻŌhiʻapilo Pond on the south shore of Molokaʻi, *Bolboschoenus maritimus* was successfully seeded during the wet season. Salinity at this site varies from 0 to 25 parts per thousand (ppt). One 5-gallon bucket was filled with seedheads and then dumped in the water at various locations along the canal, which includes 3,800 m (12,467 ft) of waterline. Seeds became concentrated at the waterline and dense areas of *B. maritimus* seedlings were only observed two years after seeding following several inundation-drawdown events. No germination was seen after seeding with *Cyperus laevigatus* (makaloa) at ʻŌhiʻapilo Pond. Biologists at the site suggest that the lack of *C. laevigatus* germination compared to *B. maritimus* may have been due to its weaker seed coat (A. Dibben-Young, Biologist, Ahupuaʻa Natives, pers. comm.).

A similar seeding technique was used to seed *B. maritimus* at Kōheo wetland on Molokaʻi where salinity can be as high as 207 ppt. This technique also proved effective at this site (A. Dibben-Young, Biologist, Ahupua'a Natives, pers. comm.).

At Hāmākua Marsh on Oʻahu's windward side, biologists attempted to seed with *Cyperus javanicus*. Seeds were dispersed by hand throughout the marsh and no supplemental water was provided. No germination has been observed over a year period. This area was also sprayed with the herbicide Habitat® prior to seeding. Upland areas surrounding the marsh were seeded with *Thespesia populnea* (milo), with only about 5% germinated observed (K. Doyle, Biologist, DLNR, pers. comm.).

Forest Starr attempted seeding with *Thespesia populnea* in sand dune areas of Keālia Pond on Maui. They embedded the large seeds in mud balls. This technique was not successful at the site. Based on his experience at this site and Kanahā Beach (also on Maui), he recommended planting hardy indigenous species rather than seeding. He also found significant natural germination of native species at Kanahā following invasive species removal and disturbance. He has heard of people transporting soil from more pristine wetlands (with native seeds banks) to more degraded wetlands (F. Starr, Biologist, Starr Environmental, pers. comm.).

Biologists on Kaua‘i have attempted seeding with the endangered *Platanthera holochila* (fringed orchid). Seeds were sowed and buried in seed packets to isolate the specific mycorrhizae required for growth of this species. No germination was seen from the sown seeds, although germination isn't expected until March 2013 once the seedlings are large enough to emerge from the moss and be visible. No germination has been observed in the buried seed packets although they were expected to have germinated after one year (W. Kishida, Kauai Coordinator, Plant Extinction Prevention Program, pers. comm.).

Information from other individuals that have not attempted seeding, but provided information to consider in future seeding efforts is included in Section 5.0 below.

5.0 DISCUSSION

5.1 Āhua Reef Study

SWCA did not observe germination within the seeded subplots during the course of three months. The three sedge species (*C. javanicus, C. polystachyos, and F. cymosa*) germinate relatively quickly and are not expected to take more than three months to germinate in appropriate conditions (Lilleeng-Rosenberger 2005). Although a tackifier slurry was used to keep seeds within the experimental area, it is possible that heavy rains washed seeds outside of the area. As shown in Figure 7, March was the wettest month at Āhua with 140 mm (5.5 inches) of total monthly precipitation. The majority of the heavy rainfall (134 mm or 5.3 inches) was recorded over a two day period on March 5 and 6, 2012.

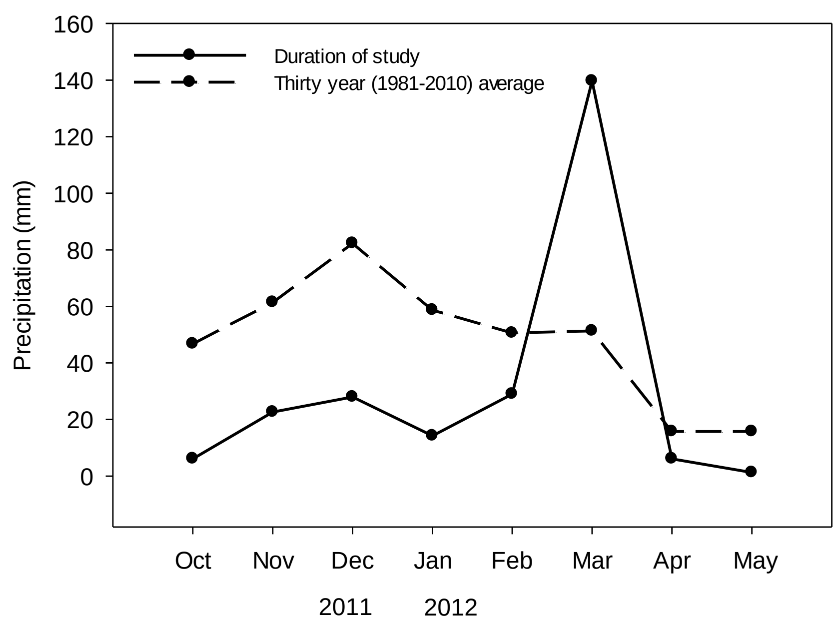


Figure 7. Total monthly precipitation over the course of the study, recorded from rain gauge located at the Honolulu International Airport (NOAA station ID 511919) ~ 3.9 km from the study site at Āhua Reef.

Another possible explanation for the lack of germination of the three sedge species at Āhua Reef could be due to high salinity. The salinity across the three ponds at the study site ranged from 65 to 126 ppt with average salinity of 96 ppt. Although SWCA did not measure soil salinity, the hypersaline pond waters probably suggest that the soils at Āhua Reef also have high salinity. Brimacombe (2003) conducted lab seed germination trials for *B. maritimus*, *Cyperus laevigatus*, *C. javanicus*, and *C. polystachyos* in 2002-2003 under different salinity, moisture, and temperature conditions. She found 0% germination at 34 ppt and reduced germination under lower salinity levels for all species. However, *C. javanicus* and *C. polystachyos* seeds germinated readily once placed in freshwater after being exposed to the high salinity levels (Brimacombe 2003).

Additionally, Brimacombe (2003) found no germination under dry conditions for all species. Germination was significantly greater under moist conditions (moist filter paper) and in saturated conditions (water just covering top of seed) compared to 1 cm (0.4 inches) of standing water. Certain areas of Āhua reef are dry due to the complex microtopography of the site, which may have contributed to poor germination results. Other site conditions, such as temperature, may also have prevented germination during the study period.

5.2 Other Unpublished Hawaiian Wetland Seeding Studies

Other than Brimacombe's (2003) work, SWCA did not find any scientific studies that investigated seeding of wetlands with native wetland Hawaiian plant species. Furthermore, based on the limited response to SWCA's survey questions about seeding in wetlands, it appears that very few wetland seeding efforts have been conducted. Also, the majority of the seeding efforts in Hawaiʻi are limited to two Hawaiian wetland plant species - *C. javanicus* and *B. maritimus.*

5.3 Natural Recruitment/ Seed Banks

Globally, evidence shows that many wetlands have persistent soil seed banks. This means that the soil contains ungerminated viable seeds that can persist in the soil for more than one year (Baskin and Baskin 2001). Wetland seed banks are mostly dominated by grasses and sedges (particularly Cyperaceae species) rather than woody species. In high saline environments, the size and diversity of wetland seed banks appears to be reduced (DeBerry and Perry 2000).

Recruitment from seed bank is often influenced by inundation and drawdown frequency and water level fluctuations (DeBerry and Perry 2000, Leck and Brock 2000). Soil disturbance (e.g., rototilling) can also increase natural recruitment of some native species.

No soil seed bank studies have been conducted in Hawaiian wetlands. However, wetland specialists, conservations, and biologists have found that in coastal or low elevation wetlands native plants often come back on their own (G. Koob, Natural Resources Conservation Service, pers. comm.; Mike Mitchell, U.S. Fish & Wildlife Service for Hanalei Wildlife Refuge, pers. comm.; S. Fisher, Director of Conservation, Hawaiian Islands Land Trust, pers. comm.). In our study, we observed natural recruitment of two native species –*Heliotropium curassavicum* (kīpūkai) and *Solanum americanum* (pōpolo). On Maui, natural recruitment of *Cyperus laevigatus*, *Sesuvium portulacastrum*, and *Lycium sandwicense* (ʻōhelo kai) has also been observed (F. Starr, Biologist, Starr Environmental, pers. comm.). Whether the seeds germinated from an existing seed bank, were brought in by birds, or arrived to sites by some other means, is unknown.

5.4 New Technologies

New technologies are currently being developed to address issues of seeding in wetlands. SubmerSeed®, a technique developed by AquaBlok Industries (Toledo, Ohio), is currently being explored in continental systems. SubmerSeed® binds the tiny seeds of wetland plants to a dense aggregate core which absorbs water and sinks, preventing the seeds from floating away (SubmerSeed 2012). SubmerSeed® was found to effectively hold seeds in place and facilitate germination of wetland plant species in controlled greenhouse conditions (Tilley and Hoag 2006), as well as in several field trials in the U.S. mainland (Indiana, New Mexico, Washington, Oregon) (E. Kraus, Technical Sales Manager, AquaBlok, Ltd, pers. comm.). According to Tilley and Hoag (2006), using SubmerSeed® is three times more effective in retaining seeds when compared with tackifier (under simulated flooding).

Direct seeding of wetlands using SubmerSeed® has not been tested in Hawaiʻi. Furthermore, this product has not been rigorously tested in saline conditions typical of coastal Hawaiian wetlands (E. Kraus, Technical Sales Manager, AquaBlok, Ltd, pers. comm.). Thus, the effectiveness of the product adhering to the surrounding substrate is unknown and needs to be investigated.

The seed morphology (size and shape) of *Cyperus javanicus, Cyperus polystachyos,* and *Fimbristylis cymosa* is compatible with the standard product formulation. AquaBlok Industries could produce up to 2,000-lbs of finished SubmerSeed® within two weeks of receiving the seed (some delays may occur between mid-September to November). The cost of 2,000-lbs of seed is $1.50/finished pound plus shipping and handling. A minimum fee of $1,000 (plus shipping and handling) would apply.

There are two primary downfalls of the SubmerSeed® technology. First, seeds must be cleaned and inert material removed before sending to the company. This can be extremely time-consuming. Secondly, invasive species concerns and regulations would need to be considered prior to introducing this product to Hawaiʻi.

Prior to implementing a SubmerSeed® study in Hawaiʻi, it would be useful to explore this opportunity by conducting a small-scale experimental seeding trial using SubmerSeed® with various wetland plant species. The study could compare the ecological and cost effectiveness of broadcasting seeds compared to using SubmerSeed®. Percent germination, time to germination and establishment of wetland plants could be monitored until seedlings are established.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the results seen in this study, broadcast seeding or using seed + tackifier slurries should not be used as the primary means of revegetation in coastal wetlands. The largest unknowns with this method are the germination and establishment rates because seeds are either washed away by tides and fluctuating water levels, are buried too deep to allow light for germination, or are lacking other germination requirements. Outplanting seedlings is more likely to result in higher cover of native species. However, new techniques being developed in the continental United States, particularly Submerseed®, should be explored to complement labor intensive, yet effective, outplanting efforts.

The original intent of this deliverable was to provide a brief wetland seeding guide for DoD managers; however, due to the minimal results in our seeding study and scant additional information available on seeding in wetlands, it is difficult to provide comprehensive recommendations. This technique is in its infancy in Hawaiʻi, as well as globally. The following provides a list of factors for managers to consider before, during, and after seeding in Hawaiian wetlands, based on available information.

1. Conduct site observations prior to seeding.

If it is not possible to control the water levels at a given wetland, then it is extremely important to observe and fully understand the site's hydrology prior to seeding. This includes rainfall and microsite topography. Not properly understanding the dynamics of water in the system can lead to unnecessary loss of time and money and decrease the chance of establishment success.

2. Determine seed pretreatment and germination requirements.

Understanding seed dormancy mechanisms of a specific species will help determine whether pretreatment is necessary prior to seeding. Seed pretreatments to stimulate faster germination can include scarification, water soaking, or chemical methods (Baskin and Baskin 2001). Most aquatic and wetland species have dormant seeds and physiological dormancy is most common. In this type of dormancy, the embryo is prevented from pushing through the seed coat (Baskin and Baskin 2001). Some native Hawaiian sedges have seeds that can remain dormant for up to 2 years in the lab (T. Kroessig, Technician, Lyon Arboretum Seed Conservation Laboratory, pers. comm.).

Generally, no seed pretreatment is necessary for native Cyperaceae species (*Cyperus* spp. and *Fimbristylis* spp.) prior to seeding (Lilleeng-Rosenberger 2005; M. Schirman, Owner, Hui Kū Maoli Ola, pers. comm.). However, Brimacombe (2003) found that *Bolboschoenus maritimus* had higher germination (in lab conditions) after scarifying and soaking in bleach for three days. Lilleeng-Rosenberger (2005) is a good reference to determine pretreatment requirements for other wetland species.

Other factors that influence germination processes should also be considered. Salinity, temperature, light, and the amount of available oxygen can affect germination (DeBerry and Perry 2000, Leck and Brock 2000). Germination was greatly reduced for *Sporobolus virginicus* (ʻakiʻaki) and *Sesuvium portulacastrum* at NaCl concentrations more than 0.26M and 0.20M, respectively (Baskin and Baskin 2001). Generally, seed germination in saline environments occurs during seasons with high precipitation, when soil salinity levels are usually reduced (Ungar 1982).

As stated in Section 5, Brimacombe (2003) found that *C. javanicus* and *C. polystachyos* failed to germinate under highly saline conditions in the lab. *Bolboschoenus maritimus* and *C. laevigatus* had little to no germination under any temperature, salinity, or moisture conditions. *Cyperus polystachyos*, which had the highest percent germination compared to other species in Brimacombe's study, germinated under a wide variety of temperature and water levels. Additionally, *Cyperus javanicus* appears to do better under cooler temperatures (such as winter or spring) (Brimacombe 2003). Although these studies were conducted under lab conditions, they may have field applicability. Further studies on the seed germination requirements of native wetland species, particularly under field conditions, will provide better choices to wetland managers in Hawaiʻi and elsewhere.

3. Consider seasonal weather and tide events.

To avoid additional watering costs, most biologists recommended seeding during the wet season (November-March). If seeding in inundated areas, seeds will likely float, eventually settling along waterlines. Seeding during the dry season will reduce chances of seed loss from the system due to high precipitation events; however, seeding in dry periods may result in labor and equipment costs associated with watering seeds. If seeding in tidal wetlands, we recommend paying attention to weather predictions, particularly large rain events, and high tide events and avoid seeding during those times. Of course, it is impossible to completely avoid random stochastic climatic events.

4. Select the most appropriate species for the site.

Species should be chosen by a qualified professional based on which species are best suited to the microtopography, hydrologic regimes, and conditions present at the site. Some wetland species (such as *Sporobolus*) do not germinate easily from seeds and likely rely on vegetative reproduction. Species such as *Sesuvium portulacastrum*, which have small seeds, are more easily and successfully produced from cuttings (M. Hibbard, Nursery Manager, Hui Kū Maoli Ola, pers. comm.). *Cyperus laevigatus* does not appear to be a good candidate for seeding due to lack of germination in field and lab trials. Some wetland species, such as *Cyperus javanicus*, can survive in wetlands and uplands. More obligate wetland species should not be seeded at sites that have wetland-upland mosaics (i.e., complex microtopography with repeated small changes in elevation over short distances).

There is some difficulty in Hawaiʻi with obtaining large (and cost effective) quantities of native seeds. There is not enough commercial demand of most species to warrant collection efforts by nurseries or other companies. However, as the need and demand for commercially available native species is growing, this hopefully will be less of an issue in the future.

The following private native plant nurseries can be contracted to provide native seeds:

- Aikane Nursery (Hawaiʻi Island)
- Aileen's Nursery (Hawaiʻi Island)
- Amy B. H. Greenwell Ethnobotanical Gardens Nursery (Kauaʻi)
- E. Nakashima Greenhouses (Hawaiʻi Island)
- Ho'olawa Farms (Maui)
- Hui Kū Maoli Ola (Oʻahu)
- Kapoho Kai Nursery (Hawaiʻi Island)
- Native Nursery LLC (Maui)
- Native Plant Source/Dennis Kim (Oʻahu)
- Nursery Solutions (Hawaiʻi Island)
- Pepperwood Hollow and Company (Hawaiʻi Island)
- Yardcore Landscapes Partnership (Maui)

5. Determine the appropriate seeding rate and method for the site.

The seeding application method used in SWCA's study was pouring a seed + tackifier solution. The seed + tackifier solution should be mixed well, allowing the tackifier to dissolve completely and seeds to be evenly mixed. This method was employed to help seeds adhere to the soil surface and reduce seed loss.

We used the highest seed:tackifier ratio recommended on the tackifier bag and by hydroseeding specialists (O. Baldos, PhD student, pers. comm.). The recommended rate per acre was:

- 60 lbs (27,215.54) of tackifier
- 4.46 lbs (2023.43 g) of pure seeds
- 10% dilution rate (18926.00 L of water).

Because nurseries typically do not provide clean seed (i.e., the material contains achenes, involucre bracts, etc.), SWCA calculated the mean number of seeds within 1 g of material (551.5 *Cyperus polystachyos* seeds, 2250.5 *Cyperus javanicus* seeds, 2,757 *Fimbristylis cymosa* seeds[1]). The rate of seeding should be at least double the actual amount of viable seed in order to account for seed predation and seedling mortality during establishment (Baldos 2009).

Tackifier is relatively inexpensive (~$50 for 25 pound bag) and can be purchased from local agriculture supplies. Seeds of wetland species range from $0.20-1.00 per sq ft. In contrast, seedling cost $1.75-2.00 per plant (M. Schirman, Owner, Hui Kū Maoli Ola, pers. comm.).

We did observe seed washout with this ratio and the seed + tackifier slurry method, however, it is unknown whether a higher tackifier rate or different application method would have reduced seed washout. It is also unknown if the higher soil salinity at Āhua Reef compromised the adhesive nature of the tackifier.

Mulch (e.g., straw, wood, fibers) can also be incorporated into the seed + tackifier solution to increase adhesiveness of seeds and tackifier to the soil surface and therefore decrease seed loss. If mulch is used, it is recommended to use only a low rate to reduce covering small seeds and thereby prohibiting germination (O. Baldos, PhD student, pers. comm.).

Other potential methods of application include broadcast seeding, drilling, and mud balls. The downfall of broadcasting is the increased risk of seed loss due to wind, water, and predation. Drilling is more time consuming and can reduce germination rates because small seeds will not receive adequate light for seed germination at even shallow depths. Other options considered for reducing seed loss include physical barriers (such as jute logs and mesh bags).

6. <u>Remember post-seeding weeding, watering, and maintenance.</u>

If long-term control of invasive species is not possible prior to seeding, it is possible that a seed bank of invasive species exists at the site. Additionally, weed seeds may move into the site via other means. Weed control can be a very important component of successful establishment of native species. Manual removal (pulling plants from the soil by hand or using various hand tools) is likely the best methods to control undesirable species after seeding to avoid impacts to native species. Typically, more weed control will be required in the wet season than the dry season; however, this may not be true for every site. Availability of water is often a major limitation in coastal wetlands. Supplemental watering may be required to ensure seed germination. Seed predation, particularly

[1] Baldos (2009) calculated as much as 15,000 *Fimbristylis cymosa* seeds in 1 g.

by birds, is another factor to consider after seeding; seeds are important components of waterbirds' diets during the nonbreeding season (Erickson and Puttock 2006).

7. Start small-scale.

Because seeding is not a widely used technique in Hawaiian wetlands, we recommend starting with a small-scale effort until further knowledge about seeding with Hawaiian wetland plants is obtained. Use this technique as a supplement to other restoration methods (e.g., outplanting and facilitating germination from the seed bank via disturbance).

7.0 ACKNOWLEDGEMENTS

SWCA gratefully acknowledges the support and input received for this project from NAVFAC Hawaiʻi and NAVFAC Pacific. Special thanks to Joel Helm, Cory Campora, Justin Fujimoto, Patricia Coleman, and Aaron Hebshi. This project would also not have been possible without assistance from Hui Kū Maoli Ola and Eagle Scout Troop 97 and their families. We would like to thank volunteers from Hickam AFB, University of Hawaiʻi, and Kupu's Urban Corps. Most importantly, SWCA acknowledges the DoD Legacy Resource Management Program and the support staff in allowing this project to take place.

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APPENDIX: COMPILATION OF SEEDING EFFORTS IN HAWAIIAN WETLANDS

Contact	Wetland Site details	Species seeded	Seeding technique	Successful?	Results/Observations/ Comments
Shahin Ansari & Tiffany Thair, SWCA Environmental Consultants	Āhua Reef coastal wetland	*Cyperus javanicus, Cyperus polystachyos, Fimbristylis cymosa*	Poured seed + tackifier solution	No	Observed little *Cyperus* germination. Heavy rainfall event could have washed seeds out of area.
Scott Fisher, Hawaiian Islands Land Trust	27 acre palustrine wetland in Waiheʻe, Maui. 6 acre palustrine wetland in Nuʻu in Kaupō, Maui	*Cyperus javanicus*, *Bolboschoenus maritimus*	Hand casted in wet season	Yes	Observed germination a month or two after seeding. More effective with *Cyperus javanicus.*
		Cyperus javanicus	Hand placing mud balls of potting soil packed with seeds	Yes	Useful for less prolific species with low seed availability and if bird predation is an issue.
Arleone Dibben-Young, Ahupuaʻa Natives	ʻŌhiʻapilo Pond, Molokaʻi	*Bolboschoenus maritimus*, *Cyperus laevigatus*	Seedheads dumped in the water at various locations along the canal	Yes	Dense *Bolboschoenus maritimus* seedlings observed along the waterline after two years. No *Cyperus laevigatus* germination observed; recommends "toss and stomp" outplant technique.
	Kōheo wetland, Molokaʻi	*Bolboschoenus maritimus*	Seedheads dumped in the water at various locations	Yes	Observed germination in highly saline environment.
Forrest Starr, Starr Environmental	Sand dune areas of Keālia Pond, Maui and Kanahā Beach, Maui	*Thespesia populnea*	Embedded large seeds in mud balls	No	No germination from mud balls. Natural recruitment was observed at these sites. Recommend planting rather than seeding this species.
Katie Doyle, Hawaiʻi DLNR	Hāmākua Marsh, Oʻahu	*Cyperus javanicus*, *Thespesia populnea*	Hand casted	No	No germination observed. Maybe due to herbicide sprayed before seeding.
Wendy Kishida, Plant Extinction Prevention Program	Bogs on Kauaʻi	*Platanthera holochila*	Seeds sown and buried in seed packets	No	No germination observed over 1 year after placing seed packets. Sown seeds need longer monitoring period.