FINAL REPORT: COSUMNES RIVER PRESERVE PERENNIAL PEPPERWEED CONTROL PROJECT

ERP 02D-P66 PROJECT REPORT

PREPARED BY:

Rachel A. Hutchinson, Joshua H. Viers,

and James F. Quinn

Department of Environmental Science & Policy

University of California, Davis

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1.0 Executive Summary ... 1

1.1. Phase I: Monitoring Perennial Pepperweed: Biology and Invasion ... 2

1.2. Phase II: Perennial Pepperweed Eradication and Ecological Monitoring ... 4

1.3. Phase III: Adaptive Management and Modeling ... 7

2.0 Recommendations ... 9

2.1. Experimental Treatments ... 9

2.2. Adaptive Management Framework ... 10

3.0 Subtask Deliverables ... 11

3.1. Task 1 Project Management ... 11

3.2. Task 2 Environmental Compliance and Permitting ... 11

3.3. Task 3 Monitoring and analysis of *Lepidium latifolium* population patterns and trends. 11

3.4. Task 4 Targeted research on *Lepidium latifolium* control. ... 17

3.5. Task 5 Adaptive Management Framework. ... 32

4.0 Final Remarks ... 47

5.0 Acknowledgements ... 47

6.0 Citations ... 48

List of Figures

Figure 1. Perennial pepperweed patches inventoried between 2003 and 2007. Patches are displayed as graduated percent cover. 12

Figure 2. Mean stem density of perennial pepperweed and flood duration of the Cosumnes River from 1996 to 2007. Perennial pepperweed stem count and density is unknown prior to 2002. 13

Figure 3. HCL/phloroglucinol root results for one patch. This particular patch was aged at three years old. 14

Figure 4. Example of the Cosumnes River Preserve Virtual Herbarium homepage and species information page. 15

Figure 5. Extent of LiDAR data collected in 2005 at the Cosumnes River Preserve. 16

Figure 6. Plot locations of all treatments conducted as part of Task 4. 17

Figure 7. Results of a pilot study to test pulling perennial pepperweed on the Experimental Floodplain. Stems were pulled in 2004 and monitored annually between 2005-2007. 22

Figure 8. Simpsons Diversity Index (1-D) for experimental controls, treatment controls, and herbicide treatments, during the pepperweed control project. 25

Figure 9. Simpsons Diversity Index (1-D) of non-chemical tarp treatments (M+D+T and M+T) and controls from 2005 to 2008. Stars indicate statistical significance of each comparative test (* <0.05, ** <0.009, ***<0.0009). Results do not include *Lepidium latifolium* data. 26

Figure 10. LiDAR first return and bare earth data color coded by tree or vegetation height (first returns), soil series (bare earth) and water (bare earth) 27

Figure 11. Plots treated by Telar® at West Bottoms after 2 years of mow broadcast treatment 29

Figure 12. Species most commonly observed in seed bank pots from soil collected at the Cosumnes River Preserve. Introduced species can be identified by a * after the species name. 31

Figure 13. Adaptive Management Cycle articulated with feedbacks from Modify to Mission, Mark, Manage, and Monitor 34

Figure 14. Decision Tree Framework for managing perennial pepperweed at the Cosumnes River Preserve. 37

Figure 15. (a-b). Results of the Leslie Matrix and Lefkovich Matrix Population Model in a stable growth scenario with herbicide treatments at different intervals. 39

Figure 16. Example of Dispersal Model Results as a Map of Probability Contours. Distance from patch centers were used to examine probability of perennial pepperweed invasion. 43

Figure 17. Probability Surface of Perennial Pepperweed Habitat Suitability 44

Figure 18. Probability contours (>= 50%) for habitat suitability over canopy LiDAR image near levee breach.. 45

List of Tables

Table 1. Treatment schedule for all experimental treatments conducted during the 2005-2011 project term. 18

Table 2. Herbicide concentration and method associated with each treatment type. 19

Table 3. Number of plots, mean perennial pepperweed stem count and standard deviation, and percent change from 2005 to 2007 for each treatment type. *indicates plots that were only treated in one year. 20

Table 4. Expanded Number of plots, mean perennial pepperweed stem count and standard deviation, and percent change from 2008 to 2009 for expanded plots. *indicates plots that were only treated in one year. 21

Table 5. Herbicide treatments, tarp treatments, and experimental controls: perennial pepperweed mean stem counts and average rate of stem change pre-treatment, one year after treatment (1YAT) and two years after treatment (2YAT). Statistical significance is indicated where *<0.05, p<0.005 (**), p<0.0005 (***). Negative rates of change indicate population decline (Hutchinson and Viers 2011). 23

Table 6. Results of *t*-tests by treatment method (CS = cut-stem; MB = mow-broadcast) and soil depth 29

Table 7. Mean, percent of total, number of plots sampled, germinants per plot, number of species per site, and number of species per plot for each experimental site sampled as part of the seed bank experiment. 30

Table 8. Binomial Logistic Regression Variables. 41

Keywords: perennial pepperweed, *Lepidium latifolium* (L.), Cosumnes River Preserve, Adaptive Management

1.0 Executive Summary

At the Cosumnes River Preserve perennial pepperweed (*Lepidium latifolium* L.) impacts a variety of habitats and threatens current and future restoration activities. The consequences of this type of infestation can be costly and extremely detrimental to natural areas. As a result perennial pepperweed has been widely studied at the Preserve and beyond. Early detection and rapid response has become the mantra of weed control experts and land managers as it is cost effective and minimizes the physical and biological impacts of large scale weed infestations. In the late nineties, perennial pepperweed was identified on key properties at the Preserve, and since then it has proliferated along roadsides, in riparian forests, on floodplains, in areas surrounding wetlands, and in grasslands. The Preserve's weed management plan identifies perennial pepperweed as a species of high-ranking threat to critical habitats because of its ability to spread and its tendency towards monospecific stands (Cosumnes River Preserve 2000). A yearly inventory of perennial pepperweed on some key properties at the Preserve (The Experimental Floodplain) from 2002 to 2004 confirmed fears that the population was increasing exponentially and that a long term, large-scale eradication plan would be necessary to control the species (Cosumnes Research Group 2005).

The Perennial Pepperweed Control Project, initiated in 2005, sought to integrate multiple co-occurring studies into one adaptive management plan (see Subtask 5.2) that could be implemented by Preserve managers. To this end, the project was wide ranging in its goals and outcomes, from the creation of an online virtual herbarium for the Preserve (see Subtask 3.3) to applying herbicides (see Subtask 4.1) and modeling patch establishment (see Subtask 5.1). This final report outlines the outcomes of the project into a comprehensive report that summarizes the findings of each individual task. Each task and subtask presented its own unique challenges and broadened our understanding of perennial pepperweed's biology, ecology, population dynamics, and eradication potential. The goals of The Perennial Pepperweed Control Project can be organized into three distinct phases:

Phase I: Monitoring Perennial Pepperweed: Biology and Invasion

- Map occurrences of perennial pepperweed
- Investigate growth patterns and new patch establishment
- Gather background datasets (including LiDAR, and Virtual Herbarium data)

Phase II: Perennial Pepperweed Eradication and Ecological Monitoring

- Develop experimental eradication treatments
- Monitor the effects of proposed eradication treatments on non-target species
- Investigate soil chemical and physical properties in relation to perennial pepperweed
- Investigate the potential pre-emergent effects of the herbicide chlorsulfuron
- Monitor the species in the soil seed bank to establish herbicide effects and the active restoration potential for experimental eradication treatments

Phase III: Adaptive Management and Modeling

- Design an adaptive management framework that integrates the results of the study and can be used by Preserve managers and others interested in weed management.
- Model perennial pepperweed growth and new patch establishment

The below sections provide detailed recommendations and results for each of the Tasks and Subtasks completed between 2005 and 2011. Full reports are available online at http://baydelta.ucdavis.edu/pepperweed/.

1.1. Phase I: Monitoring Perennial Pepperweed: Biology and Invasion

Invasion resistance is linked to a multitude of biotic and abiotic factors including biodiversity and ecosystem function, but the lack of sufficient observational data has created uncertainties as to the role that many of these factors play. The debate centers on the question of whether natural areas with high native species richness and cover are immune to invasion by non-native species (Tilman 1999, Stohlgren et al. 2003, Fridley et al. 2007). The major barrier to resolving this issue is that different trends emerge when data is collected and analyzed at broad or fine spatial scales (Fridley et al. 2007). Data collected at broad spatial scales (>30m²) contends that these areas are highly invasible because they contain rare or endemic species which are extremely sensitive to disturbance (Stohlgren et al. 2003). Additionally, areas with high numbers of native species are commonly associated with high soil fertility, which can be easily colonized by an opportunistic invader. It is suggested that these sensitive sites may become prone to invasion if natural disturbances are altered or ecosystems processes are changed (Stohlgren et al. 1999, Davis et al. 2000). Alternatively, at a fine scale (<1m²), areas that maintain diverse functional groups, or have a heterogeneous mix of species that occupy the same habitat but use different resources, will be less invasible by occupying all available habitat niches. In the absence of anthropogenic disturbances, areas high in species richness and abundance will maintain functional group diversity, and by maximizing available resource use, will inhibit nonlocal invaders (Tilman 1997, Pokorny et al. 2005, Sheley et al. 2007).

Perennial pepperweed is generally understood to multiply by its prolific underground root system, but Leninger & Foin (2009) provide evidence that the species exhibits high levels of seed production and viability at the Preserve (Leninger 2006, Renz and DiTomaso 2006). The rate at which seeds are produced at the Preserve provides strong evidence that the reported average of 3,231.5 seeds per inflorescence with a 96.4% germination rate will influence eradication success rates. In addition, Leninger & Foin (2009) found that seed viability only declines by 17% at the Preserve seven months after production and viable seed can travel up to five meters before there is a significant drop off in dispersed density. Their findings indicate that simply eradicating the plants will not wipe out a longstanding infestation and that closely monitoring treated sites will be instrumental in determining treatment success rates.

As the main study sites tended to flood on a near-annual basis, it quickly became apparent that understanding not only the local hydrology but how perennial pepperweed and perennial pepperweed eradication methods might be affected by the hydrology would play a major role in the overall findings. Perennial pepperweed, like many other wetland or flood tolerant species, is capable of responding to flood conditions by altering its root to shoot ratio, producing adventitious roots, developing aerenchyma cells, decreasing photosynthesis, reallocating carbohydrate storage, and changing its nutrient uptake and allocation (Chen et al. 2002, Chen et al. 2005). By decreasing the root to shoot ratio, the species reduces its required oxygen, water, and nutrient uptake during stressful flood conditions (Naidoo and Naidoo 1992, Joly 1994), which are common in riparian and wetland areas at the Preserve. Adventitious roots, which grow beyond the flooded soil, can provide the species with oxygen necessary for survival in an anoxic environment (Jackson and Drew. 1984) and while adventitious root production is a common adaptation of flood tolerant species, it is not common in members of the Brassicaceae (Chen et al. 2002). The species has further adaptations which allow for the slowing of photosynthesis through a series of mechanisms such as stomatal closure and ethylene production resulting leaf senescence (Bradford 1983, Chen et al. 2002), this reduction is also linked to starch accumulation in leaf structures rather than root structures as inundated plants discontinue exchanging carbohydrates from shoot to root (Chen et al. 2005). Perennial pepperweed root structures increase soluble sugars when inundated which allows them to continue important processes like respiration without using their starch stores. The build-up of sugars during flood events may be linked to perennial pepperweed's ability to recover after long periods of inundation (Chen et al. 2005). While inundated, perennial pepperweed's nutrient concentrations of N, P, K and Zn decline while Fe and Mn increase (Chen et al. 2005). The adaptive ability of perennial pepperweed under short term flood conditions make the species an ideal invader on riparian floodplains and a threat to many ecologically unique habitats at the Preserve.

To determine the scale and extent of the perennial pepperweed infestation at the Preserve, we surveyed over 1,371 acres over a period of four years using Trimble GPS units to define the total area infested. Our surveys identified over 1,100 individual patches (see Subtask 3.1). A subset of these populations, at what is known as the Experimental and Lower Floodplain, were revisited between 2005 and 2007, after an initial survey in 2004 (Cosumnes Research Group 2005). The populations that were revisited, between 312 and 456 patches a year, were used to determine annual patch growth rates and potential new patch establishment locations. We were able to determine the age of some populations using a root staining procedure, but concluded that this procedure was not useful at a large scale. New patch establishment and population growth was generally attributed to factors associated with the water year type, where wet years with long inundation periods produced fewer patches and dry years produced more patches. As the scale of the infestation was determined to be preserve-wide, we encourage eradication efforts to coincide with wet or dry growth type years, where treatment would be targeted in wet habitats during dry years and dry habitats during wet years. This treatment regime is further outlined in the adaptive management report (see Subtask 5.2).

1.2. Phase II: Perennial Pepperweed Eradication and Ecological Monitoring

Phase II was the most applied phase of the project, where patches were stratified by habitat type and randomly selected for an array of treatments and subsequent monitoring. The goal of this phase was to test a series of herbicide and non-chemical control methods, find a treatment that could be implemented with a high level of success, monitor each treatment's effect on the overall ecosystem health, and ensure that a recommended treatment would not have a negative impact on existing Preserve resources.

1.2.1. Treatment Rationale

Our treatments consisted of using a combined method of mowing and applying glyphosate or chlorsulfuron to maximize the translocation of herbicide to the below ground root structures (Renz and DiTomaso 2004, 2006). We also included other experimental treatments for which little or no background information was available, including cut-stem herbicide treatments (Subtask 4.1), a tarping experiment (Subtask 4.2), and a weed pulling experiment. To examine how the impacts of all treatment combinations (Subtask 4.1; Subtask 4.2) would affect overall ecosystem health, we collected data on the pre-treatment and post-treatment non-target vegetation response (Subtask 4.3), soil chemical and physical properties (Subtask 4.4), soil residence of chlorsulfuron (Subtask 4.5), and the composition of the soil seed bank (Subtask 4.6) at multiple properties with different environmental conditions at the Cosumnes River Preserve. Treatment and subsequent monitoring took place over a period of five years (2005-2009) and included two consecutive years of treatment, one year of expanded treatment (herbicide only), and four years of monitoring to assess treatment efficacy, non-target vegetation response, soil impacts, and soil seed bank response.

Mowing in combination with herbicide treatment increases success rates for some perennial species, including perennial pepperweed (Mislevy et al. 1999, Monteiro et al. 1999, Beck and Sebastian 2000, Renz and DiTomaso 2006). To better understand how phenological differences in mowed vs. un-mowed plots affected perennial pepperweed treatment success rates, Renz and DiTomaso (2004) tested the deposition, absorption, and translocation of applied glyphosate and analyzed root total nonstructural carbohydrates at various stages of perennial pepperweed phenology. These factors were tested by mowing experimental plots at the flower-bud stage or full flower stage followed by herbicide application at rosette, flower-bud and full flower stage. Experimental control plots were unmowed and treated with glyphosate at the flower-bud, full flowering and fruiting stage (Renz and DiTomaso 2004).

As was hypothesized, Renz and DiTomaso (2004) found that glyphosate deposition was more abundant in plants with more above ground surface area. While mowing did not result in higher overall herbicide surface deposition compared to the control, a greater percentage of herbicide was deposited in the lower portion of the pepperweed canopy in mowed infestations. This study concluded that mowing decreased the re-sprouted height of a perennial pepperweed plant, and decreased the above ground sink for applied herbicide (Renz and DiTomaso 2004).

To assess absorption and translocation of glyphosate in perennial pepperweed, Renz & DiTomaso (2004) selectively applied the herbicide to leaves in the flower-bud stage, the fruiting stage and a mowed flower-bud stage. Herbicide treated leaves were harvested after 48 hours and tested for glyphosate absorption. They found that mowed treatments absorbed more glyphosate, which was attributed to a less-developed cuticle in the leaves of the mowed plants. Translocation to root structures was assessed by harvesting roots of glyphosate-treated plants for analysis in mowed and un-mowed plants. As hypothesized, more glyphosate accumulated in the roots of mowed plants when compared to un-mowed plants. The roots of un-mowed plants contained very little herbicide translocated from the shoot to the roots. As observed in glyphosate deposition tests, perennial pepperweed generally re-sprouts to a shorter height after it is mowed allowing the herbicide to be applied in closer proximity to the roots. Root-total nonstructural carbohydrates were analyzed at different stages of perennial pepperweed phenology by harvesting roots in both mowed and un-mowed plants. Carbohydrate transport to the roots was greatest when plants were in the early stages of growth or after a mowing treatment. The authors suggest that increased carbohydrate transport to root structures in re-sprouting plants is evidence for the increased transport of glyphosate to roots in mowed plots (Renz and DiTomaso 2004). These findings support the claim that perennial pepperweed has a reduced ability to translocate herbicides to root structures from the upper canopy compared to the lower 3rd portion of its canopy.

To test if mowing increases the efficacy of multiple herbicides Renz & DiTomaso (2006) tested chlorsulfuron, glyphosate, and 2, 4-D on pepperweed infestations. Chlorsulfuron was effective regardless of mow treatment, glyphosate increased in efficacy if plants were mowed first, but 2,4-D did not increase in efficacy after a mowing treatment. Both glyphosate and chlorsulfuron were identified as good choices for perennial pepperweed control. The authors note that glyphosate has low residence time in the soil, which is valuable when using plantings to revegetate a treated area (Renz and DiTomaso 2006).

Because of the general importance placed on applying herbicide to the lower 3rd of the canopy to maximize the translocation of herbicide to the roots, we introduced an experimental cut stem, herbicide application method in an attempt to find a method with a lower herbicide application rate and one that could easily be conducted by volunteers. While this treatment style is generally applied to tree and shrub species of the woody variety, we hoped that the dense perennial root systems might react positively to this method.

In addition, we implemented a previously understudied tarping method in an attempt to eradicate underground root structures without using an often objectionable herbicide method. Tarping reduces photosynthetic light and elevates soil temperatures. While annual species are commonly controlled using a tarp method (Horowitz et al. 1983), perennial species have larger root masses and are generally not controlled by tarping (Rubin and Benjamin 1984, Linke 1994). However, seeds generally do not survive when soil temperatures are elevated above 45° C (Horowitz et al. 1983, Rubin and Benjamin 1984, Peachey et al. 2001), which could reduce the potential for perennial pepperweed to reinvade after an eradication attempt.

1.2.2. Monitoring Rationale

Depending on the degree of infestation, the success rate of the removal, and the health of adjacent habitats, sites do not always respond favorably when relieved of a target species (Ogden and Rejmanek 2005). In areas where non-native species coexist within the native community, treatment-related disturbances may further degrade ecosystems by disrupting plant community dynamics, resulting in future invasions or other impacts (Rinella et al. 2009, DeMeester and Richter 2010). It is now widely accepted that declines in species diversity, functional group diversity, and vegetation density are factors that can contribute to a community's invasibility (Ortega and Pearson 2005, Pokorny et al. 2005). These types of responses can also occur after invasive species removal and should be monitored to prevent future negative impacts. After an intensive herbicide treatment, the resultant plant community is more likely to be dominated by non-native annual grasses and other unaffected species thus reducing the functional diversity and increasing the invasibility of the area (Pokorny et al. 2005, Sheley and Denny 2006). Because of these factors, we monitored the non-target vegetation on an annual basis to look for potential negative and positive effects of different herbicide and non-chemical treatments. In general, some negative impacts were observed in both herbicide and tarp treatments. Herbicide use resulted in some conversion of native herbaceous understory to non-native annual grasses while tarp treatments resulted in large areas of bare soil, which are now open to future invasion (see Subtask 4.3). Re-vegetation may be necessary at the Preserve if negative results are observed in the response of the non-target vegetation or if the targeted species returns in years subsequent to removal.

Properties at the Preserve with many dense patches of perennial pepperweed are likely to have large numbers of seeds stored in the soil seed bank. As it can be assumed that viable seeds will remain in the seed bank after most types of eradication, the outcome of some eradication methods, especially those in which bare soil is a common result, could result in new perennial pepperweed infestations. Perennial pepperweed seedlings are capable of outcompeting less aggressive seedlings (Spenst 2006) ultimately leading to 'new' infestations. In a system like the Preserve, passive restoration processes are commonly relied upon to establish more favorable vegetation following non-native plant eradication or a disturbance event. In areas with dense, pre-treatment perennial pepperweed cover, the composition of the seed bank will be partially responsible for ensuring successful passive restoration. In some cases, perennial pepperweed removal may be most successful when sites are actively restored and re-vegetated with competitive native plant species (Eiswerth et al. 2005). To that end, the diversity and abundance of species in the seed bank, as well as any effect the perennial pepperweed removal processes had on that seed bank and resulting non-target vegetation (Subtask 4.6) was evaluated.

Soil underlying sites densely populated by perennial pepperweed was shown by Renz & DiTomaso (2004) to have higher levels of N, Ca, Mg and lower levels of acetate-extractible Na. Higher nitrogen levels in locations of perennial pepperweed growth were related to perennial pepperweed's ability to reduce N-cleaving enzymes in the soil (Blank and Young 2002). The species has a greater concentration of calcium in its tissues than the average plant and may actually input Ca to the soil, increasing soil friability. This process facilitates amelioration of sodic soils as calcium and magnesium levels increase and replace sodium on clay exchange sites. During flood events, sodium leaches from the upper soil profile, as it was previously replaced by calcium and magnesium on clay exchange sites, (Renz and Blank 2004). Even though perennial pepperweed improves sodic soils by relieving salt from the clay, it creates saline soils via the decomposition of thatch and leaf litter. (Blank and Young 2002). We investigated the overall impact of perennial pepperweed on a number of soil physical and chemical properties and found some impact, which is detailed below and in Subtask 4.4.

Both glyphosate and chlorsulfuron are effective at eradicating perennial pepperweed (Renz and DiTomaso 2006) but there is some evidence that chlorsulfuron and herbicide use in general, has a negative impact on non-target vegetation and can have a long residence time in the soil (Guo and Sun 2002, Young et al. 2002). Monitoring the effects of herbicide use on non-target vegetation is essential to an ecologically based weed management regime in order to determine an appropriate eradication method (Maxwell and Luschei 2005). Chlorsulfuron has a wide range of soil and pre-emergent effects, but is more of a broadleaf specific herbicide and does not affect grasses as strongly as it affects broadleaf herbaceous plants (DuPont 2003b). The variable residence time of chlorsulfuron depends on environmental factors such as soil temperature, moisture and pH (DuPont 2003b). Glyphosate, on the other hand, breaks down quickly in the soil and is not known to negatively affect soil physical and chemical properties (Dupont 2003a). Areas treated with glyphosate can be replanted or seeded soon after control, thus decreasing the likelihood of reinvasion (Renz and DiTomaso 2006).

We tested the pre-emergent impact of chlorsulfuron on root growth and found that its long term effects (greater than 120 days) were minimal (Subtask 4.5). While this finding is interesting and could be used as an argument for continuing to use chlorsulfuron at the Preserve, its use is now restricted to properties that are not adjacent to waterways, significantly reducing its application potential.

By identifying barriers to eradication success, such as residual herbicide effects, seed bank depletion, bare soil exposure, low adjacent species and functional group diversity, infested areas can be treated with more sensitivity and a whole ecosystem approach can be developed (Davis et al. 2000, Guo and Sun 2002, Ogden and Rejmanek 2005).

1.3. Phase III: Adaptive Management and Modeling

Phase III, as implemented by Subtask 5.1 and Subtask 5.2, was the culmination of this project wherein the results from all of the other tasks were used to develop the adaptive management framework and the perennial pepperweed growth models. While these two tasks are distinct and very dissimilar, their completion required integration of the results from all the other tasks.

We chose to use multiple modeling approaches in order to capture perennial pepperweed's growth and establishment at the Preserve. Once all relevant data were collected, including five years of population data, USGS river gage data at Michigan Bar, elevation, canopy cover, canopy height, inundation, experimental control efficacy, among others, we ran three complementary models: dispersion, physical drivers, and rapid detection. The models each predicted growth a little differently, but all predicted that new patches could establish at many of the Preserve's properties in a number of sensitive habitats. The prediction surfaces create population growth probabilities based on the correlation of environmental variables. These models provide detailed growth predictions and are explained in the sections below and in the Subtask 5.2 report. The Preserve can utilize these prediction surfaces to assist them in making restoration decisions and in allocating weed control resources.

To address population growth we modified an existing Leslie Matrix and Lefkovich Matrix Population Model for teasel (*Dipsacus* sp.) to address how experimental treatments would impact different rates of growth. This population model relied on life history traits, such as seed production and germination rates, to model individual patch growth through time. We adjusted growth rates by calculating patch growth for different years (data collected in Subtask 3.1) and establishing those as dry year, wet year, and moderate year or stable growth. The results from this population model informed our adaptive management framework buy providing us with a treatment repeat rate that would appropriately manage the species.

2.0 Recommendations

2.1. Experimental Treatments

2.1.1. Chlorsulfuron (Telar®)

2.1.1.1. *Mow Telar®*

Chlorsulfuron (Telar®) use in combination with a mow treatment is very effective at controlling perennial pepperweed patches <3 meters in size with control rates of 98% 1YAT and 99% 2YAT for all treated sites (Subtask 4.1). However, Telar® may be detrimental to riparian areas, specifically herbaceous plants and wetland areas, and is suggested for use in only grassland areas (Subtask 4.3).

2.1.1.2. *Cut Stem Telar®*

Cut stem Telar® treatments resulted in declining pepperweed populations 1YAT. However, this method is very time consuming, must be repeated within a growing season and from one year to the next to be effective (Subtask 4.1). This method may be best applied to new or small (less than 20 individuals) perennial pepperweed patches.

2.1.2. Glyphosate (AquaMaster®)

2.1.2.1. *Mow AquaMaster®*

Glyphosate (AquaMaster®) use in combination with a mow treatment is effective at controlling perennial pepperweed patches <3m with control rates of 99% 1YAT and 94% 2YAT for all treated sites. Treatment was more effective in riparian (99%) areas than in grassland (89%) areas 2YAT (Subtask 4.1). This treatment was less effective at a larger scale, with a 68.1% success rate over a 900m^2 area. In part, the larger area treatments may have been less effective because instead of treating the entire area with the Mow AquaMaster® method, we spot mowed and treated the species to reduce the impact to the non-target vegetation.

2.1.2.2. *Cut Stem AquaMaster®*

Cut stem AquaMaster® treatments resulted in declining pepperweed populations in high concentration application in both year one and year 2. This method is mostly ineffective with a low concentration dose. The cut stem method in general is very time consuming and must be repeated both within a growing season and from one year to the next to be effective (Subtask 4.1).

2.1.3. Tarping

Mow-Disk-Tarp treatments, where tarps were deployed for two growing seasons, were successful and resulted in treatment efficacies that were similar to the Mow-AquaMaster® experiment (Hutchinson and Viers 2011). Mow-Tarp treatments were highly variable and did not produce promising results for future use. The implementation of the till before tarp technique enhanced treatment results and is an essential step if tarping is to be used for perennial pepperweed eradication. However, this treatment results in high levels of bare soil cover in the years following tarp removal which is not a favorable outcome if promoting biodiversity and habitat restoration are part of the eradication objectives. In addition, the time required for installation and continued maintenance throughout the tarps lifespan made this a very time and labor consuming option.

2.2. Adaptive Management Framework

Many entities have used common approaches for weed control and management. One such approach is a pathway or cycle of management – not to be confused with adaptive management as we have described previously. This pathway initiates with prevention of establishment, such as taking proactive measures to limit exposure to infestations.

From Detection flows the Control phase (and/or Rapid Response), where different techniques are employed to limit if not eradicate weed populations. Several decision trees exist to help weed managers determine the appropriate course of action. We recommend that the Preserve develop its own set of decision trees, similar that incorporate weed-property specific decision criteria to utilize combinations of herbicides, mechanical treatment, and cultural practices (e.g., fire) – referred to here as weed management bundles – where site conditions warrant it. Factors that should be considered in developing applying weed management bundles include proximity to water features, type and stability of soils, topography, microclimates, existing and proposed land uses, and proximity of native vegetation and/or managed ecosystems. The selected bundle should be the least environmentally damaging approach given the target weed, its natural history characteristics, and its stage of infestation. Bundles typically consist of some combination of the following:

- ✓ Chemical control methods – Herbicides require their own set of practices and guidelines, but remain highly effective (Hutchinson and Viers 2011) when used appropriately.
- ✓ Cultural control methods – Cultural practices range from cultivating desirable competitors to employing ecosystem processes such as flood or fire. It can also include aids such as mulches, cover crops and the establishment of beneficial grasses, forbs, shrubs and trees. While shading can be an effective cultural control method in some cases, our analysis of tree canopy to limit pepperweed was inconclusive.
- ✓ Mechanical control methods – Mechanical control is not limited to mowing or weed whacking, but also includes large tractor work to physically disrupt plant growth and assist with the recovery of disturbed sites. We include the use of tarping here to exclude sunlight from target weeds (Hutchinson and Viers 2011).
- ✓ Biological control methods – Biological control is the use of other organisms, such as insects that feed on weeds or disrupt critical life cycle components (e.g., pollination) or microorganisms that digest seeds or rhizomes. It can also include the purposeful utilization of livestock in a weed grazing strategy. These approaches can prove tricky and often require high level permitting or implementation by governmental agencies if the organism is novel to the target location.

- ✓ Manual control methods – At the end of the day, the pulling or digging out of target weeds remains a viable control method; however, caution should be used so as to not exacerbate the number and distribution of seeds or propagules in the process of conducting manual control. Stage of plant growth at time of removal is a critical consideration for use of this method.

3.0 Subtask Deliverables

All deliverables are available online at http://baydelta.ucdavis.edu/pepperweed/. All project, task, and subtask descriptions and reports can be found on this website.

3.1. Task 1 Project Management

3.1.1. Task 1 Objective and Summary

The objective of this task was to provide technical and administrative services necessary to complete the work for this project. This included project management (Subtask 1.1), submission of quarterly progress reports (Subtask 1.2), subcontractor selection (Subtask 1.3), and data management (Subtask 1.4). This task included executing and maintaining a subcontract with The Nature Conservancy and Hart Restoration. This task also included multiple re-budgets and no cost extensions to address California state funding issues and our own time constraints. Task 1 is complete and reports were submitted on a quarterly basis. Quarterly reports were submitted to GCAP Services and are all posted online under Task 1.

3.2. Task 2 Environmental Compliance and Permitting

3.2.1. Task 2 Objective and Summary

The objective of this task was to attain all necessary permits to complete this project (CEQA/NEPA, PUPs). This included CEQA/NEPA Compliance (Subtask 2.1) and other required permits and approvals (Subtask 2.2). All aspects of Task 2 were completed during the early stages of the project; please reference the first quarterly report for more information.

3.3. Task 3 Monitoring and analysis of *Lepidium latifolium* population patterns and trends.

3.3.1. Task 3 Objective and Summary

The objective of this task was to monitor perennial pepperweed populations at the Preserve and determine the current extent of the infestation. This included a yearly inventory (2005-2007) and monitoring of perennial pepperweed populations (Subtask 3.1), testing the ability to age stems through a HCL/phloroglucinol stem aging technique (Subtask 3.2), developing a species identification handbook and online photo catalog for the Preserve (Subtask 3.3), acquiring GIS and LiDAR data (Subtask 3.4), and finally developing a weed tracking database framework (Subtask 3.5).

3.3.1.1. *Subtask 3.1 Arc-GIS Inventory of Lepidium latifolium location and population data in riparian and floodplain areas of the Cosumnes River Preserve*

As perennial pepperweed populations expand and disperse across the Preserve (Figure 1) they threaten restoration activities, vegetation succession, local habitat diversity, and downstream or adjacent diversity (Hutchinson et al. 2007b). While floods in floodplain areas can act as an environmental control that suppresses patches via sedimentation and flooding, perennial pepperweed was documented to rebound during dry years (Figure 2). In the case of the Experimental Floodplain, where large levee breaches allow for connectivity with the river, inundation is not the only factor that affects perennial pepperweed in a wet year; our findings suggest that patches disappeared due to flood scour and sediment deposition. Flood induced processes are also responsible for dispersing upstream perennial pepperweed root fragments into downstream locations via sediment deposition, where conditions that favor scour may displace and disperse existing populations further onto floodplains and downstream.

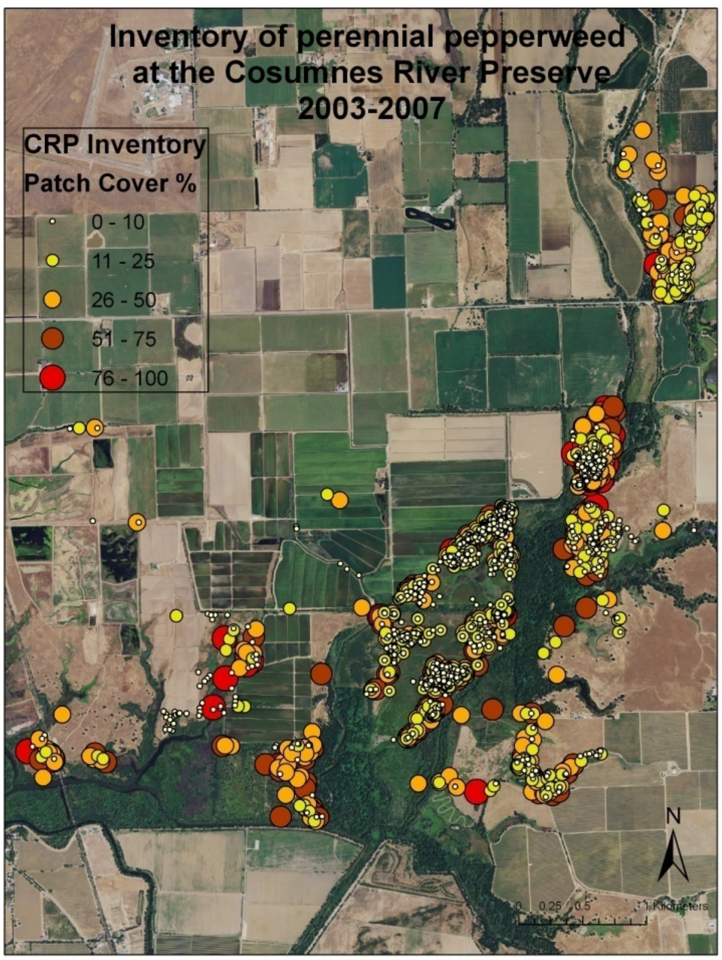


Figure 1. Perennial pepperweed patches inventoried between 2003 and 2007. Patches are displayed as graduated percent cover.

In a system like the Cosumnes River, perennial pepperweed dispersal occurs when seed or root fragments are flushed downstream or across a floodplain (Renz 2000, Orth et al. 2006). In theory, dispersal and new patch establishment should be more evident in a wet water year than a dry water year when water based transport of seed and root movement is prevalent. In the annual inventory on the Experimental and Lower Floodplain (2004-2007), dry years, not wet years, produced to most new patches. To explain this unexpected outcome we have formulated two potential establishment scenarios. The first postulates that a wet year results in more new patches than a dry year. In a wet year, seeds or root fragments are carried downstream and will settle and eventually germinate. However, due to stressful (wet) conditions, these new patches may remain in the seedling or rosette stage without bolting and producing flowers, thus making them imperceptible to surveyors. In a dry year following a wet year, those previously undetected rosettes will bolt and flower from an established root structure, resulting in many new patches. The second potential establishment scenario is that in wet years root and seed are inundated for long periods of time where they eventually become unviable and produce few new populations. In dry years, root fragments and seed are retained locally or within the same floodplain, are not inundated for long periods of time, and maintain their viability. Once locally dispersed by lower water flows or wind roots establish or seeds germinate, bolt and flower.

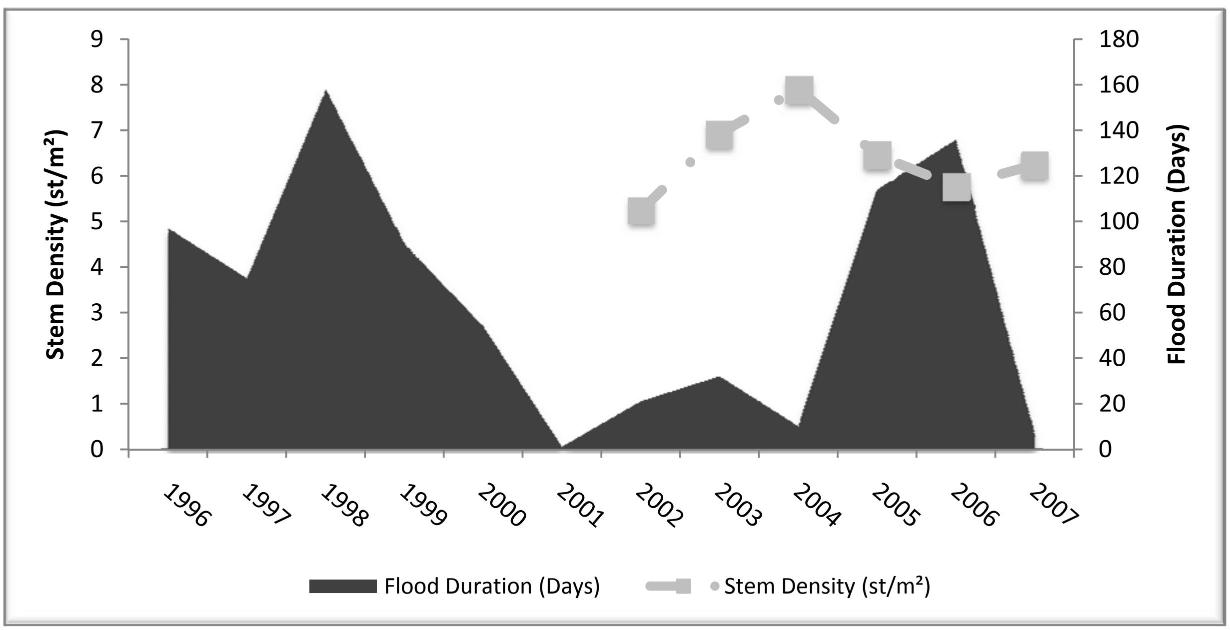


Figure 2. Mean stem density of perennial pepperweed and flood duration of the Cosumnes River from 1996 to 2007. Perennial pepperweed stem count and density is unknown prior to 2002.

As both scenarios are plausible, we expect perennial pepperweed to be more dangerous on a larger scale in wet years, but more threatening to localized habitats where it was already established in dry years. By targeting upstream and satellite patches the Preserve can begin to protect sensitive habitats from future invasion and from becoming a source to new invasions. Once a defensible space is created around and on the periphery of the floodplain, the core infestations can be removed with a higher degree of success. Treatment should be most extensive in drierdrier years, when flood-suppressed patches will not 'hide' from applicators and jeopardize eradication success in localized areas.

3.3.1.2. *Subtask 3.2 Report on ability to age Lepidium latifolium stems*

The root structures of perennial pepperweed stems tested were large enough and had clearly defined growth rings to enable us to accurately age the stems independently of the HCL/phloroglucinol procedure (Hutchinson et al. 2007a) (Figure 3). While some root segments stained "correctly" and enhanced the visibility of individual growth rings, the variability of the staining decreased the likelihood that we would use or recommend usage of this procedure in the future. It is possible that either procedural error or inapplicability of the staining for our particular species is to blame for the ineffectiveness of this procedure. This procedure may also be unnecessary for larger perennial species with well developed root structures, especially when yearly growth rings are commonly visible with the naked eye.

		
Root B: Three years of age, stained red in all areas except pith of stem.	Root C: Three years of age, stained slightly on outer woody section.	Root D: One year old, slightly stained on outer woody section

Figure 3. HCL/phloroglucinol root results for one patch. This particular patch was aged at three years old.

Accurately determining the age and age-distribution of a perennial pepperweed patch would enhance the understanding of how a patch expands (Dietz 2002). Our ability to age each individual root section gives us confidence that, if we were able to exhaustively sample a patch or weed occurrence, we would not only be able to age any perennial pepperweed stem but determine both the age and the age distribution of a patch. In rapidly expanding populations, like those at the preserve, it may be more valuable to try to determine a minimum and maximum age of the largest and presumably oldest patches. This method, combined with an inventory of populations at the preserve could help reconstruct a history of the initial invasion as well as an age distribution for a patch.

3.3.1.3. *Subtask 3.3 Handbook of local Cosumnes River Preserve vegetation and the virtual herbarium made available online*

The Cosumnes River Preserve Virtual Herbarium is available online at http://baydelta.ucdavis.edu/plants/. See Figure 4 for an example of the website homepage and an example of a species information page. The virtual herbarium catalogues over just under 475 taxa present at the preserve and provides images, biological, and ecological information about each species (Hutchinson and Viers 2007).

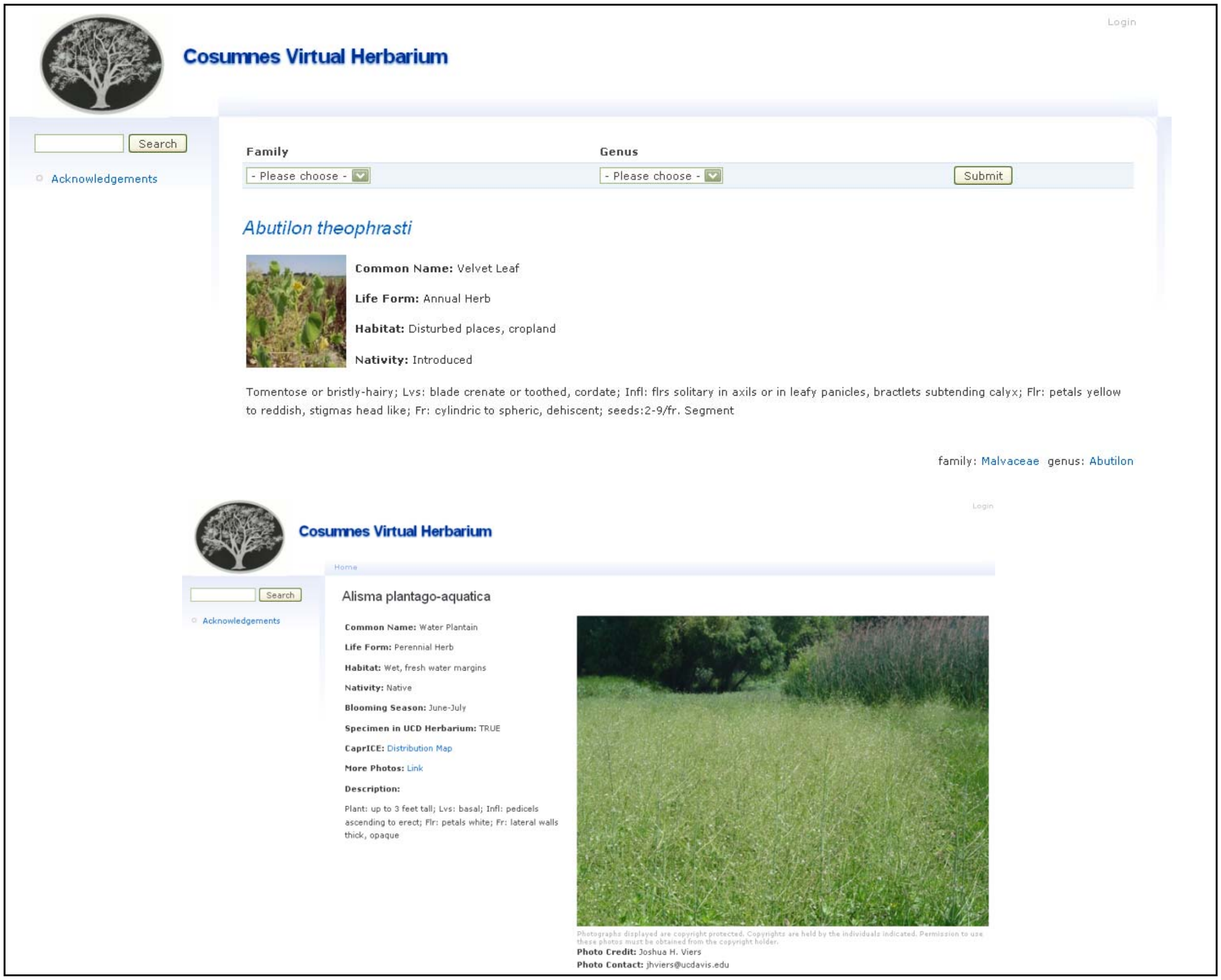


Figure 4. Example of the Cosumnes River Preserve Virtual Herbarium homepage and species information page.

3.3.1.4. *Subtask 3.4 LIDAR imagery and georeferenced weed location data for the Cosumnes River Preserve*

The LiDAR data (Figure 5) and georeferenced weed location data was made available to The Nature Conservancy and The Department of Fish and Game (Watershed 2005). Each dataset will be provided in the final data package. Georeferenced weed location information (see Figure

1) has already been provided to The Cosumnes River Preserve and the Sacramento Weed Management Area.

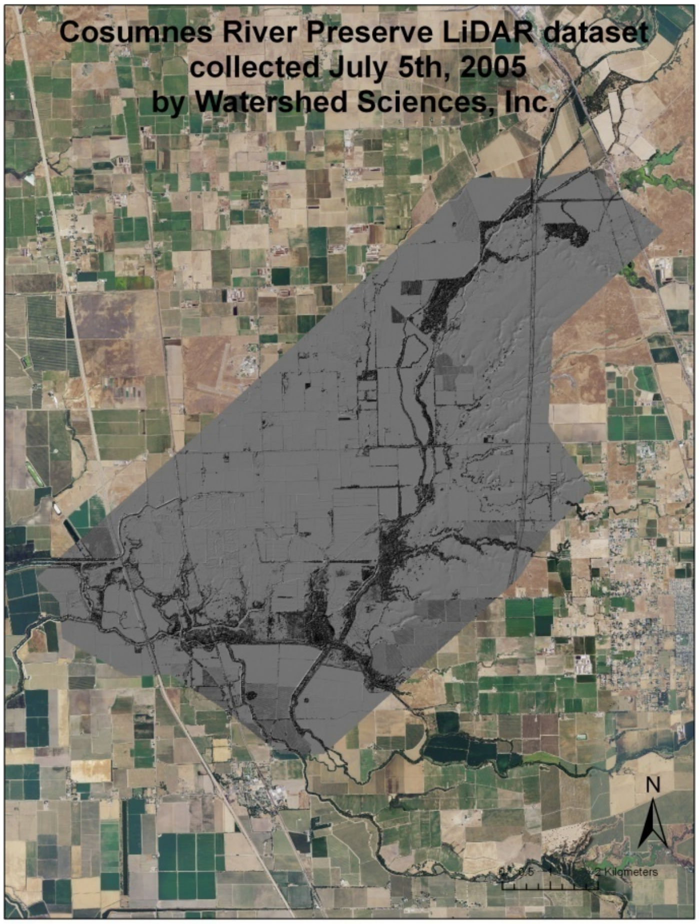


Figure 5. Extent of LiDAR data collected in 2005 at the Cosumnes River Preserve.

3.3.1.5. *Subtask 3.5 Geographically-based database framework for weed control*

The GeoWeed database *per se* proved non-essential in part because the long development time inherent in collaborative software, though ultimately resulting in more flexible and extensible software, did not produce a stable enough data tool early enough in the project to record all of the specific attributes of the experimental plots as the experiments commenced (Quinn et al. 2008). With experienced ArcGIS users, it also proved more practical to load the experimental observations directly into a high-end GIS for mapping and analysis -– an option less practical for regional or multi-organizational mapping and monitoring, such as that by undertaken by TAdN for *Arundo sp.* Nevertheless, WIMS/GeoWeed modules were useful in surveying for perennial pepperweed infestations at the larger scale of the full Cosumnes River Preserve, and the complexities the multi-factorial experiments described below provided considerable insight into how GeoWeed should be designed for broader deployment. In the longer run, we expect GeoWeed to become more used for tracking perennial pepperweed populations and management as the experimental findings here are applied by land managers at the Preserve, other TNC-managed sites, and potentially by other organizations throughout the Delta, where perennial pepperweed continues to be one of the most threatening plant invaders.

3.4. Task 4 Targeted research on *Lepidium latifolium* control.

3.4.1. Task 4 Objective and Summary

The objective of this Task 4 was to investigate experimental control methods on perennial pepperweed that could be implemented by preserve managers to control the infestation at the Cosumnes River Preserve (Figure 6). This included measuring the control success of two herbicides and two herbicide application methods (Subtask 4.1; Table 1), a non-chemical tarping (Subtask 4.2), non-target vegetation effects (Subtask 4.3), soil chemical and physical properties (Subtask 4.4), a soil bioassay (Subtask 4.5), and a soil seed bank experiment (Subtask 4.6). This task was completed in June of 2010. Final reports for all subtasks are posted online.

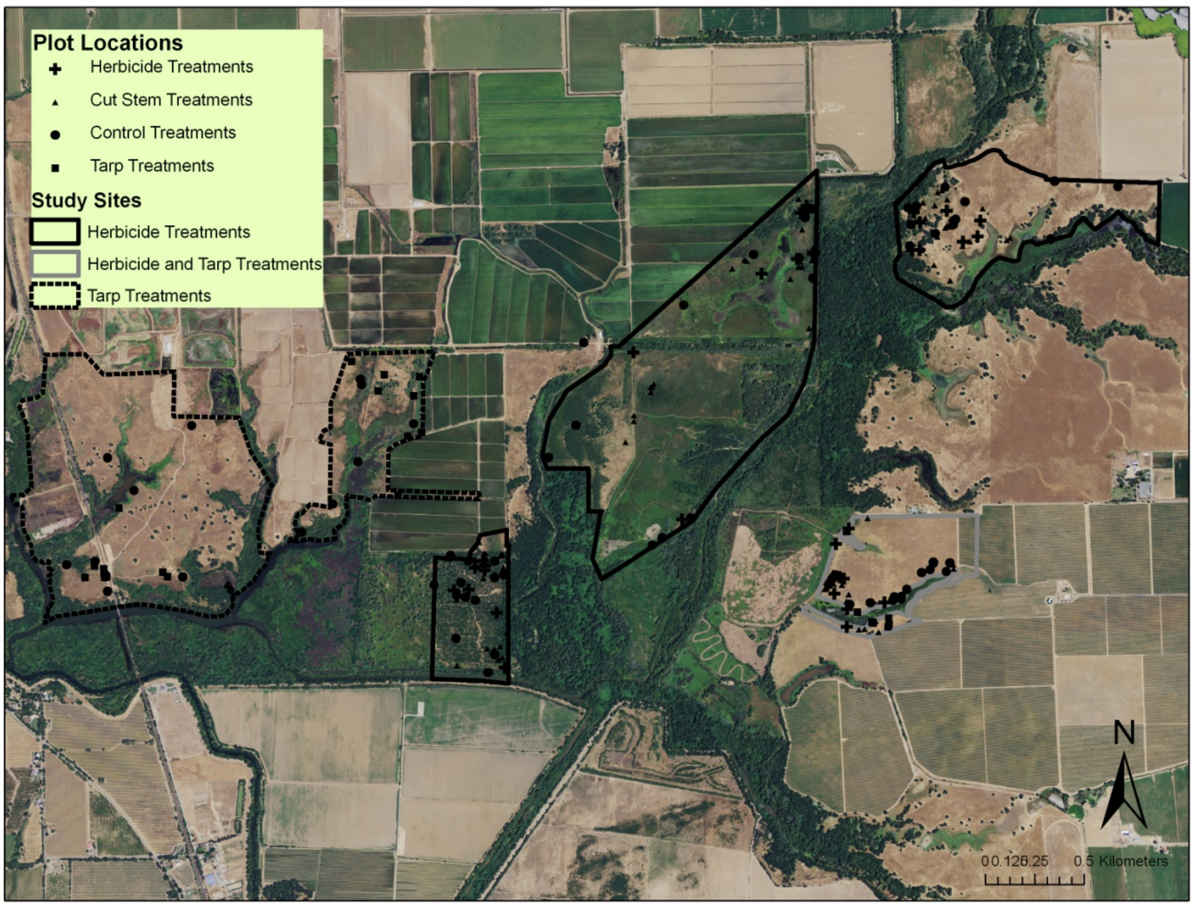


Figure 6. Plot locations of all treatments conducted as part of Task 4.

Table 1. Treatment schedule for all experimental treatments conducted during the 2005-2011 project term.

Treatment	Subtask	2005	2006	2007	2008
Mow-Telar®	4.1	x	x		
Mow-AquaMaster®	4.1	x	x		x
Mow-Control	4.1	x	x		
Cut Stem-Low Concentration Telar®	4.1		x		
Cut Stem-High Concentration AquaMaster®	4.1	x			
Cut Stem-Low Concentration AquaMaster®	4.1	x			
Cut-Stem, No Herbicide	4.1	x			
Mow-Tarp	4.2		x	x	
Mow-Disk-Tarp	4.2		x	x	
Lepidium-Control	4.1 & 4.2	x	x	x	x
No Lepidium-Control	4.1 & 4.2	x	x	x	x
Pull Treatment	---	x			

3.4.1.1. *Subtask 4.1 Report on effect of herbicide type and application method on control of Lepidium latifolium*

Combating perennial pepperweed on a site and infestation specific basis will be the crux of future eradication efforts at the preserve (Hutchinson et al. 2010b). These efforts will prioritize properties and specific populations to reduce the spread of the infestation and return sensitive habitat to its rightful place in succession. Overall, we can recommend mow broadcast spray herbicide treatments with either Telar® or AquaMaster® (Tables 2-4). AquaMaster® may be less effective in grassland sites as indicated by data collected 2YAT and even less so in more scattered populations based on the expanded plot data collected in Years 3 and 4. Telar® was very effective in both grassland and riparian areas but is not approved for use in wetland areas and fears of soil residence time in shady or areas in soils with high pH may make it unacceptable for use in more sensitive riparian and wetland areas.

While we can attribute the decrease of perennial pepperweed at some sites to certain treatments we must take a closer look when controls experience negative effects on target populations. Perennial pepperweed is susceptible to long term flooding and one year after treatment some areas of the preserve were inundated for up to 50 days (Chen et al. 2005). We recognize this environmental factor as a driver for perennial pepperweed establishment and growth and so we must recognize its effect on eradication efforts. By focusing on these environmental factors as well as treatment effects we can try to explain some discrepancies experienced in both one and two years post treatment.

Table 2. Herbicide concentration and method associated with each treatment type.

Treatment	Telar® (Chlorsulfuron)	AquaMaster® (Glyphosate)
Broadcast	0.104 kg ai/ha spraying to wet	3.33 kg ae/ha spraying to wet at 1.5% by volume
Cut Stem- High Concentration	n/a	3.33 kg ae/ha
Cut Stem- Low Concentration	**0.052 kg ha^{-1}	1.67 kg ha^{-1}

**only in 2006

One year after treatment treatments of mow broadcast herbicide with both herbicides were successful at eradicating perennial pepperweed. Two years after initial treatment we began to see some resurgence of perennial pepperweed in mow/AquaMaster® plots at grassland sites. In our yearly inventory of the Experimental Floodplain we noticed that in high water years, like 2005 and 2006, many patches disappeared but reappeared in dry years like 2007 (see Subtask 3.1). While our herbicide results have been in line with earlier pepperweed studies, the results from these studies were only one year post treatment.

Cut-stem herbicide application treatments, while effective over time, are not likely to be implemented over large areas. When used in precision application, a high concentration AquaMaster® treatment was more effective at decreasing perennial pepperweed populations than a low concentration Telar® treatment (Table 3). While AquaMaster® is effective, is not efficient for controlling large perennial pepperweed populations. However, our analyses show that this tool may be useful in sensitive areas with high tree canopy cover, relatively little slope and high amounts of silt in the soil.

At both the Silverado and North Moyer Slough sites, some treatment control plots (M-CO and CS-CO) stimulated perennial pepperweed growth. Mowing or cutting perennial pepperweed stems alone will not rid an area of infestation; in fact it may encourage growth. These findings are consistent with previous results from mowing with no herbicide application (Renz and DiTomaso 2006).

Table 3. Number of plots, mean perennial pepperweed stem count and standard deviation, and percent change from 2005 to 2007 for each treatment type. *indicates plots that were only treated in one year.

Treatment	Treatment Abbreviation	n (plots per treatment)	Mean05 (Std Dev)	Mean06 (Std Dev)	Mean07 (Std Dev)	% Controlled mean
No *Lepidium* Control	NOLELA-CO	16	0 (0)	0 (0)	0 (0)	No Change
Lepidium Control	LELA-CO	20	115.786 (98.133)	69.393 (81.937)	109.964 (107.24)	-35.0%
Mow, Broadcast Telar®	MB-CH	16	119.25 (98.48)	0.375 (0.806)	0.375 (1.088)	99.68%
Mow, Broadcast AquaMaster®	MB-GL	16	165.5 (194.616)	1.438 (2.421)	7.5 (21.429)	94.68%
Mow, No treatment	M-CO	16	141.438 (173.091)	72.5 (112.269)	81.813 (103.402)	-74.09%
Cut-stem, high concentration Telar®	CS-HC-CH*	16	122.25 (231.037)	12.688 (21.85)	37.625 (48.446)	2.52%
Cut-stem, low concentration Telar®	CS-LC-CH*	16	n/a	66.438 (96.09)	38.188 (45.782)	n/a
Cut-stem, high concentration AquaMaster®	CS-HC-GL	16	124.75 (177.23)	49.188 (106.796)	19.875 (25.835)	81.49%
Cut-stem low concentration AquaMaster®	CS-LC-GL	16	119.688 (133.183)	81 (127.969)	57.813 (57.284)	39.93%
Cut Stem, no herbicide	CS-CO	16	118 (105.979)	102.75 (126.527)	129.438 (133.949)	63.69%

Table 4. Expanded Number of plots, mean perennial pepperweed stem count and standard deviation, and percent change from 2008 to 2009 for expanded plots. *indicates plots that were only treated in one year.

Treatment	Treatment Abbreviation	n (plots per treatment)	Mean08 (Std. Dev.)	Mean09 (Std. Dev.)	n/a	% Controlled
Lepidium Control	LELA-CO	8	**95.6** **(105.6)**	**77.4** **(91.6)**	**n/a**	**-13.4**
Expanded Treatment: Mow, Broadcast AquaMaster® (900m²)	MB-30*	18	**406.9** **(457.7)**	**196.8** **(457.9)**	**n/a**	**-64.61**

Late, long duration flooding that occurred one year post-treatment may be a factor resulting in the perennial pepperweed control success at both West Bottoms and the Experimental Floodplain. These sites are the most susceptible to flooding because of their position in relation to the river channel. In turn, perennial pepperweed is negatively affected by flooding and it has been shown to survive but not thrive under flood conditions (Chen et al. 2002). This late, long duration flood may have delayed many species, including perennial pepperweed, from germinating or it may have drowned out early attempts by *L. latifolium* to sprout from perennial root structures. Flood effects can be seen in control plots (LELA-CO) on the Experimental Floodplain and at West Bottoms which both decreased significantly in stem count (see Subtask 4.1).

Other evidence that suggests a negative effect on perennial pepperweed due to flooding was found in the annual inventory of pepperweed completed in year two (2006) on the Experimental Floodplain (see Subtask 3.1). The results from the inventory confirm that the late, long duration flooding may have caused smaller perennial pepperweed populations. Using the methodology of Booth et al. (2006), we classified 2006 as a Water Year Type 8, which reflects the longest duration floods & one of the highest peak flows, and 2007 as Water Year Type 1, which reflects the shortest duration floods and the lowest peak flows (see Subtask 4.1). For this reason, recommendations for future treatment depend on hydrodynamic conditions.

The low overall treatment success and variability of the expanded plots is likely due to a few factors that should be a concern for land managers (Table 4). One of the largest factors was that the 900m² plot area was often around 25% perennial pepperweed cover and if the plot contained tall vegetation (>2m) it was difficult to ensure that all of the perennial pepperweed had been treated over such a large area. This was compounded by the fact that a consultant, rather than a researcher, treated the plots. While the contractor did a good job, maintaining a similar level of accuracy and completeness within the 900m² plot area was difficult and required a high level of supervision. In addition, in large, dense infestations it may be more important than we realized to treat the entire patch, as underground roots may persist post-herbicide treatment allowing the patch to persist.

3.4.1.1.1. Pulling Perennial Pepperweed Pilot Study

In 2004, we began a small pilot study on the Experimental Floodplain and pulled 19 perennial pepperweed patches. These populations were tracked for pulling efficacy on a yearly basis from 2004 to 2007 during the annual pepperweed inventory on the experimental floodplain.

This was conducted to test the efficacy of pulling, an easy and cheap way to manage weeds. In a related study, pulling was utilized as an eradication technique and showed that eradication can be achieved if stems are pulled multiple times a year for many years (Orth et al. 2006). Data collected from the experimental floodplain at the Preserve indicates that while initial results of stem pulling were good, over time those populations returned either by ***remnant*** underground roots or ***deposited*** seed (Figure 7).

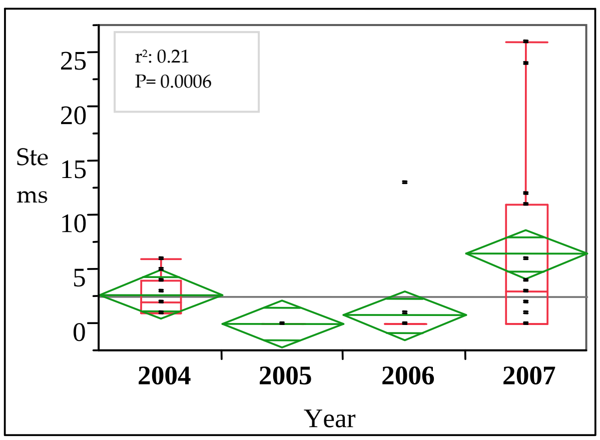


Figure 7. Results of a pilot study to test pulling perennial pepperweed on the Experimental Floodplain. Stems were pulled in 2004 and monitored annually between 2005-2007.

3.4.1.2. *Subtask 4.2 Report on effect of multi-year tarping on control of Lepidium latifolium*

We adapted non-chemical tarping techniques by tilling the soil before tarping infested areas to further stress the perennial root structures and by lengthening the standard tarp period (Hutchinson et al. 2008). By designing the experiment based on our understanding of tarping perennial plants and of the preserve, we were able to create a control regime that was measurably successful. This approach gave us the ability to test the effectiveness of site specific adaptations to an emerging methodology.

Mow, disk, tarp plots were more effective than tarping alone. There was no significant difference between mow, disk, tarp (M+D+T) and mow, tarp (M+T) treatments at all sties (Table 5; $p<0.16$). However, mow, disk, tarp plots offer more consistent results than mow, tarp plots.

The variability of the mow, tarp plots is discouraging, but by tilling before tarping the mean success rate moves from an 18% increase in pepperweed stems (M+T) to 85% decrease in pepperweed stems in mow, disk, tarp plots. We attribute this success to the root damage incurred by tilling the top layer of the soil. This tilling action was intended to further impair root structures by destroying the connections between the stems on the surface and their water source. We tested the hypothesis that the combined effect of heat, light exclusion, and root destruction would result in eradication.

Table 5. Herbicide treatments, tarp treatments, and experimental controls: perennial pepperweed mean stem counts and average rate of stem change pre-treatment, one year after treatment (1YAT) and two years after treatment (2YAT). Statistical significance is indicated where *<0.05, p<0.005 (**), p<0.0005 (***). Negative rates of change indicate population decline (Hutchinson and Viers 2011).

Treatment	n	Pre-treatment Mean ±SD	1YAT Mean ±SD %change	2YAT Mean ±SD %change
Mow-AquaMaster®	*8*	210.5±252.2	0.9±2.5* -99.6%	0.8±0.9* -99.6%
Mow-Telar®	*8*	130±93.4	0±0** -100%	0±0** -100%
Mow-Control	*8*	142.6±202.7	27.1±71.6 -80.9%	40.5±95.0 -71.6%
Experimental-Control(*h*)	*8*	101.8±99.8	33.6±70.8* -66.9%	73.4±116.5 -27.9%
Mow-Disk-Tarp	*7*	354.3±204.3	151.1±374.8* -57.4%	33.6±73.9*** -90.5%
Mow-Tarp	*8*	228.4±209.8	109.3±180.6 -52.2%	212.8±360.3 -6.8%
Experimental-Control(*t*)	*8*	188.6±99.5	285.7±296.6 51.5%	196.4±196.4 4.1%

Mow, disk, tarp treatments are of similar efficacy to Mow-Herbicide treatments (Hutchinson and Viers 2011). This finding further supports the use of tarping in herbicide restricted areas. Using a Mow-Disk-Tarp eradication method would enable organic farmers to remove source populations at the Cosumnes River Preserve where herbicide application is not allowed, such as locations adjacent to rice fields or access roads. The main downfall of this type of treatment is that it is extremely labor intensive at the outset. Additionally, tarping requires monitoring and repairs throughout the period of tarp deployment and recovery. The variability of success in mow, tarp plots suggest that other environmental factors may affect control success. These results indicate that factors like plot location, plant community, and soil type impact the efficacy of tarping.

3.4.1.3. *Subtask 4.3 Report on response of non-target vegetation to Lepidium latifolium control efforts*

Non-target vegetation was monitored to inform further weed control efforts as there is some evidence that future invasibility can be managed by careful planning, restoration, and monitoring (Hutchinson et al. 2010a). To assess the impacts of weed control on non-target vegetation, specifically perennial pepperweed, at the Cosumnes River Preserve the following questions were asked: Will one invasive species be replaced by another invasive species? Will native species be impacted by herbicide use?; What treatments cause bare soil or thatch cover to increase?; and, How is the composition of plant functional groups impacted by experimental treatments? To answer these questions, specific sites at the Cosumnes River Preserve were studied to provide insight into weed management outcomes in a variety of habitats. These results are limited by the implementation of 9m^2 plots, which do not capture entire perennial pepperweed patches and cannot be considered 'landscape scale'. To account for this uncertainty, we investigated a subset of plots that were treated with a Mow, AquaMaster® at a "patch" level (900m^2). In the process of expanding this treatment, we were able to test the hypothesis that treating populations on a larger scale would not further impact the non-target vegetation. By applying what we understood about a specific area and accepting the limitations of what was known, we were able to adapt our management regime to inform those limitations and ultimately report more useful results.

Combined with our understanding of species invasibility, evidence from the literature, and the results from the non-target vegetation monitoring and seed bank experiment, there is substantial evidence that both the density and diversity of species found at the Cosumnes River Preserve will be sufficient to restore areas treated with AquaMaster®, though perennial pepperweed seed viability may still be a factor (Figure 8.; Subtask 4.6).

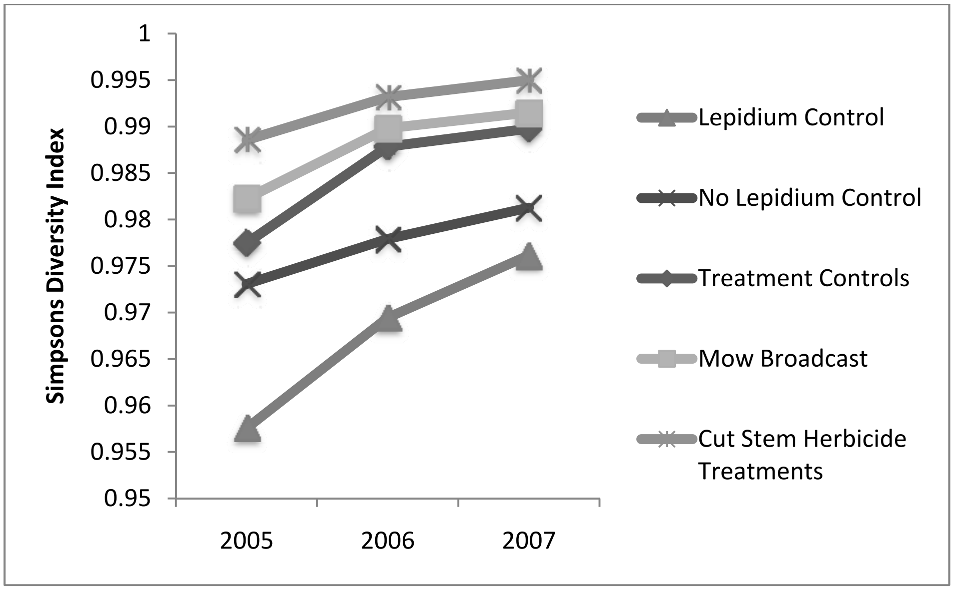


Figure 8. Simpsons Diversity Index (1-D) for experimental controls, treatment controls, and herbicide treatments, during the pepperweed control project.

In grassland areas, mow, Telar® treatments are the most effective over time (see Subtask 4.1). Non-target vegetation, bare soil, and thatch in Telar® and AquaMaster® treated plots are similarily impacted. If Telar® negatively affected germination in our grassland sites, as it is documented to negatively affect some grass species, it was not apparent from either field surveys or the seed bank study (Young et al. 2002); see Subtask 4.6). Many grassland areas are near waterways and ponds, and therefore Telar® use at the Cosumnes River Preserve needs to be carefully examined before any future application. Drought conditions during a weed control project may increase invasibility by altering the cover of non-target vegetation. Some evidence of drought stress was observed which was most apparent in the accumulation of thatch and lower vegetative cover in 2007.

Telar® application is very restricted in riparian areas at the Cosumnes River Preserve. However, perennial pepperweed in riparian areas responded to Telar® and AquaMaster® herbicide treatments very well (Subtask 4.1). In riparian plots managed with AquaMaster®, functional group diversity and distribution were less affected when compared to Telar® treated plots. AquaMaster® also appears have minor implications for native species cover after two years of treatment. Additionally, bare soil cover does not appear to change in mow AquaMaster® treated plots. Based on our observations, Telar® appears to have a greater potential for detrimental effects on native riparian vegetation than AquaMaster®.

Expanded AquaMaster® treatments did not cause any unexpected non-target effects. Because the expanded herbicide treatment was targeted for perennial pepperweed, versus treating the entire plot area as in the 9m² plots, the treated area made up a smaller percentage of the total plot area. This approach allows us to look beyond the treated area and into the adjacent vegetation to address landscape scale diversity issues, versus the smaller plot based scale. The lack of compositional differentiation between pre and post expanded plots removes some of the uncertainty surrounding the outcome of herbicide treatments on non-target vegetation. While grassland communities do appear to respond less favorably than riparian, this is likely due to a combination of annual variations in environmental factors and that a higher proportion of species in grasslands are introduced than in riparian sites.

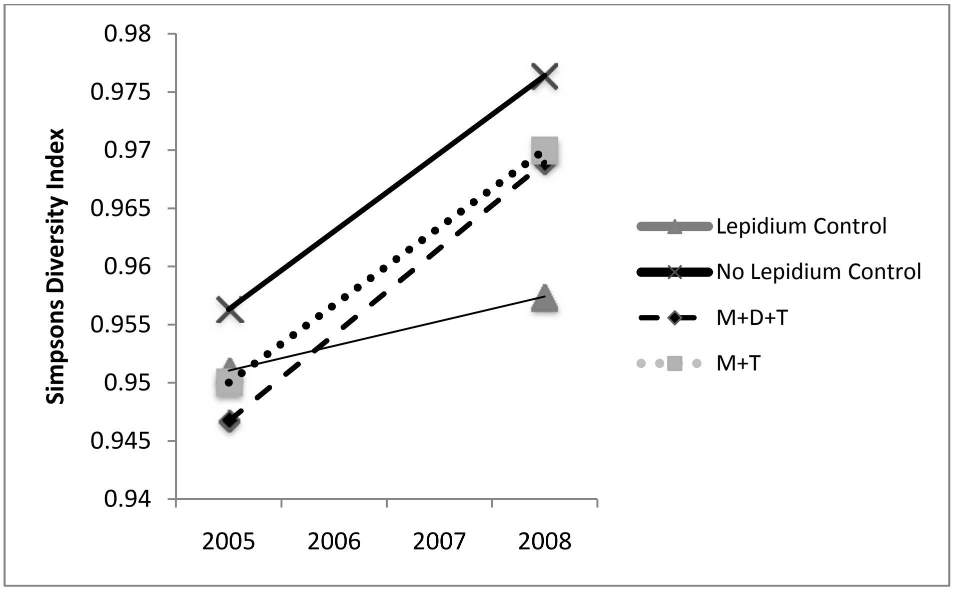


Figure 9. Simpsons Diversity Index (1-D) of non-chemical tarp treatments (M+D+T and M+T) and controls from 2005 to 2008. Stars indicate statistical significance of each comparative test (* <0.05, ** <0.009, *<0.0009). Results do not include *Lepidium latifolium* data.**

The most effective means of non-chemical perennial pepperweed control was a mow, disk, tarp treatment (Subtask 4.2). In non-target vegetation surveys of tarped areas, this study found that an increase of bare soil and low native cover post-tarping may increase future invisibility, leading to new invasive species establishment. To maintain a favorable outcome after tarping, it is recommended that the plant community is monitored for multiple years after treatment and that the possibility of restoration is considered (Figure 9).

3.4.1.4. *Subtask 4.4 Report on effect of Lepidium latifolium presence and chlorsulfuron application on soil properties*

While some variability exists, we found little difference in either soil or chemical properties in plots that contained *Lepidium latifolium* versus those that did not contain perennial pepperweed (Viers et al. 2008a). We examined Ca, Mg, and Na in three soil horizons as a function of perennial pepperweed presence (LELA-CO) and absence (NOLELA-CO) and found no statistical evidence for changes in sodicity that could be attributed to perennial pepperweed, including stem densities. In particular, we used analysis of variance (ANOVA) to determine if

Ca differed between invaded and non-invaded plots and found no detectable differences at depths of 0-10 cm ($p = 0.50$), 10-25 cm ($p = 0.90$), and 25-50 cm ($p = 0.36$). Further, we found no differences in Ca at these depths by perennial pepperweed cover category (high vs. low) using a conservative *t*-test among all pairs (see Subtask 4.4). We do note, however, a significant difference in soil Ca levels at the 25-50 cm depth between sites without perennial pepperweed and sites with low cover versus sites with high cover estimated in the field using a one-sided *t*-test in individual comparisons. High cover sites had higher levels of Ca ($\mu = 1.28$ meq L^{-1}) than low cover sites ($p = 0.04$) and sites without perennial pepperweed ($p = 0.02$) with mean differences of -0.4388 meq L^{-1} and -0.4583 meq L^{-1} respectively, which could be viewed as consistent with the findings of Blank & Young (2002). In a fashion similar to Ca, we also examined Mg and Na. Detectable differences in Mg were negligible between perennial pepperweed invaded versus non-invaded sites across depths of 0-10 cm ($p = 0.46$), 10-25 cm ($p = 0.57$), and 25-50 cm ($p = 0.15$). Detectable differences in Na were also negligible between perennial pepperweed invaded versus non-invaded sites across depths of 0-10 cm ($p = 0.49$), 10-25 cm ($p = 0.89$), and 25-50 cm ($p = 0.97$). There were no significant detectable differences in either Mg or Na by cover category (high vs. low) at any depth.

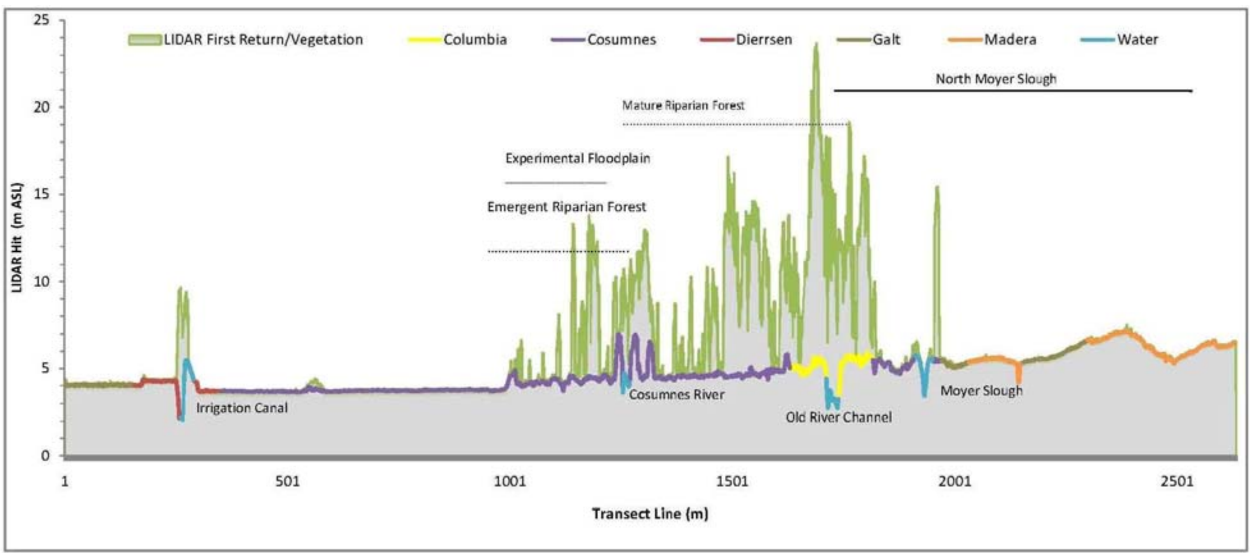


Figure 10. LiDAR first return and bare earth data color coded by tree or vegetation height (first returns), soil series (bare earth) and water (bare earth).

We used multiple analysis of variance (MANOVA) to determine if salts varied by depth across both treatment and vegetation community, as there were potential site and treatment interactions at varying depths of measurement (see Subtask 4.4). In this analysis, we determined that Calcium (Ca) significantly varied by depth within vegetation communities ($p < 0.0001$), but not across treatments ($p = 0.40$) or treatments within communities ($p = 0.62$). This same pattern was evidenced for Magnesium (Mg) where vegetation community significantly varied by depth ($p < 0.001$), but treatment varied only marginally ($p = 0.08$) and there was no indication of community by treatment interaction ($p = 0.63$). Lastly, in regards to MANOVA of soil sodicity, Na, followed a similar pattern where vegetation community variability across depths was significant ($p = 0.04$), but not treatment ($p = 0.46$) or community by treatment interaction ($p = 0.64$). In no test was treatment (i.e., perennial pepperweed presence) a significant contributor to observed variability in soil sodic conditions.

We conclude that perennial pepperweed presence or density has little to no effect on the overall physical and chemical properties that make up both alluvial and upland soils at the Cosumnes River Preserve (Figure 10). Our findings, while not consistent with studies conducted in areas that receive fewer disturbances, indicate that perennial pepperweed's soil altering abilities may be limited by individual site characteristics rather than pepperweed density (Blank 2002, Renz and DiTomaso 2004).

Our experimental treatment investigation concludes that soils in our mow herbicide treatments and control treatments responded more similarly than to our mow control treatments. This finding has little relevance to pepperweed treatment at the preserve but does raise a larger scientific question and prompts us to ask why mowing alone would have a greater impact on soil properties than mowing in combination with herbicide application.

3.4.1.5. *Subtask 4.5 Effect of herbicide application method on chlorsulfuron soil concentrations, as determined by soil bioassay using plant species with known sensitivities to chlorsulfuron*

Our experiment was intended to identify the legacy effect of chlorsulfuron on non-target vegetation through a bioassay of soils collected on an experimental seasonal floodplain in Sacramento County, California (Viers et al. 2007). We collected soil from experimental plots treated with herbicide in one of two methods: broadcast application or cut-stem swab. We found little evidence for legacy effects in the cut-stem swab application; however, we did document significant negative effects in the first two weeks following broadcast application up to 25 cm in soil depth (Table 6). This observation of negative residual effects was exacerbated by elevated pH in soils. Although negative residual effects of broadcast chlorsulfuron application were detected over a seven month period, the effects diminished over time in a linear fashion. This trend, however, showed significant continued soil residuals for floodplain-riparian sites with high silt fraction, but not high sand fraction sites that are presumably well drained. We recommend curtailing use of broadcast chlorsulfuron application in floodplain-riparian sites with either high pH or high silt fraction.

Table 6. Results of *t*-tests by treatment method (CS = cut-stem; MB = mow-broadcast) and soil depth

Treatment × Soil Depth	Mean Difference (Post - Pre cm)	*t*-Ratio	DF	Prob < *t*
CS 0 - 10 cm	1.41	-1.34	36	0.09
CS 10 - 25 cm	1.42	-1.21	34	0.12
MB 0 - 10 cm	3.63	-9.07	52	0.00
MB 10 - 25 cm	3.23	-8.62	52	0.00

Figure 11. Plots treated by Telar® at West Bottoms after 2 years of mow broadcast treatment.

Additional anecdotal evidence from the field suggests that some plots positioned in floodplain-riparian areas were adversely affected by mow-broadcast chlorsulfuron treatments after 2 years of treatment (Figure 11). While we observed no difference in seed bank germinants two years after the initial treatments, some lingering effects in the field were evident (see Subtask 4.6). Some of these effects might be explained by the lack of moisture and subsequent increase in bare soil in all plots in 2007. For example, the bioassay trials were subjected to a uniform growing environment with ample water availability, whereas field conditions are subjected to high variability in environmental conditions (e.g., water, shade, disturbance, etc.).

3.4.1.6. *Subtask 4.6 Species in the soil seed bank of experimental sites*

We identified 16,836 germinants and 115 species over a one year time period in seed bank pots. Of the species that germinated 61 (53%) were non-native and 54 (47%) were native (Hutchinson et al. 2007c). Soil collected from the Experimental Floodplain contained the highest number of seedlings per pot and Willow Slough Trail the least (Table 7). The Experimental Floodplain also contained the most species overall, and Willow Slough Trail the least (69 species and 35 respectively). However West Bottoms contained the most species per plot (Table 7). Diversity was measured using Simpson's diversity index which resulted relatively high values at all sites, excluding NMS (Figure 12). While diversity may have been low in grassland sites, more germinants were seen in grassland communities than in riparian (p= 0.0035). The most common species seen in grassland and riparian sites were Italian ryegrass (*Lolium multiflorum*) and tall flatsedge (*Cyperus eragrostis*) respectively. Together these two species make up almost 50% of the total number of germinants (*C. eragrostis* made up 31.9% of all germinated species, *L. multiflorum* 17.5%).

The germinated species composition reflected the surrounding vegetation community types, and resulted in grassland specific and riparian specific germinants with some cross over between the two sites (see Subtask 4.6). With the exception of the Willow Slough Trail, this coincides with data collected from our non-target vegetation sampling, where riparian areas include the Experimental Floodplain, Tihuechemne Slough, and West Bottoms and grassland areas include North Moyer Slough, Silverado, and the Willow Slough Trail (see Subtask 4.3).

Table 7. Mean, percent of total, number of plots sampled, germinants per plot, number of species per site, and number of species per plot for each experimental site sampled as part of the seed bank experiment.

Site	Mean (SD)	% of total	Number of Plots	Mean Germinants per Plot (Seedlings /# of Plots)	Number of Species Per Site	Species per Pot (Species / # of Plots)
Experimental Floodplain	12.37 (27.97)	25%	24	176.5	69	14.75
North Moyer Slough	19.90 (49.45)	26%	23	174.26	58	10.03
Silverado	13.91 (36.21)	25%	26	157.6	49	12.59
Tihuechemne Slough	5.64 (9.78)	2%	5	79.2	32	12.67
West Bottoms	10.38 (19.65)	18%	20	153.6	64	15.46
Willow Slough Trail	11.01 (24.29)	4%	4	156	35	15.10

Pots containing soil from riparian vegetation types had significantly more native species than grassland areas (p= 0.0023). This coincides with results from individual site analysis where the Experimental Floodplain and West Bottoms contained more native germinants than introduced germinants (p= 0.0031; and p = 0.0083 respectively). Germinants at these riparian sites were also dominated by perennial species. We identified *Cyperus eragrostis* as the native perennial species that is not only the most dominant species in the entire experiment, but is also the dominant species at both the Experimental Floodplain and West Bottoms. On average, *C. eragrostis* was approximately three times more frequent that the next most common species.

Grassland sites contained more introduced species than riparian areas (p= 0.0001). However, when we compare Silverado and North Moyer Slough, we see that both sites contain more introduced species (p=0.006 and p=0.0005 respectively), but that only Silverado contains more annual species (p= 0.04). At these two grassland sites the dominant germinating species was *Lolium multiflorum*, a nonnative, annual grass. On average, *L. multiflorum* was eight times more frequent that the next most common species (Figure 12; see Subtask 4.6).

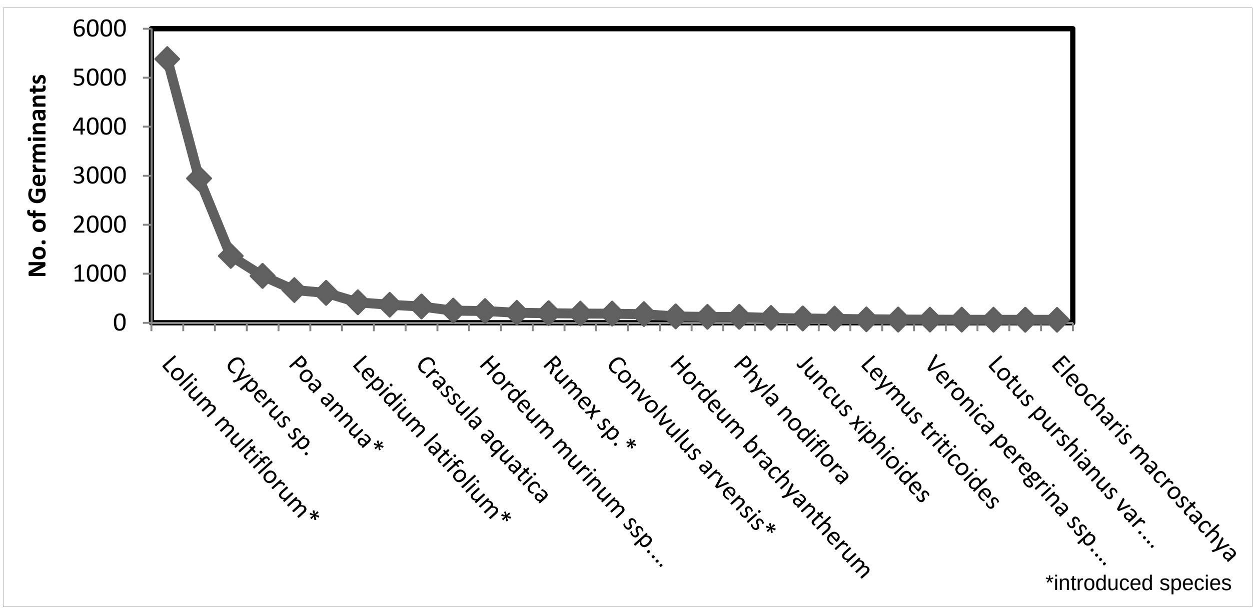


Figure 12. Species most commonly observed in seed bank pots from soil collected at the Cosumnes River Preserve. Introduced species can be identified by a * after the species name.

Based on the species diversity and density in most plots we do not think that reinvasion by perennial pepperweed is an absolute at the Cosumnes River Preserve. We do advise that in areas where bare soil is an issue in high flow years, some monitoring of 'eradicated' patches should be put in place. Restoration of small patches (<3m) does not appear to be necessary. However, most perennial pepperweed patches are greater than three meters and while we will track the species recruitment of larger areas in future studies at the preserve, we do not know at this time what the effect of removing larger infestations will be on the seed bank. We predict that the non-target vegetation and seed bank will continue to recover after herbicide use and passively restore areas previously infested with perennial pepperweed with little active restoration.

3.5. Task 5 Adaptive Management Framework.

3.5.1. Task 5 Objective

The objective of this task is to develop an adaptive management framework for perennial pepperweed control at the Cosumnes River Preserve. This includes developing a multi-scale control framework (Subtask 5.1) as well as modeling new patch establishment (Subtask 5.2).

3.5.1.1. *Subtask 5.1 Adaptive management framework in report form, including standards and guidelines in a decision tree format to aide in determination of the most appropriate weed control techniques for riparian areas and floodplains with Lepidium latifolium populations*

Adaptive management is a science-informed strategy used in resource management that identifies successful practices and reduces uncertainty while achieving articulated management goals. As a science-based approach, adaptive management utilizes available information to make informed decisions for management of complex ecosystems. The scientific method sets the foundation for adaptive management, allowing land managers to develop management actions through hypotheses testing within an experimental framework. Adaptive management constrains management flexibility through adherence to a structured process. In other words, it is not a license to manage in an ever-changing, uninformed or expedient manner.

Within the context of the California Bay-Delta region, adaptive management has been identified as a science-based mechanism to effectively achieve management and restoration goals of stressed ecosystems, but in so doing, it must recognize and embrace uncertainty. Foremost, this has an underlying requirement of gathering meaningful information on a continuing basis from which to evaluate action effectiveness. Significant challenges exist in the adaptive management of riverine systems, which are hindered by both ecological uncertainty and conflicting management decisions (e.g., flood control vs. water storage). More specifically, management of river resources can be constrained by uncertainties surrounding water ownership and regulation of water flow from dams, with cascading downstream impacts on ecosystem processes. Some management approaches in riverine systems can slow ecosystem restoration progress by failing to adapt to changing site conditions or by not incorporating new information into decision making. Under an adaptive management system, the focus is on using existing information and resources that are available, not on what information and resources should or could be available (Lee 1999).

> *"… an explicit vision of an ecosystem does not mean having a complete or detailed or even correct baseline suite of data. Adaptive management is about urgency, acting without knowing enough, and learning. One can be surprised by one's own ignorance -- and one can learn from it. The focus should be on learning, not on getting ready to learn. "* –Lee (1999)

Additionally, this approach requires that actions be implemented and monitored at appropriate temporal and spatial scales (i.e., the proposed actions and associated monitoring regimes are at the appropriate scale to test the working hypotheses and measure whether the management goals are being met). The adaptive management cycle often begins with an evaluation of trends in environmental condition and targeted species or outcome. Major driving factors, both direct and indirect, are then identified to explain observed trends. At this stage, conceptual models can be developed to elucidate physical, chemical, and biological processes. Analyses can then be conducted to determine if monitoring efforts are effectively capturing and measuring components of processes that address the hypotheses being tested. This enables managers to develop and test causal relationships between environmental drivers and processes and outcomes identified in processes. The adaptive management process helps reduce scientific uncertainty and knowledge gaps by allowing managers to implement management actions as formal scientific treatments. In this way they are able to incorporate monitoring results into an analytical framework and continuously improve their working knowledge base and refine their conceptual models.

Long-term, large scale management of the Preserve is developed and agreed by stakeholders. This process is an active and direct management approach where stakeholders are encouraged to voice their opinions and weigh their interests against the interests of the group. The Preserve is managed by multiple agencies and organizations including the Bureau of Land Management (BLM), The Nature Conservancy (TNC), The Department of Fish and Game (DFG), California Department of Water Resources (DWR), Sacramento County Department of Regional Parks, Ducks Unlimited, Inc., California State Lands Commission, Natural Resource Conservation Service, and the Wildlife Conservation Board. The ecosystem diversity coupled with the network of cooperators creates a unique opportunity for landscape scale adaptive management in California's Bay Delta region. As such, management of the Cosumnes River Preserve is subject to change based on new scientific findings, new environmental laws, or socioeconomic trends. In order to successfully manage this dynamic system, the managing partners must be highly adaptive to complete the tasks they outline for themselves with the tools they possess.

The stakeholders at the Cosumnes River Preserve used a collaborative, consensus-based approach to develop long-term, large-scale management goals for each target species and natural community and documented them in The Cosumnes River Preserve (CRP) Management Plan (Kleinschmidt 2008) in previous plans, perennial pepperweed was identified as a high-ranking threat to critical habitats within the Cosumnes River Preserve (CRP 2002). At that time, numerous infestations of perennial pepperweed were known to occur in agricultural, riparian, wetland restoration and roadside areas upstream and within sensitive Preserve lands. Root fragments and seeds were identified as potential sources for new patch establishment, transported via permanent waterways, seasonal floodwaters, and vehicle and visitor traffic. The Preserve stakeholders agreed that perennial pepperweed was a priority for eradication within the Preserve because of its highly-invasive nature, and the threat it poses to native habitats including valley oak riparian forest, mixed riparian forest, seasonal and permanent wetlands, and associated uplands.

We propose the implementation of a five-phase adaptive management cycle, referred to hereafter as the *5M approach* (Figure 13). We use this cycle as the basis for our proposed adaptive management framework, with concomitant components detailed further in the sections below. Our suggested actions directly correlate to specific CRP Management Plan goals and were developed by integrating our findings within Task 3 and Task 4 of the perennial pepperweed control experiment as well as on previous findings.

As with most weed management strategies, the proposed adaptive management framework in its most basic form is to: apply preventive measures where a weed is not present, implement control measures where a weed is already established, and establish protocols for taking

Figure 13. Adaptive Management Cycle articulated with feedbacks from Modify to Mission, Mark, Manage, and Monitor

prompt action when a non-native species first appears in a targeted management zone. The framework is intended to help resource managers: 1) eradicate invasive species from sensitive habitats; 2) define at-risk areas to invasive species invasion; 3) evaluate management strategies for specific infestation patterns; and 4) select properties or locations for immediate action that provides the largest threat to overall ecosystem function, rate of recovery from restoration activities, and biodiversity conservation objectives.

As shown in Figure 13, we have expressed the adaptive management cycle as the *5M approach*. Figure 13 illustrates the successive adaptive management phases while stressing the integration of information between phases to inform future management decisions. The cycle imitates with the *mission* phase which includes defining the problem and setting quantitative and measureable goals and objectives. Once a clear mission is established, the *mark* phase begins with the organization of information and *a priori* knowledge using schematics, process diagrams, or conceptual models to articulate processes, direct and indirect drivers, feedbacks, and areas of uncertainty. The *mark* phase is achieved through targeted research, simulation and inference, or exploration of statistical or Bayesian knowledge bases. The *mark* phase is where specific management actions are developed as treatments within an experiment and monitoring protocols are established to measure progress of management actions toward achieving goals and objectives. The *manage* phase is where management actions are conducted or where policy is implemented. Once management actions are in place, the *monitor* phase commences, where the targets of management actions are observed and outcomes are measured and recorded. It is important to note that the *monitor* phase may and should continue throughout the *modify* phase, if longer term data are needed to inform management decisions. The final, and perhaps most important, phase is *modify*. The *modify* phase includes the analysis of monitoring outcomes, the results of which will be used to influence how management adaptation will take place. Management adaptations may include modification of the mission, refinement of conceptual models, application of additional treatments, and/or assimilation of additional observational data. This is the primary learning phase of the *5m* cycle.

3.5.1.1.1. Perennial Pepperweed Management Framework

3.5.1.1.1.1. Defend

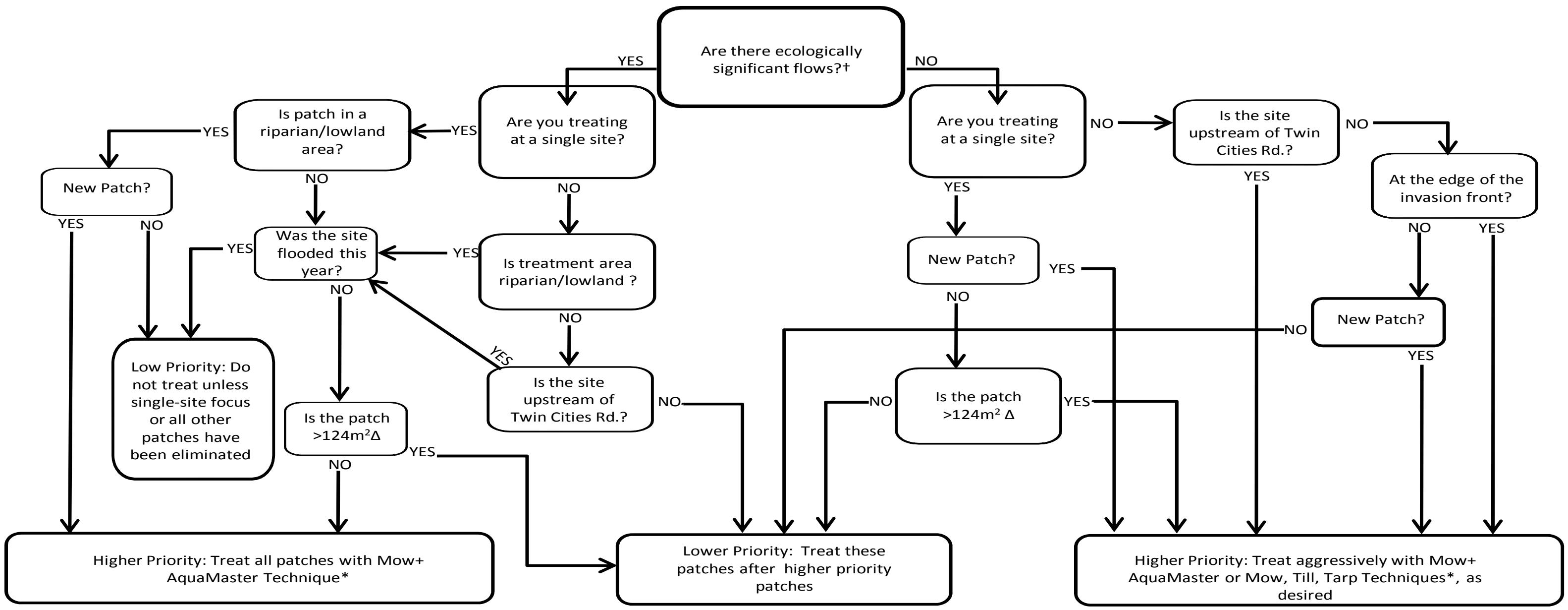
Preserve-wide Strategy- A Preserve-wide defense strategy would target locations at the Preserve that are considered sensitive to invasion because they are ecologically significant or will be restored in the near future. In effect, these places make up the core of the conservation portfolio. Sensitive habitats at the Preserve include wetlands, remnant and restored riparian forest, restored riparian habitat and oak savannah. A defense strategy is most effectively deployed during dry water years (i.e., low flows and low duration flooding in lowland riparian areas). This strategy directly defends sensitive habitats from new patch establishment and existing patch growth, which we found to be most common in years with insignificant flows (see Subtask 3.1(Hutchinson et al. 2007a). There is some evidence that in high flow years with multiple flooding events or long duration flood events, pre-existing perennial pepperweed patches are negatively impacted to the extent that they “hibernate” or are expunged from flooded areas due to scour, sediment deposition, or long duration flooding (Subtask 3.1 (Hutchinson et al. 2007a), Subtask 5.2 (Viers et al. 2008)).

Site Specific Property Strategy- If a specific property or site should be targeted for perennial pepperweed eradication, we recommend that perennial pepperweed patches be split by whether they are in riparian/lowland sites or grassland/upland sites, and whether they are new (established in that water year) or longstanding. Determining when and if to target a single site depends on available resources and the extent of the invasion on a specific site. Because upland sites do not receive as much inundation, longstanding infestations at a single site can be treated in upland sites in wet or dry years but due to flooding should only be treated in drier years in riparian sites. The rationale for this treatment schedule in riparian sites is to reduce the possibility that some patches or some percentage of a patch could "hibernate" in a wet year. In wet years, upland areas should be prioritized while in riparian areas only newly identified patches should be prioritized to reduce the impact of propagule dispersion during flood events. This schedule allows managers to prioritize allocation of limited resources since there is a high probability that treating riparian areas in wet years may leave a partially hibernating patch to return in a subsequent dry year. This effect is less common in grassland or upland sites, where the inundation period is generally shorter. Treating a newly established patch in a wet year at either site is optimal as that patch has a high probability of being the result of long distance propagule dispersal and will generally be lower in total number of individuals and have a smaller root mass than a longstanding infestation.

3.5.1.1.1.2. Attack

Preserve-wide Strategy-The Preserve-wide attack strategy focuses on eradicating the source and spatial extent of an infestation where the defense strategy focuses on a habitat or patch level strategy. Based on surveys conducted at the Preserve between 2002 and 2007, we propose that upstream areas, north of Twin Cities Road should be attacked to cut off perennial pepperweed source populations in both dry and wet years. Prioritization of these populations should favor those that regularly receive floodwaters from the Cosumnes River and therefore have a greater likelihood of sending propagules downstream. This strategy does not come without caveats of course, as it is well understood that the Preserve cannot force its neighbors to treat perennial pepperweed on private lands. And while this issue has proven to complicate weed control efforts (Epanchin-Niell et al. 2010), even without a buy-in from private landowners, reducing the overall seed and propagule load is possible in areas upstream to intact riparian habitats and this strategy is a key element to establishing an invasion front from which to defend.

Specific Property Strategy- On a specific property level, it is much easier to define the invasion front and identify the source and spatial extent of a weed invasion. Hypothetically, on this scale the invasion front can be attacked more methodically and should be considered as the fine-scale version of the preserve-wide attack strategy. Specifically, once identified, the invasion front should be directly attacked during wet or dry years to "hold the line".



†Ecologically significant flows are defined as: a period of >20 days of inundation and/or >100 m^3/s at Michigan Bar (see Booth et al. 2006)
*Monitor one and two years after treatment to determine efficacy rate and/or if a future management action like retreatment or restoration is necessary
Δ This value is based on the mean area for all patches surveyed between 2004 and 2008

Figure 14. Decision Tree Framework for managing perennial pepperweed at the Cosumnes River Preserve.

The construction of the decision tree, shown in Figure 14, reflects a synthesis of the results from the Perennial Pepperweed Control Project. This framework is the culmination of this projects Modify phase, wherein we have integrated the results of our experimental treatments, the population data, population growth models, and the environmental data (i.e. inundation and water year, soils).

3.5.1.2. *Subtask 5.2 Models of new patch establishment in the form of computer-based models and a descriptive report*

To accomplish Subtask 5.2, we implemented multiple methods to model perennial pepperweed patch establishment and growth (Viers et al. 2008b). We collaborated with recently completed studies on the application of modeling perennial pepperweed in the Bay-Delta by identifying its unique signature using hyperspectral remote sensing techniques (Andrew and Ustin 2008, Hestir et al. 2008, Andrew and Ustin 2009) and implemented a Leslie Matrix and Lefkovich Matrix Population Model (Spangenberg and Jungck 2005) using data collected in Subtask 3.1, 4.1, by Leninger (2006) and Leninger and Foin (2009), and Spenst (2006).

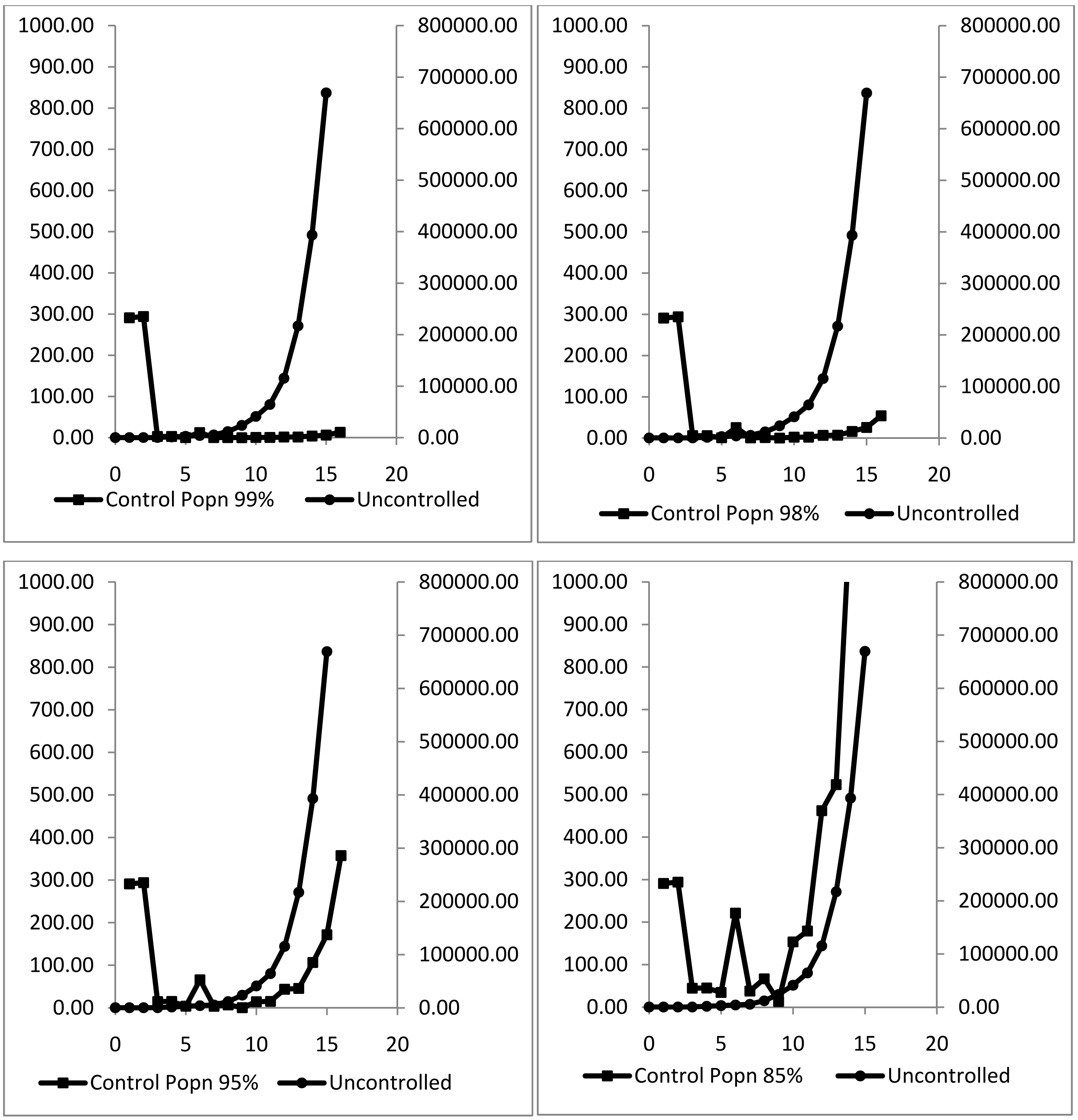
3.5.1.2.1. Leslie Matrix and Lefkovich Matrix

Within the context of the Leslie Matrix and Lefkovich Matrix Population model, we investigated stable, wet, and dry year perennial pepperweed growth (Subtask 5.2). Wet and dry years were defined by existing water year types (Booth et al. 2006) and growth patterns were assessed from surveys conducted under Subtask 3.1 and Subtask 4.1. Once growth rates were established for each of the three water year scenario types, we implemented control methods from Subtask 4.1 at between 85-99% eradication success. By doing this we were able to model reinvasion of eradicated patches based on seed rain and seed bank inputs from years prior to an eradication event. Figure 15 shows an example of a stable perennial pepperweed growth rate and the cumulative impact of annual and bi-annual herbicide treatments.

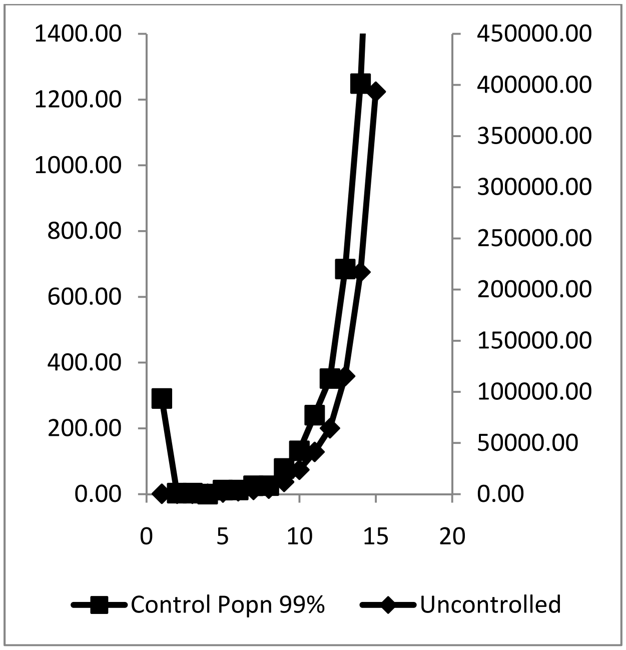
We found that successful eradication usually occurs in a modeled treatment regime that applies two treatments: one in year one and one in year three. This regime had more satisfying results over time than a single treatment, as well as having comparable results to a regime of four treatments over eight years (Figure 15 a-b). However, the results of the modeling exercise indicate that if large numbers of seeds are able to remain viable in the soil after eight years and four herbicide applications, the population will return to its uncontrolled growth pattern.

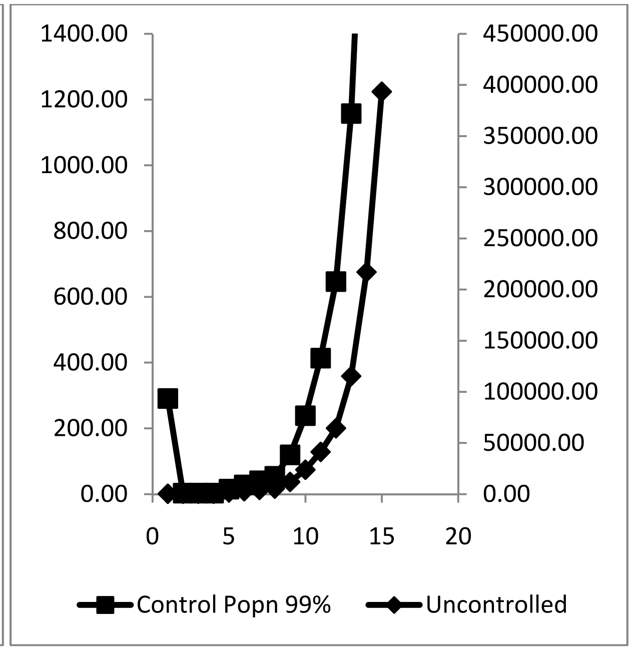
Figure 15. (a-b). Results of the Leslie Matrix and Lefkovich Matrix Population Model in a stable growth scenario with herbicide treatments at different intervals.

a. *Herbicide Control Once Every Two Years. Perennial pepperweed stem growth in an uncontrolled patch and in a patch that is treated with herbicides every two years for eight years (a total of 4 treatment applications) with a 99%, 98%, 95% and 85% success rate.*



b. *Left: Herbicide Control in Year 1. Perennial pepperweed stem growth in an uncontrolled patch and in a patch that is treated with herbicides once with 99% success and uncontrolled growth. Right: Herbicide Control in Year 1 and Year 3. Perennial pepperweed stem growth in an uncontrolled patch and in a patch that is treated with herbicide in year 1 and year 3 with 99% success.*





3.5.1.2.1. Model of Physical Drivers

Because ongoing studies identified a few key physical environmental factors associated with perennial pepperweed growth patterns, (Andrew and Ustin 2008, Hestir et al. 2008, Andrew and Ustin 2009) we chose to look some of those by constructing binomial logistic regression (LR) models to predict perennial pepperweed presence and potential spread (Table 8). We used a set of mapped occurrences at 3m x 3m cellular resolution as true positives (n = 15999) and random locations (n = 59859) as pseudo-absences. The true positives represent 6 years of repeat monitoring and delineation with differentially corrected GPS; thus, the positional and taxonomic accuracy is quite good. The probable absences are based on near exhaustive searches throughout the 6 year period at some point or another; thus, there exists the possibility of a new, undetected infestation during that time period.

Table 8. Binomial Logistic Regression Variables.

Variable	Rationale	Transformation	Source
Distance to Water	Pathway to Establishment, Hydric Soils	LN	CRP Geodatabase
Tree Canopy Height	Increased Competition in Canopy Gaps	LN	LiDAR; see sub-task 3.4
Productivity	Proxy for Soil Fertility	None	HyMap; see Hestir et al. 2008
Slope	Difficulty of Establishment	LN	LiDAR; see sub-task 3.4
Relative Elevation	Relationship to Floodwaters	None	LiDAR; see sub-task 3.4; interpolated
Curvature	Microtopography; Localized Concavity	None	LiDAR; see sub-task 3.4
Aspect	Microtopography; Localized Exposure	Cosine	LiDAR; see sub-task 3.4
Distance to Road	Conduit for Invasion	LN	CRP Geodatabase

We constructed the competing LR models to take into account perceived and measured predictors of perennial pepperweed occurrence to develop habitat suitability surfaces. The parameters in Table 8 were developed in ArcGIS (v.9.2) as continuous surface variables so that the model results could be mapped back into the GIS as a probability surface. Models were evaluated for uncertainty (R2) and specificity (receiver-operating-characteristic area under the curve; ROC AUC). Two of the listed variables, aspect and distance to road, were evaluated for inclusion into the models, but were ultimately dropped due to insignificance as predictors. Ultimately, the results of the habitat suitability model exercise can be combined with dispersal model results, and early detection mechanisms, to guide weed management activities.

3.5.1.2.1. Model of Dispersion

Our early detection mapping strategy used a two-tiered approach: first we generated a continuous map of the probability of perennial pepperweed presence using a logistic regression model, and second we set a threshold to classify all pixels with > 75% perennial pepperweed cover as being "perennial pepperweed dominated". Eight of the 64 2005 HyMap flightlines of the Delta (acquired 23 June 2005 and 28-29 June 2005) intersected the CRP. The portions of these flight lines encompassing CRP were cropped and mosaicked together. A minimum noise fraction (MNF) transformation was applied to the hyperspectral mosaic. Logistic regression models were developed in JMP IN (v. 5.0, SAS Institute, Cary, NC) to predict the per-pixel probability of the occurrence of pepperweed. The regression was trained using all pixels with >75% perennial pepperweed cover from the CRP field inventory (n=930) as well as a random sample of pseudo-absence points (n=16,413). Since the CRP field survey did not collect absence data, the pseudo-absence points are a random sample of pixels selected from the region most comprehensively surveyed for perennial pepperweed. Known perennial pepperweed pixels were excluded from the random sample, and remaining pixels were assumed to indicate perennial pepperweed absence. A prediction formula using MNF bands 2-11, 15, and 17 optimized the discrimination of perennial pepperweed from other land cover types (evaluated using R^2). This model was assessed by regressing the estimated probability of perennial pepperweed occurrence (p) against percent cover estimates from the CRP inventory data. The value of p corresponding to 75% cover by perennial pepperweed was identified and pixels were classified as "perennial pepperweed dominated" if their predicted value exceeded this threshold.

By using proximity analysis of pepperweed infestation as a function of distance from pepperweed patch centroids, we were able to show a strong polynomial logistic relationship (Figure 16). The dispersal model indicates that to achieve 85% certainty of encounter for newly established patches, one would need to look within a 25m radius of an existing patch center. By using the 95% confidence intervals of the dispersal model, this search radius either contracts to 10m (upper 95% CI) or expands to 50m (lower 95% CI). In essence, if the concern over new establishment is high, then using the broader radius is warranted. Likewise, if fewer resources are available, a narrower search radius would have the same probability of encounter in the restricted interval. Of course these results can be mapped back to the landscape as a probability surface (Figure 16) to help guide future weed management actions.

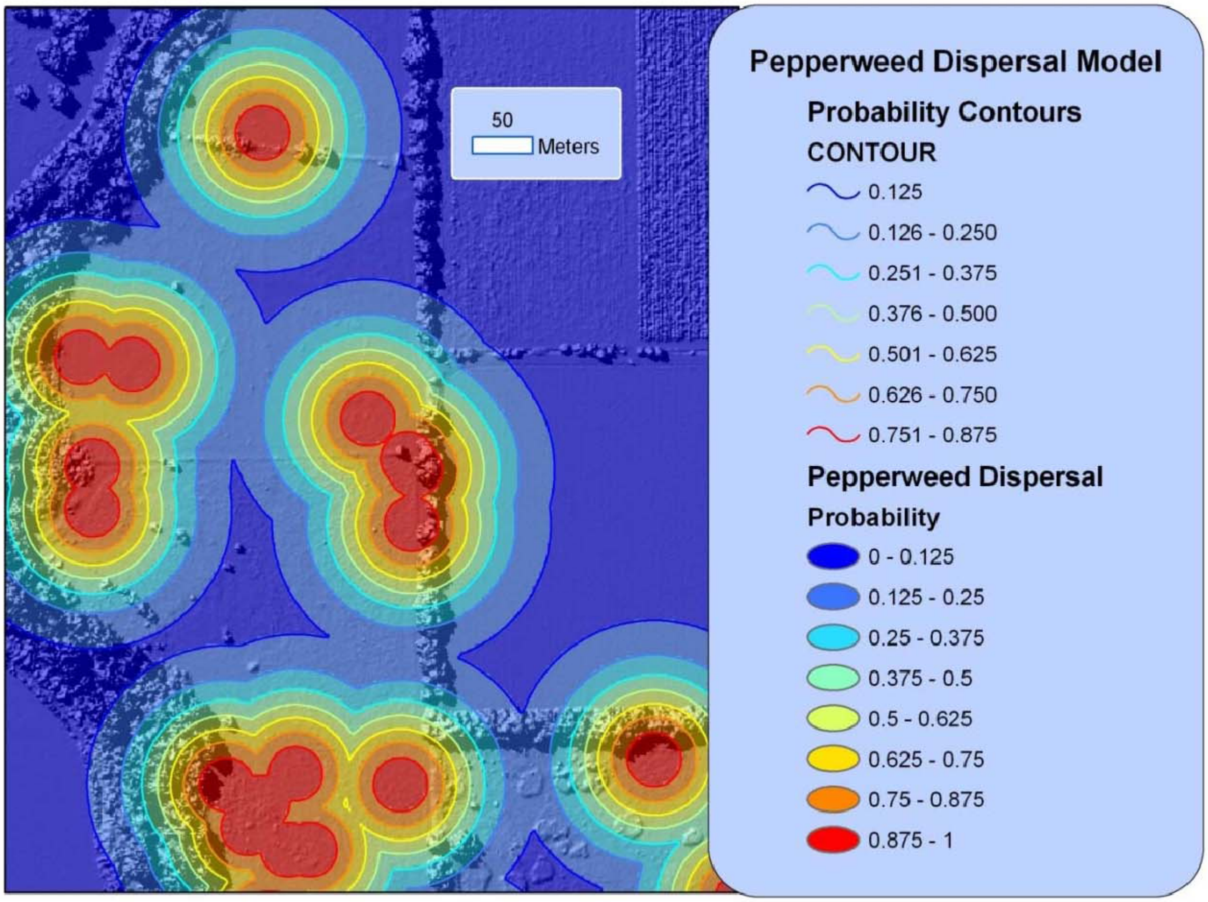


Figure 16. Example of Dispersal Model Results as a Map of Probability Contours. Distance from patch centers were used to examine probability of perennial pepperweed invasion.

We compared the output of two competing binomial logistic regression models predicting habitat suitability for further perennial pepperweed invasion. The first model (LR 1) includes broad parameterization of interaction effects and three microtopographic predictors (i.e., relative elevation, curvature, and slope). The second model (LR 2) is a reduced, parsimonious model that includes only polynomial effects and their linear components and a single microtopographic factor (i.e., slope). The results of this comparison show that the complex parameterization model (LR 1) performed adequately; all but one of the terms was significant (X2 < 0.05), it explained roughly 37% of the observed uncertainty, and had a very high specifity (ROC AUC = 0.89). The parsimonious model (LR 2) maintained this specificity while reducing parameter complexity (ROC AUC = 0.87), explained a similar fraction of the uncertainty (R2 = 0.32), and was comprised entirely of significant predictor variables.

The following map catalogs the results of the physical driver habitat suitability modeling exercise. Using the parsimonious model (LR 2), we mapped the logistic form of the linear equation to produce a probability surface of habitat suitability (Figure 17), with corresponding upper and lower 95% confidence intervals. The strong weighting of distance to water was quite evident from the surface models, as was the aversion to tree canopy and steep topographic slopes. The range of probabilities exhibited by the confidence interval map images shows the spatial variability inherent to this exercise. However, there is constancy in the general vicinity of high suitability which is consistent with our field observations. When used in conjunction with results from the dispersal modeling exercise, high priority areas for weed management can be identified.

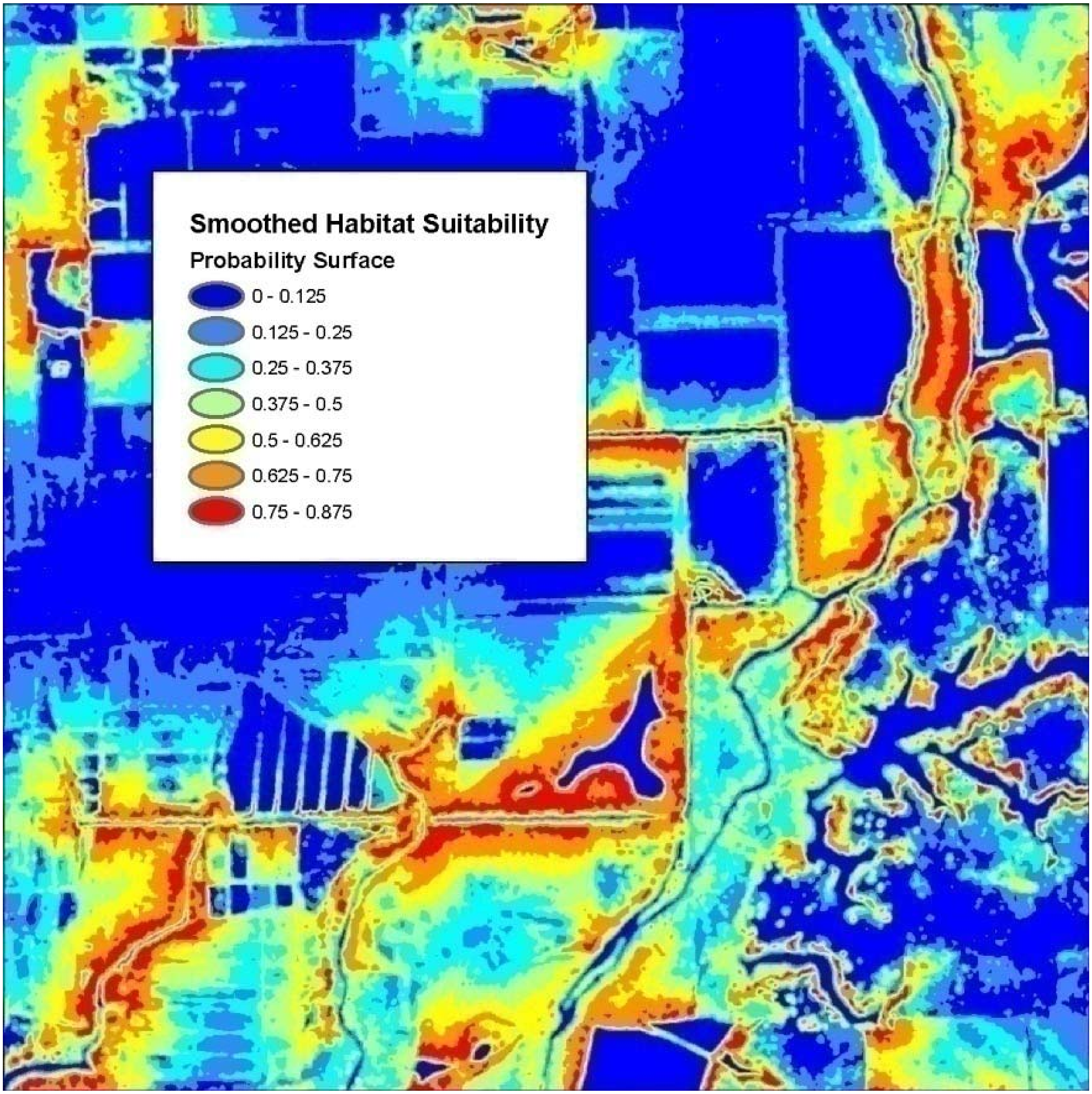


Figure 17. Probability Surface of Perennial Pepperweed Habitat Suitability.

3.5.1.2.1. *Model of Rapid Detection*

Classification accuracy was assessed with the 930 CRP pepperweed sites with > 75% perennial pepperweed cover. As with the training data, a random sample of different pseudo-absence points (63439 pixels) from the entire image mosaic was used to represent perennial pepperweed absence. Accuracy statistics presented may be conservative since some of these random points may indeed contain perennial pepperweed although the same presence points were used in both training and validation (Figure 18). To assess the contribution of phenological variation to omission errors, we divided perennial pepperweed dominated pixels into phenological classes using a K-means unsupervised classification on the same MNF bands as used by the regression model. Phenology of these classes was determined through visual inspection and verified with three physiological indexes: the normalized difference vegetation index (NDVI; (Tucker 1979)), the normalized difference water index (NDWI; (Gao 1996)), and the cellulose absorption index (CAI; (Nagler et al. 2000)).

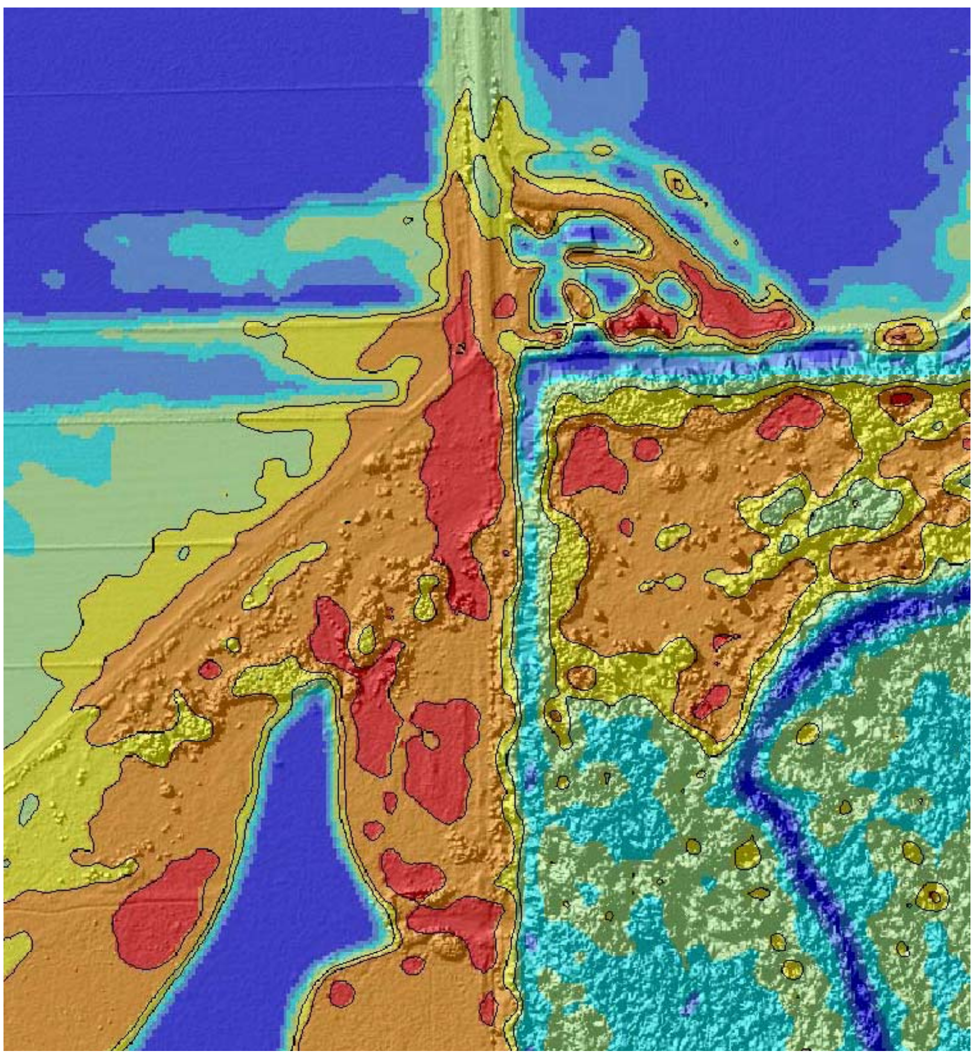


Figure 18. Probability contours (>= 50%) for habitat suitability over canopy LiDAR image near levee breach.

The predicted value (p) provided a reasonably good indicator of the percent cover of perennial pepperweed within a pixel ($R^2 = 0.49$, n = 2,787). The final classification distinguished perennial pepperweed from pseudo-absence pixels with user's and producer's accuracies of perennial pepperweed detection of 56.4% and 63.2% respectively, and Kappa coefficient relative to the perennial pepperweed class of 0.63.

The K-means classifier found five distinct groups of perennial pepperweed dominated pixels. These groups fell out along a gradient of dryness/senescence and were interpreted as completely senescent (n=1), shaded by or under a tree canopy (n=77), flowering (n=277), fruiting (n=363), and senescing (n=190). These interpretations were supported by the physiological indexes. NDVI, NDWI, and CAI all showed significant effect of group ($p<0.0001$; ANOVA) and, for each index, all groups were significantly different from each other at the $p=0.05$ level (Tukey). The detection rate of these classes ranged from 0% (senescent) to 73.3% (fruiting), with fruiting and flowering phenologies showing the highest detection rate. The fruiting, flowering, and senescing phenology classes are the most relevant to a remote sensing study. When just these three classes were used to evaluate the classifier performance, the producer's accuracy of the classifier increased to 69.3%

4.0 Final Remarks

From a management perspective it will be increasingly important to evaluate the extent of the perennial pepperweed infestation at the Cosumnes River Preserve and target areas for defense and attack. Full implementation of the recommended adaptive management cycle should decrease the negative impacts of perennial pepperweed on a Preserve wide scale. Reducing the frequency of new populations in uninvaded and restoration areas is an obtainable goal which will increase overall habitat heterogeneity and ecosystem function. The importance of setting weed management goals becomes increasingly important in managed natural areas, like the Preserve, which must allocate what are sometimes extremely limited resources. By implementing an adaptive management framework, specific areas can be targeted so that when resources are available they are allocated appropriately and with a clear objective or goal.

It is also important not to lose sight of the implications of upholding specific objectives. In the case of perennial pepperweed, reducing population size and extent will have profound positive effects on ecosystem function and specifically to sensitive riparian habitats. Because perennial pepperweed is a highly competitive species that has proliferated at the Preserve, control can, at first glance, appear to be somewhat elusive and very challenging. Our results indicate that eradication will require not only vigilance, but also broad systems approach to make sure that limited resources are applied in the most effective manner. Approaching the the problem at different scales (such as at a patch, site, vegetation type, and infestation extent) will help reduce overall uncertainty about success rates and identify locations where control efforts will have higher impact and benefits for ecosystem functions and native biodiversity. .

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