Title

The Role of Invasive Erodium Species in Restoration of Coastal Sage Scrub Communities and Techniques for Control

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The Role of Invasive *Erodium* Species in Restoration of Coastal Sage Scrub Communities and Techniques for Control

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in

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by

Kristin Anne Weathers

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Dedication

For Pat, Gabrielle and Rosalind

To all the possibilities the future holds

ABSTRACT OF THE DISSERTATION

The Role of Invasive *Erodium* Species in Restoration of Coastal Sage Scrub Communities and Techniques for Control

by

Kristin Anne Weathers

Doctor of Philosophy, Graduate Program in Plant Biology
University of California, Riverside, December 2013
Drs. Edith B. Allen and Milton E. McGiffen Jr., Co-Chairpersons

Three studies were conducted to investigate effects of invasive *Erodium* species on re-establishment of native species in the California coastal sage scrub (CSS) plant community, and how both chemical and non-chemical techniques might be used to reduce *Erodium* and increase success of restoration efforts. First, the effects of a range of *Erodium* densities were tested on the establishment of native shrubs and forbs in two experimental sites, one a seeding experiment and the other a weeding experiment. Analyses were done to detect a threshold value where *Erodium* density decreased the establishment of the native species, and showed that *Erodium* species inhibited the establishment of native shrubs between 61 and 66 *Erodium* plants/m^2. *Erodium* species often germinate at very high densities (thousands of plants/m^2), indicating land managers will often need to actively control *Erodium* species densities in order to restore CSS vegetation after disturbance. Second, varying treatments of the non-chemical agricultural technique of solarization were tested without irrigation, as supplementing water may not be possible in some wildland situations. Laying sheets of clear plastic over tilled soil during the hot summer months reduced invasive annuals the most of all the treatments, even without the addition of water. Third, chemical control experiments tested a variety of herbicides with different modes of action and at varying rates at two sites. Some herbicides labeled as grass-specific also have activity on *Erodium* species but do not damage most CSS native forbs and shrubs, and were tested in a variety of concentrations. Chemicals tested in this study did not provide season-long control of *Erodium* species at rates allowed by the label, but one above-label rate proved effective. Multiple applications of herbicides with this mode of action (e.g., fluazifop) within approved rates should be tested to determine efficacy on *Erodium*. The broadleaf-selective chemical triclopyr provided the best control but will have to be used with caution in the CSS community as it also has activity on native shrubs and forbs. The broad spectrum herbicide glyphosate had good control at one site, but the second site had germination of a second cohort of *Erodium* after the first cohort was sprayed.

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Introduction

Four exotic species of the genus *Erodium* -- *E. cicutarium, E. botrys, E. brachycarpum* and *E. moschatum* -- are present in southern California wildlands, including the endangered coastal sage scrub community (CSS). Originally from the Mediterranean region, they have been in California for 200 years or more (Mensing and Byrne 1998). These species germinate earlier in the growing season than native species, immediately after the first rains, and can germinate in very high numbers. Due to high densities and early phenology, they have been shown to have detrimental effects in some California plant communities (Gordon and Rice 1993, Gordon and Rice 2000, Brooks and Matchett 2003, Gillespie and Allen 2008).

These *Erodium* species are not usually the most abundant invaders of southern California plant communities. Invasive Mediterranean grasses are widespread in southern California and many native plant communities such as native grasslands, forblands and CSS have been replaced by invasive grass communities dominated by grasses of the genera *Bromus, Avena, Vulpia, Hordeum* and *Schismus* (Minnich and Dezzani 1998, Freudenberger et al. 1987). However, when invasive grasses are removed from some CSS restoration sites, invasive forbs, especially *Erodium* spp., may germinate in high numbers and become the dominant species. While some native forbs return, native shrubs often fail to establish from seed (Allen et al. 2005, Cox and Allen 2008). Often it is unclear whether this failure of shrub establishment is due to competition from *Erodium* or other invasive forbs, or other factors such as unsuitability of the site (Cox and Allen 2008). Once areas of CSS are disturbed, they often do not recover to shrubland after the disturbance is discontinued (Stylinski and Allen 1999).

Better understanding the dynamics affecting the restoration of the CSS plant community is of particular importance because this is one of the most endangered plant communities in southern California. Much of the plant community has been lost to development but remaining stands are being converted to exotic grasslands through increased fire regimes caused by grass invasion, historical grazing and air pollution (Allen et al. 2000). Because of continual invasion pressure and the lack of plant community recovery, active restoration of CSS is necessary, as is identifying constraints or thresholds that prevent shrub recovery within active restorations (Suding and Hobbs 2009).

Erodium species may have a complex role of both positive and negative impacts in the CSS community, particularly within the context of exotic grass invasion. Research from several plant communities indicates that *Erodium* species could be having a significant negative impact on both the shrubs and the forbs of the CSS plant community. For instance, *Erodium botrys* has decreased the emergence, growth, and survivorship of blue oak seedlings primarily through reduction of soil moisture (Gordon and Rice 2000); *Erodium cicutarium* has decreased the diversity of native annuals in the Chihuahuan and Mojave deserts (Schutzenhofer and Valone 2006, Brooks and Matchett 2003). However, many studies have shown that *Erodium* species are not as competitive with the native annuals as exotic grasses (Gillespie and Allen 2004) and even facilitate the native forbs to persist in a matrix of exotic grasses (Cox and Allen 2008). One study in Israel found that a native *Erodium* served as a nurse plant for other desert annuals, thus facilitating their establishment (Lortie and Turkington 2002).

The first chapter of this dissertation examines *Erodium* species as a constraint limiting the establishment of two native species, one shrub and one forb, that are common species in the CSS community. The goal is to determine the threshold density and cover at which two *Erodium* species have a negative effect on the native species density and cover. If an appropriate predictive variable (*Erodium* density or percent cover) could be identified that causes a significant decrease in native establishment, this value could then be identified as a threshold or breakpoint at which land managers should take steps to control *Erodium* in a restoration site to increase the chances of restoration success.

Once this breakpoint or threshold is identified, a method to control *Erodium* density needs to be chosen. Since *Erodium* species are less competitive with natives than exotic grasses but ubiquitous throughout California, they are not generally targeted for weed control efforts. Only one species, *Erodium cicutarium*, is listed in the California Invasive Plant Inventory Database (California Invasive Plant Council 2013) and is considered low to moderately invasive and only locally problematic (not a state-wide threat). However, it normally occurs in a matrix of exotic grasses, and would not be dominant until the grasses are controlled (Gillespie and Allen 2004). Therefore, the next two chapters of this dissertation investigate possible control methods.

The first methods investigated are modifications of solarization, a technique widely used in agriculture to control weeds. The technique involves laying clear plastic over tilled, wet soil during the hottest summer months. This creates a greenhouse effect, heating the soil to temperatures high enough to kill most of the seeds present prior to seeding a crop. This technique has been tested in wildlands with success using both clear plastic in the summer and adding irrigation and using black plastic following California's winter rainfalls so additional irrigation did not have to be applied (Moyes et al. 2005, Marushia and Allen 2011). My study compared both clear and black plastic in the summer and winter without adding irrigation to determine which was most effective in destroying weeds in a Mediterranean climate. Different levels of soil disturbance were tested to determine if solarization is effective with less soil disturbance than the tilling treatments used in agriculture.

The final chapter focuses on chemical control of *Erodium* species. Since *Erodium* is a dicot, broadleaf or broad spectrum herbicides would normally be used for control. However, since the majority of the native species in the CSS system are also dicots, herbicides would have to be spot applied or applied prior to any seeding or planting when the entire area is invaded. Research has shown that *Erodium* species are susceptible to a family of herbicides that are usually grass-specific (Christopher and Holtum 1998). Some of these products are labeled to control *Erodium* in other countries, but these specific products are not available in the U.S. Other chemicals in the same family are used on grasses in the U.S. and have been shown to control *Erodium* in the Mojave Desert (Steers and Allen 2010), but the rate used was higher than the single application rate allowed by the label for broadcast application. The value of being able to use a grass-specific herbicide to control *Erodium* in CSS is that managers would be able to spray over native plants in the first years of restoration to help minimize competition from *Erodium* and grass as the native plants become established. For this final chapter I compare both label and above-label rates of grass-specific, broadleaf and general herbicides at two different wildland sites with different *Erodium* species to test which herbicides were the most effective in controlling *Erodium*.

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Chapter 1

Identifying thresholds for the management of *Erodium* in Coastal Sage Scrub Restoration Sites

Abstract

Identifying thresholds in disturbed plant communities can aid restoration efforts by determining when and if additional management efforts are necessary for success. *Erodium* species are typically subdominant invaders in the coastal sage scrub community. Shrubs often fail to establish in plots where exotic grasses, the dominant invaders, are removed, and instead other invasives fill the gaps. However, some studies have shown that the presence of *Erodium* helps native forbs establish in an exotic grass matrix. We planted increasing densities of *Erodium* with the native shrub, *Artemisia californica,* and the native forb, *Cryptantha intermedia* in a wildland site. Plots at a second wildland site with high *Erodium* cover were hand weeded to the same densities as the seeding experiment. Piecewise regression and Kruskal-Wallis tests were performed to identify a threshold(s) population density of *Erodium* where establishment of natives was inhibited. Effects of *Erodium* on native forbs were not consistent between the two sites, but a threshold between 61-66 *Erodium*/m^2 was identified at which the establishment of *Artemisia* was inhibited at the seeded site. A threshold could not be identified at the wildland site, but there was a decrease in shrub recruitment between the plots that were weeded to 50 *Erodium*/m^2 and 100 *Erodium*/m^2. Maintaining *Erodium* densities below 61-66 plants/m^2 will improve native shrub establishment from seed in coastal sage scrub restorations.

Introduction

Many types of thresholds have been discussed in ecology and agriculture. A major focus in ecology has been to identify thresholds that are likely to cause system shifts. These can be small changes in biotic or environmental conditions that promote sudden and possibly irreversible change in the system being studied. However, many of these constructs are hard for land mangers to apply, although there has been discussion in the literature as to how to make thresholds concepts more relevant to land management (Suding and Hobbs 2009, Suding 2004, Hobbs 2001).

In restoration ecology, the threshold concept has been used to describe how many damaged ecosystems resist restoration, i.e. not recovering after a management action or proceeding on a different trajectory than intended. Such a pattern suggests at least one restoration threshold exists that prevents the system from returning to a less degraded state. Unsuccessful attempts at restoration often occur because there are multiple constraints on an ecological system, but the management actions address only one (Suding 2004, Whisenant 1999). Identifying restoration thresholds helps to prioritize management activities and locations, as well as improve restoration success and efficiency by allowing managers to address multiple constraints simultaneously (Suding 2004, Hobbs 2001).

Crop science has used the threshold concept to develop weed management decision models (Wilkerson 2002, Coble and Mortensen 1992). Often these models include an economic threshold based on the value of crop yield lost, and therefore are not applicable to wildlands restoration and management where no commodity is produced. However, decision models can be useful for wildland managers who are faced with many management needs and few economic and human resources. For example, invasive species have become so numerous and widespread that guidelines for deciding which species to prioritize for control and under what situations to prioritize control are necessary information (National Invasive Species Council 2005). Restoration efforts require significant time and effort, and identifying the weed control thresholds that enable establishment of a target species may help better manage labor and other resources and thus improve restoration success.

Much of the coastal sage scrub (CSS) plant community of southern California has been lost to development, increased fire regimes, and vegetation type conversion due to invasion by annual Mediterranean grasses and forbs (Minnich and Dezzani 1998, Allen et al. 2005a). Even when disturbance has been absent for years or the exotic grasses are removed the communities often do not recover even with the addition of seed (Stylinski and Allen 1999, Cox and Allen 2008b). While some native forbs may return, native shrubs do not and there is a high cover of exotic annual forbs (many in the genus *Erodium*) (Allen et al. 2005b, Cox and Allen 2008b).

There have been conflicting reports on the effect of *Erodium* species in plant communities, which suggests these species have complex interactions with other species. For instance, some studies document positive effects of *Erodium* including allowing establishment of native forbs when a matrix of exotic grasses alone did not (Cox and Allen 2011, Gillespie and Allen 2004). A study in Israel showed that a native *Erodium* species facilitated establishment of desert native annuals (Lortie and Turkington 2002). Other studies document a negative effect of *Erodium* species on native species. *Erodium botrys* reduced the establishment and growth of a native tree species (Gordon and Rice 1993, 2000), and *Erodium cicutarium* decreased the diversity of herbaceous desert annuals (Schutzenhofer and Valone 2006). Additionally, some researchers were unable to determine whether the failure of shrubs to establish in CSS restoration projects was due to competition from the *Erodium* species or lack of suitability of these sites for shrubs for other reasons (Allen et al. 2005b). Different results among these studies may be due to different densities of *Erodium*, or to lack of controlled conditions to test impact of *Erodium* on native species.

Regression techniques can be a powerful technique to detect thresholds (Cottingham et al. 2005). Piecewise regression fits two or more lines to a data set and identifies the point at which a change in slope occurs. This technique has been used to identify a variety of different types of thresholds in agricultural studies to optimize management (McDonald et al. 2010, Tolk and Howell 2008), forestry (Furukawa et al. 2011) and natural systems (Schooler et al. 2010, Toms and Lesperance 2003). Toms and Lesperance (2003) demonstrated the use of piecewise regression techniques for identifying edge effects and found that piecewise regression is a useful, but often overlooked, method of identifying ecological thresholds.

My goals were 1) to identify at which densities *Erodium* species constrained the establishment of native shrubs or native forbs in the CSS community, 2) determine if the relationship between the natives and *Erodium* was linear, or could piecewise regression be used to identify a potential action threshold for control of *Erodium* during restoration of a CSS community, and 3) determine whether this threshold value is different for native shrubs and native annual forbs.

Methods

Parallel experiments were installed at two sites. A seeding experiment with an additive experimental design in which seven densities of *Erodium* (0, 25, 50, 100, 250, 500 and 1000 plants/m^2) were seeded with a native shrub and a native forb was installed at Agricultural Operations (AgOps) at the University of California Riverside (hereafter seeded farmland site) in December 2009. An analogous weeding experiment was established at the Barnett Ranch Open Space Reserve in San Diego County in January 2010 (weeded wildland site). This experiment was a removal experiment in which ambient densities of *Erodium* were allowed to germinate then weeded down to the first six densities listed above. The seventh, i.e., highest density was left unweeded. Both density and percent cover were measured for all species involved, to determine if one of these variables provided a more definite threshold value by which management decisions could be made.

Seeded Farmland Experiment

For the seeding experiment on tilled soil at AgOps two native species were chosen to represent the two main functional groups of the CSS community, the perennial shrub *Artemisia californica* and the annual forb *Cryptantha intermedia*. The seven densities of *E. cicutarium* listed above were planted with a single density of each native species (100 plants/m^2). Each native species was seeded in separate plots, thus there was a maximum of two species per plot and competitive interactions between the two native species were avoided. To test the competitive interaction between the native species and *E. cicutarium*, the natives were also seeded in single species plantings equal to the total plot densities of the competition plots (Table 1-1). All species and density combinations were arranged in a randomized complete block design with six replicate blocks. In total there were 52 1m x 1m plots with a 1 m buffer between plots. Plots were hand seeded the third week of December 2009.

The plots were irrigated with approximately 64 mm (6.4 mm twice a day for 5 days) of water the first week after seeding to initiate germination. Because plants failed to germinate, the plots were irrigated a second time with 6.4 mm twice a day for three days, during the first full week of January 2010. After these two irrigation pulses the plants germinated and no other irrigation was applied. In addition to the irrigation, the plots received 185 mm of precipitation between January and March 2010. In total, the plots received 287 mm of water between installation and sampling.

Density and percent cover of each *Erodium* species was measured at peak flowering. Percent cover estimates and density counts were taken for the full 1 m^2 plot. Weeds that emerged from the seedbank were removed several times until sampling in April 2010. Weeds were also removed from buffers between plots to avoid edge effects. Annuals senesced in May and were not sampled again, but plots with shrubs were resampled in December 2010 so that shrub performance could be evaluated several months later to see whether the early competition from *Erodium* continued to affect shrub growth and establishment. Percent cover estimates, average shrub height, and density counts of remaining *A. californica* were collected in December 2010*.* A subset of the shrub biomass was clipped, dried, weighed and regressed against plot volume, so biomass could be estimated for all plots.

Weeded Wildland Experiment

The weeded wildland site was historically grazed but not plowed, and had *A. californica* and other coastal sage scrub vegetation on the top of most hills, although the hillsides and valley areas were dominated by annual invasive species. *Erodium botrys* was the dominant *Erodium* species at the Barnett Ranch location, and exotic annual grasses (*Avena, Bromus*, and *Hordeum* spp.) were secondary in abundance. Precipitation was 465 mm in the 2009-2010 growing season, according to a nearby weather station (MesoWest 2013). Once *Erodium* species germinated in January 2010, the plots were thinned by hand weeding to six densities (0, 25, 50, 100, 250, 500 plants/m^2), leaving one unweeded control per block; all other exotics were removed. *Erodium* densities were as high as 3000 plants/m^2 at the time of the initial weeding. Plots were 1 m^2 with a 1m buffer between plots. The weeding treatments were extended 10 cm beyond the plot boundary to prevent edge effects from confounding plot sampling. Each one-meter plot was divided in half, with one-half seeded with *Artemisia californica* and the other half seeded with the native forb *Cryptantha intermedia*. Plots were arranged in a randomized complete block design with three replicate blocks. Blocks were positioned on two hill tops half-way or more toward the tops of the hills, since prior experiments showed better shrub establishment on the hillsides (unpublished observations). Plots were sampled using 1/8 m^2 quadrats placed in the lower outside corner of each subplot with at least a 6 cm buffer. Since only a few individuals of the seeded species were observed in any of the plots but many native forbs were germinating from the seedbank, a decision was made to leave all natives in the plots and weed out only exotics.

Analysis

Piecewise regression analysis was performed to identify possible breakpoints or thresholds between each set of dependent and independent variables (see Schwarz 2011). A simple piecewise regression model joins two lines sharply at a breakpoint. The general equation is represented as $y = \beta_0 + \beta_1(X) + \beta_2(X\text{-}C)$, where β_0 is the intercept, β_1 is the slope before the breakpoint, β_2 is the difference in the slope after the breakpoint and C is the breakpoint. The model was then fit using JMP version 9. The best fit was determined via an iterative least squares solution using initial conditions selected from an empirical break point and linear regression. After the breakpoint was identified, an attempt was made to calculate a profile-likelihood confidence interval (JMP 2013, Schwarz 2011), as recommended by Toms and Lesperance (2003). The confidence interval calculation was initially performed using an alpha level of 0.05 and this was lowered incrementally until both a lower and upper CI could be calculated, if they could be calculated at all, i.e. alpha = 0.10.

The dependent values analyzed at the seeded farmland site were *E. cicutarium* percent cover and *E. cicutarium* density, and the independent variables analyzed were spring-measured *A. californica* percent cover, *A. californica* density, *C. intermedia* percent cover, and *C. intermedia* density; and fall-measured *A. californica* percent cover, *A. californica* density and *A. californica* biomass. Some of the fall-measured data sets were log-transformed prior to analysis to improve fit. At the seeded farmland site, four plots, one each with seeded *Erodium* densities of 0, 100, 250, 500 per m^2, were damaged by overspray from herbicide application from an adjacent unrelated experiment along the irrigation lines, so they were excluded from analysis.

At the weeded wildland location the dependent variables were *E. botrys* percent cover and density and the independent variables collected were native shrub density, native shrub percent cover, native forb density and native forb percent cover. Only native shrub density by *Erodium* density provided any result from the piecewise regression, so Kruskal-Wallis tests were performed on each independent variable to see if differences could be detected based on the initial weeding treatment.

Results

Seeded Farmland Experiment

Erodium had a negative influence on growth and establishment of *Artemisia* and *Cryptantha* at the farmland site. Piecewise regression was performed using either *Erodium* percent cover (Table 1-2) or *Erodium* density (Table 1-3) as the predictive variable for native shrub and forb establishment. Many of the plots had high percent cover of *Erodium* even at low densities. *Erodium* plants were very large with vegetation heights of 30-40 cm in most plots. In the shrub plots there were no percent cover values for *E. cicutarium* lower than 60%. The forb plots had a few plots with < 60% cover, but most plots had percent cover values for *Erodium* between 70-100%. *Erodium* percent cover values may have been more evenly distributed under drier conditions. *Cryptantha* density was the only variable of those measured on the native species for which a significant breakpoint was calculated when *Erodium* percent cover was the dependent variable use (Table 1-2). At 80% *Erodium* cover, the density of *Cryptantha* plants decreased sharply (Figure 1- 1). The other three variables examined against *Erodium* percent cover, *Artemisia* density, *Artemisia* percent cover and *Cryptantha* percent cover either required too high an alpha level entered in the regression analysis to calculate a breakpoint and confidence intervals, or could not be analyzed at all due to possible autocorrelation.

The piecewise regression results for *Erodium* density against data collected in the spring showed a breakpoint for *Artemisia* and *Cryptantha* percent cover (Table 1-3). The *Artemisia* percent cover results predicted a threshold change at an *Erodium* density of 61 plants/ m^2 (Figure 1- 2A), and the change in percent cover of *Cryptantha* occurred at 24 *Erodium* plants/ m^2 (Figure 1- 2B), which corresponds to the lowest seeding density in the study, 25 *Erodium*/ m^2.

Piecewise regression was also run for the fall densities, percent cover and biomass of *Artemisia* against *Erodium* density measured at spring sampling to determine if differences in the density treatments changed during the summer (Table 1-4). The *Erodium* senesced by May but *Artemisia* continued to grow through summer and fall with no further competition, so any differences between plots in the fall represent effects from initial spring seeding densities of *Erodium*. A significant breakpoint with confidence intervals could not be calculated for either density or percent cover of *Artemisia* in the fall, however a breakpoint was detected when piecewise regression was run on the shrub biomass. Two biomass relationships were calculated: *Artemisia* biomass in kg/ m^2 and *Artemisia* biomass per shrub (where the plot biomass was divided by the number of shrubs in the plot). The estimated threshold value for *Artemisia* biomass per m^2 was 66 *Erodium*/ m^2, which was similar to the breakpoint of 61 for spring *Artemisia* density (Figure 1- 3A). The breakpoint for biomass per shrub occurred at 25 *Erodium*/ m^2 (Figure 1- 3B). This would suggest that competition from *Erodium* influenced the size of the shrubs in the first year at lower densities than densities that inhibited germination or establishment of the shrubs.

In the absence of competition (i.e., no *Erodium*) the percent cover of *Artemisia* increased 10-fold between the spring and fall samplings, while *Artemisia* in plots with any density of *Erodium* scarcely changed in size between the two samplings (Figure 4A). Fall shrub biomass vs. seeding densities of *Erodium* showed the same pattern in that large shrubs were found in the no-competition plots and small ones were found in any of the plots with *Erodium* seeded, even the lowest densities of *Erodium* (Figure 4B). This indicates that *Erodium* exerted enough competitive influence on *A. californica* to significantly inhibit second season growth, even at relatively low field densities of *Erodium*.

Weeded Wildland Experiment

Piecewise regression was not able to estimate a significant breakpoint for any of the native plant variables measured. Native shrub density was the only variable for which a breakpoint could be estimated; however, the confidence intervals could not be estimated (data not shown). This was likely due to having fewer data points; this was a much smaller experiment since handweeding the plots was more labor intensive than seeding. Also, in some of the unweeded plots the *Erodium* self-thinned dramatically; one replicate had a density of 208 *Erodium*/ m^2, while the two others had densities of 526 and 673 *Erodium*/m^2. The other weeding treatments also experienced significant self-thinning. Two of the 500 *Erodium*/m^2 treatments had *Erodium* densities of 100 *Erodium*/m^2 or less at the time of spring sampling. This left a large range of high *Erodium* density values with very few data points and large standard error.

Since piecewise regression did not provide meaningful results, Kruskal-Wallis tests were run for native shrub and forb density and native shrub and forb percent cover against the initial weeding densities. Means and standard deviations for the native plant densities and percent cover against initial weeding densities are shown in Table 1-5. The calculated chi-square value for native shrub density is not significant at $\alpha = 0.05$ level. The Kruskal-Wallis test for native shrub percent cover showed a significant difference between treatments by initial weeding density at an alpha level of 0.5 with a p-value of 0.0468. Visual examination of means and standard deviations suggests decreases in means between 50 and 100 *Erodium*/ m^2 and again between 250 and 500 *Erodium*/ m^2. Unlike the shrub plots, results for the forbs showed no relationships with *Erodium* density. Chi-squared levels were insignificant for both native forb cover and density by initial weeding treatment.

Discussion and Conclusions

Threshold values for *Erodium* management were determined for the seeded farmland but not the wildland site. Higher variability, fewer plots, and self-thinning of the *Erodium* at the wildland site all contributed to the lack of significance for the piecewise regression analysis. Examination of the means and standard deviation at the weeded wildland site provided some information regarding the treatments. Results for the two functional groups were different between sites; the means from the shrub plots at the wildland site seemed to support the threshold findings in the seeding experiment while the forb plots did not.

For the shrubs, it was possible to determine a threshold using *Erodium* density but not *Erodium* percent cover. The failure of percent cover as a threshold indicator was likely due to the lack of range of percent cover (all > 60%), not because cover of *Erodium* had no relationship to shrub density. In the thinning experiment where *A. californica* cover but not density was significant, but the corresponding *Erodium* densities were similar to those of the seeding experiment. The *Erodium* density threshold where significant inhibition of shrub establishment occurred in the seeding experiment was between 61-66 *Erodium cicutarium* plants/m^2, and the weeding experiment indicated a drop in percent cover of *A. californica* where initial *Erodium* densities were between 50 and 100 plants/ m^2. This suggests that *A. californica* shrubs will establish in areas where densities of *Erodium* species are between 50-100 plants/m^2. This density range was lower than germination densities of *Erodium* plants observed at Barnett Ranch and in other studies (Cox and Allen 2008a). This result also parallels studies showing that high densities of *Erodium* species prevented the establishment of native woody species (Gordon and Rice 2000), whereas establishment of *A. californica* was inhibited by comparatively low densities of exotic grasses (Eliason and Allen 1997). The *A. californica* biomass data from the seeding experiment indicate *Erodium* density not only inhibited initial establishment but also dramatically reduced shrub growth into the second growing season. Both Gordon and Rice (2000) and Eliason and Allen (1997) found that exotic species, including *Erodium botrys* in the Gordon and Rice study, rapidly decreased soil moisture availability and this may be one of the primary reasons woody species including *Artemisia* struggle to establish and survive in a neighborhood of exotic species.

Unlike the shrub data, results for native forbs were disparate between the two sites. *Cryptantha* was seeded in the plots at Barnett Ranch but did not germinate, so direct comparisons for this species cannot be made. In the seeding experiment *C. intermedia* did very poorly in all plots where *Erodium* was present. This was indicated by a calculated threshold of 24 *Erodium* plants/m^2 when the lowest seeding density was 25 *Erodium*/ m^2. However, in the weeding experiment native forb densities were similar between even the lowest and highest *Erodium* densities. Much of this disparity is likely explained by differences in plant size and percent cover between the two sites. The seeding experiment had only a couple of plots with cover of *Erodium* less than 60%, and they showed a decrease in the density of *Cryptantha* seedlings at 80% cover of *Erodium*. The plots at the Barnett Ranch weeding experiment had highest cover of 68%, even at the highest densities of *Erodium botrys*. Supplemental irrigation at the seeded site is the likely cause of the difference between the two sites. The early season irrigation followed by immediate rain would have provided both abundant water and cool temperatures that would favor *Erodium* over *Cryptantha* germination. *Erodium* has earlier phenology than *Cryptantha* and other native forbs (Chiariello 1989). Since *E. cicutarium* at the seeded site was very large from early irrigation, it may have prevented *Cryptantha* from establishing even at moderate densities, while this was not the case for the weeding/wildland site. Microenvironmental differences and annual species phenological responses to limited resources often confound results of experiments testing density-dependence or interspecific competition (Antonovics and Levin 1980).

The germination and establishment of *A. californica* is restricted by densities of *Erodium* species much lower than densities observed germinating at CSS study sites. The estimated threshold density of 61-66 *Erodium* /m^2 from the seeded site was supported by the weeding experiment results even though a threshold could not be calculated from the weeding experiment data. The results still suggest that native CSS shrubs, in particular *A. californica*, would establish better from seed if the mean density of *Erodium* species were 50-100 plants /m^2 or less in restoration sites. This possible threshold should be tested on a scale larger than 1 m^2 plots to determine effectiveness.

The CSS community faces many factors which act as constraints on restoration. Competition from invasive grasses, increased fire regimes and N deposition all maintain positive feedbacks that move CSS communities back to a degraded state even after restoration efforts (Suding 2004, Allen et al. 2005a). *Erodium* density may not be the primary constraint that prohibits many CSS restorations from achieving the desired stable shrub community. In fact, the weeding experiment reflects observations from other wildland studies that many native forb species establish in the presence of *Erodium* species (Allen et al. 2005, Gillespie and Allen 2004). In experimental removals of exotic grasses and *Erodium*, native forbs expanded into plots that had exotic grasses removed and could compete with *Erodium cicutarium*, but when *Erodium* was removed the grasses expanded to the detriment of native forbs (Cox and Allen 2011). *Erodium* species have been in present in California for more than 250 years (Minnich 2008) and are widespread throughout the state, so complete elimination of exotic *Erodium* species from CSS communities is impossible in any case.

However, having a threshold level of *Erodium* for new shrub establishment in CSS may still be an important tool for managers. Because moving CSS communities back to a self-sustaining stable state is difficult to achieve with current scientific knowledge (Suding 2004), land managers may choose interventions to conserve selected CSS native species instead of producing stable restorations (Hobbs 2011). Threshold values for *Erodium* density could be very useful for prioritizing interventions in CSS communities. Land managers could begin to use these simple threshold values to make management decisions in a way more similar to those used for weeds in agriculture. Having a value that designates when *Erodium* densities are low enough to increase establishment of key species, and applying control measures to achieve this threshold, may increase the success and reduce costs of restoration or re-establishment efforts. Threshold values might be useful in selecting potential sites for restoration or informing timing of periodic interventions to help maintain the diversity of a CSS community.

These results suggest that managing *Erodium* during restoration will increase the success of *A. californica* establishment from seed. This research also provides managers an action threshold at which to control *Erodium* to improve shrub establishment. Based on these studies an initial action threshold (or the density where control measures of *Erodium* should be implemented) of 50-100 *Erodium* plants/m^2 is recommended. Thresholds for native annual forb establishment could not be established, but they would likely also benefit from reductions below the highest densities of *Erodium*.

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Tables and Figures

Table 1-1. Seeding treatments by species and total plot densities at AgOps site

Treatment groups	*Erodium* densities	Native densities	Total plot densities
Erodium cicutarium X *Artemisia californica*	0, 25, 50, 100, 250, 500 and 1000 plants/m^2	100 plants/m^2	100, 125, 150, 200, 350, 600 and 1100 plants/m^2
Erodium cicutarium X *Cryptantha intermedia*	0, 25, 50, 100, 250, 500 and 1000 plants/m^2	100 plants/m^2	100, 125, 150, 200, 350, 600 and 1100 plants/m^2

Table 1-2. Results of piecewise regression analyses for the percent cover of *Erodium cicutarium* against the native species percent cover and density at seeded farmland site.

Response variable	Percent cover of *Erodium* where breakpoint occurred	Standard error	Lower CI	Upper CI	alpha
Artemisia density	76	10.6	61.8	86.8	0.30
Artemisia % cover	Durbin-Watson test showed potential auto-correlation so piecewise regression was not performed				
Cryptantha density	80	9.1	61.8	92.3	0.1
Cryptantha % cover	57.5	43.0	Tested to 0.5 alpha level and no confidence interval was determined		

Figure 1-1. Chart of the piecewise regression for density of *Cryptantha* as determined by percent cover of *Erodium*, over actual data points. The breakpoint of 80 percent cover was significant at p=0.1.

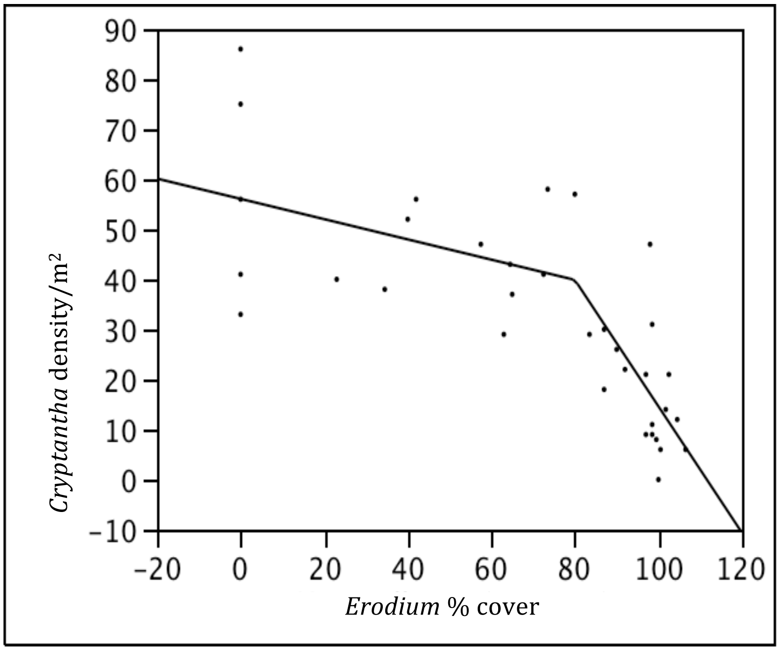
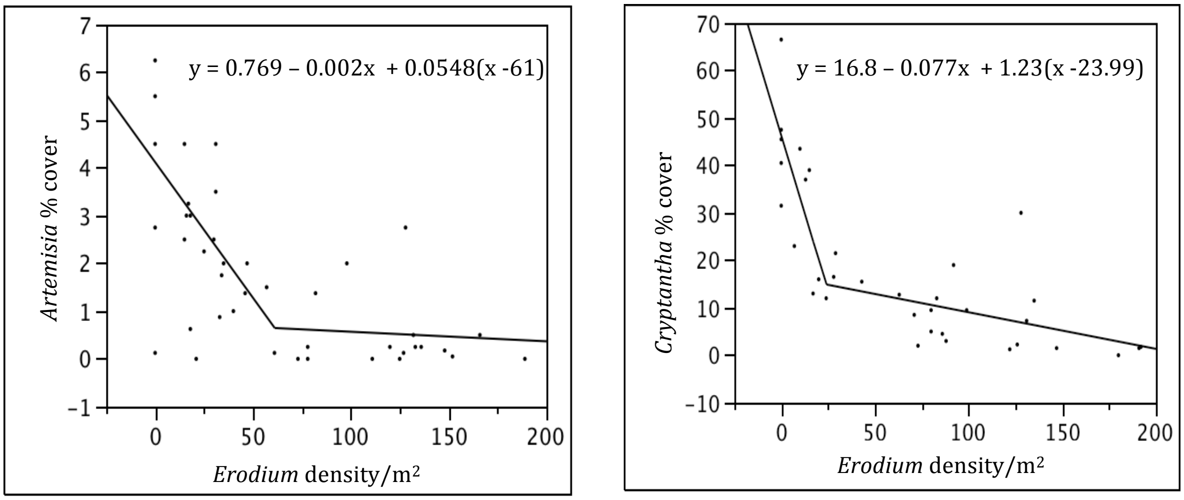


Table 1-3. Results of piecewise regression analyses for the density/m² of *Erodium cicutarium* against native species density and percent cover at seeded farmland site.

Response variable	Density of *Erodium* where breakpoint occurred	Standard error	Lower CI	Upper CI	alpha
Artemisia % cover	61	13.66	33.68	81.67	0.10
Artemisia density	66	27.19	34.42	106.46	0.15
Cryptantha % cover	24	5.91	15.68	44.36	0.05
Cryptantha density	31	16.55	13.37	53.54	0.30

Figure 1- 2. Chart of the piecewise regression for the percent cover of *Artemisia* (A) and the percent cover of *Cryptantha* (B) as determined by density of *Erodium*. Points are the actual data points from the seeded farmland site. The determined breakpoint was 61, p = 0.10, for *Artemisia* percent cover and 24, p = 0.05, for *Cryptantha* percent cover.


A.

B.

Table 1-4. Results of piecewise regression for the spring density of *Erodium cicutarium* against *A. californica* shrub density, percent cover and biomass sampled in the fall (second growing season) at the seeded farmland site.

Response variable	Density/m^2 of *Erodium* where breakpoint occurred	Standard error	Lower CI	Upper CI	Alpha
Fall density of *A. californica*	73	34.53	Confidence Intervals could not be calculated		
Fall % cover of *A. californica*	36	4.25	31.30	40.15	0.40
Fall biomass/plot	66	11.34	16.80	81.92	0.10
Fall biomass/shrub	25	4.50	18.54	40.12	0.05

Figure 1-3. Chart of the piecewise regression results for the fall-sampled total *Artemisia* biomass per m^2 (A) fall-sampled biomass per shrub of *Artemisia* (B) as determined by density of *Erodium* during the spring sampling. Points are the actual data points from the seeded farmland site. The determined breakpoint was 66, p = 0.10, for biomass per m^2 and 25, p = 0.05, for biomass per shrub.

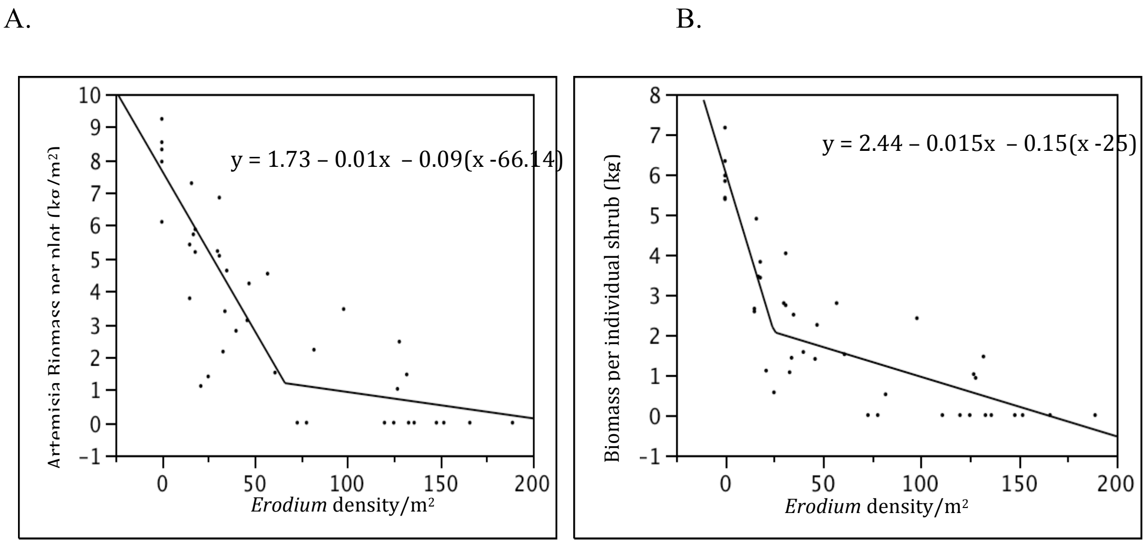
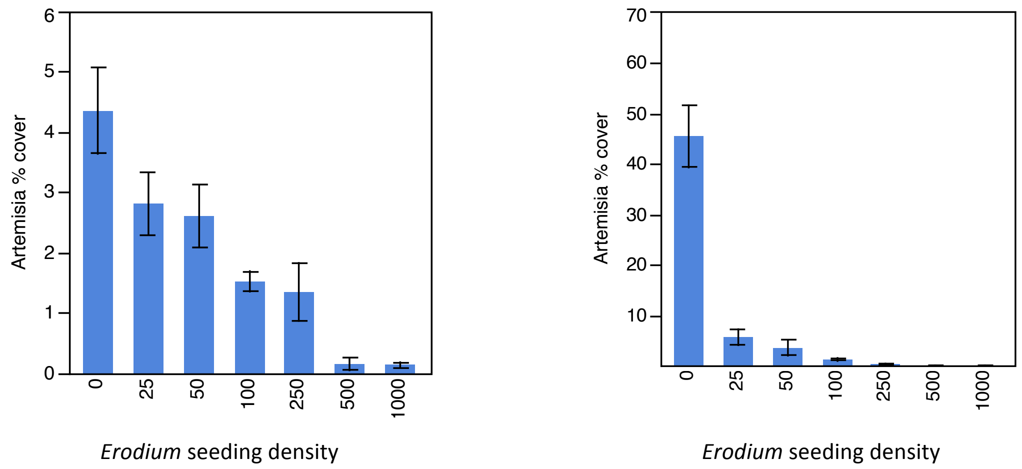


Figure 1-4. Mean percent cover of *A. californica* by *Erodium* seeding density/m^2 during a) the spring sampling and b) fall sampling.



A.

B.

Table 1-5. Means, standard error and Kruskal Wallis results for density (count/m^2) and % cover of native shrubs and forbs against the initial weeding treatments of *Erodium* at the Barnett Ranch location (n=3).

***Erodium* weeding density**	**Native shrub density (count/m^2)**	**Standard Error**	**Native shrub % cover**	**Standard Error**	**Native forb density (count/m^2)**	**Standard Error**	**Native forb % cover**	**Standard Error**
0	6.3	3.2	3.9	0.9	16.0	8.6	45.9	9.4
25	11.3	3.2	3.2	0.9	16.3	8.6	10.2	9.4
50	9.3	3.2	2.3	0.9	23.0	8.6	20.6	9.4
100	0.7	3.2	0.3	0.9	31.3	8.6	28.7	9.4
250	3.0	3.2	0.6	0.9	25.7	8.6	30.0	9.4
500	0.3	3.2	0.0	0.9	19.0	8.6	18.8	9.4
unweeded	0.0	3.2	0.0	0.9	20.3	8.6	15.8	9.4
C^2	**10.6702**		**12.7741**		**2.8980**		**8.2251**	
p	**0.0991**		**0.468**		**0.8215**		**0.2221**	

Chapter 2

Comparison of winter and spring solarization to reduce exotic annual plants for restoration in a Mediterranean climate

Abstract

Solarization has been shown to be effective in reducing invasive species seedbanks in agricultural soils, but has had less application to wildland areas. This technique traditionally involves tilling the soil, applying irrigation and laying plastic sheeting to trap solar energy and heat the soil. Since irrigation and soil disturbance would be problematic in many wildland situations, several alternative treatments were applied to test which would be the most effective. These included multiple combinations of seasonal timing, plastic color and level of soil disturbance, but relying strictly on natural soil moisture. The plots were set up at a preserve in inland southern California which has hot dry summers and cool wet winters. The experiment was observed for two years after treatment. The exotic seedbank was not completely controlled in any treatment. Exotic grasses were better controlled than exotic forbs (primarily *Erodium cicutarium*). Vegetation had to be removed by scraping or tillage to improve contact of plastic with soil. Mowing was less effective and promoted more exotic grass growth. Clear plastic in the summer provided the best control, but black plastic in winter or summer also provided enough exotic plant reduction to release native forbs present in the seedbank. Even without the ability to irrigate, solarization can be considered as a weed control method in wildland situations where chemical control is not possible, and vegetation can be removed to improve contact of plastic with soil.

Introduction

The presence of large numbers and types of invasive species in highly degraded plant communities pose multiple challenges to restoration of native plant communities including secondary invasion, propagule pressure (Colautti et al. 2006, Lockwood et al. 2005) and seasonal priority effects (Wainwright et al. 2012), among others. Many southern California plant communities have become highly degraded and invaded by Mediterranean grasses (Minnich and Dezzani 1998, Minnich 2008). Restoration efforts often begin with grass control through herbicide or fire, but the resulting plant community is often dominated by exotic forbs instead (Allen et al. 2005, Cox and Allen 2008a, Gillespie and Allen 2004, Moyes et al. 2005). For successful establishment of native species, multiple growing seasons of herbicide application are necessary to control exotic forbs, or some method must be found to kill seeds of exotic species in the seedbank so they cannot germinate to compete with seeded native species.

Seed of exotic grasses and exotic forbs often greatly outnumber native seed in the seedbank. Cox and Allen (2008b) surveyed seedbanks in invaded coastal sage scrub sites and adjacent areas that had already converted to exotic grasses. In the sites that were dominated by exotic annual grasses, exotic grasses averaged over 7000 seedlings m^{-2}, exotic forbs averaged 4700 seedlings m^{-2} (*Erodium brachycarpum* comprised 4300 of those seedlings) and native forbs averaged only 400 seedlings m^{-2}. Native shrub seedlings were practically non-existent at only 0.5 seedlings m^{-2}. Seedbank samples from sites still dominated by native shrub cover had lower exotic densities and higher native densities than the seedbanks from the grass dominated plots, but the exotic seed densities still outnumbered the native seed densities and shrubs averaged only 7 seedlings m^{-2}. Many other studies have noted that native seedbanks of highly invaded sites in Southern California lack both shrub and forb seed and that seeding treatments are necessary to establish native shrubs and increase the diversity and biomass of native forbs (Cione et al. 2002, Seabloom et al. 2003, Talluto et al. 2006).

Both exotic grasses and forbs, particularly species of *Erodium*, display early phenology, germinating much earlier and more densely than native species, giving them priority access to water, nutrients and space (Wainwright et al. 2012). Both exotic grasses and *Erodium* have been shown to negatively impact native perennial species in the establishment phase at least in part by reducing soil moisture (Eliason and Allen 1997, Gordon and Rice 2000). This propagule pressure combined with seasonal priority effects can make establishment of natives difficult even with invasive control and native seeding treatments.

To deal with this problem, restoration must be preceded by intensive weed control to reduce the native seedbank. Solarization is a technique used in agriculture to destroy weed seed and pathogens in the topsoil prior to planting, and which has been used to deplete the weed seedbank in small-scale trials in wildland settings with initial success (Moyes et al. 2005, Marushia and Allen 2011, Stapleton and Jett 2006). Solarization is a labor- and resource-intensive process, which involves placing sheets of polyethylene plastic over tilled moist soil for at least six weeks during the hottest summer months.

Studies from agriculture have shown that the highest soil temperatures and most successful propagule destruction are achieved using thin, clear plastic on moist soil during the hottest and longest days of the year (Horowitz et al. 1983, Elmore 1997). However, transporting water to restoration sites may not be feasible. One solution to the irrigation difficulties is to time placement of plastic with natural rain events. Unfortunately, southern

California's Mediterranean climate, where rain comes during the cool winter months and the summers are hot and dry, may reduce the effectiveness of plastic treatment if summer irrigation is not available. However, Marushia and Allen (2011) used black plastic in the wet winter months and achieved a more successful reduction of weeds than either herbicide or mowing. Black plastic has been shown to be less successful at conducting heat than clear plastic, but it interferes with plant growth and reproduction by inhibiting light while providing some heat transfer; this combination may be useful in cooler climates where clear plastic could actually promote growth if temperatures are not hot enough (Elmore et al. 1997, Stapleton et al. 2000.

Solarization is considered most effective on tilled soil without vegetation so the plastic has maximal contact with the soil surface (Elmore et al.1997). Wildland managers may be reluctant or unable to disk the soil, particularly over large areas, but plastic may be placed on level land over mowed vegetation. The effectiveness of this approach is unknown, but warrants further study. My goal was to test the timing of plastic application (winter or spring), combined with plastic color (clear or black) and level of soil disturbance (tilled, scraped, mowed) to determine which combination was most effective under ambient soil moisture conditions.

Site

The solarization experiment was done at the Motte Rimrock Reserve, a 289-hectare property, located 24 km south of the University of California, Riverside. The Reserve is dominated by coastal sage scrub vegetation, and provides habitat to several rare species, including the federally endangered Stephen's kangaroo rat and the threatened California gnatcatcher. The reserve receives an average of 330 mm of annual precipitation, most falling during October-April, the growing season in this Mediterranean-type climate. The average maximum annual temperature is 37 °C, average minimum temperature is 2 °C, and the elevation range is 482- 605 m. Precipitation during the three years of the experiment was 201 mm in 2007-08, 160 mm in 2008-09, and 293 mm in 2009-10 (July-June water year).

Prior to being donated to the University of California, one parcel of the property was a privately owned camping resort, including a former golf driving range where the plots for this experiment were established. The abandoned driving range is approximately 4 hectares in size and was covered mainly in invasive annual plants. A pre-treatment vegetation survey in 2008 found 27 % cover of exotic grasses, comprised mostly of *Bromus rubens* and with smaller percentages of *Bromus diandrus, Hordeum murinum, Vulpia myuros* and *Schismus barbatus*. At the time of pre-treatment sampling many of the grasses were not distinguishable to species so individual % cover numbers could not be collected for most species. Exotic forbs comprised 19 % of the vegetative cover, 15 % of which was *Erodium cicutarium*, and 4% was *Brassica geniculata* with incidental occurrence of other Brassicaceae species. The remaining living cover (54 %) was native forbs, of which 35% cover was *Amsinckia menziesii*, a native forb that is wide spread in California and inhabits disturbed areas (Calflora 2012). *Plagiobothrys* species were 9 % of the cover and *Stephanomeria* species were 5%. Other native species with less than 2% cover included *Pectocarya sp.*, *Calandrinia ciliata*, *Camissonia sp.*, *Crassula connata*, *Hemizonia sp.*, *Lotus strigosus* and *Lupinus sp*. (Nomenclature follows Hickman 1993).

To the east of the driving range the topography rises and coastal sage scrub vegetation dominates the hillsides, including *Artemisia californica, Eriogonum fasciculatum*, *Encelia farinosa*, and *Salvia apiana*. The understory was almost entirely composed of annuals, a high percentage of which are the same exotic species noted above. The restoration seed mix included dominant species from this native vegetation.

The soil of the Motte Reserve is Cieneba rocky, sandy loam on 15 to 50 percent slopes (Knecht 1971). This is a coarse-grained, excessively drained upland soil with 2-10 percent rocky outcrops. The pH ranges from 5.6 - 6.5, the depth to bedrock is 25-55 cm and the erosion potential is high. Soil collected at the time of the pre-treatment survey (January 2008) was measured for carbon, nitrogen and phosphorus; mean total N was 0.15 %, total C was 1.67%, KCl-extractable ammonium N was 5.34 ppm, extractable nitrate N was 3.50 ppm and Olsen P was 20.8 ppm.

Methods

The experiment was constructed as a 3x3x2x4 factorial split plot design in a randomized complete block that tested three soil preparation treatments, three plastic treatments, and two seasonal timing treatments in 4 replicate blocks. The subplots were seeded and unseeded treatments. An un-manipulated control was also added to each block for comparison as needed. Plots were 2 m^2 with one-meter buffers between plots.

The three soil preparation treatments disturbed the soil to three different depths. A mowing treatment, done with a gas-powered string trimmer, reduced the height of the standing vegetation so plastic could be placed with little to no soil disturbance. A scraping treatment removed vegetation and the top 1-2 cm of soil. This was achieved using the flat side of a landscape rake and could potentially be mimicked on a large scale through the use of agricultural tools such as harrows and land planes or by running the blade of a bulldozer over the ground's surface. A rototiller was used to simulate an agricultural disking treatment that disturbed the soil to approximately 15 cm.

The three plastic treatments were black plastic, clear plastic, and no plastic. Both the black and clear plastic were 0.15 mm sheeting that does not puncture easily and is readily available at home supply stores. The treatments were applied in two different seasons. The first was initiated the first week of February, 2008, left in place for eight weeks, and is referred to as the winter treatment. The second seasonal treatment was installed in April in an attempt to retain residual soil moisture from winter precipitation, since the area typically receives no precipitation from April to October. The plastic was then left in place until fall to take advantage of the highest summer temperatures. The hardware store plastic worked well for the winter treatments, but during the summer season treatments the clear plastic shattered after a few weeks in the sun. After two replacements, the clear plastic was replaced with a .038 mm UV- resistant plastic in mid-July. To compare the temperature effects of the different plastic colors, a HOBO ® (www.onsetcomp.com) data logger was placed underneath the plastic in the scraped treatments and covered with 1-2 cm soil in the plots for a total of 8 data loggers. During the summer treatment period an additional 4 HOBO data loggers with thermocouples were placed in the no-plastic scraped plots.

Only 2 of 3 treatments were seeded for the subplots because of a shortage of seed, which was required to be collected on site at the Motte Rimrock Reserve. The subplots of the scraped and tilled treatments received seed. The mowed plots had dense litter and regrowth after treatment, so successful establishment of seed was considered less likely on these plots based on previous experience in invaded CSS vegetation (Cione et al. 2002). The seeds were broadcast by hand at rates approximating 5 kg/hectare for the shrub species (*Encelia farinosa* and *Eriogonum fasciculatum*) and 2.5 kg/hectare for the forb species (*Plagiobothrys canescens*, *Salvia columbariae*, *Lasthenia californica*). Seed were broadcast by hand the first week of December 2008 at the onset of the first fall rains.

Plots were monitored for two growing seasons following seeding treatment. Data collected were density and percent cover of vegetation by species in 1.0 X 0.5 m quadrats. Quadrats were placed at least 20 cm inside the plot boundary and the location was marked so that the readings were done in the same place both seasons.

The whole plot data were analyzed with full-factorial ANOVA analysis to compare effects of the three whole plot treatments, and to detect interactions between plastic treatment, soil disturbance level and season of application. These primary analyses were run only on the unseeded plots, since not all treatments had seeded subplots. The subset of treatments with seeded and unseeded plots was analyzed separately to test for the effectiveness of the seeding treatment.

For analysis, plant species were placed into functional groups of exotic grasses, exotic forbs and native forbs. The native forb *Amisinckia menziesii* was analyzed separately because it was very common in the pre-treatment and post-treatment vegetation. Preliminary analyses showed that including *Amisinckia menziesii* with the native forbs obscured treatment effects of the other native forbs. No native shrubs were present in the plots. Statistical tests were run on both the density and percent cover data for all live vegetation, each functional group, and *Erodium cicutarium* alone, as that was the dominant exotic forb on site and also a species of primary interest in this study.

Results

The mean daily high temperature recorded during winter treatment was 35 ^{o}C in the clear plastic scraped treatment and 29 ^{o}C in the black plastic scraped treatment. No temperature sensors persisted in the no-plastic controls, so no data are available. Mean summer temperatures was 61 °C in the clear plastic scraped plots and 59 °C in the black plastic, scraped plots. Mean temperature in the no-plastic scraped treatment was 45 °C.

Density of all live vegetation

All plant species measured in the plots and their mean densities and cover are listed in Table 2-1. *Amsinckia menziesii* and *Plagiobothrys canescens* were the dominants of 28 native forb species and there was one native grass. By comparison there were 10 exotic species, of which *Bromus rubens*, *B. diandrus*, *Erodium cicutarium* and *Brassica geniculata* were dominant. Native species had a mean cover of 48.8 %, and exotic species cover was 58.1 %.

Total plant density of unseeded plots was used as a metric to indicate how effective the treatments were at reducing the overall seedbank. Full factorial analyses for both the 2009 and 2010 growing season data showed that the same whole plot treatments, specifically plastic treatment and season of treatment, were significant at $P < 0.05$ for density of total live vegetation (Table 2-2).

Patterns of total plant density in response to plastic treatment, season, and soil disturbance were in general similar between the two years (Figure 2-1). Winter-treated plots had mean higher plant densities than summer-treated plots, and clear plastic treatments had significantly lower density than no-plastic treatments in both years. However, in 2009, the black plastic treatments reduced plot densities as effectively as the clear plastic treatments, but in 2010, the clear plastic treatments still had lower mean densities than the no-plastic treatments, while the black plastic did not.

The significant interactions between the whole plot factors were different between the two years measured (Table 2- 2). In 2009, the soil treatment by season of treatment interaction was significant because the tilled winter treatments had plot densities similar to the summer treated combinations, while the scraped winter treatments and mowed winter treatments had higher mean plot densities. The three-way interaction between the whole plot factors was also significant in 2009. However in 2010, the second growing season after treatment, the only significant interaction was plastic treatment by season of treatment. This was because the clear plastic treatments applied in the summer had much lower mean plant densities than all other plastic treatment-by-season combinations.

Percent cover of all live vegetation

The results for the percent cover of all live vegetation were less consistent between the two growing seasons than the density results. In 2009, all whole plot treatments and two interactions were significant (Table 2- 3). In 2010, season of treatment was the only whole plot factor that remained significant and plastic treatment by season of treatment was the only significant interaction. Mean percent cover of all vegetation was lower in the summer-treated plots than the winter-treated plots two growing seasons after treatment (Figure 2- 2) and both clear plastic and black plastic placed in the summer had lower total plant cover than other plastic-by-season combinations.

Exotic grass density

Plastic treatment and season were the significant whole plot factors influencing the density of exotic grass in both years sampled (Table 2- 4). In both years, the summer treated plots had lower grass density than winter treated plots, and both black and clear plastic treated plots had lower mean grass density than those not covered in plastic. Mean grass density did not vary between the two plastic treatments (Figure 2- 3).

In 2009, there were no significant interactions; however in 2010 the plastic treatment by season-of-treatment interaction was significant. Both clear and black plastic treatment placed in the summer had lower mean grass densities than all other plastic treat ment by season of treatment combinations.

Exotic grass percent cover

In 2009, the plastic treatment and season of treatment were the only significant whole plot factors affecting the percent cover of exotic grass, corresponding with the density data. In 2010, all three whole plot factors had a significant effect on the percent cover of grass (Table 2- 5). In both years, percent cover of exotic grass was lower in the summer-treated plots, as well as lower in both black and clear plastic treated plots compared to the plots not treated with plastic. In addition the grass cover was higher in the mowed plots than in the scraped plots. The tilled plots did not differ in mean grass cover from either of the other two soil treatments (Figure 2- 4). There were no significant interactions for percent cover of exotic grass.

Erodium Density

Since *Erodium cicutarium* was the most dominant exotic forb at Motte Rimrock Reserve, the density and percent cover of *E. cicutarium* alone were analyzed in addition to the exotic forb functional group. Plastic treatment caused significant differences in *E. cicutarium* density compared to controls in both 2009 and 2010 (Table 2- 6), but the patterns were opposite between years. In 2009, results in the black and clear plastic treatments were both lower than the no-plastic treatment, and in 2010 the two plastic treatments had higher *Erodium* density than the no-plastic treatment (Figure 2- 5). Soil treatment was a significant factor in 2009 because *Erodium* density was higher in the scraped plots than in either the mowed or tilled plots; however, in 2010, this relationship was no longer significant.

Interactions between whole plot factors produced significantly different *Erodium* densities. There were four significant interactions in 2009, and in 2010 three remained: soil treatment by plastic treatment, plastic treatment by season of treatment, and the three-way interaction between the whole plot factors (Table 2- 6). Soil treatment by plastic showed that the mowed/black plastic treatment combination had the highest average *Erodium* density, although it was only significantly higher than the tilled/clear plastic treatments, tilled/no-plastic treatments and the mowed/no-plastic treatments.

The three-way interaction of plastic treatment/soil treatment/season was also significant (Table 2- 6). The interactions occurred in the scraped and tilled treatments; *Erodium* density in the black plastic treatments increased between the winter and summer seasons, but in the clear plastic treatments the density decreased between winter and summer season. For the no-plastic treatments, *Erodium* density was higher in the scraped plots treated in the winter than those treated in the summer, but lower in the tilled plots receiving winter treatment than those receiving summer treatment.

Percent cover of *Erodium*

The percent cover of *Erodium* had very similar patterns to density. In 2009, the type of soil treatment was significant to the percent cover of *Erodium*, with higher cover in the scraped treatment than either mowed or tilled treatments, but by 2010 this difference was gone (Table 2- 7). In both years, season was significant to the amount of cover of *Erodium*, but as with the density data, the relationship reversed (Figure 2- 6). In 2009 winter-treated plots had higher *Erodium* cover while in 2010 summer-treated plots had higher cover. Plastic treatment was also significant in 2010 where both black and clear plastic treatments had higher mean percent cover of *Erodium* than the no-plastic treatments.

Only two interactions were significant in 2009 (plastic by season and the combination of all the whole plot factors) but by 2010 there were three significant interactions for percent cover of *Erodium* in the plots: plastic treatment by season of treatment, soil treatment by plastic treatment, and the three-way interaction of soil treatment by plastic treatment by season (Table 2- 7). Black plastic in the summer had higher cover of *Erodium* than all other plastic-by-season treatments except for clear plastic in summer. However, clear plastic in summer was not significantly higher in cover than clear plastic in winter. The no-plastic treatments and the black plastic winter treatment had the lowest *Erodium* cover. Again, the no-plastic treatments may have had low *Erodium* due to the high cover of grass. All soil treatment by plastic combinations had higher *Erodium* cover than the mowed/no-plastic treatments except for the tilled/no-plastic treatments.

The three-way interactions for percent cover of *Erodium* are very similar to the ones for *Erodium* density (Table 2- 7).

Density of all exotic forbs

The data for all exotic forbs was analyzed to determine if the patterns differed from those of *Erodium* alone. The other primary exotic forb present was *Brassica geniculata*, so most differences present will represent differences in response between these two species.

In 2009 and 2010, soil treatments and plastic treatments had a significant effect on exotic forb density (Table 2- 8). In both years, the scraped treatments had a higher mean density of exotic forbs than the mowed treatments. This is different from the results of *Erodium* alone where soil treatment was not a significant factor on density. In 2009, the tilled treatments had lower mean exotic forbs than the scraped, but by 2010 this was no longer true. The results of the plastic treatments on exotic forb density reversed between years just as was true for *Erodium* alone. In 2009, the two plastic treatments had lower densities of exotic forbs than the no-plastic treatment, but in 2010 the two plastic treatments had higher densities of exotic forbs than the no-plastic treatment (Figure 2- 7). This is likely due to the fact that in 2009 initial disturbance in the no-plastic plots had removed exotic grass and provided a competitive release for exotic forbs in the seedbank, but by 2010 the grass had recovered and was again the dominant growth form in the plant community.

The interaction between soil treatment and plastic treatment was also significant in both years. In 2010, this was mostly due to the fact that the mowed, no-plastic treatment had very low exotic forbs, likely due to high grass density.

Finally, the three-way interaction of soil treatment by plastic treatment by season of treatment was also significant both years. Like *Erodium* alone, this results shows that the density of exotic forbs was affected by other species' responses to the treatment combinations and not just to the treatments alone. This also suggests than many of the treatment combinations were less effective at destroying the exotic forb seed than the exotic grass seed. In 2009, the soil treatment by season treatment was significant because the plots scraped during the winter season had higher average exotic forbs than the other soil treatment by season combinations, but by 2010 (the second growing season after the scraping disturbance) the exotic forbs density was high enough that this relationship was no longer significant (Table 2- 8).

The analysis for the soil treatment by plastic treatment interactions for all exotic forbs was, again, very similar to the patterns when *Erodium* was analyzed alone for this interaction. Mowed by no-plastic treatment combination had lower densities of exotic forbs than all other combinations. The tilled/no-plastic treatment had lower densities than all of the plastic treated plots of either color, with the exception of the tilled/clear plastic treated plots (Table 2- 8).

Percent cover of all exotic forbs

In 2009, season of treatment was the only significant whole plot factor affecting the percent cover of exotic forbs, with winter treated plots having higher exotic forb cover than summer treated plots (Table 2- 9, Figure 2- 8). While season was again a significant factor in 2010, the relationship was reversed; exotic forb cover was higher in the summer treated plots. The plastic treatment was also significant in 2010 with both the black and clear plastic treatments having higher exotic forb density than the no-plastic treatments.

In 2009, two interactions were significant for exotic forb cover: plastic treatment by season of treatment and the interaction of all three whole plot factors (Table 2- 9). The plastic by season interaction occurred because the percent cover of exotic forbs was higher in the plots treated with clear plastic in the winter than those treated in the summer, while the black plastic and no-plastic treatments had approximately equal levels of exotic forb cover between treatment seasons. The three-way interaction reflects several differences in combinations of treatment effects. However, by 2010, interactions between factors no longer had a significant effect on exotic forb cover.

Native plant density

In 2009, all factors and all interactions between factors were significant for native forb density in unseeded plots. In 2010, season of treatment was no longer a significant factor and only two of the interactions, soil treatment by plastic treatment and plastic by season treatment, remained significant in the effects tests (Table 2- 10). Figure 2- 9 shows the mean densities for the whole plot factors. In both years, native forbs were denser in the scraped than the tilled treatments and the tilled treatments had denser native forbs than the mowed treatments. In 2009, mean native forb density was less than 10 plants/m^2 in both plastic treatments, while the no-plastic plots were higher at 15 plant/m^2. However, in the following season, native density was higher in the black plastic treatments (averaging almost 40 plants/m^2) than in the no-plastic treatments, and the clear plastic treatments had intermediate levels of native forbs and therefore were not different from either of the other two treatments.

For the soil treatment by plastic treatment interaction in 2010, the scraped/no-plastic treatments had the densest native forbs per square meter, while mowed/no-plastic had the lowest. Of the treatments with significant soil disturbance, tilled soil/no-plastic had the lowest density of native forbs. For the plastic treatment by season combinations, black plastic treatment in winter had the highest densities of native forbs although not significantly higher than the clear plastic/winter treatments because of high variability between the plots. No-plastic/winter and clear plastic/summer had the lowest native densities per square meter; however, the other features of these two plot combinations were different. The no-plastic/winter combinations had high densities and cover of grass and the clear plastic/summer combinations had low grass density and cover and higher percent covers of bare ground. Soil treatment by plastic treatment by season was not a significant interaction (Table 2- 10).

For *Amsinckia menziesii,* a native forb that was excluded from the native forb functional group analysis, season of treatment was the only significant whole plot factor with densities being lower in the summer treated plots than the winter treated plots. The plastic treatment by season of treatment was also significant with clear plastic/summer, black plastic/summer and no-plastic/winter having lower *Amsinckia* densities than the black plastic/winter, clear plastic/winter and no-plastic/summer treatments.

Percent cover of native forbs

For percent cover of native forbs, soil treatment and plastic treatment were the significant higher whole plot treatments (Table 2- 11). The scraped and tilled treatments had higher percent cover of native forbs than the mowed treatments; while the black and clear plastic treatments had higher percent cover than the no-plastic treatments (Figure 2-10).

Soil treatment by plastic treatment also had a significant interaction influencing native cover in 2010. Tilled/black plastic had the highest cover of natives, but it was not significantly higher cover than the scraped/no-plastic, tilled /clear plastic, scraped/ black plastic or mowed/ black plastic. Mowed/no-plastic had the lowest percent cover of natives.

When the percent cover of *A. menziesii* was analyzed the only significant factor was the interaction between plastic by season of treatment and the relationships were the same, only stronger, described above for density of *Amsinckia*.

Seeded vs. unseeded plots

There was no difference in total native plant density between seeded and unseeded plots. However, percent cover of native forbs was higher in seeded plots than unseeded plots (Figure 2- 11). Seeded species were also analyzed individually and the only species that had higher densities in seeded plots than unseeded plots was *Salvia columbariae* (Figure 2- 12).

Discussion

Despite the lack of soil moisture, clear plastic in the summer was still the most effective treatment for reducing exotic annual cover and density two years after treatment. That treatment combination reduced total plant density more than any other treatment combinations. Plots treated with clear plastic in the summer averaged roughly 100 plants per m^2, while all other treatment combinations averaged between 200 and 600 plants/m^2.

There are some differences in how functional groups responded to plastic treatments. Exotic grass density was reduced equally effectively by both colors of plastic in summer. *E. cicutarium* was lower the first year after treatment in both clear and black plastic/summer plots than in no-plastic plots, but the second year after treatment *E. cicutarium* was higher in the black plastic/summer-treated plots than both the clear plastic and no-plastic/summer treated plots. The results for *E. cicutarium* need to be interpreted within the context of grass density. *Erodium* was very low in both plots with high grass density, likely due to competition from the grass, and *Erodium* was low in some of the plots with low total plant density, which would indicate effectiveness of the treatment. For example, the mowed/no-plastic treatment combinations, which had the lowest *Erodium* densities overall, were very high in grass; the summer/mowed/no-plastic treatment had 489 grass plants/m^2, while the winter/mowed/no-plastic had 1439 grass plants/m^2. In contrast, the summer/tilled/clear plastic had only 16 grass plants/m^2, indicating lower *Erodium* densities in these plots were due to greater effectiveness of the summer plastic treatment, not competition from exotic grasses. The clear plastic/summer treatments all had grass densities that averaged 21 or fewer grass plants/m^2, suggesting that this combination of season and plastic was the best at reducing densities of both grass and *Erodium* two seasons following initial treatment.

Since this was also the treatment combination that had lowest total vegetation density, this suggests that the clear plastic/summer treatment was not as effective on *E. cicutarium* as it was on exotic grasses, but was still the most effective at reducing *E. cicutarium* seed in the seedbank. The exotic grass was likely more susceptible to solarization treatment combinations because the dominant species on site, *Bromus rubens*, does not form a persistent seedbank (Forcella and Gill 1986, Laude 1956) and relies on dispersal and broad germination requirements to compete with other species (Salo 2004). In contrast, *E. cicutarium* does form a persistent seedbank (Roberts 1986) and has an impermeable seed coat (Rice 1985, Young 1975). The density increase in *E. cicutarium* between 2009 and 2010 in the black plastic summer treated plots, suggest that this treatment did not destroy much of the *Erodium* seed in the seedbank, but either interrupted the species germination cues for the upcoming season or enforced a secondary dormancy on the seed. Other species of *Erodium* have a specific diurnal temperature pattern for germination to be cued (Rice 1985) and if *E. cicutarium* requires similar cues, the plastic coverage in the summer could have interfered with those cues (Benech-Arnold 2000; Dahlquist et al. 2007). Alternatively, *E. cicutarium* seed might have dispersed from adjacent untreated plots. The latter is less likely, as no vegetation pattern resulting from edge effects of *E. cicutarium* propagule pressure from untreated to treated plots was noted.

The density of all exotic forbs was affected by soil treatment. In the first growing season the scraped treatments had the highest density of exotic forbs; the second year there was no difference between scraped and tilled treatments, but both were still higher in exotic forbs than the mowed treatment. This may be because the tilling treatment buried some of the exotic forb seed too deep for germination. Blackshaw (1992) found that *E. cicutarium* had the greatest germination at 1 cm depth and did not germinate at all below 8 cm. *E. cicutarium* displayed a trend, but not significance, of higher densities in scraped plots in 2009. The other exotic forbs in the plots may have been more sensitive to burial or the inclusion of multiple species may have increased the differences between the treatments enough make them statistically significant.

All treatments had higher native forb densities than the mowed/no-plastic treatment combinations, which had very high grass densities. Again when comparing the treatments where grass was reduced for the season-by-plastic treatment combinations, the clear plastic/summer treatment combinations had lowest native forb densities. This once again indicates that the clear plastic summer treatment was the most effective in reducing the seedbank. *A. menziesii* was excluded from the native analysis because, although native, it was present in the community at high densities prior to treatment. It is considered an agricultural pest (UC IPM Online) and, in natural communities, a closely related species to *Amisinckia* species common in the Mojave Desert, *A. tessellata*, was found to be competitive when planted with *Bromus rubens* (Abella et al. 2011). *A. menziesii* was analyzed separately and the densities were lower in the plastic/summer treatments, where total vegetation density was lower and the no-plastic/winter treatment where grass densities were higher, supporting the evidence from agricultural settings that the summer treatments, particularly with clear plastic, were the most effective at reducing the weed seedbank over all (Horowitz et.al. 1983, Standifer et al. 1984, Stapleton 2000).

In this study, the survival of some seed, particularly the exotic and native forbs, is likely due to the lack of additional water for summer solarization. Studies have shown that summer solarization with clear plastic and water added prior to plastic application does control exotic forbs such as *E. cicutarium* and *Brassica geniculata* (Moyes et al. 2005, Stapleton and Jett 2006, Porter 1983). In fact, projects testing moist summer solarization in wildlands reported no recruitment from the seedbank the following season (Moyes et al. 2005, Lambrecht and D'Amore 2010).

In spite of the degradation of the initial clear plastic applied under summer temperatures, and the necessary replacement with a UV-resistant plastic, the summer-treated clear plastic plots may have achieved higher temperatures due to longer overall treatment time and a thinner plastic, both of which contribute to more effective solarization (Elmore et al. 1997). However, Horowitz et al. (1983) did not find much difference in effectiveness between 4 and 8 weeks of solarization, so the extra time of plastic application on dry soil may have had little additional impact on the seedbank.

While the seeding treatments did not increase overall density of seeded natives in these plots, this is likely due to poor seed viability. Laboratory attempts to germinate the locally-collected seed prior to seeding resulted in very low to no germination. *S. columbariae* was the only species that responded to a dormancy-breaking treatment in a lab setting, in this case soaking. All of the previously discussed studies of solarization in wildland settings have had successful recruitment of seeded natives after solarization treatment (Moyes et al. 2005, Marushia and Allen 2011, Stapleton and Jett 2006, Lambrecht and D'Amore 2010).

Not surprisingly, without the addition of water, solarization did not completely eliminate the seedbank. However, both the clear plastic/summer/tilled and clear plastic/summer/scraped treatments had 70% or greater cover of bare ground the first growing season. The second growing season after treatment, the clear plastic/summer tilled treatment had 60.5% cover of bare ground and the clear plastic/summer/scraped treatments had 39% bare ground in 2010. This reduces competition from exotic species and should allow native seed or transplants to establish.

Conclusions

Even in the absence of summer irrigation, summer solarization with clear plastic was effective in reducing the exotic seedbank, although not as effective as other studies have shown for solarization in moist soil (Horowitz et al. 1983, Moyes et al. 2005). It was more effective than winter solarization on moist soil, but under cooler temperatures. Nevertheless, either winter or summer solarization may be considered for wildland exotic control when tillage or scraping can be applied to improve contact of plastic with soil. Both treatments reduced, but did not eliminate the exotic seedbank. However, reducing the seedbank and exotic plant cover should make follow-up weed treatment for invasive forbs, such as hand pulling, spot spraying or flaming more feasible for land managers. Solarization is still an effective technique for wildland restoration even if additional water cannot be applied prior to plastic application, and should be considered under circumstances where alternatives to chemical control are desired.

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Tables and Figures

Table 2-1. Mean percent cover and density of each species identified in the solarization plots in 2010.

Species	Mean % cover 2010	Mean density/m² 2010
Native forbs		
Amsinckia menziesii	12.8	20.1
Calandrinia ciliata	1.1	0.02
Camissonia bistorta	1.7	1.3
Conyza canadensis	0.1	0.05
Crassula connata	1.0	0.26
Croton californicus	0.1	0.02
Eremocarpus setigerus	0.1	0.05
Eriogonum gracile	0.04	0.08
Eriogonum thurberi	0.2	0.01
Eschscholtzia californica	0.3	0.02
Hemizonia fasciculata	1.1	4.1
Hemizonia paniculata	0.18	0.8
Lessingia sp.	0.3	0.04
Lotus hamatus	1.3	0.1
Lotus purshianus	0.1	0.8
Lotus salsuginosus	1.5	0.05
Lotus sp.	0.3	0.04
Lotus strigosus	0.2	0.4
Lupinus bicolor	1.2	0.6
Microseris lindleyi	1.9	0.2
Pectocarya linearis	0.2	1.4
Pectocarya penicillata	1.5	0.02
Plagiobothrys canescens	11.0	16.2
Salvia columbariae	3.4	0.3
Stephanomeria virgata	7.3	12.6
Trifolium gracilentum	0.25	0.05
Trifolium variegatum	0.5	0.02

Species	Mean % cover 2010	Mean density/m² 2010
Native grasses		
Vulpia octoflora	1.1	0.3
Exotic forbs		
Brassica geniculata	6.7	6.4
Erodium cicutarium	7.4	27.2
Lactuca serriola	0.3	0.02
Exotic grass		
Bromus diandrus	9.0	0.2
Bromus rubens	23.8	120.4
Hordeum murinum	1.8	1.6
Hordeum vulgare	5.5	0.2
Lamarkia aurea	0.25	0.02
Schismus barbatus	1.9	4.0
Vulpia myuros	7.2	4.8

Table 2-2: ANOVA results for mean density of all live vegetation, 2009 and 2010.

<u>2009</u>

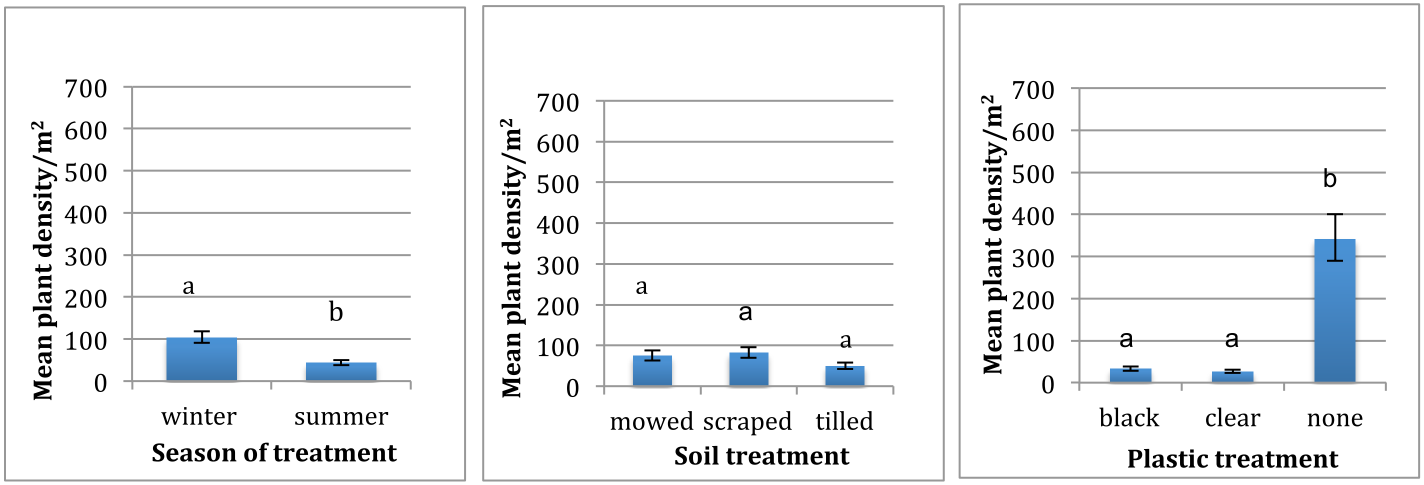
Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	2.7595	0.0728
Plastic	2	76.0174	<.0001*
soil treatment*plastic	4	2.4316	0.0593
Season	1	21.3775	<.0001*
soil treatment*season	2	6.6071	0.0028*
plastic*season	2	1.7438	0.1851
soil treatment*plastic*season	4	3.4366	0.0146*
Block	3	0.2938	0.8297
soil treatment*block	6	0.7236	0.6327
plastic*block	6	1.5108	0.1949
season*block	3	1.3696	0.2633

<u>2010</u>

Source	**I**	**F Rat**	**Prob >**
soil treatment		1.82	0.17
Plastic		6.61	0.002
soil treatment*plastic		0.93	0.45
Season		6.17	0.016
soil treatment*season		0.59	0.55
plastic*season		3.40	0.040
soil treatment*plastic*seaso		1.78	0.14
Block		0.76	0.51
soil treatment*block		0.66	0.67
plastic*block		0.75	0.60
season*block		0.89	0.44

Figure 2-1: Mean density of all live vegetation for each whole plot factor in 2009 and 2010.

2009



2010

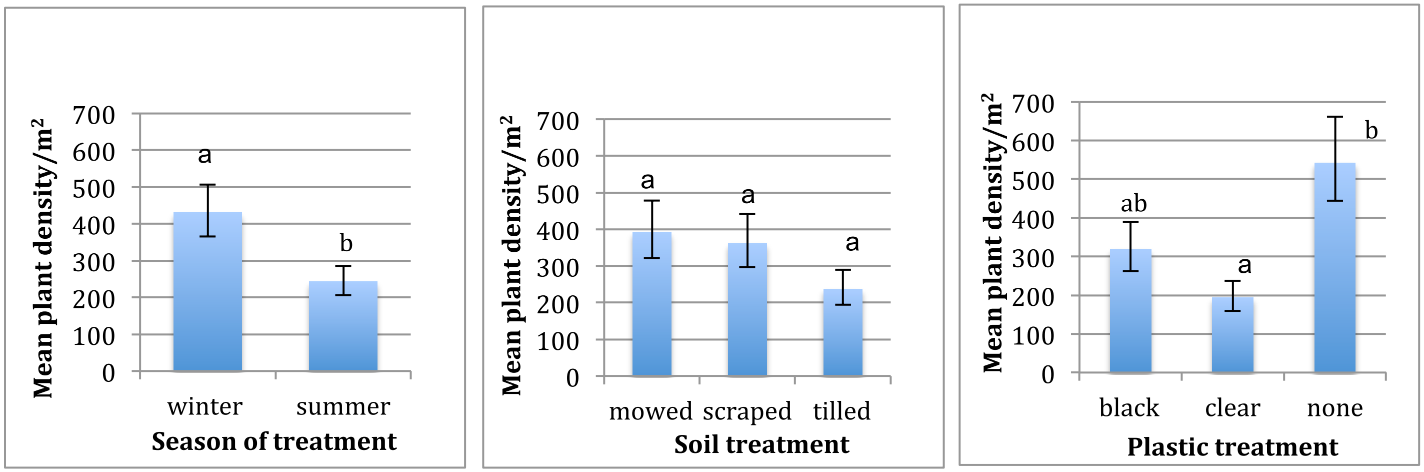


Table 2-3: ANOVA results for mean percent cover of live vegetation, 2009 and 2010

2009

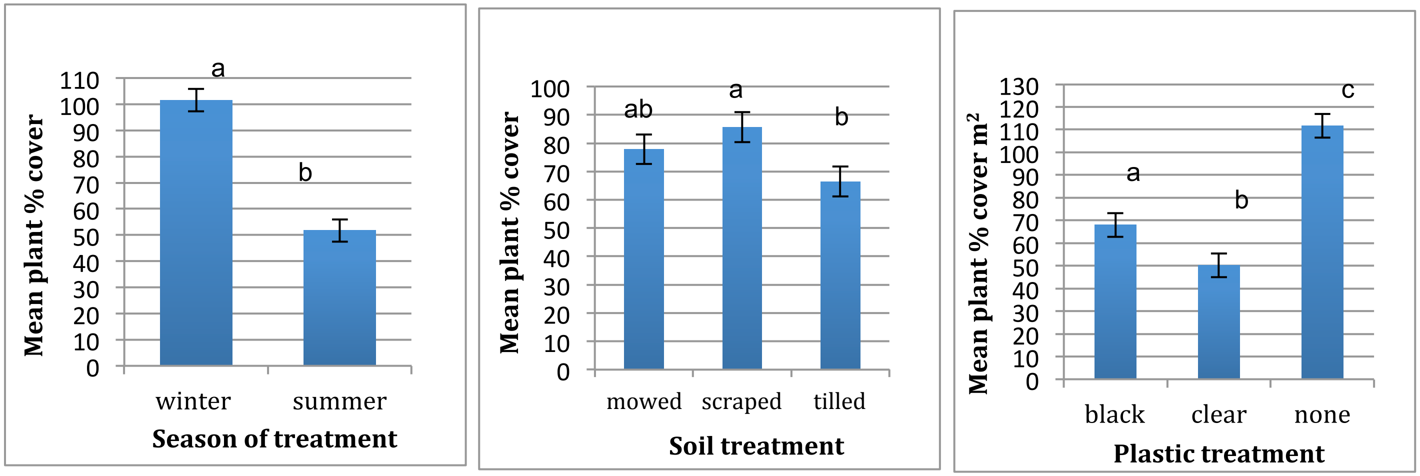
Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	3.3794	0.0419*
Plastic	2	36.4228	<.0001*
soil treatment*plastic	4	0.1679	0.9538
Season	1	67.3840	<.0001*
soil treatment*season	2	1.8359	0.1699
plastic*season	2	10.9711	0.0001*
soil treatment*plastic*season	4	3.5189	0.0130*
Block	3	4.4260	0.0077*
soil treatment*block	6	1.6045	0.1743
plastic*block	6	0.6004	0.7280
season*block	3	0.8607	0.4703

2010

Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	1.4401	0.2466
Plastic	2	1.4975	0.2335
soil treatment*plastic	4	0.5173	0.7233
Season	1	13.0703	0.0007*
soil treatment*season	2	0.8444	0.4359
plastic*season	2	3.1992	0.0493*
soil treatment*plastic*season	4	1.7658	0.1505
Block	3	1.0370	0.3843
soil treatment*block	6	1.0804	0.3878
plastic*block	6	0.6688	0.6751
season*block	3	0.7227	0.5435

Figure 2-2.   Mean percent cover of live vegetation for each whole plot factor in 2009 and 2010

2009



2010

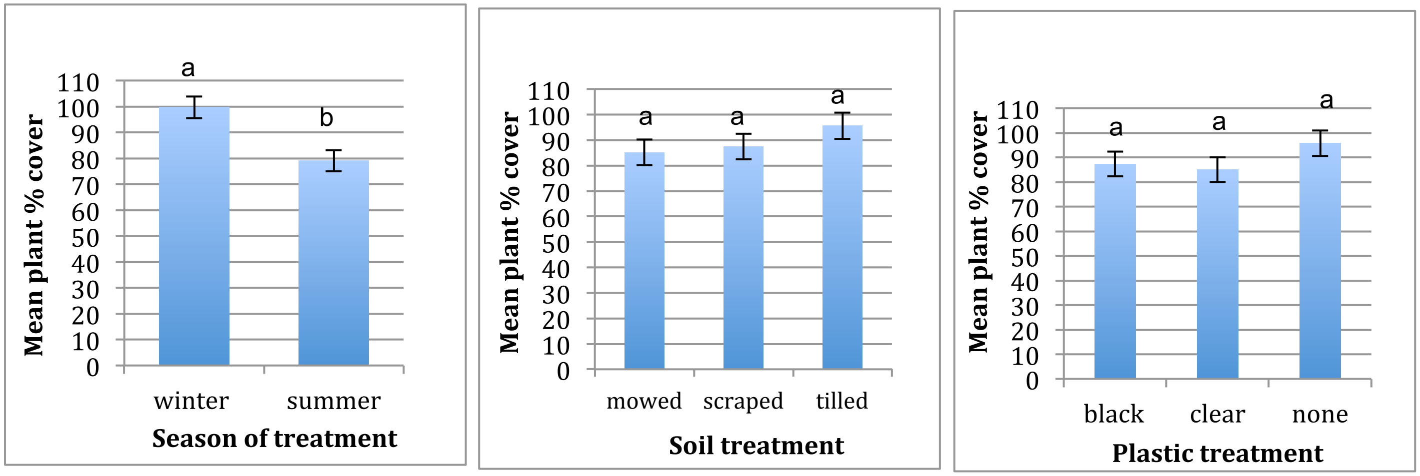


Table 2-4. ANOVA results for mean density of exotic grass, 2009 and 2010

2009

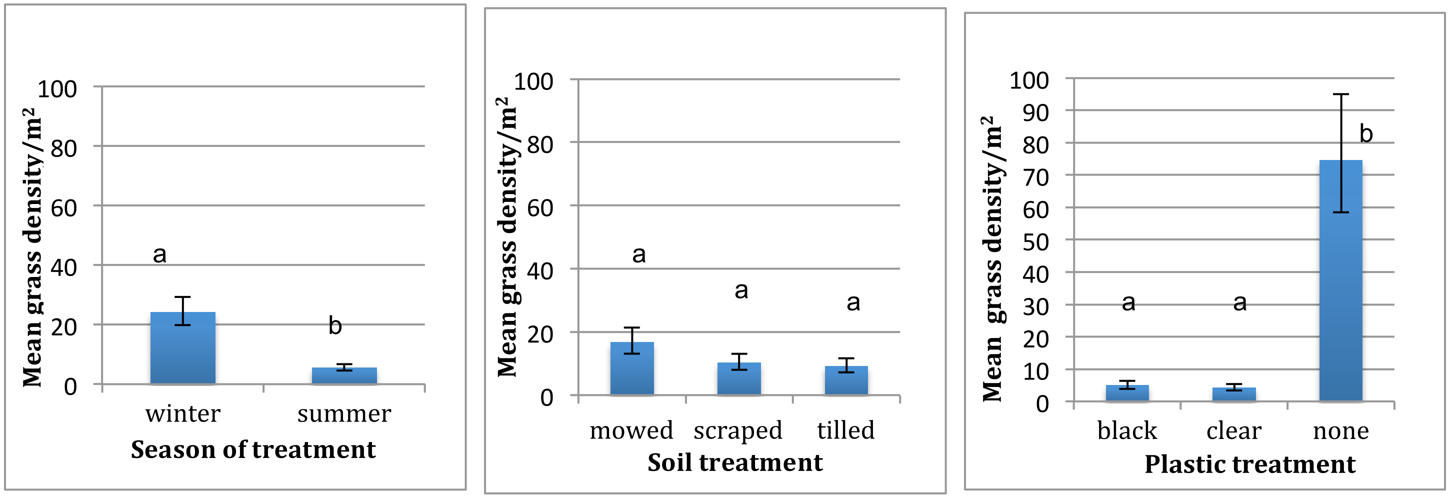
Source	DF	F Ratio	Prob > F
soil treatment	2	1.7378	0.1862
Plastic	2	44.2133	<.0001*
soil treatment*plastic	4	1.7544	0.1525
season	1	27.2957	<.0001*
soil treatment*season	2	2.5021	0.0919
plastic*season	2	0.0930	0.9114
soil treatment*plastic*season	4	2.0403	0.1026
block	3	0.3922	0.7591
soil treatment*block	6	0.8557	0.534
plastic*block	6	0.2739	0.9465
season*block	3	1.4128	0.2505

2010

Source	DF	F Ratio	Prob > F
soil treatment	2	2.4834	0.0935
plastic	2	19.7660	<.0001*
soil treatment*plastic	4	1.6995	0.1645
season	1	24.2615	<.0001*
soil treatment*season	2	1.0223	0.3670
plastic*season	2	4.0196	0.0239*
soil treatment*plastic*season	4	1.2011	0.3217
block	3	1.2078	0.3164
soil treatment*block	6	1.0201	0.4238
plastic*block	6	0.2852	0.9412
season*block	3	0.2396	0.8683

Figure 2-3. Mean density of exotic grass for each whole plot factor in 2009 and 2010.

2009



2010

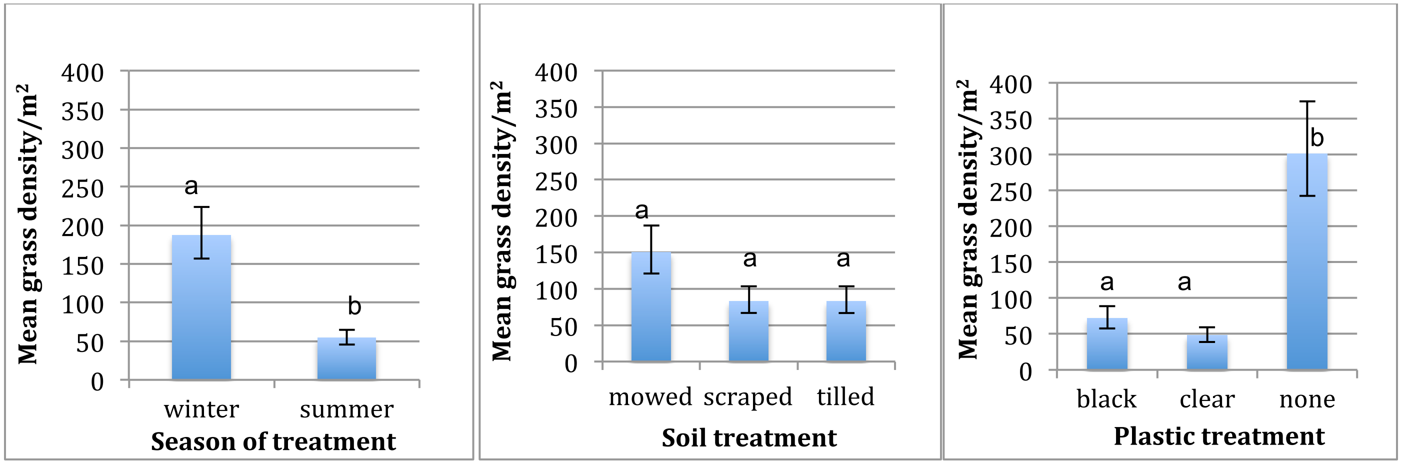


Table 2-5. ANOVA results for mean cover of exotic grass, 2009 and 2010

2009

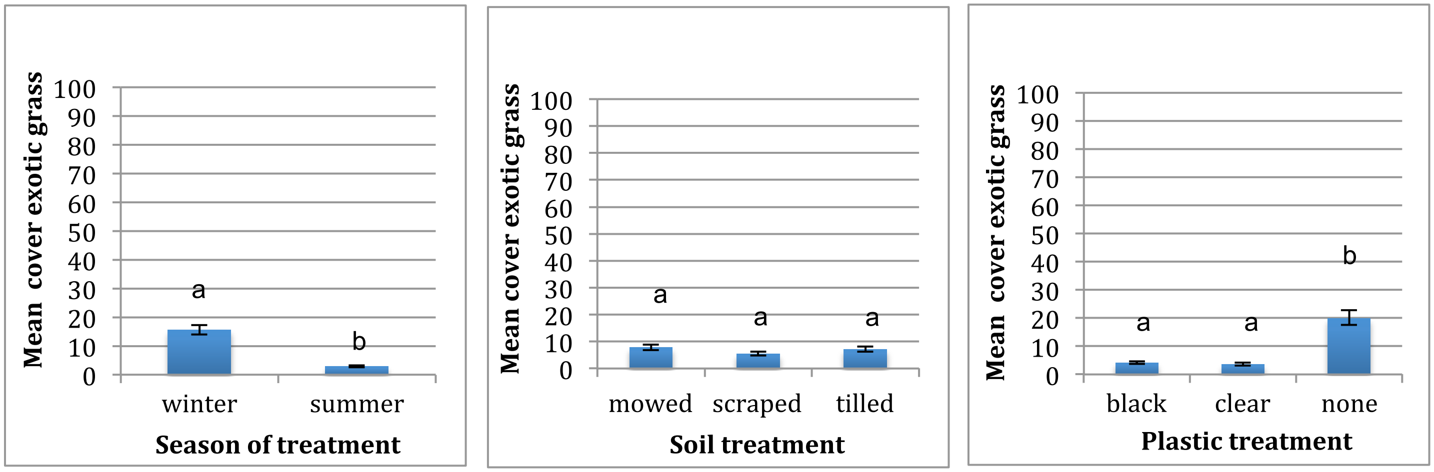
Source	DF	F Ratio	Prob > F
soil treatment	2	2.1061	0.1322
plastic	2	51.9906	<.0001*
soil treatment*plastic	4	1.5243	0.2091
season	1	124.1202	<.0001*
soil treatment*season	2	1.5517	0.2217
plastic*season	2	2.1564	0.1262
soil treatment*plastic*season	4	1.5359	0.2058
soil treatment*block	6	1.1719	0.337
plastic*block	6	0.6056	0.7245
season*block	3	0.699	0.5573

2010

Source	DF	F Ratio	Prob > F
soil treatment	2	3.4291	0.0402*
plastic	2	27.6330	<.0001*
soil treatment*plastic	4	1.6259	0.1823
season	1	25.5753	<.0001*
soil treatment*season	2	0.2130	0.8089
plastic*season	2	2.0991	0.1332
soil treatment*plastic*season	4	0.6133	0.6550
block	3	3.1591	0.0326*
soil treatment*block	6	3.9886	0.0038*
plastic*block	6	0.9973	0.4425
season*block	3	0.5828	0.6303

Figure 2-4. Mean cover of exotic grass for each whole plot factor in 2009 and 2010

2009



2010

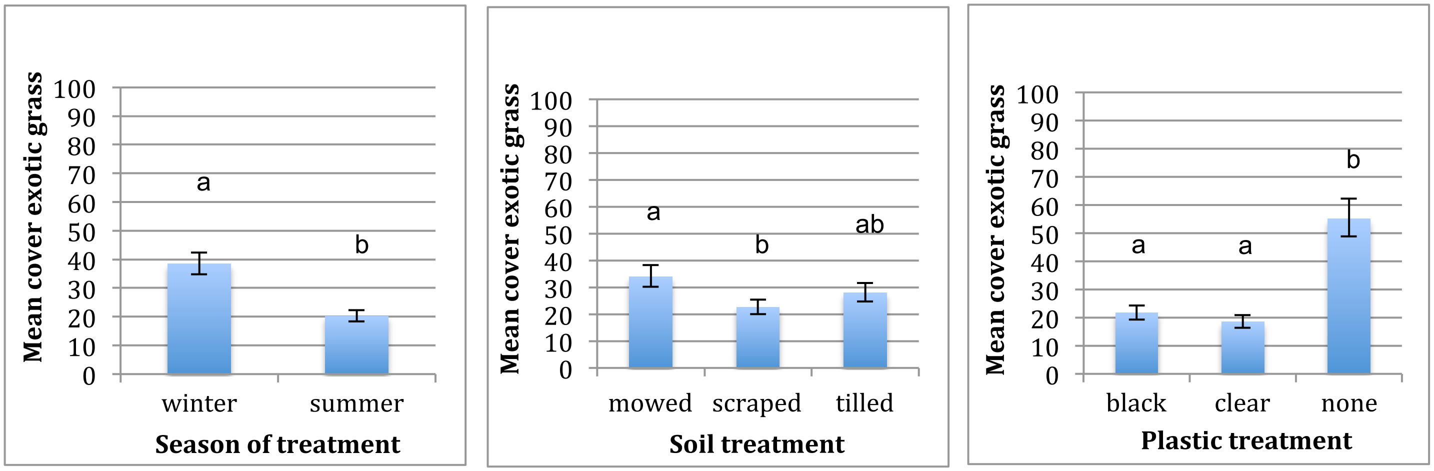


Table 2-6. ANOVA results for mean density of *Erodium cicutarium*, 2009 and 2010

2009

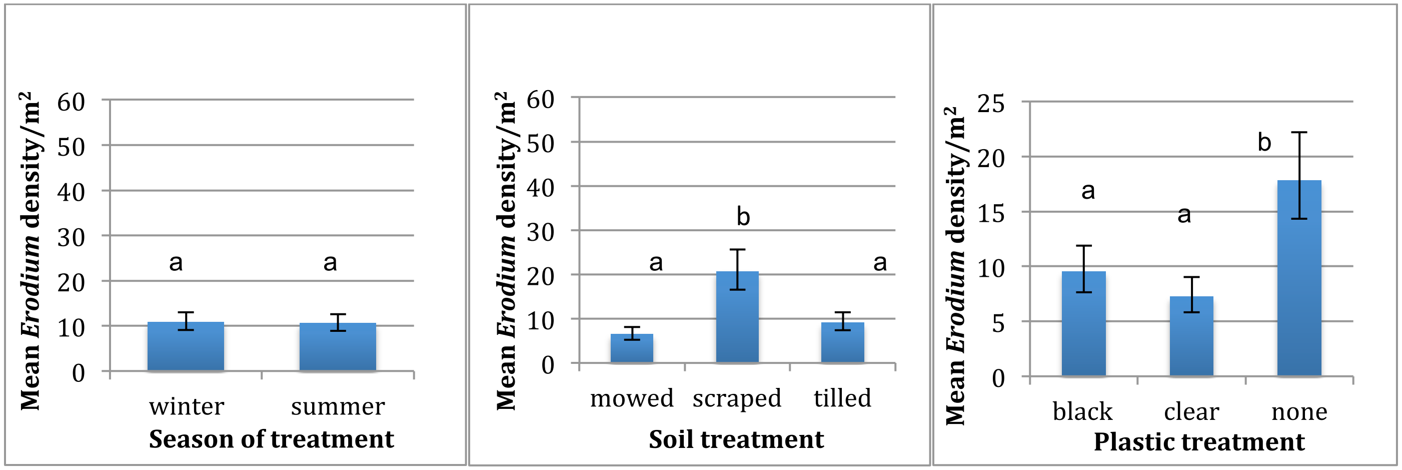
Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	7.2509	0.0017*
plastic	2	4.4233	0.0169*
soil treatment*plastic	4	6.4153	0.0003*
season	1	0.0119	0.9134
soil treatment*season	2	4.0423	0.0235*
plastic*season	2	1.3669	0.2641
soil treatment*plastic*season	4	7.0237	0.0001*
block	3	0.1167	0.9499
soil treatment*block	6	0.4777	0.8216
plastic*block	6	0.8612	0.5301
season*block	3	0.4732	0.7024

2010

Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	1.2149	0.3052
plastic	2	10.7049	0.0001*
soil treatment*plastic	4	3.9358	0.0074*
season	1	1.2866	0.2620
soil treatment*season	2	1.7472	0.1845
plastic*season	2	4.1261	0.0218*
soil treatment*plastic*season	4	4.9394	0.0019*
block	3	1.0098	0.3961
soil treatment*block	6	0.7996	0.575
plastic*block	6	0.5901	0.7365
season*block	3	0.9382	0.4296

Figure 2-5. Mean density of *E. cicutarium* for each whole plot factor in 2009 and 2010.

2009



2010

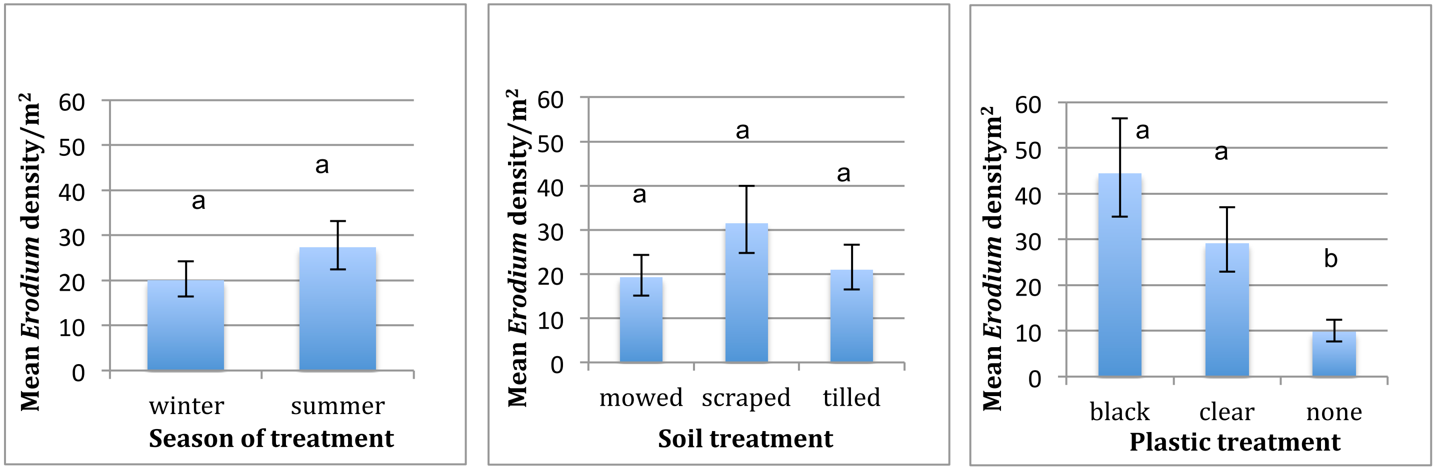


Table 2-7. ANOVA results for mean cover of *Erodium cicutarium*, 2009 and 2010

2009

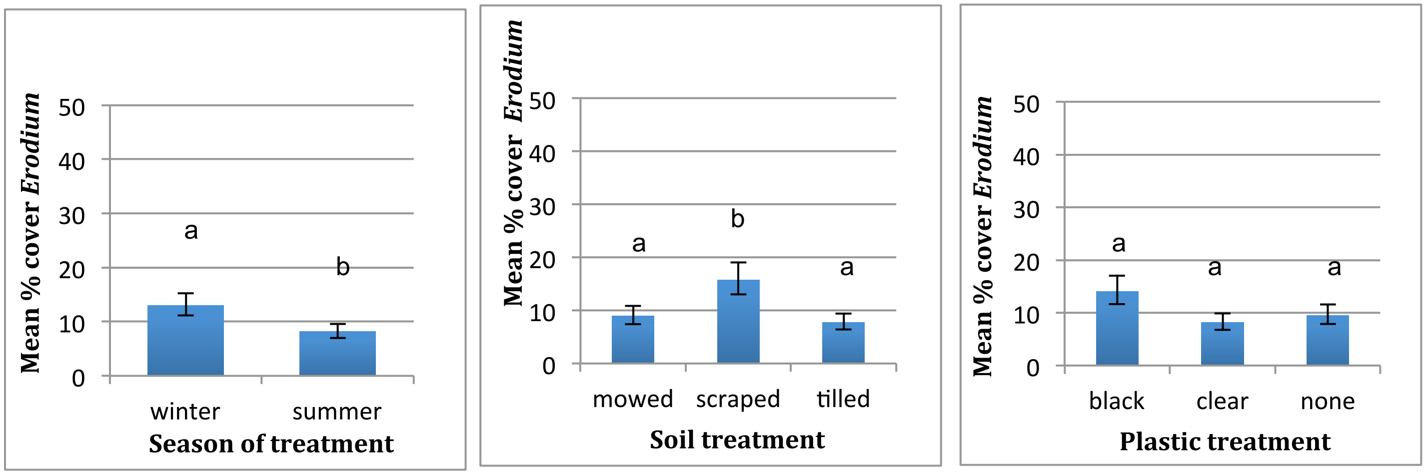
Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	3.8565	0.0276*
plastic	2	2.1532	0.1265
soil treatment*plastic	4	2.4563	0.0573
season	1	4.5135	0.0385*
soil treatment*season	2	0.4141	0.6631
plastic*season	2	4.0262	0.0238*
soil treatment*plastic*season	4	8.2662	<.0001*
block	3	1.7670	0.1652
soil treatment*block	6	0.8172	0.562
plastic*block	6	1.0619	0.3984
season*block	3	0.1363	0.9379

2010

Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	0.0527	0.9487
plastic	2	18.0644	<.0001*
soil treatment*plastic	4	3.3606	0.0164*
season	1	11.1888	0.0016*
soil treatment*season	2	2.2117	0.1201
plastic*season	2	4.5012	0.0159*
soil treatment*plastic*season	4	2.8653	0.0325*
block	3	0.7143	0.5481
soil treatment*block	6	0.4818	0.8185
plastic*block	6	0.4864	0.8152
season*block	3	1.1897	0.3239

Figure 2-6. Mean cover of *E. cicutarium* for each whole plot factor in 2009 and 2010

2009



2010

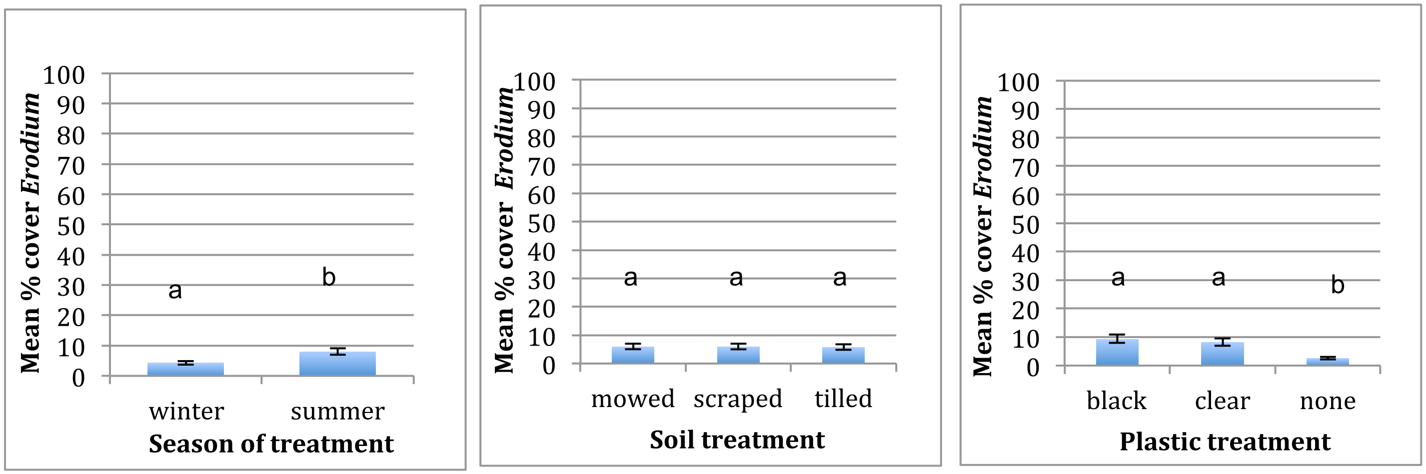


Table 2-8. ANOVA results for mean density of exotic forbs, 2009 and 2010

2009

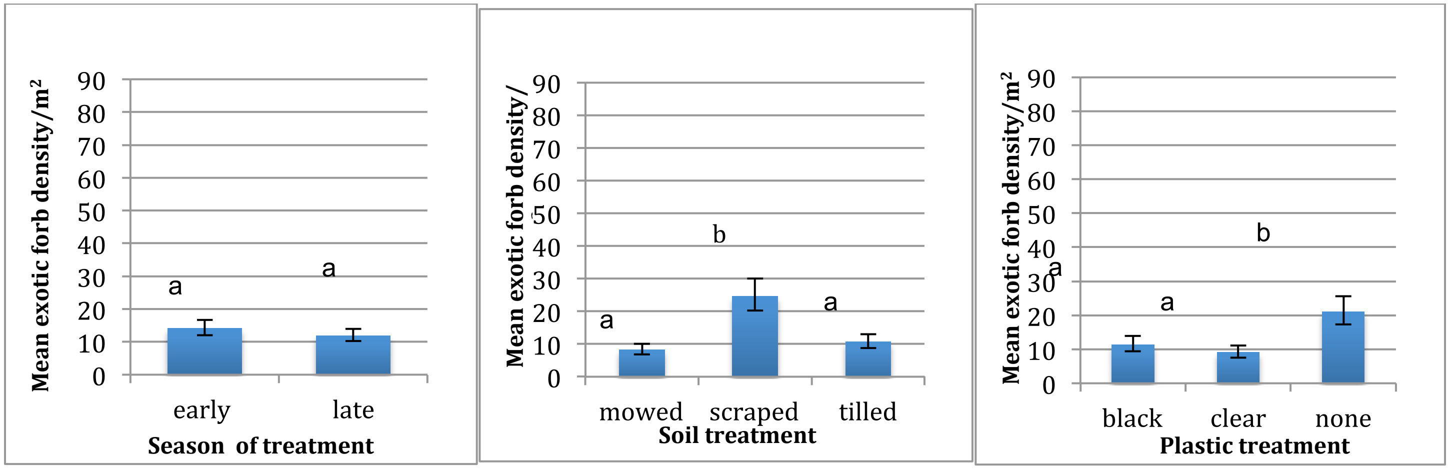
Source	DF	F Ratio	Prob > F
soil treatment	2	8.3020	0.0008*
plastic	2	4.7914	0.0124*
soil treatment*plastic	4	9.1014	<.0001*
season	1	0.5473	0.4628
soil treatment*season	2	4.3413	0.0182*
plastic*season	2	2.2540	0.1153
soil treatment*plastic*season	4	7.4368	<.0001*
block	3	0.0494	0.9853
soil treatment*block	6	0.4003	0.8752
plastic*block	6	0.5156	0.7936
season*block	3	0.8949	0.4507

2010

Source	DF	F Ratio	Prob > F
soil treatment	2	4.0432	0.0234*
plastic	2	15.1062	<.0001*
soil treatment*plastic	4	3.9127	0.0076*
season	1	0.8114	0.3719
soil treatment*season	2	1.6138	0.2091
plastic*season	2	1.1791	0.3158
soil treatment*plastic*season	4	3.3390	0.0167*
block	3	0.2135	0.8866
soil treatment*block	6	1.0201	0.4238
plastic*block	6	0.2852	0.9412
season*block	3	0.2396	0.8683

Figure 2-7. Mean density of all exotic forbs for each whole plot factor in 2009 and 2010

2009



2010

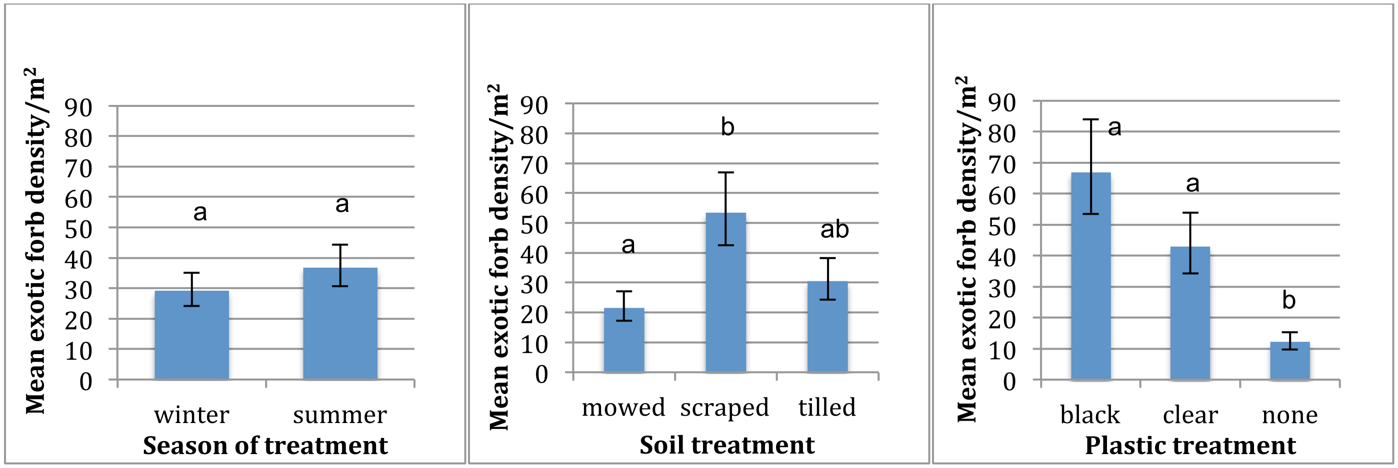


Table 2-9. ANOVA results for mean cover of exotic forbs, 2009 and 2010

2009

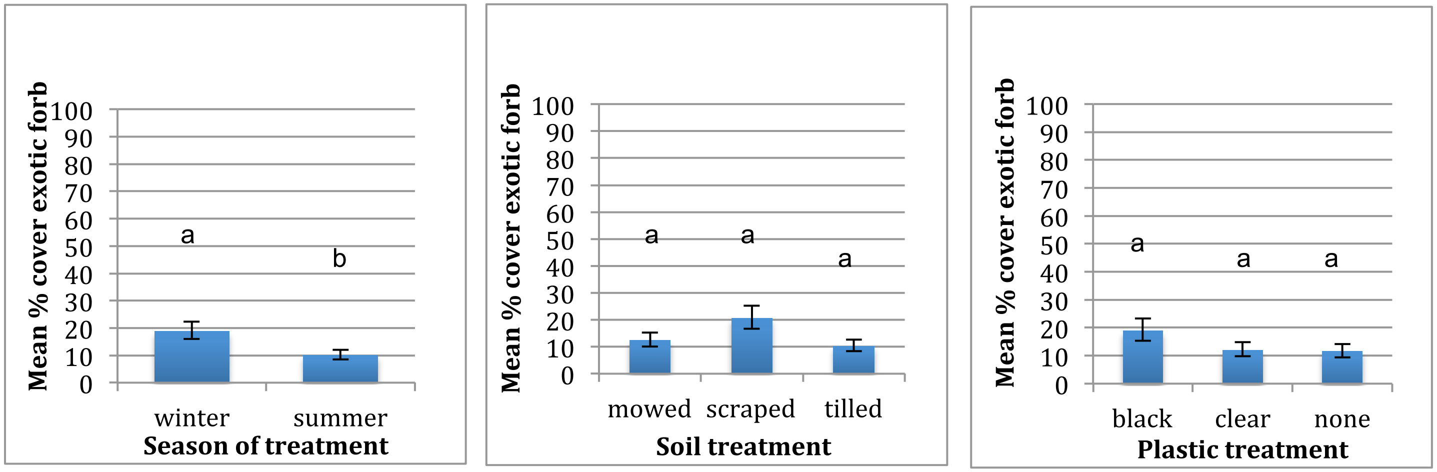
Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	2.9774	0.0598
plastic	2	1.7307	0.1874
soil treatment*plastic	4	2.4715	0.0561
season	1	6.8254	0.0118*
soil treatment*season	2	0.1634	0.8497
plastic*season	2	4.4648	0.0163*
soil treatment*plastic*season	4	5.7365	0.0007*
block	3	0.2746	0.8434
soil treatment*block	6	0.8751	0.5202
plastic*block	6	0.9072	0.4977
season*block	3	1.013	0.3952

2010

Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	0.9817	0.3818
plastic	2	25.1365	<.0001*
soil treatment*plastic	4	2.0171	0.1063
season	1	11.1901	0.0016*
soil treatment*season	2	0.8039	0.4533
plastic*season	2	2.0064	0.1452
soil treatment*plastic*season	4	1.6286	0.1817
block	3	0.3310	0.8029
soil treatment*block	6	0.1859	0.9794
plastic*block	6	0.9078	0.4975
season*block	3	0.9052	0.4457

Figure 2-8. Mean cover of all exotic forbs for each whole plot factor in 2009 and 2010

2009



2010

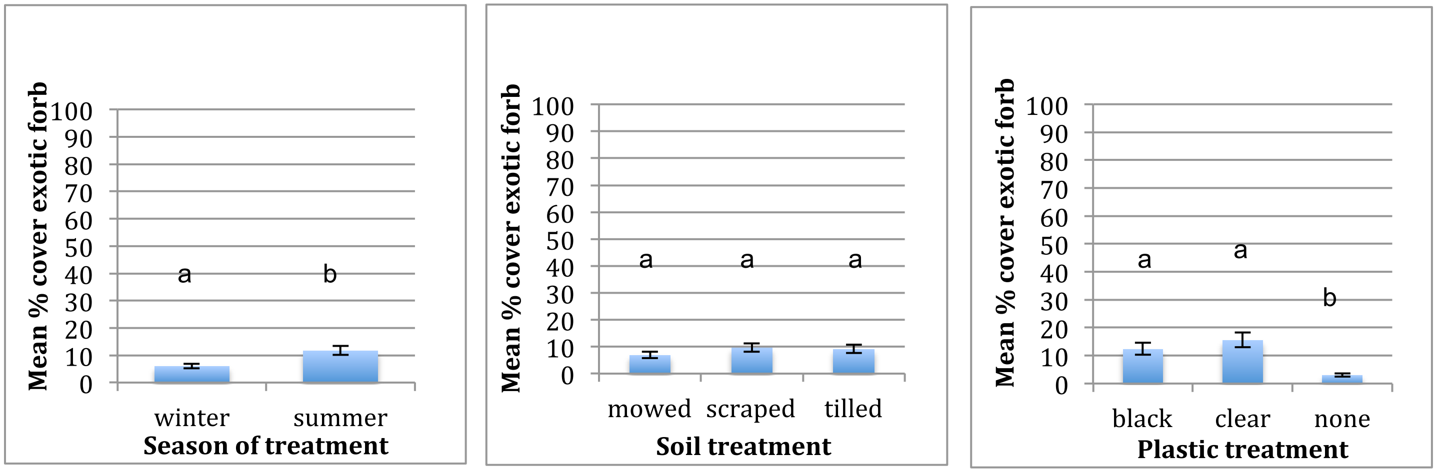


Table 2-10. ANOVA results for mean density of native forbs, 2009 and 2010.

2009

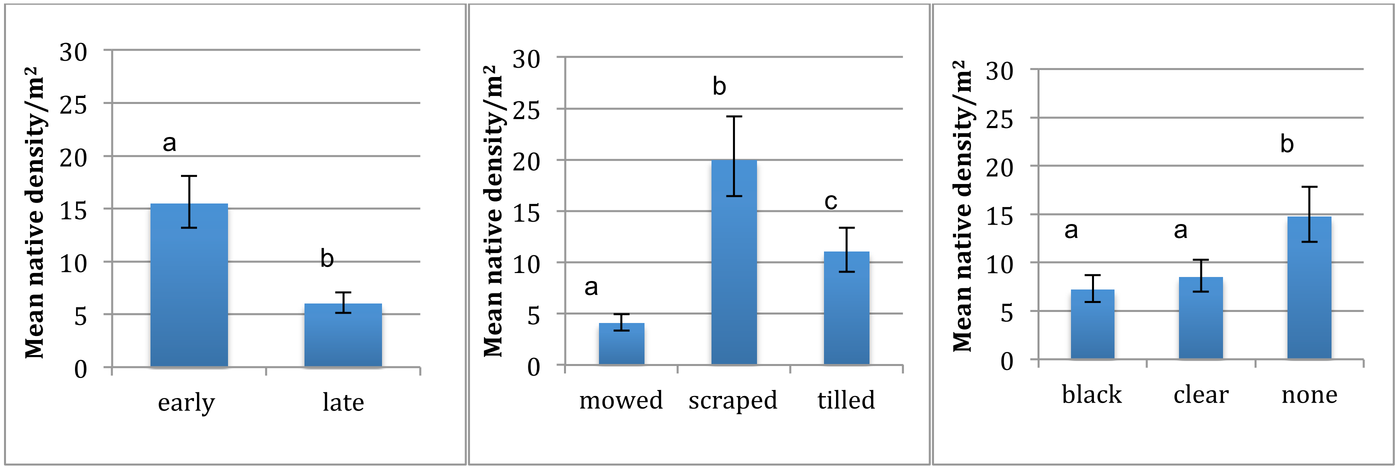
Source	DF	F Ratio	Prob > F
soil treatment	2	17.2311	<.0001*
plastic	2	3.7611	0.0299*
soil treatment*plastic	4	10.1082	<.0001*
season	1	17.7938	0.0001*
soil treatment*season	2	4.2343	0.0199*
plastic*season	2	9.1882	0.0004*
soil treatment*plastic*season	4	2.6761	0.0421*
block	3	1.5021	0.2251
soil treatment*block	6	0.3372	0.9138
plastic*block	6	0.2281	0.9656
season*block	3	0.0726	0.9744

2010

Source	DF	F Ratio	Prob > F
soil treatment	2	20.7351	<.0001*
plastic	2	6.1688	0.0040*
soil treatment*plastic	4	11.8228	<.0001*
season	1	1.9707	0.1664
soil treatment*season	2	0.3445	0.7102
plastic*season	2	8.0526	0.0009*
soil treatment*plastic*season	4	0.8725	0.4869
block	3	5.7330	0.0018*
block*plastic	6	0.1407	0.9898
block*season	3	0.6440	0.5918
block*soil treatment	6	0.6939	0.6560

Figure 2-9. Mean density of native forbs for each whole plot factor in 2009 and 2010

2009



2010

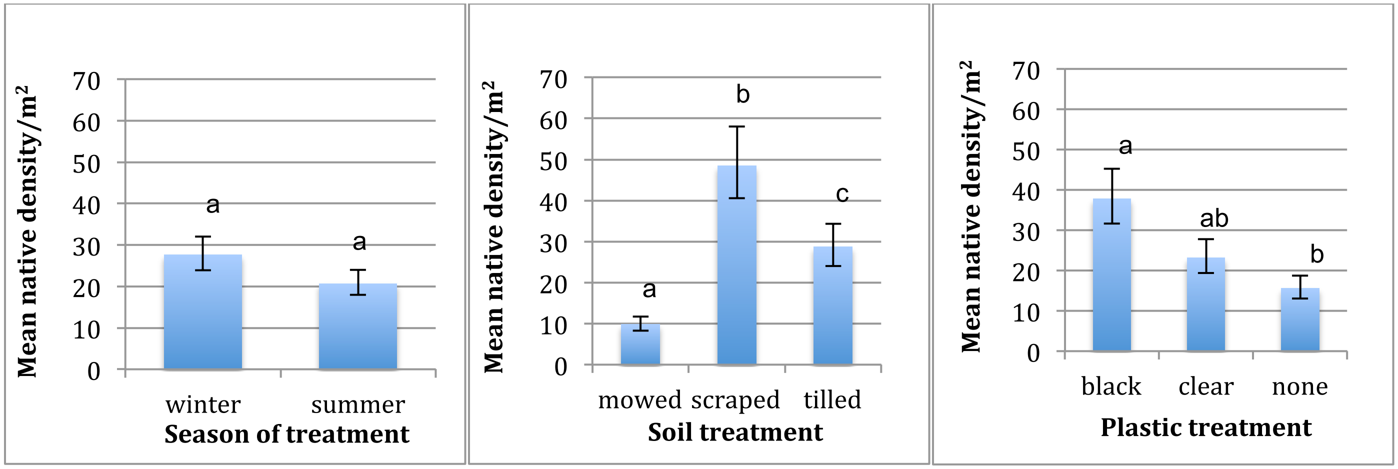


Table 2-11. ANOVA results for mean cover of native forbs, 2009 and 2010

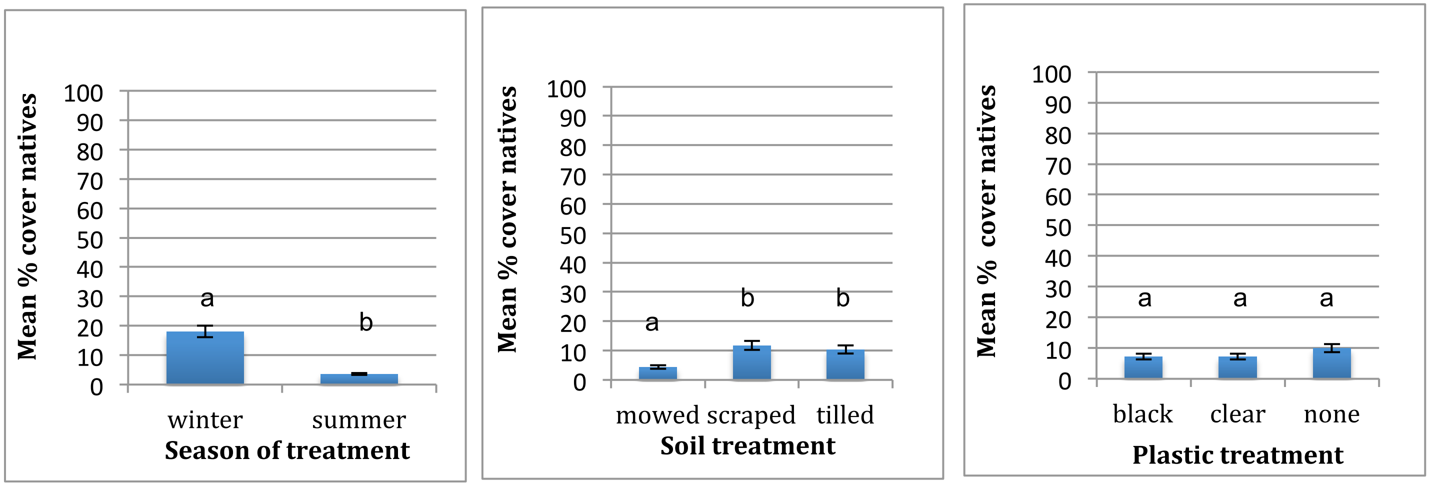
2009	**DF**	**F Ratio**	**Prob > F**
Source			
soil treatment	2	16.3438	<.0001*
plastic	2	1.8952	0.1607
soil treatment*plastic	4	12.4541	<.0001*
season	1	110.0387	<.0001*
soil treatment*season	2	1.3524	0.2677
plastic*season	2	40.7733	<.0001*
soil treatment*plastic*season	4	0.2436	0.9122
block	3	6.4105	0.0009*
soil treatment*block	6	1.1481	0.3552
plastic*block	6	0.8749	0.5229
season*block	3	0.4807	0.6978

2010

Source	**DF**	**F Ratio**	**Prob > F**
soil treatment	2	20.3221	<.0001*
plastic	2	14.4916	<.0001*
soil treatment*plastic	4	10.2105	<.0001*
season	1	0.8119	0.3719
soil treatment*season	2	0.6268	0.5384
plastic*season	2	1.9038	0.1596
soil treatment*plastic*season	4	0.1789	0.9483
block	3	4.6294	0.0062*
soil treatment*block	6	1.2346	0.3126
plastic*block	6	0.4368	0.8492
season*block	3	0.4508	0.7184

Figure 2-10. Mean cover of native forbs for each whole plot factor in 2009 and 2010

2009



2010

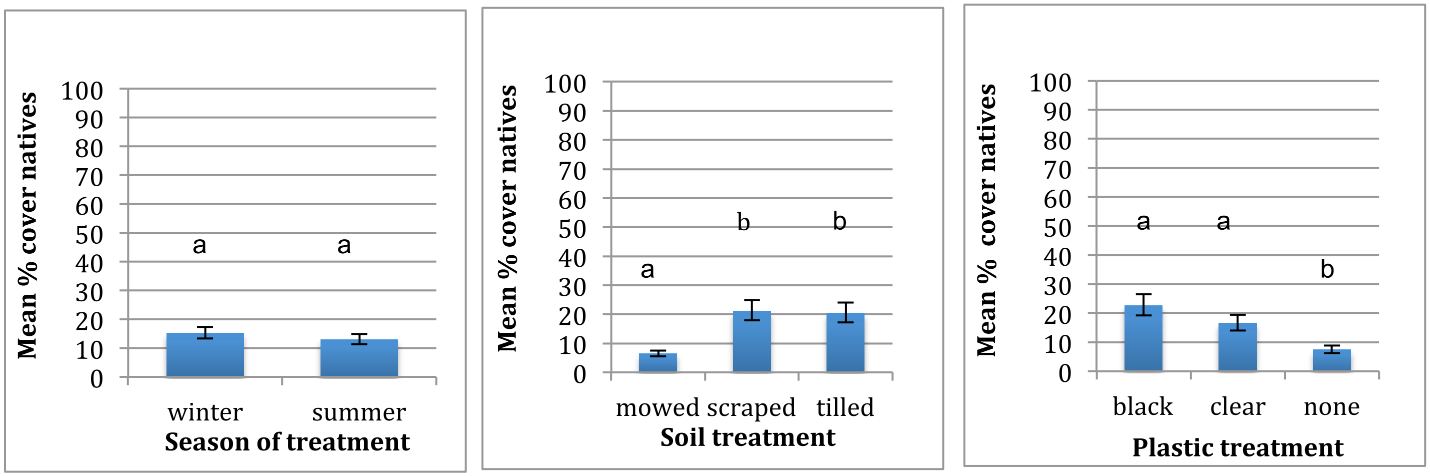


Figure 2-11. Native forb density and percent cover in seeded vs. unseeded subplots, (averaged for tilled and scraped treatments with both summer and winter solarization).

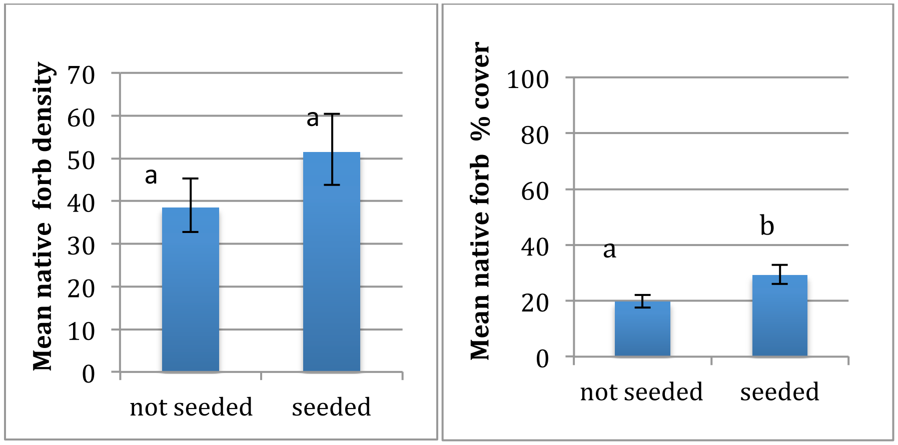
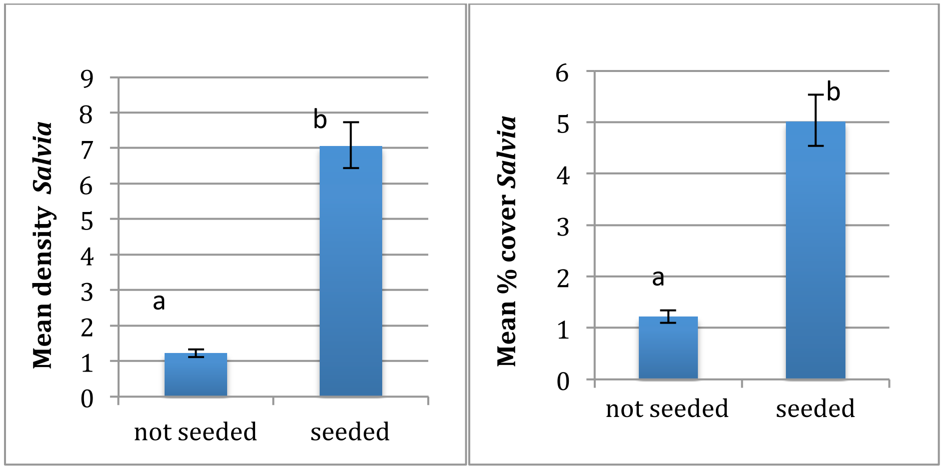


Figure 2-12. *Salvia columbariae* density and percent cover in seeded vs. unseeded subplots



Chapter 3

Reducing *Erodium* competition through chemical methods

Abstract

Five herbicides -- 2 broadleaf-specific, 2 grass-specific and one broad-spectrum -- were tested at varying concentrations. The grass-specific herbicides were tested because *Erodium* species are susceptible to the ACC-ase inhibition that usually does not affect other dicots. Broad-leaf selective chemical triclopyr was the only herbicide that provided season-long control of *Erodium* species with a single application across sites and years. However, this herbicide will have activity on native shrubs and forbs, so careful application will be required in CSS stands and restoration sites. The broad-spectrum herbicide glyphosate was effective at one site where vegetation was dense, but not at the second site where the first herbicide application opened bare ground for germination of a second cohort of *Erodium*. A single label-rate application of any of the grass-specific herbicides did not control *Erodium* species. Rates of the ACCase-inhibitor fluazifop higher than those allowed by the label controlled *Erodium* at one site. The other site appeared to have a second cohort of *Erodium* that germinated after application in both the fluazifop and glyphosate plots. In some sites, multiple applications of fluazifop during the growing season that are within rates allowed by the label might have reduced *Erodium* enough to allow native shrubs to establish. Future studies should consider multiple label rate applications of fluazifop for *Erodium* control in CSS communities.

Introduction

Exotic invasive species often displace native species, reduce diversity of native plant communities, and inhibit wildland restoration efforts (Corbin and D'Antonio 2012, D'Antonio and Vitousek 1992, D'Antonio and Meyerson 2002, Pimentel et al. 2005). Control efforts are expensive (Pimentel et al. 2005) and may be unsuccessful, especially when multiple species of invasive plants are present at a site. Removal of one invader often results in the spread of another, rather than improved establishment and diversity of native species (Allen et al. 2005, Cox and Allen 2008).

A hierarchy of invasive species complicates the establishment of native plants in the coastal sage scrub (CSS) plant community of Southern California. Invasive *Erodium* species have been in California for over 200 years (Mensing and Byrne 1998) and are widely distributed. They often occur in a matrix with non-native Mediterranean grasses, the primary invaders of CSS. However, when the grasses are removed by fire or herbicide *Erodium* spp. will form a dense carpet that may prevent the establishment of native shrubs and forbs (Allen et al. 2005; Cox and Allen 2008, 2011). Studies in other plant communities have documented negative effects of *Erodium* species on native plants. Gordon and Rice (1993, 2000) found that *Erodium botrys* reduced the establishment and growth of a native tree species, and Schutzenhofer and Valone (2006) found that *Erodium cicutarium* decreased the diversity of herbaceous desert annuals.

Control of *Erodium* spp., even temporarily for the purpose of allowing shrubs to establish, can be difficult. Since *Erodium* occurs in high densities (Talbot et al. 1939, Cox and Allen 2008), hand removal is not possible, and its rosette growth form makes mowing an ineffective treatment. Herbicide application is one method that could be used on a wide scale; however, broadleaf herbicides effective against *Erodium* species will likely also damage or kill the native forbs and shrubs that land managers are trying to establish on site. An alternative herbicide specific to *Erodium* that did not affect other dicotyledonous species was discovered in experiments to control weedy grasses. Studies in Australia showed that some *Erodium* species (including *E. cicutarium* and *E. moschatum,* species common in California) are susceptible to haloxyfop, a grass selective herbicide that inhibits lipid synthesis (Christopher and Holtum 1998, 2000). Haloxyfop is not labeled for use in the U.S. However, a study in the Sonoran desert found that when a related herbicide, fluazifop, was applied for grass control it also controlled *E. cicutarium* (Steers and Allen 2010). Fluazifop may provide an excellent management option in plant communities that have been invaded by *Erodium* spp., particularly in communities like CSS in which the dominant invaders are exotic grasses, and the native species are primarily dicots resistant to the lipid synthesis-inhibiting mode of action.

The goals of this experiment were to determine 1) the rates at which fluazifop controlled *Erodium* in two field sites, 2) if fluazifop was equally effective on two different species of *Erodium*, 3) how fluazifop compared to other commonly used herbicides with different modes of actions to control *Erodium* species, and 4) how other species in the plant community (in these two field sites mostly exotics) responded to the herbicides used.

Methods

The study was conducted over two seasons at two highly disturbed former CSS sites, one in central San Diego County, California and one in southern San Diego County. The area has a Mediterranean climate, so plant growth occurs during the cool, wet winter and spring seasons. Both sites were historically used for ranching and portions of both sites burned in wildfires in 2003.

The first site was Barnett Ranch Open Space Reserve (BROR), south of the town of Ramona. The site is located at an elevation of approximately 430 m on a south-facing slope. The plant community is disturbed Diegan coastal sage scrub and non-native grassland. The research area is dominated by exotic species, primarily *Erodium botrys* (broadleaf filaree) and *Bromus rubens* (red brome). Average annual rainfall is 420 mm. Precipitation at the site for the years of the study was 302 mm for the 2008-2009 growing season and 453 mm for the 2009-2010 growing season.

The southern site was Rancho Jamul Ecological Reserve (RJER), located on level ground at approximately 305 m elevation. The surrounding plant community is classified as non-native grassland. *B. rubens* and *Erodium cicutarium* (redstem filaree) are the dominants. Several other species, mostly invasive species including *Erodium moschatum* (white-stemmed filaree) and *E. botrys*, *Vulpia myruos*, *Centaurea melitensis, Brassica geniculata, Raphanus sativa* and *Amsinckia menziesii* make up the major proportion of the plant community at this site. Average annual rainfall is 305 mm. Precipitation at RJER was 218 mm for 2008-2008 and 297 mm for the 2009-2010 water year.

The experimental design was a randomized complete block with four replications. The plots were 1.8 m x 6.1 m (6 ft x 20 ft). Five herbicides (2 grass-selective, 2 broadleaf-selective and a broad spectrum) were tested. Triclopyr and aminopyralid, both plant growth regulators that affect broadleaf species of plants, and glyphosate, an amino acid synthesis inhibitor effective on both monocots and dicots, were tested at both the high and low label rates. Fluazifop and clethodim, both Acetyl CoA Carboxylase (ACCase) inhibitors that are generally selective for grasses but not most broadleaf weeds, were tested at five and three rates, respectively. The resulting 15 treatments are listed in Table 3- 1. Some of these rates were tested at rates higher than label recommendations to better determine the chosen ACCase-inhibitor's efficacy on *Erodium* species. The 0.56 kg/ha rate of clethodim and the 0.63 kg/ha, and 1.26 kg/ha rate of fluazifop are above the recommended rates for a single application, but are within the total quantity allowed for multiple treatments in one season. Herbicides were applied under a special use permit for research.

Herbicide was applied in a 1.8 m (6 foot) swath using a CO_2 backpack sprayer with a handheld boom equipped with five 8002 VS nozzles. Applications took place in late January or early February in 2009 and 2010 when the *Erodium* and *Bromus* species that dominate each site were well established, but had not begun to bolt or flower.

Visual herbicide injury ratings were made at 2, 4 and 8 weeks post-spray. Separate ratings were given to both the dominant *Erodium* species at the site and the dominant non-native grass species. Plant injury was rated on a scale of 0 to 10, where 0 = no apparent damage to plants and 10 = all plants dead. Ratings 1-9 estimated the approximate percent of dead or damaged vegetation for each species. A rating of 2 would indicate that only 20% of the plants or roughly 20% of a portion of most plants displayed tissue damage. Ratings were conducted without knowing which treatment plot was being rated, and the control plot was not set to 0 by default.

Vegetation composition was measured by visually estimating foliar cover in a 1.0 m x 0.5 m quadrat. Frames were placed in the center of each plot, and percent cover of individual plant species, bare ground and litter were recorded. Quadrat location was marked so that quadrat locations could be relocated and data taken in the same location for both years of study, with the exception of 1 plot that had an anthill in the sampling location the second year of sampling. Plant density for each species present was measured post-spray at the same time and in the same quadrat as the percent cover estimates.

Both percent cover data and density data were log transformed. Injury rating data from BROR was arcsine transformed. Transformation did not improve normality of data from RJER, except the 2010 reading at the 8-week interval which was log transformed. This reading had several instances of missing data as will be discussed below.

Since the treatment plots at RJER had three species of *Erodium* present, some species were combined or excluded from analysis. *E. cicutarium* was the most common and evenly distributed. *E. moschatum* occurred intermixed with *E. cicutarium* but at much lower percent cover. *E. botrys* occurred in distinct patches and primarily in one block within the plots. *Erodium* percent cover and density statistics were evaluated for all *Erodium* species together and then for two smaller *Erodium* species (*cicutarium* and *moschatum*) together since they are hard to distinguish and from a practical perspective they would likely be managed together. In 2010, one control plot at RJER was excluded from analysis because it had 0% cover of *Erodium*.

The injury ratings were performed by assessing *E. cicutarium* and *E. moschatum* together. *E. botrys* was not included in injury rating at RJER because its distribution in the plots was patchy and limited primarily to one block. Plots in this block with greater than 80% coverage of *E. botrys* and low to no cover of the other species of *Erodium*, were excluded from injury rating analysis. This was three plots in 2009 and two in 2010.

All data was analyzed using ANOVA, and Tukey's HSD to assess differences between treatments. Reported differences were tested for significance at $p < 0.05$. Analysis was performed on data for *Erodium* species, *Bromus* species, all non-native grass as a functional group, and all non-*Erodium* forbs as a functional group. Data were analyzed for each year and site separately.

Results and Discussion

Barnett Ranch Open Space Reserve

E. botrys herbicide response at BROR may bedivided into two primary groups, those that provided good season-long control of *Erodium* and those that generally provided poor control (Table 3- 2). Analysis of both percent cover and density data was statistically nearly identical across years.

The high rates (2.24 kg/ha) of triclopyr or glyphosate had the lowest mean percent cover and densities of *E. botrys* during both the 2009 and 2010 growing seasons. In 2009, the lower (1.12 kg/ha) rates of either glyphosate or triclopyr as well as the high (0.12 kg/ha) rate of aminopyralid caused similar decreases in percent cover and density of *E. botrys* as the high rates of triclopyr and glyphosate. In 2010, the glyphosate 1.12 kg/ha treatment was not as effective as either triclopyr treatment or the high rate of glyphosate. Eight weeks after application, regrowth and some flowering was evident in some of the glyphosate 1.12 kg/ha plots though plants were small and percent cover was less than 20%.

The grass-specific herbicides clethodim and fluazifop-p-butyl did not reduce the percent cover or density of *E. botrys* from the control at any rate of application. The injury ratings for *E. botrys* (Table 3- 2) generally agree with the density and percent cover data, but changes in the injury level from time of herbicide application to vegetation sampling are documented, and there were differences in injury between the two treatment years. At the 2-week assessment in 2009, *E. botrys* had the most visual injury in both glyphosate treatments and the high aminopyralid treatment. However, by the 8-week assessment all triclopyr and glyphosate treatments had mean injury ratings between 9 and 10 (indicating nearly complete destruction of the plants) while aminopyralid was significantly less at 7.8. The grass-specific herbicides had mean injury ratings of 5 or less, with the exception of the highest fluazifop treatment. In 2009, fluazifop 1.26 kg/ha had a mean damage rating of 7.8 at the 4-week assessment and 6.8 at the 8-week assessment. However, in 2010 the ratings for fluazifop 1.26 kg/ha were only 5 at the 4-week assessment and 2 at the 8-week assessment.

E. botrys was not among the species tested by Christopher and Holtum (2000) for susceptibility to haloxyfop acid; however, one of the six species of *Erodium* they tested was found to be resistant to the chemical, and 30% of the plants survived treatment. It is possible that *E. botrys* also is resistant to lipid synthesis inhibitors. Although the mechanism of this resistance is unknown in *Erodium*, some species of grass resist lipid synthesis inhibitors through quick metabolism of herbicides to the inactive form (Shimabukuro et al. 1979). It is possible that *E. botrys* is more resistant to lipid synthesis inhibitors than other species of *Erodium* or that fluazifop is less effective at controlling *Erodium* species than haloxyfop.

For the non-native grasses, only the glyphosate treatments and the high rates of clethodim and fluazifop had statistically lower percent covers and densities than the control plots in 2009 (Table 3- 3). The injury ratings for exotic grass at BROR in 2009 (Table 3- 3) support these results. At the 2-week assessment, the grass specific herbicide treatments showed more damage than the control plots; however, none of them were rated higher than a 5 (approximately 50% injury to the plants). The glyphosate treatments were the only plots with ratings above 5, at 9.3 and 9.5. At the 4-week injury assessment only the 1.26 kg/ha fluazifop treatment had as much injury to the grasses as the glyphosate treatments. However, by 8 weeks, the 0.63 kg/ha and 0.32 kg/ha fluazifop treatments showed as much damage to exotic grasses as the glyphosate and higher rate fluazifop treatments.

The grass herbicides were generally more effective in control of exotic grass in 2010. All ACCase treatments, with the exception of the fluazifop 0.11 kg/ha treatment, reduced the cover of grass significantly from the control plots. Density results were less conclusive due to higher variability in the density counts and lower overall plot densities in general than the preceding year. The highest level of clethodim significantly reduced the grass density as did the 0.21 kg/ha, 0.32 kg/ha and 1.26 kg/ha treatments with fluazifop.

As with the *Erodium* results, the glyphosate treatments provided less effective season-long control for the grass in 2010 than in 2009 as assessed by the damage ratings. The 1.12 kg/ha rate of glyphosate provided less reduction of percent cover compared to the 2.24 kg/ha rate of glyphosate and the ACCase treatments. At the 2-week injury rating for 2010, glyphosate 2.24 kg/ha had the highest injury rating with a mean of 10, however the 0.28 kg/ha and 0.56 kg/ha rates of clethodim and the 0.32 kg/ha rates of fluazifop all had similar injury ratings with a mean of 6.5 or greater. By the 4-week assessment all of the ACCase treatment means were in the most effective group, but the glyphosate 1.12 kg/ha injury had decreased to 5.8, statistically lower than the most damaged treatments. At 8 weeks the 0.21 kg/ha, 0.32 kg/ha, 0.63 kg/ha and 1.26 kg/ha fluazifop treatments all had damage ratings of 10.

The only other category measured with significant percent cover in the plots at BROR was litter. The glyphosate treatment plots where both *Erodium* and non-native grass where controlled had almost 100 % cover of litter. BROR had very low cover of exotic forbs other than *Erodium* and native cover was also negligible. The lack of native cover in the plots is likely due to shading by the heavy litter cover (Xiong and Nilsson 1999, Jutila and Grace 2002). Adjacent experimental plots at BROR that had been raked free of litter had a much higher percentage of native forbs (unpublished data).

Rancho Jamul Ecological Reserve

In 2009, both triclopyr treatments and the fluazifop 1.26 kg/ha treatment provided the most reduction in percent cover of *Erodium* (Table 3- 4). However, the triclopyr 2.24 kg/ha treatment was the only treatment with statistically lower density of *Erodium* species than the control plots. This is likely due to high variability in density of *Erodium* between plots. Mean densities in the control plots are in the middle range of all the plot densities, so those means were not significantly different from the majority of treatments, but there were some differences between treatments. The within-label rates of fluazifop had higher densities of *Erodium* than the fluazifop 1.26 kg/ha, glyphosate 2.24 kg/ha and both triclopyr treatments. This was likely because the lower fluazifop rates killed the exotic grasses in the plots allowing additional *Erodium* plants to germinate.

In 2010, the pattern was similar, but more distinct (Table 3- 4). Both triclopyr treatments and fluazifop 1.26 kg/ha were again the only treatments that reduced the percent cover of *Erodium* species from the control plots. The 2010 density results showed the same pattern. The 0.63 kg/ha rate of fluazifop and both rates of glyphosate had statistically higher percent cover and density of *Erodium* than the most effective treatments. At this site, the aminopyralid 0.12 kg/ha rate did not provide any statistically significant reduction in percent cover or density of *Erodium* species.

When *E. cicutarium* and *E. moschatum* data were analyzed without *E. botrys* data (Table 3- 5), the results are nearly the same – both triclopyr treatments and the fluazifop 1.26 kg/ha per acre treatments provided the best control for reduction of both percent cover and density. The injury ratings at RJER were performed by assessing *E. cicutarium* and *E. moschatum* together (Table 3- 5). In 2009, the clethodim treatments did not display greater injury to the control plots at any time. The 0.63 kg/ha and 1.26 kg/ha fluazifop rates, the glyphosate treatments and the triclopyr treatments displayed the most injury across all three assessment times. The lowest three application rates of the fluazifop and the aminopyralid treatments had intermediate injury ratings at 2 weeks; however by the 8-week assessment the label-rate fluazifop treatments were no longer different from the control. In 2010, the pattern was similar except that the label rates of fluazifop were not different than control at any point in time and the 0.63 kg/ha application of fluazifop displayed less damage than the most effective group of herbicides at the 4-week assessment. At the 2010 8-week assessment the fluazifop 1.26 kg/ha and both triclopyr treatments had mean ratings of 9 or above. However, none of the treatments were statistically more injured than the control plots. This is likely because several of the control plots had missing values for the 8-week rating period as there was no live *Erodium* in the plots. *E. cicutarium* was noted as sparse or dying during earlier sampling intervals and by week 8 seemed to have disappeared. One control plot had a high cover of *Centaurea melitensis* and the other of *Vulpia myuros*.

Fluazifop did provide control of *Erodium* species at RJER at the highest application rate. This rate is above the rates allowed by the label for a single application broadcast spray. Steers and Allen (2010) used a volumetric spot spraying rate of 0.57 kg/ha (somewhat lower that my second highest rate of 0.63 kg/ha, but also above label for a single application) when they documented control of *E. cicutarium* in Sonoran desert plots. Controlling *Erodium* species with multiple applications of fluazifop at lower rates should be tested as it may still be useful in restoration projects to spray over native forbs and shrubs.

Glyphosate and aminopyralid provided less control of *Erodium* species at RJER than *E. botrys* at BROR. *Erodium* species may have multiple cohorts with different germination cues (Rice 1987), and may germinate if conditions allow after initial herbicide application. With higher rainfall, BROR has denser and taller vegetation than RJER. As mentioned above, this caused a significant litter layer in some of the BROR plots that may have prevented new germination or emergence of *Erodium* plants after herbicide application. Very small (~4 cm tall) but flowering *Erodium* plants that appeared to be a second cohort of germination were noted in RJER herbicide plots between 8 weeks after herbicide application and may account for the lack of season long control by glyphosate at RJER. Glyphosate binds to soil particles and becomes inactive after application, although some studies have shown soil activity 10-12 days after application (Sprankle 1975, Thompson et al. 2000), while triclopyr had activity in the soil 39-69 days following application (Thompson et al. 2000). Aminopyralid has residual soil activity (Mikkelson et al. 2011, Ferrell et al. 2006), but was less effective at controlling the *Erodium* than the triclopyr.

The non-native grass community at RJER had higher densities and cover of non-brome grass species than BROR, so data were analyzed for *Bromus* species (*B. rubens, B. diandrus*), *V. myuros,* and all other non-native grass species. As expected, the grass-specific herbicides and the glyphosate treatments reduced the cover and density of *Bromus* (Table 3- 6) significantly from the control plots, while the broadleaf-selective herbicides did not. The pattern differed slightly when all species of non-native grass were analyzed together (Table 3- 7). In 2009, the non-native grasses followed a pattern similar to the *Bromus* species, however the exotic grass density for the lowest rate of clethodim and two lowest rates of fluazifop were not significantly lower than in the control plots. In 2010, percent cover and density across all levels of the fluazifop treatments were not statistically different than the control plots. The two highest rates of clethodim had lower percent cover and density than the control.

The difference between the results for *Bromus* species and all non-native grass is likely due to the presence of *Vulpia myuros* in the fluazifop plots. *Vulpia* was not present in sufficient quantities to provide meaningful statistical results when analyzed independently, but several plants were observed to be undamaged by herbicide in the fluazifop-treated plots. A related species, *V. bromoides,* is resistant to ACCase inhibiting herbicides (Yu et al. 2004) so land managers may need to monitor *Vulpia* populations where management plans include frequent or long-term use of herbicides with this mode of action.

Conclusions

If season long control of *Erodium* is the goal at a site, triclopyr can be recommended as it provided the best control across sites and years. The long residual soil activity of triclopyr should be considered if seeding is part of the restoration plan following herbicide application, by delaying seeding until the following growing season. However, triclopyr is also active on shrubs and forbs that dominate CSS, so it would not be a good choice for broadcast spraying in sites where native species are present. Glyphosate also provided excellent control at one of our sites, but was less effective at the other. The site where it was less effective had much smaller, shorter plants that disarticulated quickly once controlled. This left more bare ground for a second wave of germination within the same growing season. In this and similar plant communities, multiple applications of glyphosate within one growing season may be necessary to control *Erodium* species. However, since glyphosate has a shorter residual time in the soil, it might be a more desirable choice prior to seeding natives.

The within-label application rates for a single application of fluazifop (0.11 kg/ha, 0.21 kg/ha and 0.32 kg/ha) and clethodim (0.56 kg/ha) did not provide season-long control of *Erodium*, although it did control grasses. However, the label does allow for multiple applications with a maximum up to 1.26 kg/ha in a season. Thus, multiple applications at restoration sites during the growing season might control later-germinating cohorts of *Erodium* to improve establishment of native shrubs and seeds and should be investigated further. Although many land managers often do not have time to visit weed management sites multiple times, the investment of extra time and money at specific restoration sites could help native species establish and protect investments made in native seed and other restoration strategies.

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Tables and Figures

Table 3-1. Herbicide treatments applied. * indicates above recommended rates for a single application, but within the total quantity allowed for multiple treatments in one season.

Metric units	English units	Specificity	Mode of action
Control	Control		
aminopyralid 0.05 kg/ha	aminopyralid 3 oz/acre	Broadleaf weeds	Plant growth regulator/Auxin mimic
aminopyralid 0.12 kg/ha	aminopyralid 7 oz/acre	Broadleaf weeds	Plant growth regulator/Auxin mimic
clethodim 0.14 kg/ha	clethodim 17 oz/acre	Grass	ACCase inhibitor
clethodim 0.28 kg/ha	clethodim 34 oz/acre	Grass	ACCase inhibitor
clethodim 0.56 kg/ha*	clethodim 68 oz/acre	Grass	ACCase inhibitor
fluazifop 0.11 kg/ha	fluazifop 06 oz/acre	Grass	ACCase inhibitor
fluazifop 0.21 kg/ha	fluazifop 12 oz/acre	Grass	ACCase inhibitor
fluazifop 0.32 kg/ha	fluazifop 18 oz/acre	Grass	ACCase inhibitor
fluazifop 0.63 kg/ha*	fluazifop 36 oz/acre	Grass	ACCase inhibitor
fluazifop 1.26 kg/ha*	fluazifop 72 oz/acre	Grass	ACCase inhibitor
glyphosate 1.12 kg/ha	glyphosate 1 qt/acre	Broad spectrum	Amino acid synthesis inhibitor
glyphosate 2.24 kg/ha	glyphosate 2 qt/acre	Broad spectrum	Amino acid synthesis inhibitor
triclopyr 1.12 kg/ha	triclopyr 1 qt/acre	Broadleaf	Plant growth regulator/Auxin mimic
triclopyr 2.24 kg/ha	triclopyr 2 qt/acre	Broadleaf	Plant growth regulator/Auxin mimic

Table 3-2: Percent cover, density and injury rating results for *Erodium botrys* Barnett Ranch Open Space Reserve. Means followed by different letters are significantly different.

Herbicide treatment (rate in kg/ha)	**Percent Cover**		**Density (plants per m^2)**		**2-week injury**		**4-week injury**		**8-week injury**	
	2009	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**	**2009**	**2010**
Control	63.8 a	46.0 a	689.0 a	277.5 a	0.0 h	0.3 e	0.3 f	0.3 h	0.0 f	1.5 d
aminopyralid 0.05	64.3 a	37.5 ab	190.5 ab	130.5 a	6.0 cd	8.8 a	5.3 cd	5.8 cd	5.8 cd	7.8 ab
aminopyralid 0.12	13.8 ab	7.5 cd	22.5 bcd	17.5 bc	7.5 abc	8.8 a	7.5 c	7.3 bc	7.8 bc	9.5 a
clethodim 0.14	55.0 ab	65.0 a	311.5 ab	342.0 a	0.8 gh	1.0 cde	1.5 e	0.5 h	0.0 f	1.5 d
clethodim 0.28	64.3 a	66.0 a	244.5 abc	243.5 a	1.5 fg	0.3 e	1.8 e	0.8 gh	0.5 f	1.8 d
clethodim 0.56	78.3 a	60.0 a	376.0 a	330.5 a	1.8 fg	0.8 de	1.5 e	0.8 gh	0.5 ef	2.3 cd
fluazifop 0.11	69.5 a	57.3 a	155.5 a	215.0 a	2.0 fg	1.0 cde	1.3 ef	2.3 fg	0.3 f	0.8 d
fluazifop 0.21	82.8 a	61.5 a	566.5 abc	302.0 a	2.5 efg	2.5 bcd	2.3 e	2.3 fg	0.5 ef	1.3 d
fluazifop 0.32	50.0 a	69.0 a	145.5 a	236.5 a	2.8 ef	3.0 bc	3.3 de	2.5 efg	0.8 ef	1.3 d
fluazifop 0.63	71.0 a	62.8 a	551.5 abc	333.0 a	3.5 def	3.0 bc	5.4 cd	3.5 def	3.0 de	1.8 d
fluazifop 1.26	47.3 ab	73.0 a	236.5 ab	333.0 a	5.0 cde	4.0 b	7.8 bc	5.0 cde	6.8 bc	2.0 cd
glyphosate 1.12	3.6 bc	17.3 bc	15.0 cd	87.0 ab	8.8 ab	7.8 a	9.3 ab	8.4 b	9.8 a	6.0 bc
glyphosate 2.24	0.1 c	0.3 e	0.5 d	3.5 cd	9.0 a	8.8 a	10.0 ab	10.0 a	10.0 a	9.3 a
triclopyr 1.12	3.6 bc	3.6 de	11.5 d	10.0 cd	6.3 c	7.3 a	6.8 c	8.4 b	9.0 ab	7.0 ab
triclopyr 2.24	0.0 c	0.6 e	0.0 d	1.0 d	7.0 bc	8.8 a	9.3 ab	9.8 a	10.0 a	9.3 a

Numbers in a column followed by the same letter do not differ significantly according to Tukey's Honestly Significant Difference test at the 5% level.

Percent cover and density data were transformed using a logarithmic transformation prior to analysis.

Injury rating data were transformed using an arcsine transformation prior to analysis.

Means shown are untransformed.

Table 3-3: Percent cover, density and injury ratings for non-native grass Barnett Ranch Open Space Reserve. Grass species include *Avena barbata, Avena fatua, Bromus diandrus, Bromus hordeaceus, Bromus rubens, Hordeum murinum,* and *Vulpia myuros.* Means followed by different letters are significantly different.

Herbicide treatment (rate in kg/ha)	Percent Cover		Density (plants per m^2)		2-week injury		4-week injury		8-week injury	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Control	58.1 ab	18.2 ab	866.0 a	166.5 a	0.0 d	0.3 d	0.0 e	1.0 ef	0.0 e	2.8 bcd
aminopyralid 0.05	26.2 abcd	38.0 a	444.5 a	169.5 a	1.3 cd	0.0 d	0.8 de	0.8 ef	0.3 e	0.3 d
aminopyralid 0.12	63.6 a	24.1 ab	904.0 a	105.5 ab	1.8 bcd	0.0 d	0.5 de	0.3 f	0.0 e	0.0 d
clethodim 0.14	28.3 abcd	1.9 cde	210.5 abc	34.0 abcd	3.8 bc	5.5 bc	5.3 bc	7.3 bcd	4.8 d	5.5 abcd
clethodim 0.28	8.5 abcde	3.8 cde	99.5 abc	16.0 abcd	3.5 bc	6.5 abc	5.8 bc	7.8 abcd	6.3 cd	7.5 abc
clethodim 0.56	4.2 cde	0.2 e	48.0 abcde	6.5 d	2.8 bc	8.5 ab	7.0 bc	9.0 abc	9.0 abc	9.8 ab
fluazifop 0.11	33.0 abc	9.5 bcd	500.0 a	81.0 abcd	2.0 bc	3.5 cd	4.0 c	7.8 abcd	4.5 d	5.5 abcd
fluazifop 0.21	5.8 bcde	4.0 cde	167.0 abc	10.0 cd	2.3 bc	5.5 bc	3.5 cd	8.5 abc	7.3 bcd	10.0 a
fluazifop 0.32	6.3 bcde	0.6 de	172.0 abcd	8.0 bcd	4.3 bc	8.0 abc	6.0 bc	9.0 abc	9.0 abc	10.0 a
fluazifop 0.63	2.3 de	2.7 cde	20.5 bcde	16.5 abcd	4.8 b	7.0 abc	6.8 bc	8.3 abc	9.3 abc	10.0 a
fluazifop 1.26	5.8 e	0.8 de	0.5 e	8.5 cd	4.3 bc	7.0 abc	8.8 ab	9.3 ab	10.0 a	10.0 a
glyphosate 1.12	2.9 de	6.8 abc	70.5 cde	44.0 abcd	9.3 a	7.8 ab	9.8 a	5.8 cd	9.8 a	4.3 abcd
glyphosate 2.24	0.8 e	1.9 cde	2.0 de	15.5 abcd	9.5 a	10.(a	9.8 a	10.0 a	10.0 a	7.3 abcd
triclopyr 1.12	54.5 a	24.8 ab	628.5 a	125.5 a	1.5 bcd	0.0 d	0.8 de	1.8 ef	0.0 e	0.5 cd
triclopyr 2.24	33.8 abc	21.7 ab	543.5 ab	115.0 abc	1.5 bcd	0.3 d	0.3 e	3.8 de	1.8 e	2.5 cd

Numbers in a column followed by the same letter do not differ significantly according to Tukey's Honestly Significant Difference test at the 5% level.

Percent cover and density data were transformed using a logarithmic transformation prior to analysis.

Injury rating data were transformed using an arcsine transformation prior to analysis.
Means shown are untransformed.

Table 3-4: Percent cover and density of all *Erodium spp*. at Rancho Jamul Ecological Reserve. Means followed by different letters are significantly different.

Herbicide treatment (rate in kg/ha)	all *Erodium* species			
	Percent cover		Density	
	2009	2010	2009	2010
Control	54.3 a	40.0 a	145.5 abcd	342.0 a
aminopyralid 0.05	51.0 a	23.3 a	236.0 abcd	76.0 a
aminopyralid 0.12	27.8 ab	21.0 a	80.0 abcd	85.0 a
clethodim 0.14	65.0 a	24.9 a	328.5 ab	242.0 a
clethodim 0.28	48.8 a	34.1 a	192.5 abcd	302.5 a
clethodim 0.56	63.3 a	47.9 a	473.3 ab	551.0 a
fluazifop 0.11	61.8 a	33.2 a	510.7 a	244.0 a
fluazifop 0.21	56.8 a	17.8 a	568.0 a	472.5 a
fluazifop 0.32	44.3 a	26.6 a	639.0 a	154.0 a
fluazifop 0.63	18.3 abcd	28.2 a	115.0 abcd	288.0 a
fluazifop 1.26	3.1 bcd	1.1 bc	27.5 cde	9.0 b
glyphosate 1.12	16.0 abc	38.6 a	33.0 abcde	309.5 a
glyphosate 2.24	13.4 abcd	9.8 ab	22.5 bcde	68.0 a
triclopyr 1.12	6.4 cd	0.8 bc	28.0 de	9.5 b
triclopyr 2.24	0.3 d	0.0 c	2.0 e	0.0 b

Numbers in a column followed by the same letter do not differ significantly according to Tukey's Honestly Significant Difference test at the 5% level.

Data were transformed using a logarithmic transformation prior to analysis.
Means shown are untransformed.

Table 3-5: Percent cover and density of *Erodium cicutarium* and *E. moschatum* at Rancho Jamul Ecological Reserve. Means followed by different letters are significantly different.

Herbicide treatment (rate in kg/ha)	Percent cover		Density (plants/m2)		2-week injury		4-week injury		8-week injury	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Control	43.1 a	13.3 abcd	130.5 abc	89.3 a	0.0 g	0.0 e	0.0 g	2.5 f	0.0 e	3.5 ab
aminopyralid 0.05	53.7 a	23.3 a	309.3 ab	76.0 ab	4.5 ef	3.3 cde	5.8 cde	6.3 def	5.5 bcd	3.3 ab
aminopyralid 0.12	27.8 abc	21.0 a	80.0 abc	85.0 a	5.0 ef	4.8 bcd	6.6 bcd	2.3 abcd	7.3 abc	5.8 ab
clethodim 0.14	64.3 a	13.9 abcd	324.5 ab	172.5 a	1.0 g	0.8 e	0.8 fg	3.0 def	1.5 de	4.0 ab
clethodim 0.28	48.8 a	33.7 a	192.5 ab	301.5 a	1.0 g	0.5 e	0.5 g	2.8 def	2.3 de	4.3 ab
clethodim 0.56	55.7 a	31.2 a	466.7 ab	316.7 a	0.5 g	2.5 de	0.8 fg	0.3 def	2.3 de	2.3 b
fluazifop 0.11	60.7 a	23.6 abc	510.7 a	218.7 a	3.5 f	3.3 cde	1.5 fg	1.8 ef	2.5 de	3.7 ab
fluazifop 0.21	56.8 a	17.7 ab	568.0 a	472.0 a	6.0 de	2.5 de	3.3 ef	3.8 cdef	3.0 de	4.8 ab
fluazifop 0.32	33.3 ab	17.9 abc	615.5 a	105.5 a	7.0 cd	2.5 de	5.0 de	3.0 def	4.0 cde	3.0 ab
fluazifop 0.63	5.4 bcd	13.7 abcd	88.5 abcd	200.7 a	8.5 abc	6.3 abc	8.0 abc	5.3 bcde	7.5 abc	3.8 ab
fluazifop 1.26	3.1 bcd	0.8 bcd	27.5 cd	6.5 bcd	9.3 ab	7.5 ab	9.5 a	9.8 a	9.0 ab	9.0 ab
glyphosate 1.12	15.4 abc	35.5 a	32.5 abcd	306.5 a	8.5 abc	8.3 ab	8.9 ab	7.4 abc	7.4 abc	2.5 b
glyphosate 2.24	13.4 abcd	9.8 abcd	22.5 bcd	68.0 abc	9.5 a	9.0 a	9.3 a	8.3 ab	8.4 ab	3.5 b
triclopyr 1.12	6.4 cd	0.8 cd	28.0 cd	9.5 cd	7.5 bcd	8.5 a	9.8 a	10.0 a	9.0 ab	9.3 a
triclopyr 2.24	0.3 d	0.0 d	2.0 d	0.0 d	8.5 abc	9.8 a	10.0 a	10.0 a	9.8 a	10.0 a

Numbers in a column followed by the same letter do not differ significantly according to Tukey's Honestly Significant Difference test at the 5% level.

Data were transformed using a logarithmic transformation prior to analysis.

Means shown are untransformed.

Table 3-6: Percent cover and density of *Bromus* spp. at Rancho Jamul Ecological Reserve. Means followed by different letters are significantly different.

Herbicide treatment (rate in kg/ha)	Percent Cover				Density (plants per m^2)				2-week injury				4-week injury				8-week injury			
	2009		2010		2009		2010		2009		2010		2009		2010		2009		2010	
Control	51.1	a	42.4	a	188.5	ab	120.5	a	0.0	d	0.0	b	0.0	f	0.0	b	0.0	e	0.0	b
aminopyralid 0.05	38.0	a	36.0	a	47.8	ab	53.8	a	0.3	d	0.0	b	0.3	f	0.0	b	0.0	e	0.0	b
aminopyralid 0.12	38.3	a	21.8	a	116.0	a	36.5	a	0.0	d	1.8	b	0.8	f	1.8	b	3.0	cde	2.5	b
clethodim 0.14	2.0	cd	0.4	b	41.3	ab	0.8	c	2.8	cd	9.0	a	3.8	e	10.0	a	8.5	abc	10.0	a
clethodim 0.28	0.5	cd	0.0	b	10.3	ab	0.0	c	4.0	bc	9.8	a	6.5	cde	10.0	a	9.5	a	10.0	a
clethodim 0.56	0.0	d	0.0	b	0.0	b	0.0	c	2.3	cd	9.8	a	9.3	ab	10.0	a	9.5	a	10.0	a
fluazifop 0.11	4.3	bcd	1.0	b	30.3	ab	2.8	bc	1.5	cd	7.8	a	3.8	e	9.8	a	6.3	abcd	10.0	a
fluazifop 0.21	0.1	d	0.1	b	0.3	b	0.3	c	1.5	cd	8.0	a	4.0	e	10.0	a	7.0	abc	10.0	a
fluazifop 0.32	0.1	d	0.8	b	0.8	b	1.5	c	2.3	cd	9.5	a	4.8	de	10.0	a	8.3	abc	10.0	a
fluazifop 0.63	0.0	d	0.0	b	0.0	b	0.0	c	2.3	cd	9.0	a	7.8	bcd	10.0	a	8.3	abc	10.0	a
fluazifop 1.26	0.0	d	0.0	b	16.0	ab	0.0	c	2.0	cd	10.0	a	8.5	bc	10.0	a	8.8	abc	10.0	a
glyphosate 1.12	0.3	cd	0.0	b	2.0	ab	0.0	c	8.3	ab	9.3	a	9.5	ab	9.8	a	9.0	ab	10.0	a
glyphosate 2.24	0.3	cd	0.0	b	0.5	b	0.0	c	9.0	a	9.5	a	10.0	a	10.0	a	10.0	a	7.5	a
triclopyr 1.12	36.3	ab	27.8	a	88.5	ab	49.0	a	0.8	cd	1.5	b	0.0	f	2.8	b	1.0	de	0.0	b
triclopyr 2.24	17.1	abc	11.9	a	47.5	ab	20.8	ab	0.3	d	2.5	b	0.0	f	4.0	b	3.8	bcde	0.0	b

Numbers in a column followed by the same letter do not differ significantly according to Tukey's Honestly Significant Difference test at the 5% level.

Injury rating data were transformed using an arcsine transformation prior to analysis.

Means shown are untransformed.

Table 3-7. Percent cover and density of all non-native grass species at Rancho Jamul Ecological Reserve. Means followed by different letters are significantly different.

Herbicide treatment (rate in kg/ha)	all non-native grass species							
	Percent cover				Density			
	2009		2010		2009		2010	
Control	51.3	a	48.4	a	197.3	ab	135.8	a
aminopyralid 0.05	40.0	a	50.5	a	62.5	ab	81.9	a
aminopyralid 0.12	40.3	a	28.3	a	121.3	a	46.3	abc
clethodim 0.14	3.5	bcd	11.8	abc	44.8	ab	39.8	abc
clethodim 0.28	0.6	d	0.6	bc	10.5	ab	1.8	bcd
clethodim 0.56	0.0	d	0.0	c	1.5	b	0.0	d
fluazifop 0.11	6.8	abcd	13.8	abc	51.8	ab	32.0	abcd
fluazifop 0.21	5.9	bcd	19.4	a	21.8	ab	65.3	a
fluazifop 0.32	1.1	cd	9.8	ab	1.0	b	29.5	ab
fluazifop 0.63	1.5	cd	6.8	abc	5.0	ab	14.5	abcd
fluazifop 1.26	2.8	cd	14.5	abc	21.0	ab	32.0	abcd
glyphosate 1.12	0.3	d	0.0	bc	2.0	b	0.0	cd
glyphosate 2.24	0.4	d	0.0	c	0.5	b	0.0	d
triclopyr 1.12	37.2	ab	34.9	a	48.0	ab	67.3	a
triclopyr 2.24	18.8	abc	16.5	a	92.8	ab	31.3	ab

Numbers in a column followed by the same letter do not differ significantly according to Tukey's Honestly Significant Difference test at the 5% level.

Density data was transformed using a logarithmic transformation prior to analysis.

Means shown are untransformed.

Conclusions

Erodium species have a complex role in the coastal sage scrub (CSS) plant community. The results of my dissertation suggest that *Erodium* species inhibit the establishment of *Artemisia californica,* one of the dominant shrubs in CSS throughout its range. This corresponds with previous studies that documented *Erodium* species inhibiting the establishment of another woody species, the blue oak (Gordon and Rice 1993, 2000) and exotic grasses inhibiting the establishment of *A. californica* (Eliason and Allen 1997). It also appears that this inhibition of *A. californica* establishment occurs at much lower densities than those at which *Erodium* often germinates in natural communities, indicating that control methods should be taken in the early phases of a restoration or after a fire that removes exotic grasses. I was able to quantify a threshold between 61-66 *Erodium*/m^2 at one site, above which *A. californica* establishment was reduced. This threshold number provides a metric that could guide managers in prioritizing management actions in disturbed CSS and restoration sites, allowing more shrubs to establish from seed.

The relationship between native annual forbs and *Erodium* density remained unclear. In the seeding study tested in this dissertation, the native forb *Cryptantha intermedia* established poorly in the presence of *Erodium*, at any density. This was likely due, in part, to the large size and high percent cover of the *Erodium* plants at this site. At the second site, where *C. intermedia* was seeded into different weeded densities of *Erodium botrys*, *C. intermedia* did not germinate even in plots with no *Erodium*. However, other native forbs that volunteered from the seedbank did well and no relationship of percent cover or density of native forbs to *Erodium* density was found. Other studies on *Erodium* showed it to have both a detrimental and facilitative (at low densities) relationship with native annuals in different situations, or at least to have a lesser detrimental effect than exotic grasses, allowing native forbs to exist in its presence (Allen et al. 2005, Gillespie and Allen 2004, Gillespie and Allen 2008, Schutzenhofer and Valone 2006, Cox and Allen 2008, Lortie and Turkington 2002). Studies of density-dependent and competitive relationships between annuals may also be confounded by differences in environmental or microsite conditions (Antonovics and Levin 1980).

Since *Erodium* may germinate in high densities when grasses are controlled by herbicide or fire (Allen et al. 2005, Cox and Allen 2008, Gillespie and Allen 2008), managers may find it necessary to control *Erodium* during a restoration or after a fire to allow native shrubs to establish. The CSS community is also experiencing many pressures from invasive species, air pollution, and increased fire regimes that are causing remaining stands to convert to exotic grasslands (Minnich and Dezzani 1998, Allen et al. 2000). Land managers may need to plan regular interventions in shrub communities with extensive grass invasion plus *Erodium* in the understory to allow shrub seedlings to regenerate from seed. Conserving the shrub canopy is an important management goal, as CSS is habitat for endangered animal species such as the California gnatcatcher, *Polioptila californica* (Hobbs et al. 2011, Beyers and Wirtz 1995). Both non-chemical and chemical control strategies were investigated for this dissertation.

The non-chemical strategies investigated adaptations of solarization – an agricultural technique which uses thin, clear plastic laid over tilled, irrigated soil during the hot summer months to sufficiently increase soil temperatures to kill weed seed and other pathogens in the top 5 -30 cm of soil (Elmore 1997, Stapleton 2000). Two variations of the technique have been successfully used in wildland situations previously: one using the traditional method of clear plastic during the summer with hand cultivation and wetting the soil prior to placement (Moyes et al. 2005), the other using black plastic during California's wet winter season so supplemental irrigation was not needed (Marushia and Allen 2011). I tested combinations of season of treatment, plastic color and extent of tilling in the absence of irrigation to determine which combination was more effective in controlling *Erodium* and other invasive species in California's Mediterranean climate. Clear plastic placed in the summer over tilled soil was still the most effective treatment combination for controlling exotic grasses and forbs even in the absence of irrigation. In this experiment the solarization plots did not have the high densities of *Erodium* seen at some my other experimental sites or in sites where exotic grasses were removed by herbicide (Cox and Allen 2008). However, the mean density of *Erodium* was 3.3/m^2 in the summer-placed, clear plastic, tilled plots, which was a 96% reduction compared to the highest mean *Erodium* density of 85.5/m^2 in the winter-placed, black plastic mowed plots, and well below the 66 plants/m^2 threshold value in the clear plastic-summer treated plots and much lower than plots with higher densities of *Erodium*. I was unable to establish shrubs at the site, but seed collected on site was very low in quantity and viability during the years the study was in place.

In the final chapter of my dissertation I investigated which herbicides were most effective on *Erodium* species. Identical experiments were set up at two sites – one where the primary *Erodium* species was *Erodium botrys,* and a second where the most abundant *Erodium* species *E. cicutarium* was intermixed with *Erodium moschatum* and patches of *Erodium botrys*. Of particular interest was the effectiveness of grass-specific ACC-ase inhibiting herbicides, which have some activity on *Erodium* species but not on most other dicots (Christopher and Holtam 1998, 2000). The products labeled for *Erodium* species are not available in the U.S., but related products were observed to have activity on *Erodium* species (Steers and Allen 2010). My study used a single application of herbicide in a growing season at multiple rates for each herbicide tested. Triclopyr provided the most complete season-long control of *Erodium* species. Glyphosate was effective at one site, but recovery or germination of a new cohort of *Erodium* occurred at the second site. Both of these herbicides will injure native shrubs and forbs that comprise the CSS community, so spraying would have to be selective prior to restoration activities. The grass-specific herbicides did not control *Erodium* at either site for the entire season at rates allowed under the label. However, the highest rate with a concentration above label controlled *Erodium* at one site and, like glyphosate, appeared to control the first cohort of *Erodium* at the other site, but a second *Erodium* cohort did germinate in the plots. Future studies to test multiple applications and very early growing season timing of herbicide applications may be worthwhile to test the potential for ACC-ase inhibitors to control *Erodium*. Even when multiple applications are required, broadcast of a selective herbicide may be both a cost-efficient and labor-efficient way to reduce *Erodium* in the interspaces between established shrubs and potentially allow new shrub seedlings to establish.

While *Erodium* species are not the primary invasive threatening CSS communities, they do inhibit one of the primary shrubs of the community, *A. californica*, from establishing from seed. Thus there is a need to control *Erodium* species prior to restoration activities when their densities greater are than 61-66 plants/m^2 (or other densities that are determined for specific sites), and possibly even in established shrub communities with high *Erodium* densities in the understory. Both solarization using clear plastic in the summer and herbicide applications of triclopyr or glyphosate are methods that effectively control *Erodium* species. However, both of these methods are damaging to CSS native species and therefore have limitations in either timing or area for applications where shrubs are established or in the process of establishing. Selective methods to control *Erodium* in CSS communities should be explored in future studies.

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