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RESEARCH ARTICLE

Control of Exotic Annual Grasses to Restore Native Forbs in Abandoned Agricultural Land

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Abstract

Exotic annual grasses are a major challenge to successful restoration in temperate and Mediterranean climates. Experiments to restore abandoned agricultural fields from exotic grassland to coastal sage scrub habitat were conducted over two years in southern California, U.S.A. Grass control methods were tested in 5 m^2 plots using soil and vegetation treatments seeded with a mix of natives. The treatments compared grass-specific herbicide, mowing, and black plastic winter solarization with disking and a control. In year two, herbicide and mowing treatments were repeated on the first-year plots, plus new control and solarization plots were added. Treatments were evaluated using percent cover, richness and biomass of native and exotic plants. Disking alone reduced exotic grasses, but solarization was the most effective control in both years even without soil sterilization, and produced the highest cover of natives. Native richness was greatest in solarization and herbicide plots. Herbicide application reduced exotics and increased natives more than disking or mowing, but produced higher exotic forb biomass than solarization in the second year. Mowing reduced grass biomass and cover in both years, but did not improve native establishment more than disking. Solarization was the most effective restoration method, but grass-specific herbicide may be a valuable addition or alternative. Solarization using black plastic could improve restoration in regions with cool, wet summers or winter growing seasons by managing exotic seedbanks prior to seeding. While solarization may be impractical at very large scales, it will be useful for rapid establishment of annual assemblages on small scales.

Key words: ***Castilleja exserta*, *Euphydryas editha quino*, *Plantago erecta*, Quino checkerspot butterfly.**

Introduction

The process of returning agricultural land to native vegetation has long been of interest to plant ecologists, but research has often focused on succession, the natural process of regeneration (Stylinski & Allen 1999; Bonet 2004; Otto et al. 2006). When a specific habitat type is desired, or succession is arrested by invasive species, active restoration is required (D'Antonio & Meyerson 2002). Old fields may require intensive restoration techniques to manage the soil, seedbank, and vegetation to transition the community from a managed landscape back to a self-sustaining wildland ecosystem (Banerjee et al. 2006; Kulmatiski et al. 2006; Standish et al. 2007).

In southern California, historic ranch and agricultural lands now constitute much of the valuable open space used to mitigate urban development, but these lands are generally dominated by exotic annual grasses and have little ecological value. In order to meet current state and federal laws, mitigation often requires habitat restoration for specific threatened and endangered species (Bowler 2000). One such species is *Euphydryas editha quino*, or Quino checkerspot butterfly (QCB), a once-common native butterfly found throughout California's coastal sage scrub (Mattoni et al. 1997; U.S. Fish and Wildlife Service 2003). Although urbanization is the primary cause in the decline of the QCB, vegetation conversion of coastal sage scrub to annual grasslands is also an important factor (Wilcove et al. 1998; U.S. Fish and Wildlife Service 2003). QCBs rely on specific larval foodplants, especially the native species *Plantago erecta* (California or foothill plantain) and *Castilleja exserta* (owl's clover), to complete their life cycle (Osborne & Redak 2000; Pratt et al. 2001; U.S. Fish and Wildlife Service 2003). These native annuals, like many of California's native forbs, have become increasingly uncommon as grazing, fires, and other disturbance regimes have converted sage scrub ecosystems to exotic annual grasslands dominated by *Bromus* spp. (brome grasses) and *Avena* spp. (wild oats).

Exotic annual grasses alter the function of native ecosystems by competing with native shrubs and forbs for moisture and light, increasing fire frequency, and transforming the soil fauna (D'Antonio & Vitousek 1992; Stylinski & Allen 1999; DiTomaso 2000; Cione et al. 2002). Invasive annual

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grasses have transformed not only coastal sage scrub ecosystems, but also native perennial grasslands, arid shrublands, and warm desert ecosystems throughout the world. Eliminating or reducing these annual grasses is usually the greatest challenge and first priority for restoration in most exotic grasslands, including coastal sage scrub ecosystems (Eliason & Allen 1997; Allen et al. 2005). Several methods of managing exotic annual grasses have been tested, including controlled burns (DiTomaso 2000; Cione et al. 2002; Moyes et al. 2005), mowing (Stampfli & Zeiter 1999; DiTomaso 2000; Huhta et al. 2001), herbicide (Wilson & Gerry 1995; Cione et al. 2002; Huddleston & Young 2005), soil amendments (Wilson & Gerry 1995; Huddleston & Young 2005), native seed additions (Seabloom et al. 2003), and grazing (Kimball & Schiffman 2003). While all these methods reduce annual grass density or cover, and may prevent further seedbank inputs, such methods have only short-term effects because they seldom reduce the seedbank.

The most effective way to manage weeds is to manage the seedbank, removing the source of competition and reducing the need for future vegetation management and disturbance (Horowitz et al. 1983; Elmore et al. 1997; Swanton & Booth 2004). Methods of seedbank control include continuously mowing or disking annual grasses, but several seasons are usually required, and both timing and diligence are important factors (DiTomaso 2000; Huhta et al. 2001; Wilson & Clark 2001). Continuous disking repeatedly mixes soil horizons and can also break down the structural integrity of soils (Whisenant 1999). Pre-emergence herbicides may prevent weed seeds from germinating (Whisenant 1999), but herbicides cannot be used in situations where herbicide application is prohibited or is of environmental concern. Appropriately timed burns are effective for weed seed control (DiTomaso et al. 2005), but are not permitted in many conservation reserves. Finally, solarization, or solar heat sterilization, can be used to control the seedbank in the top layer of soil by heating it to the point where seeds, pathogens, and other organisms cannot survive (Horowitz et al. 1983; Elmore et al. 1997; Melander & Jorgensen 2005). While the term solarization generally refers to soil sterilization, "tarping" may be used to denote everything from soil sterilization to plant suppression, and may not involve total sterilization of soil. Furthermore, not all projects require or prefer sterilization, instead, aiming to retain some soil biota. Therefore, a gradient of applications exist. Solarization and tarping are commonly used for weed control in small plots for landscaping (Elmore et al. 1997), or may be combined with fumigation at large scales for short periods of time in agricultural production (Noling & Becker 1994), but these methods have seldom been tested in restoration (Bainbridge 1990, 2007; Schultz 2001; Wilson et al. 2004; Moyes et al. 2005).

This research was conducted to find the most effective method for re-establishing coastal sage scrub in abandoned farmland in order to restore annual forb species for the QCB and foster its recovery. Success was defined by elimination or reduction of annual grass cover and biomass, and increases in native species cover, richness, and biomass, especially the establishment of the QCBs preferred larval foodplants, *P. erecta* and *C. exserta.*

Methods

Study Site

Johnson Ranch, a preserve in western Riverside County, CA, consists of abandoned agricultural land and remnant Riversidian coastal sage scrub (CSS). The region has a Mediterranean-type climate with hot, dry summers and a mild, winter, rainy growing season. Average annual precipitation for the past 50 years has been approximately 30 cm with the greatest rainfall in the months of December through March (Western Regional Climate Center 2007). The site was sold to Riverside County for mitigation and conservation of threatened and endangered (T&E) species. Johnson Ranch and other adjoining lands are cooperatively managed by California Fish and Game, the Center for Natural Lands Management (CNLM), and others (see http://www.cnlm.org for more information). Although much of Johnson Ranch has been cultivated since at least 1930, the land has remained fallow since it was acquired in 2000. Johnson Ranch is now heavily dominated by exotic annual grasses, primarily *Avena* spp. (wild oats) and *Bromus diandrus* (ripgut brome). Remnant CSS patches are composed of *Eriogonum fasciculatum* (California buckwheat) interspersed with exotic grasses and both exotic and native forbs, including the QCB larval foodplants *P. erecta* and *C. exserta*. The CNLM manages Johnson Ranch using a variety of methods, including mowing and annual spring burns, but has not reseeded native species, and the land continues to be dominated by exotic annuals.

We chose a relatively level site at Johnson Ranch in fall 2004 that had been burned the previous summer. The site has an elevation of 430 m and is located at 33° 34'04.58" N, 117° 04'54.58" W. The experiment began in the 2004–2005 growing season (subsequently called the "2005 plots") and was repeated during 2005–2006 (the "2006 plots"). We initiated plots in two different years to determine whether different precipitation regimes affected the treatments. We resampled the 2005 plots in spring 2006 in order to observe two years of growth response to the treatments.

Experimental Design and Treatments, 2005 Plots

Year 1: For the first year, we established a randomized complete block design of 5 blocks to compare 4 treatments: mowing, grass-specific herbicide, solarization, and a control (5 blocks $\times$ 4 treatments $=$ 20 seeded plots). Each sampling area measured 5 m^2 with a 0.5 m buffer zone on each side, making the entire plot 6 m^2 (Figure 1).

Early fall rains caused a flush of exotic grass germination in October 2004, which was disked to kill the grass and break the soil crust. Solarization was initiated in November 2004 by spreading 6×6-m pieces of 0.15 mm thick black plastic on the newly disked soil. The plastic was applied when soil was moist, during the growing season, because solarization is not effective on dry soil (Elmore et al. 1997). We sealed the

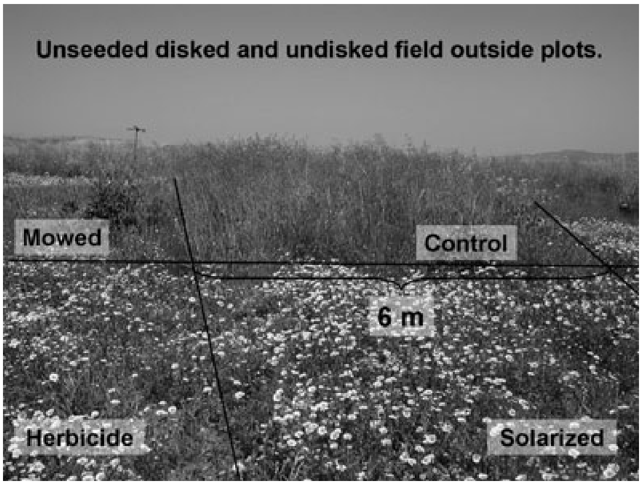

Figure 1. Plot layout and treatments on 14 April 2005, at peak flowering. Photo is taken across two blocks to show all four seeded treatments.

Table 1. Native species mix and planting rates.

Scientific Name	*kg/ha*
Amsinkia intermedia	1.12
Antirrhinum coulterianum	1.12
Calandrinia ciliata	0.56
Camissonia bistorta	0.25
Castilleja exserta	1.12
Cryptantha intermedia	1.12
Eriogonum fasciculatum	4.48
Hemizonia pungens	2.24
Keckiella antirrhinoides	1.12
Lasthenia californica	0.56
Layia platyglossa	1.12
Lessingia filaginifolia	4.48
Nemophila menziesii	4.48
Phacelia distans	1.68
Plantago erecta	5.6
Salvia columbariae	1.12

plastic to the soil by digging a 10-cm-deep trench around each plot and burying the edge of the plastic, taking care to keep tight contact between the plastic and soil surface. The plastic remained in place until early January 2005 (about 2 months duration).

All plots including controls were then seeded with a mixture of *Eriogonum fasciculatum* and native forbs on 25 January 2005 (Table 1). The forb mixture included QCB larval foodplants, known nectaring sources and dominant native forbs found in local coastal sage scrub remnants. All plots treated in 2005 are known as 2005 plots.

All seeds were obtained from S&S Seeds, Inc. (Carpinteria, CA, U.S.A.) using various sources that were as close to Johnson Ranch as possible to minimize the introduction of non-local genotypes. Seeds were hand broadcast at roughly 1900 native seeds/m^2 or about 28 kg/ha.

Fusilade II was applied to exotic grasses with a light spray nozzle using 68 ml/ha on 7 February 2005. Plots were mowed to a height of 10–20 cm using a handheld "weed-whacker" twice during the first year (7 February and 22 March 2005). Control plots received the same initial disking treatments as all the other treatments. They were seeded, but no weed control treatments were applied.

Year 2: In Year 2, 2006, the 2005 herbicide and mowing plots from 2005 were retreated. Fusilade II was reapplied in Year 2 on 6 March 2006 at the same rate as in Year 1, resulting in two consecutive years of herbicide treatment after one initial seeding. Mowing was reapplied in Year 2 on 6 March and 17 April 2006. The 2005 control and solarization plots were not retreated, but were measured in 2006.

Experimental Design and Treatments, 2006 Plots

Year 2: The undisked areas around the 2005 plots were burned again in the summer of 2005 in preparation for new solarization plots initiated in 2006. Precipitation arrived in November 2005, as opposed to October in 2004, so the 2006 plots were delayed. We disked an area adjacent to the 2005 (Year 1) plots in early December 2005, after initial grass germination, and established a second set of 5 randomized complete blocks. The new treatment blocks contained only control and solarization plots. New herbicide and mowing plots were not established. Instead, herbicide and mowing treatments were repeated on first-year plots to mimic ongoing restoration. In total, there were 5 new blocks × 2 new treatments = 10 new 2006 plots, plus 5 blocks ×2 treatments repeated on 2005 plots = 10 plots, making 20 plots treated in 2006. Plots established in 2006 are known as 2006 plots.

Later precipitation delayed application of the plastic until 3 January 2006. Plastic was again spread on moist, newly disked soil, and removed on 17 February (after about 1.5 month duration).

The new control and solarization plots were seeded on 17 February 2006 with the same mixture as used in 2005.

Data Collection, 2005 and 2006

Each treatment plot was subdivided into four quadrants. One 0.5 m^2 plot was randomly chosen and marked within each quadrant, producing four measured subplots per treatment plot. Each plot was assessed for percent cover by species on the same day as seeding (pretreatment), and once after herbicide and mowing treatments when the forbs were at peak flowering (post-treatment).

We also collected data in 10 random 0.5 m^2 plots in the disked (but unseeded) and undisked portions of the site outside the treatment areas in 2005 and 2006. Disked, unseeded areas from 2005 were re-disked as a fire break for the 2005 plots, and could not be resampled. Instead, we collected data in new undisked and disked plots in 2006.

Post-treatment data were collected on 14 April 2005 and 3 May 2006. Biomass was harvested by functional group (native forb, non-native forb, non-native grass) using 0.25 m^2 frames in a random, nonmarked area in each plot, and was then dried and weighed. Because herbicide plots tended to be patchy, two samples were collected and averaged. We also collected five biomass plots in the disked and undisked portions of the site each year. Biomass was collected within a week of the post-treatment data collection. HOBO H8 Pro Data Loggers (Onset, Pocasset, MA, U.S.A.) measured the temperature on the soil surface under the plastic in solarization treatments and in control plots in 2006.

Data Analysis

Cover, richness, and biomass data for seeded plots were averaged across subplots within plots, then averaged across plots within treatments. Cover, richness, and biomass data for disked and undisked plots was averaged within treatment. Treatment averages were compared within years using analysis of variance (ANOVA) in JMP 6.0 (SAS 2005). Treatments were analyzed across years using a nested ANOVA (treatment within year). Cover of QCB foodplants was analyzed within each year with ANOVA, and across years by nested ANOVA.

Student's t test was used to compare pairs of data and to compare differences in temperatures between solarized and control plots, and Tukey's HSD test was used for pairwise comparisons of more than two datasets. Both were performed using JMP.

Results

Johnson Ranch received about twice the average rainfall (60 cm) in 2004–2005 with most of the precipitation falling in October (13 cm), January (17.4 cm), and February (12.6 cm) (California Irrigation Management Information System 2005). In contrast, precipitation was low in 2005–2006, with only 11 cm in October (2.21 cm), January (1.8 cm), February (5 cm) and March (1.32 cm). Air temperatures in 2004–2005 ranged from 4°C to 15°C, with a median of 11.6°C, during the growing season months (October–April), while in 2005–2006 they ranged from 4 to 21°C with a median of 12.7. Average daytime soil surface temperatures in 2006 were significantly higher in solarized plots than in control plots (21 vs. 17.3°C, $p<0.001$) and reached a maximum of 43°C.

Overall, solarization and grass-specific herbicide (Fusilade) proved to be the most effective methods of weed control in both the 2005 and 2006 plots. Solarization resulted in no exotic species cover prior to seeding, mowing, and herbicide treatments in 2005 and reduced exotic species cover in 2006 (Table 2). Solarization was also the most effective method for reducing exotic cover after these treatments (Table 3). Disking alone reduced annual grasses and increased the presence of unseeded natives in 2005, but there was no benefit from disking alone in 2006 (Table 3). Seeding and disking together (control plots) did not significantly increase native cover over undisked or disked plots in Year 1 or 2 in the 2005 plots, but did increase native cover in the 2006 plots (Table 3).

Mowing reduced exotic plant cover only in 2005 (Table 3), and did not significantly increase native cover more than unseeded plots in either year (Table 3). Herbicide decreased exotic cover over disking alone, but was not significantly different from control or mowing treatments in either the 2005 or 2006 plots (Table 3). Herbicide increased native cover more than when there was no treatment at all, but was not significantly different from disking, control, or mowing treatments in 2005 (Table 3). In 2006, however, herbicide application resulted in significantly greater native cover than any other treatment except solarization (Table 3). Solarization was by far the most effective treatment, with the greatest native cover in both first- and second-year plots in both 2005 and 2006 (Table 3). It also had the lowest cover of exotic species, although the difference was not significantly different from other treatments in 2006 plots (Table 3). Solarization also produced the greatest percent cover of the QCB foodplants *P. erecta* and *C. exserta* (Figure 2).

In general, native species richness increased with increasing intensity of treatment. Disking did not reduce the number of exotic species, but solarization significantly reduced exotic richness before seeding (Table 3). Exotic richness was

Table 2. Percent cover and richness of native and exotic plants species after disking and solarization, but before seeding, mowing and herbicide treatments in 2005 plots, Year 1, on 25 January 2005, and on 17 February 2006.

			Undisked		*Disked*		*Solarized*	
			Natives	*Exotics*	*Natives*	*Exotics*	*Natives*	*Exotics*
Cover	**2005**	Cover	11.1*	116.7^A	13.65	51.3^B	1.01	0.03^C
		SE	2.53	8.03	7.23	9.72	0.19	0.03
	2006	Cover	0.21	27.4^A	0.55	10.4^B	0.00	8.0^B
		SE	0.20	4.14	0.18	0.42	0.00	0.72
Richness	**2005**	Richness	1.3^{ab}	3.2^A	1.8^a	2.8^A	0.6^b	0.1^B
		SE	0.30	0.49	0.47	0.98	0.09	0.05
	2006	Richness	0.2^a	2.9^A	1.0^b	2.8^A	0.0^a	1.0^B
		SE	0.13	0.48	0.29	0.21	0.00	0.11

For all posthoc tests, treatments are compared within years, within plant type. Lowercase denotes statistical differences in native cover among treatments and uppercase denotes statistical differences in exotic cover. SE = standard error. All ANOVA comparisons across treatments except 2005 natives*, $p < 0.01$. Nested ANOVA across years, cover: year effect for exotics, $p < 0.001$, natives, $p = 0.03$. Cover effect, exotics, $p < 0.001$, natives, not significant. Nested ANOVA across years, richness: year effect for exotics, not significant, natives, $p < 0.001$. Richness effect, exotics and natives, $p < 0.001$.
* Native ANOVA in 2005 not significant.

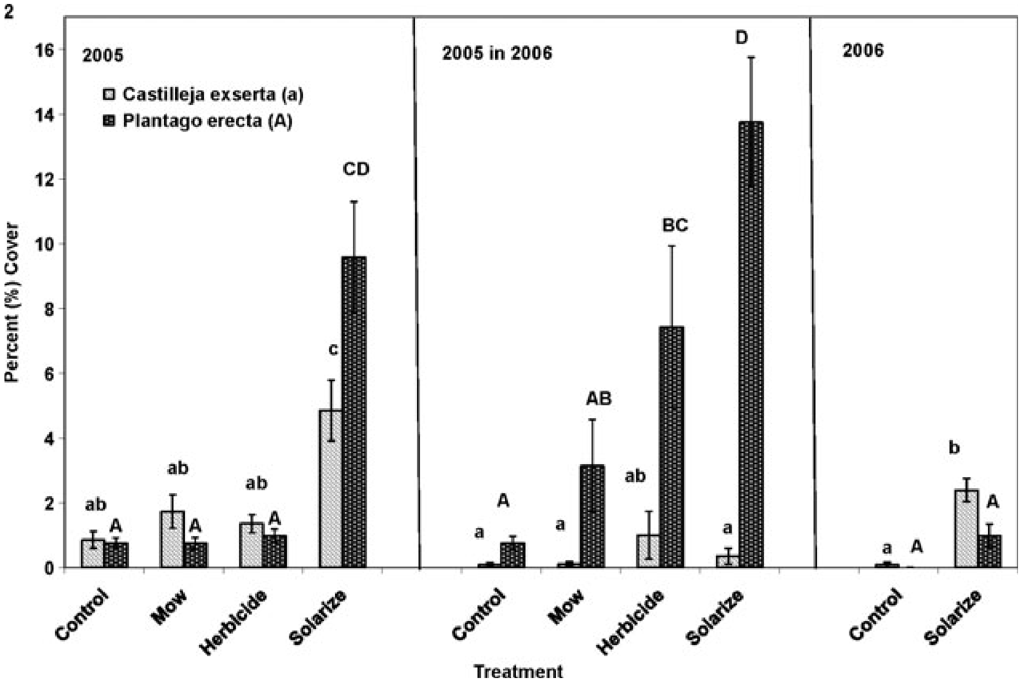

Figure 2. Average total percent cover of Quino checkerspot butterfly larval foodplants *Plantago erecta* and *Castilleja exserta* after treatments in 2005 and 2006, with 2005 ANOVA: *C. exserta,* not significant, *P. erecta*, $p = 0.046$. 2006 ANOVAs: *C. exserta* and *P. erecta*, $P < 0.001$. Across years, all treatments nested ANOVA (chart), *C. exserta,* $p = 0.045$, *P. erecta*, $p < 0.001$. Different lowercase or capital letter superscripts denote significant differences in mean values of *Castilleja exserta* or *Plantago erecta*.

slightly higher in control and mowing treatments in 2005, and disking resulted in a greater number of native species even without seeding (Table 3). Both herbicide and solarization had greater numbers of native species than other treatments in 2005 (Table 3). Solarization was the most successful treatment in terms of richness (Table 3). Results varied somewhat in Year 2 (2006): mowing, herbicide, and solarization plots from 2005 did not differ in native species richness (Table 3). Likewise, there were no significant differences in native richness in seeded 2006 plots, but disking alone again increased the number of native species naturally occurring from the seedbank (Table 3). The maximum native richness was comparable to results from 2005 in 2006 solarization plots (Table 3).

Silene gallica (common catchfly), one of only two common exotic forbs in our plots, was the most dominant exotic species in all treated plots during 2005, with sample plot cover varying from 3 to 40% (data not shown). However, exotic dominance changed in the 2005 plots in Year 2 to annual grasses such as *Lolium multiflorum* (Italian ryegrass) and *B. diandrus* in control, mowed, and solarized plots (Table 4). In herbicide plots, *Hirschfeldia incana* (shortpod mustard), the other exotic forb, replaced *S. gallica* as the most dominant exotic species. For control plots, *Avena spp.* remained the dominant exotic plant in the 2005 plots in Year 2. *Convolvulus arvensis* (bindweed) was the most dominant exotic weed in the 2006 solarized plots, with cover ranging from 14 to 58% (data not shown).

Biomass of annual grasses was dramatically reduced with disking and vegetation removal treatments. Undisked plots had exotic grass biomass over 600 g/m^2 in both years, while disked and control plots were significantly less (110 and 263 g/m^2). Mowing, herbicide, and solarization plots produced even less annual grass biomass (49, 0, and 1 g/m^2). Exotic forb biomass was similar across all treatments in Year 1 (80–120 g/m^2) but in Year 2, herbicide plots in their second year had the greatest exotic forb biomass (115 g/m^2). Exotic forb biomass was again similar across treatments in the 2005 plots in Year 2 whether disked, control, or solarized (32–56 g/m^2). Native forb biomass was greatest in solarization plots (79 g/m^2 in the 2005 plots in Year 1, 255 g/m^2 in the 2005 Year 2 plots, and 219 g/m^2 in the 2006 plots). Solarization plots in Year 1 were not significantly different in native forb biomass from disked (27 g/m^2) and herbicide plots (42 g/m^2), but both solarization plots had significantly greater native forb biomass than all other treatments during Year 2 (data not shown). The biomass values, in general, followed the percent cover values (Table 3) except that the exotic grass biomass was proportionally higher than the percent cover for control and the undisked field outside the experimental plot. This occurred when grass cover was in some cases near or greater than 100% (because of layering of the vegetation), so biomass data are a better reflection of the actual dominance of grass.

Table 3. Percent cover and species richness of native and exotic plants after all treatments in 2005 plots, Year 1, on 14 April and in 2006 plots on 3 May.

				Unseeded				*Seeded**							
				Undisked		*Disked*		*Control*		*Mowed*		*Herbicide*		*Solarized*	
				Natives	*Exotics*	*Natives*	*Exotics*	*Natives*	*Exotics*	*Natives*	*Exotics*	*Natives*	*Exotics*	*Natives*	*Exotics*
Cover	2005	2005 new plots	Cover	2.6^{a}	109.9^{A}	30.1^{b}	78.2^{B}	24.2^{ab}	63.3^{BC}	17.5^{ab}	42.5^{CD}	40.8^{b}	40.2^{CD}	92.5^{c}	15.5^{D}
			SE	1.49	4.58	6.09	8.47	4.44	6.60	2.62	3.17	5.00	4.53	12.02	3.71
	2006	2005 plots	Cover	N/A	N/A	N/A	N/A	2.47^{a**}	95.5^{A**}	9.5^{a}	81.2^{A}	39.6^{b}	48.0^{AB}	108.7^{c**}	20^{B**}
			SE	N/A	N/A	N/A	N/A	0.43	3.38	4.22	4.35	10.28	7.04	3.82	5.00
		2006 new plots	Cover	0.45^{a}	80.9^{A}	10.6^{a}	79.9^{A}	41.8^{b}	89.0^{A}	N/A	N/A	N/A	N/A	112.5^{c}	44.5^{AB}
			SE	0.40	14.10	2.94	10.29	7.61	5.26	N/A	N/A	N/A	N/A	12.19	8.87
Richness	2005	2005 new plots	Cover	0.5^{a}	1.6^{A}	2.5^{b}	2.0^{A}	4.5^{c}	4.5^{B}	4.9^{cd}	4.3^{B}	6.7^{d}	2.6^{A}	9.1^{e}	1.8^{A}
			SE	0.22	0.22	0.34	0.26	0.71	0.25	0.52	0.18	0.36	0.24	0.61	0.22
	2006	2005 old plots	Cover	N/A	N/A	N/A	N/A	1.8^{ab}	4.8^{ABC}	3.1^{bc}	5.05^{BC}	4.6^{c}	2.9^{AB}	4.7^{c}	3.0^{AB}
			SE	N/A	N/A	N/A	N/A	0.22	0.22	0.90	0.24	0.38	0.23	0.36	0.19
		2006 new plots	Cover	0.3^{a}	1.6^{A}	2.8^{ab}	5.3^{c}	7.2^{d}	5.8^{C}	N/A	N/A	N/A	N/A	8.6^{d}	2.9^{AB}
			SE	0.21	0.31	0.42	0.65	0.38	0.34	N/A	N/A	N/A	N/A	0.34	0.31

For all posthoc tests, treatments are compared within years and within plant type. Lowercase denotes statistical differences in native cover among treatments and uppercase denotes statistical differences in exotic cover. N/A = not applicable. SE = standard error. All ANOVA comparisons across treatments within years $p < 0.001$. Nested ANOVA across years, cover: year effect, exotics and natives, not significant. Cover effect: exotics and natives, $p < 0.001$. Nested ANOVA across years, richness: year effect for exotics, $p < 0.001$, natives, not significant. Richness effect for exotics and natives, $p < 0.001$.

*previously disked.

**Not retreated.

Table 4. Most common species found in the 2005 plots in each treatment per year.

	Undisked		*Disked*		*Control*		*Mowed*		*Herbicide*		*Solarized*	
Native species (forbs)	*Year 1*	*Year 2*	*Year 1*	*Year 2*	*Year 1*	*Year 2*	*Year 1*	*Year 2*	*Year 1*	*Year 2*	*Year 1*	*Year 2*
*Amsinkia menziesii**	38.5					8.3		8.7				
Calandrinia ciliata **	57.7	77.8	77.7		63.1	8.1	52.8	7.5	66.8	10.7	2.2	
Castilleja exserta					3.5		9.8				5.2	
*Eremocarpus setigerus**			11.6		5.7		7.9		4.4			
Euphorbia albomarginata						23.3		6.3	3.9			
Lasthenia californica					8.8		7.8		7.3	3.9	30.4	5.9
Layia platyglossa					5.4	11.3	9.3	16.6	6.3	8.4	39.2	69.2
*Lupinus bicolor**				100.0								
Phacelia distans						8.3		17.3		48.6		
Plantago erecta						30.4		32.9		18.8	10.4	12.6
Exotic species												
Avena spp. (grass)	66.0	83.4	19.4		17.8		13.8					
Bromus diandrus (grass)			15.4	75.5		59.5		16.0				26.4
Hirschfeldia incana § (forb)				9.3	18.9	11.6	13.5	12.8	16.9	69.5	19.9	15.3
Lolium multiflorum § (grass)	19.8		22.5		22.2	15.6	27.8	50.6				29.5
Silene gallica (forb)			29.1		27.8		38.6	7.1	76.0	22.3	67.8	17.5

Percentage is the % cover for each group (native or non-native). "Most common" equals approximately 80–90% of the total exotic or native species cover for the treatment and year represented.
* From existing seedbank only.
** From existing seedbank and seeded mix.
§ May be either annual or biennial.

Discussion

Native annual growth was promoted in this restoration experiment by overcoming both seed dispersal and recruitment limitations, a result that has been found in Australian old field ecosystems (Standish et al. 2007) and in California annual grasslands elsewhere (Seabloom et al. 2003). Direct seeding overcame the lack of native seedbank, while controlling exotic grasses improved native seedling recruitment. Solarization was successfully applied in another southern California exotic grassland by Moyes et al. (2005) to establish two perennial species. Our research finds that solarization is also useful for establishing annual native forbs, a component of CSS restoration that is often neglected, but critical to recovery of some CSS animals such as the QCB as well as plant diversity (Bowler 2000; U.S. Fish and Wildlife Service 2003). This contrasts with a similar experiment conducted in cooler climates, where solarization reduced overall cover but did not promote native forbs or continue to have effects in the second year (Wilson et al. 2004).

Controlling annual grasses by disking and winter solarization of the seedbank with black plastic produced the best results for restoration. Results were achieved with only 40–60 days of solarization, suggesting that even a relatively short solarization period in midwinter, or under cool, sunny conditions can greatly improve the success of native plant restoration. However, winter is not the optimal season for solarization for soil heating even in this Mediterranean-type climate, although it is the best time from the standpoint of soil moisture. Solarization is generally accomplished by applying clear plastic to moist soil early in the summer and leaving it in place as long as possible through the hottest temperatures of the year. The clear plastic behaves like a greenhouse, trapping heat underneath (Horowitz et al. 1983; Bainbridge 1990). Clear plastic is a more sure method because the soil is much more likely to reach high temperatures long enough to thoroughly sterilize the soil.

Summer solarization has drawbacks for restoration in southern California and other arid ecosystems, as well as for cool-climate regions where temperatures may not be consistently warm enough for long enough to raise temperatures under clear plastic. In cooler, wetter ecosystems such as northern Europe or the Pacific northwest, water may be abundant but hot days may be limited. Solarization with black plastic may be an appropriate alternative method for these ecosystems as well. Solarization relies heavily on soil water to conduct heat, and without it, solarization is not effective (Horowitz et al. 1983; Elmore et al. 1997; Melander & Jorgensen 2005). In Mediterranean ecosystems, soils are seldom wet enough late in the spring or summer for successful solarization, and irrigation is often unavailable or prohibitively expensive. We applied black plastic in winter to take advantage of the natural fall and winter precipitation, and relied on the black color to transmit heat directly to the soil surface. Disking was important to this method because it killed the first cohort of grass, and also because it removed litter and created an even soil surface, sealing the plastic as closely as possible to the soil surface. In our study, soils reached a maximum of 43°C during the second year.

Because soil heating under the plastic was only a few degrees higher than control plots, the successful results of solarization in these experiments were not likely due to sterilization of the seed bank. Solarization was effective enough in the first year to prevent annual grass germination two years in a row, but did not reduce annual *Silene gallica* or perennial *Convolvulus arvens*e, forbs that were the dominant exotic species in the 2005 and 2006 plots, respectively. *C. arvensis* was similarly resistant to solarization in other trials (Elmore et al. 1993). Instead of sterilizing the soil, black plastic application may have maintained the soil at field capacity and caused high humidity on the soil surface, conditions that are known to decompose *Avena fatua* seeds (Simpson 1990, p. 115), A similar method has been employed in agricultural systems, termed "biological soil disinfestation" (BSD). BSD uses organic amendments and a warm, wet environment to increase soil microbial respiration and produce anaerobic conditions that kill pathogens (Momma et al. 2006; Messiha et al. 2007). Weed seeds have not been considered in studies of BSD, however. Alternatively, solarization with black plastic may alter environmental conditions to induce secondary dormancy. Temperatures above 23°C have been found to induce secondary dormancy in *A. fatua* seeds that are fully soaked or have high moisture content (Simpson 1990, p. 129). With temperatures in our experiment exceeding 40°C, such conditions would certainly have existed in this experiment and may have controlled grasses in the first year. Dormancy may also be induced by anoxia, as in *Echinochloa crus-galli*, another weedy grass species (Honek & Martinkova 1992). While anoxia often occurs under plastic mulch, highly anaerobic conditions were unlikely as there were evident air pockets under the plastic. However, very little grass occurred in second-year solarized plots, indicating either that grass seeds were killed by the initial treatment, remained dormant through the second year, or that competition with the established forb community suppressed grass seedlings and prevented grass recovery.

Replacing grasses with exotic forbs in solarization and herbicide plots allowed the successful recruitment and establishment of native forbs. The dominance of exotic forbs over exotic annual grasses in herbicide and solarization treatments parallels findings in several other studies; whether annual grass control is achieved through herbicide, hand-weeding, or solarization, exotic forbs consistently replace the exotic annual grasses (Shipley & Keddy 1994; Gillespie & Allen 2004; Allen et al. 2005). In a study conducted in a nearby reserve, Cox and Allen (2008) found that annual grass removal resulted in an increase in *Erodium cicutarium*, an exotic forb. However, native annuals were better able to compete with *E. cicutarium* than with annual exotic grasses. A competitive hierarchy existed between exotic grasses, exotic forbs, and native forbs which could be utilized to encourage native annual forbs (Cox & Allen 2008). In the case of Johnson Ranch the same competitive hierarchy is likely at work, since native annuals were clearly more successful competing with exotic forbs in the herbicide and solarization plots than competing with annual grasses in mowed and control plots.

As in all restoration projects, precipitation played an important role in the results of this study. Year 1 was one of the wettest years on record for southern California, and this undoubtedly contributed to successful native plant establishment in the first year. In fact, the plentiful 2005 rains likely allowed species such as *P. erecta* to reseed successfully, resulting in high rates of cover for 2005 plots in 2006. Rains that followed disking in November and December of 2005 also provided ample moisture for the native forb seedbank to germinate. Surprisingly enough, very little exotic grass germinated with these later rains; the only grasses that returned throughout most of the disked area in winter 2005 were remnants left between passes of the disk. This emphasized the importance of thorough disking when controlling annual grasses, but also showed that disking alone can be effective as a treatment.

Mowing has been widely applied in weed control and restoration because it is relatively low-cost and can be applied on a large scale (Whisenant 1999; DiTomaso 2000). Mowing has been beneficial in grassland systems where native plants were already an established component of the flora (Wilson & Clark 2001), and operates well in combination with herbicide (Renz & DiTomaso 2004; Renz & DiTomaso 2006) but generally serves to maintain plant communities or slow their invasion (Stampfli & Zeiter 1999; Huhta et al. 2001). Mowing has been consistently applied for weed control to promote shrub regeneration at Johnson Ranch (Maher & Stanton 2005). This method has potential near remnant patches that can act as ongoing seed sources, and takes multiple years for weed control. However, if more rapid establishment of endangered species is required, our research shows that management resources may be better invested in more intensive strategies such as disking, solarization, and/or grass-specific herbicide application coupled with seeding.

Shrub recruitment is an important part of coastal sage scrub restoration since it may reduce fire return intervals and resist annual exotic grass reinvasion (Cione et al. 2002). Although no shrub seedlings were found in the first year, healthy seedlings were found (although seldom sampled in plot frames), and were evenly interspersed during the second year with densities of approximately one shrub per 2 m^2. Because the forb and grass densities were high in all plots in the first year, we believe that the shrub seedlings were often too small to find. In the second year, however, shrub seedlings occurred in most 2005 plots. Because QCBs occur in an open shrub canopy with forb-filled interspaces (Osborne & Redak 2000), we considered shrub recruitment in this study to be appropriate and desirable.

Solarization requires a large amount of plastic and labor, and the initial cost is likely to be higher than other methods. However, it is the only seedbank management method that can functionally eliminate the weed seedbank from a restoration site (Horowitz et al. 1983; Standifer et al. 1984; Bainbridge 1990). There is potential for solarization to be used successfully and cost-effectively on a large scale (Stapleton & Jett 2006). The agricultural industry uses 0.03 mm plastic on several acres at a time using specialized equipment. However, these plastics are usually intended for short-term use, to be applied in combination with fumigants to sterilize the soil before planting (Standifer et al. 1984; Noling & Becker 1994; Elmore et al. 1997). Larger-scale solarization attempts for 4–6 weeks will likely need to use heavier plastics such as the 6-mm used here. It will be most useful for abandoned farmlands and other relatively level lands where most or all of the existing vegetation is undesirable. Solarization may be particularly successful if combined with grass-specific herbicide, such as the one tested in this research. Because solarization can only be applied in the first year, herbicides such as Fusilade can control reinvading grasses once the restored plant community is in place. Variability in precipitation may cause challenges when applying this technique in climates with cool season moisture and growing seasons where no irrigation is available, but black plastic solarization may provide an effective alternative to clear plastic summer solarization. Research to obtain a greater understanding of impacts of cool season application of plastic on the seed bank is underway. Additional research will focus on applying solarization on a large scale.

Implications for Practice

- Disking annual invasive grasses soon after germination can reduce grasses and promote native annual establishment.
- Seeding following disking is effective if a grass-specific herbicide and/or solarization are applied in combination, but seed is wasted following one or two seasons of mowing.
- Cool-season solarization with black plastic can be a useful alternative to summer solarization in climates with a winter growing season and no available irrigation for dry-season summer solarization, or in climates with cool summers.
- Solarization in combination with grass-specific herbicides may be a successful method to restore native annual forbs while controlling exotic annual grasses.

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