Integration of Prescribed Burning, Aminopyralid, and Reseeding for Restoration of Yellow Starthistle (*Centaurea solstitialis*)-Infested Rangeland

Guy B. Kyser, Arthur Hazebrook, and Joseph M. DiTomaso

Yellow starthistle (*Centaurea solstitialis*) is among the most invasive plant species in the western United States. The long-term management of yellow starthistle should include an integrated approach that incorporates establishment of competitive vegetation. In this study, conducted in two locations at Fort Hunter Liggett in Monterey County, California, we evaluated the combination of prescribed burning, the herbicide aminopyralid, and reseeding of native broadleaf and grass species on both yellow starthistle control and native plant restoration. Both study sites were burned in late October 2009. Over the following season, aminopyralid was applied at three timings and native plant species were seeded at three timings, using both a drill-seeder and broadcast spreader. Evaluations over the next 3 yr showed that aminopyralid provided complete to nearly complete control of yellow starthistle when applied between January and March, and this level of control was maintained for two seasons. Native plants failed to establish when broadcast seeded, regardless of the timing. December and January drill seeding timings were the most successful in establishing native species. There was a strong herbicide and drill seed timing interaction effect on native grass cover at both study sites. Over the course of the study the native perennial grass *Stipa cernua* was the most successful seeded species to establish, but establishment was slow and required 3 yr. Our results indicate that a January or March aminopyralid treatment integrated with a native perennial grass drill seeding program in January offers the greatest probability of both successful yellow starthistle control and perennial grass establishment.

Nomenclature: Aminopyralid; yellow starthistle, *Centaurea solstitialis* L.; *Stipa cernua* Stebbins & Love.

Key words: Herbicide, invasive, prescribed fire, rangeland, restoration, weed control.

Yellow starthistle (*Centaurea solstitialis* L.) is one of the most widespread invasive plant species in the western United States, and is estimated to occupy about six million hectares (~15 million acres) of rangelands and annual grasslands (Duncan et al. 2004). A number of chemical and nonchemical tools are available for the management of yellow starthistle, and these control methods are often used in an integrated approach (DiTomaso et al. 2000, 2006c).

Among the herbicides used for yellow starthistle control, clopyralid (Transline®) has been extremely effective both pre- and postemergence (DiTomaso et al. 1999b). In addition to herbicides, timely prescribed burning has also given excellent control of yellow starthistle, but requires three consecutive annual burns when used as a sole control tool (DiTomaso et al. 1999a). In an integrated strategy shown to be successful on annual California grassland, a summer prescribed burn was used to stimulate germination of the yellow starthistle soil seedbank the following fall. When the resulting flush was treated with a winter application of clopyralid, yellow starthistle cover that year and the following year was reduced by greater than 99% (DiTomaso et al. 2006b). The yellow starthistle seedbank was also reduced by over 99%. Burning has also been shown to also facilitate more effect control of other invasive plants when used in an integrated approach. For example, in Texas grasslands, burning conducted during the growing season, followed by a glyphosate treatment, effectively reduced the abundance of the invasive perennial grass *Bothriochloa ischaemum* (L.) Keng (Simmons et al. 2007). However, the timing of fire treatments was critical and

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* First and third authors: Specialist and Cooperative Extension Weed Specialist, Department of Plant Sciences, University of California, Davis, CA 95616; second author; Environmental Engineer, General Dynamics Information Technology, Fort Hunter Liggett, CA 93928. Corresponding author's E-mail: jmditomaso@ucdavis.edu.

Management Implications

In previous studies we showed that a properly timed summer burn followed by application of the herbicide clopyralid in winter gave excellent control of yellow starthistle for two seasons. However, following management of a severe yellow starthistle infestation, resident vegetation often does not recover sufficiently to resist reinvasion, and it is often difficult to reseed native species in a Mediterranean climate characterized by seasonal rainfall and drought. In this study we evaluated the effect of prescribed burning followed by application of the similar herbicide aminopyralid at three timings (November, January, and March), crossed with drill or broadcast seeding of native species at three timings (December, January, and March). We assessed both yellow starthistle management and native plant restoration. Prescribed fire followed by January to March aminopyralid treatment gave 2 yr of near complete control of yellow starthistle. The November treatment did not provide season-long control of late-germinating starthistle. Broadcast seeding of native plants failed to establish any species. Of the three drill seed timings, only December and January resulted in successful establishment of just one native perennial grass species, even with above-average rainfall in the first 2 yr of the study. Neither a native annual grass nor several broadleaf species were able to establish or sustain their populations over time. Over the three seasons of the study, *Stipa cernua* established most successfully. There was a strong interaction effect for herbicide and drill seed timing, with January being the optimal timing for both herbicide application and perennial grass seeding. This timing not only offers the greatest probability of both successful yellow starthistle control and perennial grass establishment, but also can be used in a single-entry program that reduces costs by consolidating activities to one timing.

increased invasion of *B. ischaemum* when conducted during the dormant season.

For yellow starthistle control, the herbicide aminopyralid has been shown to be about four times more active, by rate of active ingredient, than clopyralid (Kyser et al. 2011). Both compounds are pyridine carboxylic acid herbicides with broadleaf selectivity. They act as auxin-mimics and are particularly active on species in the Asteraceae and Fabaceae (DiTomaso et al. 1999b, Kyser et al. 2011). In addition, they have similar foliar and soil residual activity (Senseman 2007). Aminopyralid is more effective in controlling several perennial thistles (Bukun et al. 2009, DiTomaso and Kyser 2006, Enloe et al. 2008, Wilson et al. 2010), as well as controlling a few other species not susceptible to clopyralid [e.g., coast fiddleneck, *Amsinckia intermedia* Fisch. & C.A. Mey.; =*Amsinckia menziesii* (Lehm.) Nelson & J.F. Macbr. var. *intermedia* (Fisch. & C.A. Mey.) Ganders] (Kyser et al. 2011).

In the Central Valley of California, the ideal application timing for clopyralid was from December through April, but treatments in February maximized production of desirable forage, particularly annual grasses (DiTomaso et al. 1999b). The timing profile for application of aminopyralid was similar to clopyralid (Kyser et al. 2011). Yellow starthistle was completely controlled with the lowest registered rate (53 g ae ha^{-1}, = 0.75 oz ae ac^{-1}) when plants were in the seedling to early rosette stage from December through February. As with clopyralid, plots treated with aminopyralid in the rosette stage produced twice as much grass forage compared to untreated plots.

Without followup management, removal of an invasive species can leave a niche open for reinfestation by the same or another invasive. To provide sustainable management and prevent a rapid return to invasive species dominance in grasslands, it may be necessary to establish competitive perennial grasses that are functionally similar. For example, Bakker and Wilson (2004) showed that desirable C_3 perennial grasses showed a stronger correlation than dissimilar C_4 grasses in competing with the nonnative C_3 perennial grass *Agropyron cristatum* (L.) Gaertn. in grasslands of Canada. They concluded that resistance to invasion was strongly dependent on the species within the community and restoration seed mixes should be tailored to match the functionality of invaders. In the Central Valley of California, establishment of the deep-rooted perennial grass *Elymus glaucus* Buckley prevented the subsequent survival of yellow starthistle (Young et al. 2009). In this case, *Elymus glaucus* was functionally similar to yellow starthistle in its water use pattern. A similar study in a different region of the state showed that the establishment of another functionally similar perennial grass, *Stipa pulchra* Hitchc. [= *Nassella pulchra* (Hitchc.) Barkworth], also gave resistance to invasion by yellow starthistle (Reever-Morghan and Rice 2005).

Both clopyralid and aminopyralid have been shown to be useful in perennial grass restoration programs (Almquist and Lym 2010; Enloe et al. 2005; Wilson et al. 2010). For example, clopyralid treatment significantly reduced yellow starthistle and allowed establishment of pubescent wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey var. 'Luna'] with a single treatment in a Great Basin climatic zone in northern California (Enloe et al. 2005). However, seeding native species has not always proven successful; this can be caused by the timing of the revegetation program, or to various climatic or environmental conditions that occur following seeding (Kyser et al. 2007). In California's Mediterranean climate, reseeding efforts often fail because of sporadic rainfall patterns, particularly at the beginning and end of the rainy season (i.e., October through November and April through May). In addition, even growth regulator herbicides, such as aminopyralid, can injure seeded grasses when applied preemergence to early postemergence (Kyser et al. 2012). This can be a significant impediment to restoration of yellow starthistle-infested rangeland with seeded desirable perennial grasses.

In this study, we used an integrated approach combining prescribed burning, herbicide treatment, and native plant restoration to achieve long-term sustainable management of yellow starthistle. Because aminopyralid is similar to clopyralid in its mode of action and soil residual activity, and has greater activity on yellow starthistle, we hypothesized that it should show results similar to clopyralid when integrated with burning (DiTomaso et al. 2006b). The primary goal of this study was to evaluate whether reseeding could be successfully conducted in tandem with this integrated management strategy. The specific objectives of the study were to (1) evaluate yellow starthistle control with burning followed by aminopyralid at three application timings (fall, winter, or early spring); (2) evaluate establishment of revegetation species following seeding at three timings (fall, winter, or early spring), in combination with yellow starthistle management; and (3) compare two planting techniques (drill vs. broadcast seeding) for success in the revegetation effort. While drill seeding increases seed/soil contact and, thus, the success of establishment compared to broadcast seeding (Cox and Anderson 2004), it is often more expensive and is less feasible than broadcast seeding in steep or rocky areas.

Materials and Methods

Study Site. The study was established at two locations at Fort Hunter Liggett (U.S. Army Garrison) in Monterey County, California in 2009. Fort Hunter Liggett is a United States Army garrison and training center of 66,000 ha (163,090 ac), occupying much of southwestern Monterey County between the crest of the Santa Lucia Mountains to the west and the Salinas River Valley to the east. Its topography ranges from steep, low-elevation mountains vegetated by chaparral, live oak woodlands, and mixed evergreen forests to valley bottoms covered by a mosaic of annual and perennial grasslands, coastal scrub, foothill woodlands, blue oak woodlands, and valley oak savanna. Mean daily maximum summer temperatures range from 26 C (79 F) to over 40C, while mean daily maximum winter temperatures range from 0 C to 18 C. Precipitation occurs in a Mediterranean pattern, with most rainfall between November and April. Yellow starthistle was first mapped at the site in 1964, and at that time infested 672 ha. By 1998 it had spread to over 8,000 ha (Osborne 1998).

Both study locations (''Mission'' and ''Back'') were in valley bottom grassland within mixed oak-foothill pine woodland. The sites were separated by 3 km (1.9 miles). The Mission site was at 36.05°N, 121.25°W (375 m elevation; 1230 ft elevation), and the Back site was at 36.08°N, 121.26°W (395 m elevation). Mission site soil was Arroyo Seco gravelly loam with 2% organic matter in the top 30 cm (12 in), and Back site soil was Elder sandy loam with 2.5% organic matter. Both sites average approximately 260 frost-free days per year. The annual

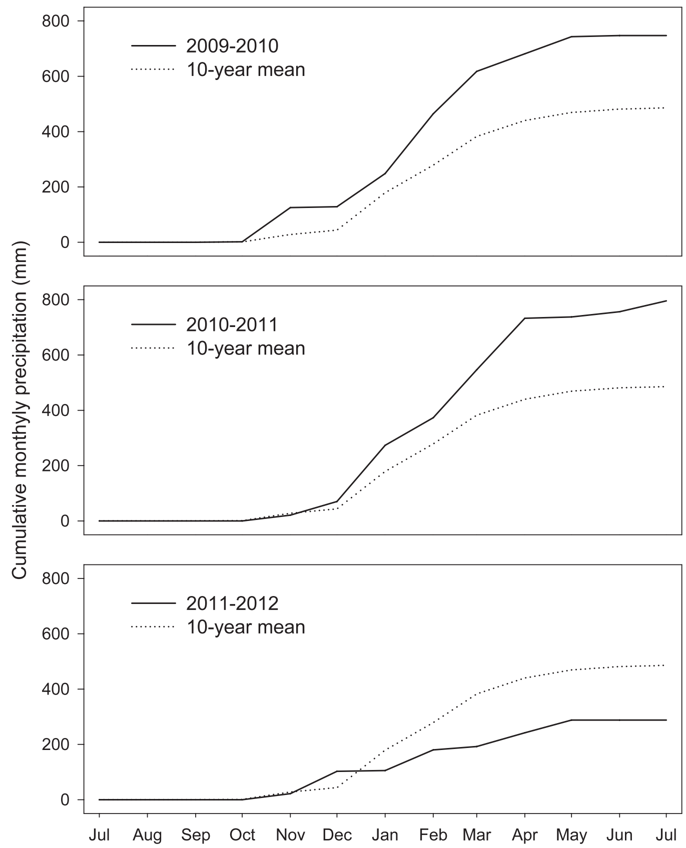

Figure 1. Cumulative monthly precipitation at Fort Hunter Liggett from July to June for 2010, 2011 and 2012. Dotted lines represent mean precipitation for 10-yr period from 2001 to 2010.

average precipitation at these sites (2001 to 2010) was 48 cm, with a range of 16 to 75 cm (Figure 1). In the year the study was established (July 2009 to June 2010), total rainfall (75 cm) was 156% of average (http://www.raws.dri.edu/cgi-bin/rawMAIN.pl?caCFHL). Similarly, the total rainfall from July 2010 to June 2011 was 166% of normal at 80 cm. In contrast to these two wet years, rainfall from July 2011 to June 2012 was only 60% of normal at 29 cm.

Prescribed Burn. Both sites were burned in late October 2009 (Table 1). The prescribed fires achieved essentially complete burns, leaving very little standing material. Burning for yellow starthistle control is most effectively conducted before flowering (early summer) to prevent current year seed production (DiTomaso et al. 2006a,b,c). However, because Fort Hunter Liggett is mountainous, hot, and often windy in summer, the burn was delayed until fall when the fires could be more easily managed. Following the burns, a heavy flush of yellow starthistle seedlings emerged with the first fall rains.

Experimental Design. Each study site was established in a randomized strip-plot design with herbicide treatment

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Table 1. Treatments, times, and rates and/or methods at both the Mission and Back sites.

Treatment	Times	Rates and/or methods
Burning	October 2009	Prescribed fire
Seeding (native perennial and annual grasses and broadleaf species)	December 9, 2009	Drilled (17–22 kg ha^{-1}), broadcast (13–19 kg ha^{-1})
	January 11 2010	Drilled (17–22 kg ha^{-1}), broadcast (13–19 kg ha^{-1})
	March 11, 2010	Drilled (17–22 kg ha^{-1}), broadcast (13–19 kg ha^{-1})
Herbicide (aminopyralid)	November 24, 2009	53 g ae ha^{-1} in 187 L ha^{-1} (= 20 gal ac^{-1}) with 0.25% NIS[1]
	January 28, 2010	53 g ae ha^{-1} in 187 L ha^{-1} with 0.25% NIS
	March 19, 2010	53 g ae ha^{-1} in 187 L ha^{-1} with 0.25% NIS
	February 23, 2012	53 g ae ha^{-1} in 187 L ha^{-1} with 0.25% NIS
Evaluation (visual cover estimates)	July 20, 2010	Yellow starthistle at full flowering and peak size; establishment success of seeded native species
	May 3, 2011	Establishment success of seeded native species at peak flowering
	August 1, 2011	Yellow starthistle at full flowering and peak size
	May 23, 2012	Establishment success of seeded native species at peak flowering

[1] Non-ionic surfactant.

timing as the main effect, and seeding time and method randomized as the vertical factor (Figure 2). Aminopyralid (Milestone®, Dow AgroSciences, Indianapolis, IN) application plots (main plots) were 21 m long by 9 m wide. These were crossed by seeding strips 3 m wide, making subplots 3 m by 9 m. Treatments were replicated three times at each site.

Treatments included all combinations of four aminopyralid treatments and seven seeding treatments, for a total of 28 subplots per block (Figure 2). Aminopyralid was applied at 53 g ae ha^{-1} (3 oz Milestone® ac^{-1}) at three timings (Table 1), plus an untreated control. Applications were made with a CO_2 backpack sprayer at 207 kPa (30 psi) and a 3-m boom with six 8002 nozzles. The spray volume was 187 L ha^{-1} (20 gal ac^{-1}), and all treatments included 0.25% v/v nonionic surfactant (Activator 90®, Loveland Products Inc., Greeley, CO). Applications were made on November 24, 2009, January 28, 2010, and March 19, 2010.

Restoration treatments included three reseeding times by two seeding methods (drill seeded and hand broadcast) plus an unseeded treatment. A native seed mix was planted on December 9, 2009, January 11, 2010, or March 11, 2010 (Table 1). The native species were chosen based on two criteria, current or historic presence within grasslands at Fort Hunter Liggett, and availability through relatively local native seed producers (< 300 km from treatment area). Seeding rates were 17 to 22 kg ha^{-1} (15 to 20 lb ac^{-1}) with the drill seeder and 13 to 19 kg ha^{-1} (12 to 17 lb ac^{-1}) with the hand spreader. The seed mix included 66.7% by weight of a mixture of annual broadleaf seed [*Eschscholzia californica* Cham., *Layia platyglossa* (Fisch. & C.A. Mey.) A. Gray, *Acmispon americanus* (Nutt.) Rydb. (= *Lotus purshianus* Clem. & E.G. Clem.), *Lupinus nanus* Benth.] and the native annual grass *Festuca microstachys* Nutt. [= *Vulpia microstachys* (Nutt.) Munro], 12.5% each (total of 25%) of the native perennial grasses *Stipa cernua* Stebbins & Love [= *Nassella cernua* (Stebbins & Love) Barkworth] and *Elymus triticoides* Buckley [= *Leymus triticoides* (Buckley) Pilg.], and 8.3% *Eriogonum fasciculatum* Benth., a native subshrub. *Eriogonum* seed was collected on site, and the remaining seeds were obtained from S&S Seeds (www.ssseeds.com, Carpenteria, CA). Drill seeding was done with a rangeland drill planter (Truax FLEX II-88 seed drill, www.truaxcomp.com, New Hope, MN) and broadcast seeding using a hand crank spreader (www.earthway.com, Bristol, IN).

The first application date, November 24, 2009, was prior to all plantings; some yellow starthistle cotyledons were present. At the second application (January 28, 2010), seedlings from the December planting were 5 to 8 cm tall, seedlings from the January planting were just emerging, and yellow starthistle was in the cotyledon to early seedling stage. At the third application (March 19, 2010), November seedlings were 5 to 12 cm tall, January seedlings were less than 8 cm tall, and yellow starthistle was in rosettes to 30 cm diameter, some beginning to bolt.

By August 2011, yellow starthistle had begun to recover in all plots at both sites, including the January and March treatment timings. This relatively rapid recovery may have been caused by the timing of the prescribed burn in October 2009, which was too late to prevent yellow starthistle seed production in that year. To ensure that we could make a final evaluation for seeded species establishment, we simulated a follow-up maintenance program for yellow starthistle (DiTomaso et al. 2006b). We treated all plots with 53 g ae ha^{-1} aminopyralid on February 23, 2012 and achieved complete control of yellow starthistle throughout the study area in 2012.

The first year evaluation was conducted July 20, 2010, with yellow starthistle at full flowering and peak size (Table 1). Three 1-m quadrats were thrown along the

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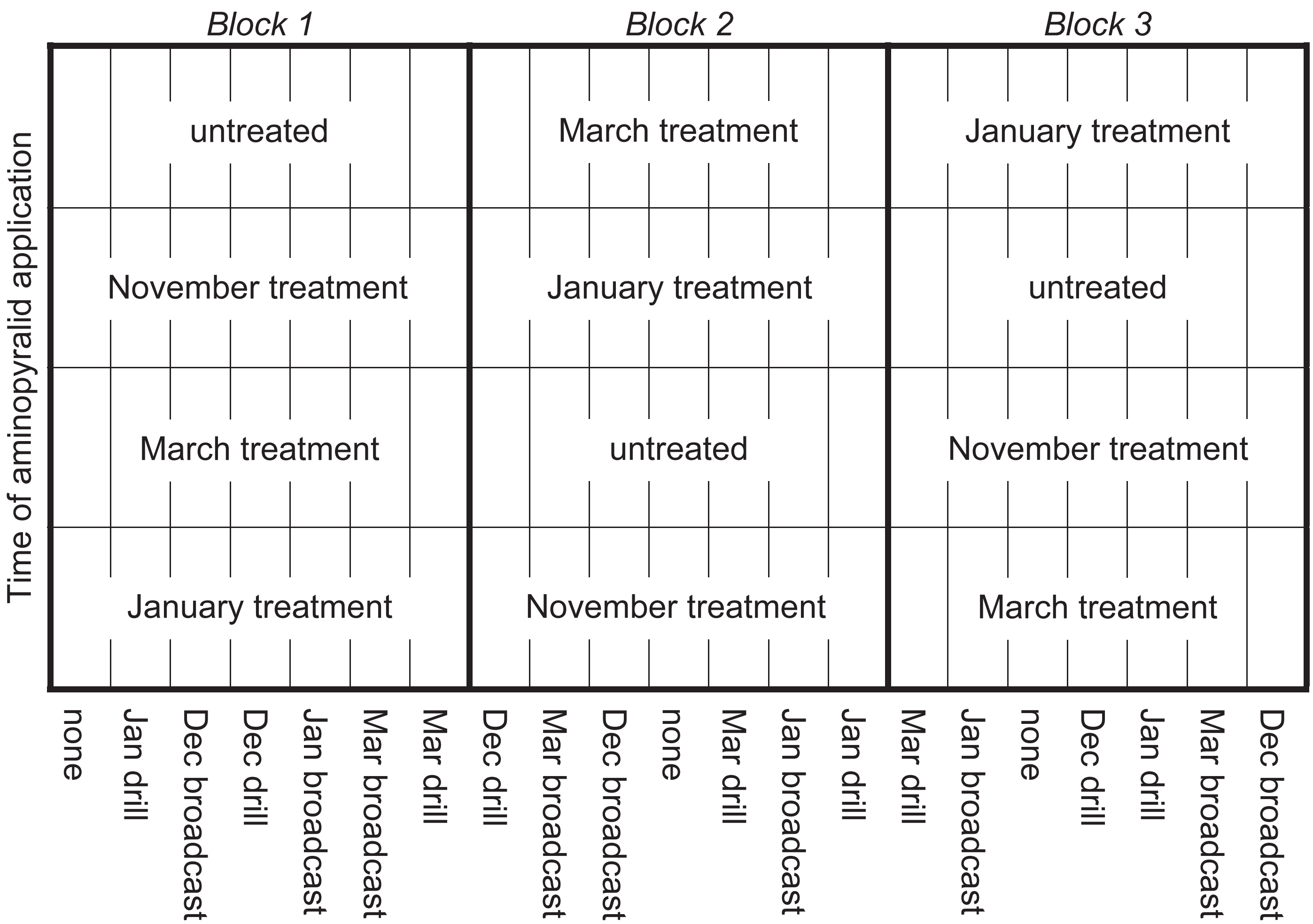

Figure 2. Plot map of Back site with split-plot design. Herbicide treatment timing is main plot with seeding technique/timing as split plot.

center of each subplot, and vegetative cover of each species was visually estimated in each of the three sub-subplots. For some analyses, species were grouped into native grasses, introduced annual grasses, legumes, or forbs. The forb class included all broadleaf species other than yellow starthistle. Subplots were evaluated again on May 3, 2011, when native species were at peak flowering, to determine the establishment success of seeded species; at this time yellow starthistle was in the bolting to early spiny stage but had not initiated anthesis. We evaluated again on August 1, 2011 to determine yellow starthistle cover at peak size.

By 2 yr after initial aminopyralid treatment, yellow starthistle had begun to recover in all previously treated plots. Consequently, to simulate a follow-up management program, all plots were treated on February 23, 2012 with 53 g ae ha^{-1} aminopyralid. The final evaluation was conducted on May 23, 2012 to again determine the establishment success of the reseeded species.

Data Analysis. Total cover of each species or vegetation class was compared among treatments using ANOVA for a strip-plot design with the Fit Model procedure in JMP (SAS Institute Inc. 2008. JMP v. 8.0). Factors included treatment time, seeding type, time by type, block, block by time (random), and block by type (random). Most of the data were normal and homoscedastic; however, in analyzing cover of seeded grasses we used a square root transformation ($x' = [x + 0.5]^{0.5}$) to deal with problems in distribution and variance. Strip-plot ANOVA for 2010 found no significant effect for broadcast seeding treatments, so in subsequent analyses (i.e., for evaluating interaction of timing of aminopyralid application with timing of seeding) we omitted the broadcast seeding treatments and used only drill-seeded plots. In analyzing for year-to-year changes in cover of dominant species, we used cover from all drill-seeded plots ($n = 36$) and means were separated using paired *t*-tests.

Results and Discussion

Yellow Starthistle Control. In the summer of 2009, before the first applications were made, both the Back and

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Table 2. Total cover of yellow starthistle for each aminopyralid treatment timing, in evaluations from 2010 to 2012 for both Mission and Back sites. Values are means over all seeding treatments. Means are separated using the Tukey-Kramer HSD test. The probability of treatments occurring by chance is indicated for each factor.

Site	Time of application	Yellow starthistle cover at each evaluation date			
		July 2010	May 3, 2011	August 1, 2011	May 23, 2012[a]
		%			
Mission	November 2009	17.3 b	32.3 b	52.8 a	0
	January 2010	0.3 c	1.3 c	11.7 b	0
	March 2010	0 c	0.1 c	0.7 b	0
	None	43.4 a	50.0 a	47.4 a	0
	Probability F	< 0.0001	< 0.0001	< 0.0001	—
Back	November 2009	20.8 b	15.0 b	89.4 b	0
	January 2010	0.3 c	0.6 c	12.9 c	0
	March 2010	0.2 c	0.2 c	4.6 d	0
	None	84.3 a	50.7 a	100.0 a	0
	Probability F	< 0.0001	< 0.0001	< 0.0001	—

[a] All plots received an additional aminopyralid treatment on February 23, 2012 to prevent reestablishment of yellow starthistle.

Mission sites were observed to have high yellow starthistle infestations (pers. obs., A. Hazebrook). In the untreated plots in 2010, the Back site had a heavy infestation of yellow starthistle, with nearly twice the cover of the Mission site (Table 2). In August 2011, the untreated plots in the Back site had complete cover of yellow starthistle with plants up to 2 m in height. Regardless of the level of infestation, control results were similar for both sites at all timings. Treatment with aminopyralid in January and March gave nearly complete control of yellow starthistle in 2010, and over 95% control the following year (2011). These results are similar to those reported for clopyralid when used following a prescribed burn (DiTomaso et al. 2006b).

November application of aminopyralid provided only partial control of yellow starthistle at both sites (Table 2), probably because soil residual activity started to decline by spring. The year of application had a relatively long rainy season, and by the end of the season, residual aminopyralid from a November application was not sufficient to control late season germinants. In November-treated plots, the cover of starthistle increased to the level of untreated plots by 2011.

These results support our previous findings (Kyser et al. 2011) that aminopyralid treatment at the lowest registered rate can provide complete to nearly complete control of yellow starthistle when applied between January and March. Our results also support previous evidence that an integrated approach incorporating a prescribed burn, followed by herbicide treatment the following growing season, can give longer suppression of yellow starthistle compared to using either technique alone (DiTomaso et al. 2006b). We found this strategy to be as effective using aminopyralid as we previous demonstrated using clopyralid, despite the October prescribed burn used in this study. It is likely that a more timely burn at the beginning of flowering (generally from mid June to early July) would not only prevent seed production in the year of the burn but would depletes the yellow starthistle seedbank by promoting germination after fire, allowing subsequent herbicide control of the flush of seedlings.

Native Plant Establishment. In unseeded plots at the Mission site in 2010 (Table 3), there was relatively high cover of resident *Elymus triticoides*, a native perennial grass (10.6%), and native forbs (6.2%), predominantly *Amsinckia intermedia* and *Heterotheca oregona* (Nutt.) Shinners. *Elymus triticoides* was sporadically distributed throughout the plots, including the seeded plots, making it difficult to distinguish between newly seeded plants and young plants derived from the resident population. In contrast, the Back site had no resident native grasses, but had good cover of native forbs, particularly *Deinandra lobbii* (Greene) Greene (= *Hemizonia lobbii* Greene).

Drill seeding native species in December and January resulted in a two-fold increase in native grass cover at the Mission site in 2010 compared to unseeded plots (Table 3). Although this was not statistically greater than the unseeded plots, it was significantly higher than the January broadcast treatment, as well as the March broadcast and drill-seeded plots. Unlike native grasses, there were no differences in native forb cover among seeding treatments at the Mission site. At the Back site, drill seeding significantly increased both native grass and forb cover. For native grasses, both December and January drill seeding resulted in significantly more cover compared

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Table 3. Cover of native grasses and forbs (both resident and seeded species) in drill seeded vs. broadcast seeded plots at the Mission and Back sites on July 20, 2010, the first growing season after treatment. Values are percent vegetative cover for each species or cover class. Values followed by different letters indicate differences as determined by the Tukey-Kramer HSD test. The probability of treatment differences occurring by chance is indicated for each factor.

			Mean cover	
Site	Seeding treatment	Timing	Native grasses[a]	Native forbs
			%	
Mission	Drill	December	22.4 a	9.9
	Drill	January	20.4 a	6.7
	Drill	March	4.4 b	7.7
	Broadcast	December	12.4 ab	7.6
	Broadcast	January	7.8 b	7.1
	Broadcast	March	7.1 b	6.1
	None	—	10.6 ab	6.2
	Probability > F		< 0.0001	0.8368
Back	Drill	December	4.3 a	39.0 a
	Drill	January	3.7 ab	23.4 b
	Drill	March	0.0 c	15.6 b
	Broadcast	December	1.5 bc	20.1 b
	Broadcast	January	1.2 c	19.5 b
	Broadcast	March	0.0 c	27.8 ab
	None	—	0.0 c	15.7 b
	Probability > F		0.0001	< 0.0001

[a] Used square root transformation $P' = \sqrt{P + 0.5}$ for analysis; actual values are presented.

to unseeded plots. For native forbs, only the December drill seed timing gave significantly higher cover.

Broadcast seeding treatments did not significantly increase cover of native grasses or forbs at either site in 2010 (Table 3). Because broadcast seedings failed to establish at any timing, all subsequent analyses were conducted using only drill-seeded plots.

At the Mission site in 2010, the increase in native grasses in drill-seeded plots, compared to unseeded plots, was primarily because of establishment of the annual *Festuca microstachys* and to some degree the perennial *Elymus triticoides* (Table 4). Cover of *F. microstachys* remained high in the wet spring of 2011 but declined in the drought year of 2012. The cover of *E. triticoides* remained relatively steady over the 3 yr, but as discussed previously this was at least partly caused by the presence of an established resident population. At the Back site, *F. microstachys* cover was less than that at the Mission site, but was likewise highest in 2010 (2.6%). This population was ephemeral and was barely, or not at all, present in 2011 and 2012. Similarly, the two seeded native broadleaf species *Eschscholzia californica* and *Acmispon americanus* established at both sites in 2010, but neither species sustained its population into 2011 and 2012.

Of the seeded species, the perennial grass *Stipa cernua* established most successfully. This species established slowly at both sites, but continued to increase steadily over time (Table 4). By 2012, *S. cernua* was the only seeded species maintaining a significant presence at either site, though more so at the Mission site (7.7% cover) than the Back site (2.4% cover).

Resident (nonseeded) species also fluctuated over the 3 yr of the study. Nonnative annual grasses significantly increased in the drought year of 2012 in both sites (Table 5). In the Mission site, the predominant forbs in 2010 included *Amsinckia intermedia*, *Heterotheca oregona*, and *Erodium cicutarium* (L.) L'Hér. ex Aiton. While both *E. cicutarium* and *H. oregona* remained widespread in the Mission site in 2011, neither was present in 2012. This was likely due both to the spring drought in the final year of the study and to some degree of suppression by the 2012 aminopyralid treatment. In contrast, both native and non-native grasses were tolerant of aminopyralid; the increase in some species following the herbicide application may reflect competitive release from yellow starthistle.

At the Back site, forb cover in 2010 was dominated by *Erodium cicutarium* and *Deinandra lobbii* (Table 5). This was presumably caused by stimulation in their germination and establishment following the 2009 prescribed burn. A number of authors have reported increases in *Erodium* (Brooks 2002, DiTomaso et al. 1999a, Stechman 1983) and tarweeds, which include species such as *D. lobbii*

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Table 4. Changes in seeded native species cover from July 20, 2010 (season following seeding) to 2012. Means are for all drill-seeded plots for all application timings (N = 36 for each mean value). Scientific nomenclature according to *The Jepson Manual. Vascular Plants of California* (Baldwin et al. 2012). Year-to-year means were separated for each species using paired *t*-tests; values in rows followed by the no letters or the same letter are not different ($\alpha = 0.05$).

			Cover at each evaluation date		
Site	Species	Plant type	July 20,2010	May 3, 2011	May 23, 2012
			%		
Mission	*Elymus triticoides*	perennial grass	3.4 b	5.4 a	4.5 ab
	Stipa cernua	perennial grass	1.1 b	0.7 b	7.7 a
	Festuca microstachys	annual grass	11.4 a	12.0 a	0 b
	Eriogonum fasciculatum	perennial forb	0	0	0
	Eschscholzia californica	annual or perennial forb	1.2 a	0.1 b	0 b
	Layia platyglossa	annual forb	0 b	0.1 a	0 b
	Acmispon americanus	annual legume	3.7 a	0.3 b	0 c
	Lupinus nanus	annual legume	0 ab	0.1 a	0 b
Back	*Elymus triticoides*	perennial grass	0 b	0 b	0.7 a
	Stipa cernua	perennial grass	0.1 b	0.1 b	2.4 a
	Festuca microstachys	annual grass	2.6 a	0.2 b	0 a
	Eriogonum fasciculatum	perennial forb	0	0	0
	Eschscholzia californica	annual or perennial forb	1.9 a	0 b	0 b
	Layia platyglossa	annual forb	0	0	0
	Acmispon americanus	annual legume	3.7 a	0 b	0 b
	Lupinus nanus	annual legume	0.1 a	0 b	0 b

(Connolly 2000, Stechman 1983, Williams 2000), following fire events. As at the Mission site, forb cover (both seeded and resident) significantly declined in 2011 and remained low in 2012 (Tables 4 and 5).

The results of the three drill seeding treatments indicate that December and January seeding timings were more successful in establishing native species. However, not all native plants were able to sustain their populations over time, and some did poorly even in the first year when rainfall was well above normal. Of the seeded species, *Stipa cernua* sustained the highest level of establishment at both sites by 2012. Although this study monitored the population of seeded species for only 3 yr after seeding, it is possible that the cover of *S. cernua* would continue to increase at the site in future years, providing long-term sustainable suppression of yellow starthistle.

Interaction of Herbicide Treatment Timing and Drill Seed Timing. Analysis of the interaction between herbicide treatment timing and the timing of native plant seeding included only the drill seeding treatments, as broadcast seeding did not show a significant increase in native plant cover (Table 3). While the previous analyses indicated that the most effective time to treat with aminopyralid was January to March, the most successful reseeding timing was December or January. When comparing the interaction among the various herbicide treatment and drill seeding timings, there was a strong interaction effect on native grass cover at both study sites.

At the Mission site in 2010 and 2011, total native grass cover was significantly higher in plots treated with aminopyralid in January and March, combined with drill seeding in December and January (Table 6). There was no increase in native grasses in plots not treated with aminopyralid. Plots drill-seeded in March had consistently lower native grass cover than December and January seeded plots, though this difference was not always significant.

In 2012, these differences were no longer readily apparent. The lack of a persistent interaction effect among seeding and treatment timings may have been due the impact of drought on *Festuca microstachys* during that growing season (Table 4). It may also have been masked by the fairly high percentage cover of resident native perennial grasses. Because *Stipa cernua* was not previously present at either site and was the only nonresident seeded species to successfully establish by 2012, we made a separate analysis of the interaction of herbicide treatment and drill seed timing on *S. cernua* cover at the Mission site (Table 7). This species established slowly; differences in cover were generally not significant during 2010 and 2011, but by 2012 *S. cernua* cover was significantly higher in plots originally seeded in January.

For the Back site, we evaluated the interaction between herbicide application and drill seed timing for the two

Table 5. Changes in most prominent resident species cover (> 1% in any year) from July 20, 2010 (season following seeding) to 2012. Means are for all drill-seeded plots for all application timings (N = 36 for each mean value). Native species are indicated in bold. Scientific nomenclature according to *The Jepson Manual. Vascular Plants of California* (Baldwin et al. 2012). Year-to-year means were separated for each species using paired *t*-tests; values followed by the same letter within each row are not different (α = 0.05).

Site	Species	Plant type	Cover at each evaluation date: July 20, 2010	May 3, 2011	May 23, 2012
			%		
Mission	*Avena barbata* Link	annual grass	1.4 ab	1.0 b	2.8 a
	Bromus diandrus Roth	annual grass	4.5 c	6.1 b	11.1 a
	Bromus hordeaceus L.	annual grass	2.1 c	7.4 b	11.8 a
	Festuca myuros L.[a]	annual grass	0.7 c	2.3 b	7.6 a
	Amsinckia intermedia	**annual forb**	1.4 a	0 b	0 b
	Erodium cicutarium	annual forb	1.4 b	8.0 a	0 c
	Heterotheca oregona	**perennial forb**	4.1 a	3.1 a	0 b
Back	*Bromus hordeaceus*	annual grass	0.4 b	2.5 a	3.4 a
	Bromus madritensis L.+ *B. tectorum* L.	annual grass	0.4 b	0.6 b	2.8 a
	Festuca myuros[1]	annual grass	0.4 c	1.2 b	9.4 a
	Cerastium glomeratum Thuill.	annual forb	0 b	1.7 a	0 b
	Croton setigerus **Hook.**	**annual forb**	1.4 a	0.2 b	0 c
	Erodium cicutarium	annual forb	4.8 a	0 b	0 b
	Deinandra lobbii	**annual forb**	21.6 a	0 b	0 b

[a] Formerly *Vulpia myuros* (L.) C.C. Gmel.

seeded native perennial grasses, *Stipa cernua* and *Elymus triticoides*. As at the Mission site, cover of the two grasses in 2010 was significantly greater with January or March aminopyralid treatments and December or January drill seed timings (Table 8). In 2011, cover was greater for January and March aminopyralid applications, but only for the December drill seed timing. In the final year of the study, 2012, cover was again greater in January and March

Table 6. Interaction of drill seed timing with herbicide application timing on total native grass cover (resident plus seeded) at the Mission site from 2010 to 2012. Separation with Student's *t*-test; within each site, values followed by the same letter are not different at α = 0.05.

Year of evaluation	Drill seed timing	Total native grass cover — Aminopyralid application timing: November	January	March	Untreated
		%			
2010	December	16.0 bcde	42.9 a	23.4 abcd	7.4 def
	January	16.0 bcde	29.9 ab	26.8 abc	9.1 def
	March	1.6 ef	10.7 cdef	3.4 ef	1.9 f
	unseeded	15.1 bcde	10.0 def	8.9 ef	8.2 ef
2011	December	18.8 bcde	30.1 abc	38.0 ab	3.9 efg
	January	26.4 abcd	27.3 abcd	47.2 a	6.1 efg
	March	1.7 fg	10.7 defg	5.9 efg	1.4 g
	unseeded	14.1 cdef	7.1 efg	17.4 cdef	10.0 efg
2012	December	4.2 b	10.3 ab	10.2 ab	4.8 b
	January	27.3 a	21.3 ab	19.2 ab	13.2 ab
	March	7.3 ab	17.0 ab	5.8 ab	5.5 ab
	unseeded	8.8 ab	10.2 ab	17.2 ab	13.7 ab

Table 7. Interaction of drill seed timing with herbicide application timing on *Stipa cernua* cover at the Mission site from 2010 to 2012. Separation with Student's *t*-test; within each site, values followed by the same letter are not different at $\alpha = 0.05$.

		Stipa cernua cover			
		Aminopyralid application timing			
Year of evaluation	Drill seed timing	November	January	March	untreated
		%			
2010	December	0 b	0 b	0.6 b	0 b
	January	0.6 b	2.7 ab	4.6 a	1.1 ab
	March	0 b	2.8 ab	0.3 b	0 b
	unseeded	0 b	0 b	0 b	0 b
2011	December	0 b	0 b	0 b	0 b
	January	0 b	0.6 ab	5.0 a	0.2 b
	March	0 b	0.6 ab	2.2 ab	0 b
	unseeded	0 b	0 b	0 b	0 b
2012	December	1.2 de	3.3 de	3.5 cde	1.0 de
	January	23.5 a	18.8 a	10.8 abc	13.2 ab
	March	4.0 bcde	6.8 bcd	2.0 de	3.7 cde
	unseeded	0 e	0 e	0 e	0 e

aminopyralid applications, and for both the January and March drill seed timings.

It is possible that the delayed positive interaction between the March drill seed timing and the January and March herbicide treatment was caused by low germination rates of the perennial grasses planted so late in the 2010 season. The seed may have maintained dormancy until the following season, established at low levels in 2011, and then established more vigorously in 2012. A similar trend was also observed at the Mission site (Table 7), although not as dramatic as at the Back site.

The results of the interaction analysis comparing herbicide treatment and drill seed timing provide a more detailed understanding of an integrated strategy for controlling yellow starthistle while establishing native perennial grasses in the South Coast Range of California.

Table 8. Interaction of drill seed timing with herbicide application timing on total native grass cover at the Back site from 2010 to 2012. Native grasses included only seeded species (*Elymus triticoides* and *Stipa cernua*). Separation with Student's *t*-test; within each site, values followed by the same letter are not different at $\alpha = 0.05$.

		Total native grass cover			
		Aminopyralid application timing			
Year of evaluation	Drill seed timing	November	January	March	untreated
		%			
2010	December	2.6 bc	10.2 a	4.2 b	0.3 c
	January	1.7 bc	9.4 a	3.5 b	0 c
	March	0 c	0.1 c	0 c	0 c
	unseeded	0 c	0.1 c	0 c	0 c
2011	December	0 c	0.9 ab	1.2 a	0 c
	January	1.0 ab	0.2 bc	0.6 abc	0 c
	March	0 c	0 c	0 c	0 c
	unseeded	0 c	0 c	0 c	0 c
2012	December	0 b	0.5 b	0 b	0.2 b
	January	5.1 a	5.2 a	4.4 a	4.1 ab
	March	2.5 ab	6.5 a	7.4 a	0.2 b
	unseeded	0 b	0.6 b	0 b	0 b

Our data indicate that treating with aminopyralid between January and March provided nearly complete control of yellow starthistle, and drill seeding in January provided the most consistently successful establishment of native perennial grasses three seasons after the treatment.

Unfortunately, no planting time resulted in sustained establishment of native annual broadleaf species or a native annual grass. Although drought is often responsible for revegetation failures (Stromberg et al. 2007), our study sites received well above average precipitation both in the season of establishment and the following season. Thus, we conclude it is more practical and cost effective to focus restoration efforts on perennial grasses in most Mediterranean climates of California.

Following fire events in Oregon rangelands infested with medusahead [*Taeniatherum caput-medusae* (L.) Nevski], Sheley et al. (2012) demonstrated that a single-entry approach at the optimum timing for both herbicide application and perennial grass seeding can reduce the cost of both operations, making revegetation of medusahead-infested rangeland more affordable. A similar strategy could be used for the management of yellow starthistle and revegetation of native perennial grasses in California. Our results from this study indicate that the combination of a January aminopyralid treatment and drill-seeding native perennial grasses offers the greatest probability of both successful yellow starthistle control and perennial grass establishment.

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