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Integrating prescribed burning and clopyralid for the management of yellow starthistle (*Centaurea solstitialis*)

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Prescribed burning and the herbicide clopyralid are very effective tools for the management of yellow starthistle. However, repeated use of either can be impractical or can present other problems. The potential solution is the development of an effective integrated weed management strategy using a combination of the two approaches. In small plot studies (0.2 ha), we tested one of five possible treatments: (1) untreated control, (2) 2 consecutive yr of clopyralid (0.105 kg ha^{-1}), (3) 2 consecutive yr of prescribed summer burning, (4) first-year clopyralid followed by second-year prescribed burning, and (5) first-year prescribed burning followed by second-year clopyralid. Treatments were made in 1999 and 2000 at three study sites in California (San Benito, Yuba, and Siskiyou counties). In 2001, the year following the final treatment, 2 consecutive yr of clopyralid or first-year burning followed by second-year clopyralid consistently reduced yellow starthistle cover in the following year by 92 to 100%. However, at the Yuba site, clopyralid alone increased medusahead and ripgut brome cover. Although 2 consecutive yr of burning was effective in Yuba, very high levels of starthistle infestation in San Benito were not completely burned in the second year because of the lack of available consumable fuel. Clopyralid treatment the first year followed by prescribed burning in the second year stimulated yellow starthistle germination and did not reduce the infestation. In a large-scale study conducted at two sites (13 and 81 ha) in southern Monterey County, we used a first-year burn followed by either 2 yr of clopyralid (0.158 kg ha^{-1}) or a single year of clopyralid (0.210 kg ha^{-1}) and a subsequent burn. Results were in close agreement with those found in the small-scale studies. In the year following the final treatment, control of yellow starthistle was greater than 99% when the burn was followed by 2 yr of clopyralid. In contrast, when a prescribed burn was used in the last year of the program, the level of control was not as good, probably because of the increased germination of the remaining soil seedbank. These results indicate that a first-year prescribed burn followed by a second-year clopyralid treatment can provide consistently good control of yellow starthistle, as well as reduced levels of noxious annual grasses, including medusahead and ripgut brome.

Nomenclature: Medusahead, *Taeniatherum caput-medusae* (L.) Nevski ELYCM; ripgut brome, *Bromus diandrus* Roth BRODI; yellow starthistle, *Centaurea solstitialis* L. CENSO.

Key words: Fire, grassland, invasive plant management, rangeland, seedbank, species richness.

Yellow starthistle is an exotic noxious weed that is one of California's worst rangeland and grassland problems. Since its introduction near the San Francisco Bay Area in about 1850, it has spread steadily throughout California and other western states (Gerlach 1997; Maddox 1981; Maddox and Mayfield 1985). The plant currently infests approximately 5 million ha of rangeland, native grassland, orchards, vineyards, pastures, roadsides, wasteland areas, parks, and wildlands in California (DiTomaso et al. 1999a; Pitcairn et al. 1997) and an estimated 6 million ha in the 17 western states (Duncan and Clark 2005). Although soil disturbance and high light favor its establishment, yellow starthistle is also capable of invading areas undisturbed by humans or livestock activity (DiTomaso et al. 1999a) and has invaded a number of relatively pristine nature preserves.

Several control methods have been developed to manage yellow starthistle in California, including mowing (Benefield et al. 1999; Thomsen et al. 1997); animal management, such as timed grazing by sheep, goats, and cattle (Thomsen et al. 1993); competitive planting of grasses and clovers to prevent seedling recruitment (Enloe et al. 2005; Thomsen et al. 1996); large-area burns (DiTomaso et al. 1999a; Miller 2003); PRE and POST herbicides (DiTomaso et al. 1999b); and biological control (Pitcairn et al. 2004; Turner and Fornasari 1992). Of these, prescribed burning and the herbicide clopyralid have proven to be most successful for control of large yellow starthistle infestations. Despite their success, management efforts must be continued for at least 3 yr to significantly deplete the soil seedbank.

Fire has long been an important factor in the development and continuance of most grassland systems (Vogl 1974). Our previous results indicate that periodic burning in California grassland ecosystems can reduce yellow starthistle infestations, enhance native plant diversity, and increase survival of competitive native perennial grasses (DiTomaso et al. 1999a; Miller 2003). However, prescribed burning is not without risks. Grassland fires can negatively impact air quality, compromise establishment of biological control agents, and lead to catastrophic wildfires should they escape containment. Consequently, repeated use of prescribed burning is often discouraged, and permits are difficult to obtain. In addition, it is often difficult to burn 2 consecutive yr due to an inadequate fuel load the second year.

Clopyralid at low rates (105 to 280 g ha^{-1}) provides excellent control of yellow starthistle seedlings and rosettes (DiTomaso et al. 1999b). In addition to its foliar (POST) activity, clopyralid can also have season-long soil (PRE) activity. With this combination of PRE and POST activity, effective control can be achieved under a wide application-timing window, extending from December through April (DiTomaso et al. 1999b). Maximal grass forage production, however, occurs when treatments are made between January and March in most locations in California.

Despite the effectiveness of clopyralid for yellow starthistle management, continuous use of the herbicide can lead to other problems. For example, legume species are important components of rangelands, pastures, and wildlands, and repeated clopyralid use over multiple years can have a long-term detrimental effect on their populations. In addition, repeated applications can select for other undesirable species, particularly annual grasses, such as medusahead, ripgut brome, or barb goatgrass (*Aegilops triuncialis* L.). Furthermore, a Washington population of yellow starthistle developed resistance to repeated use of picloram, and this population was also cross-resistant to clopyralid, which has a similar mode of action (Callihan and Schirman 1991; Miller et al. 2001). Thus, the potential exists for the development of resistance to clopyralid if the herbicide is used year after year.

Integrating or rotating multiple control methods into a management strategy can minimize the probability of selecting for other noxious weed species, developing herbicide resistance, or suppressing legume populations. The objectives of this study were to evaluate the impact of clopyralid, prescribed burning, and combinations of these two methods on yellow starthistle control and rangeland health, as determined by changes in plant diversity and desirable forage quality and quantity. The long-term goal of this work is to develop a sustainable, integrated management approach that maximizes yellow starthistle control while optimizing rangeland function.

Materials and Methods

Small-scale Study

Site Establishment

The experimental plan was replicated at one site in each of three counties in 1999: San Benito, Yuba, and Siskiyou, California. These sites represent three different ecosystems, including coastal range, Sierra Nevada foothills, and the intermountain region. At each location, a 3.2 to 4 ha area, heavily infested with yellow starthistle, was separated into 15 plots, each approximately 0.2 ha (30 by 60 m). Five treatments (three replicates each) were established in a randomized complete-block design. The treatments included (1) untreated control, (2) 2 consecutive yr of late winter or early spring clopyralid at 0.105 kg ae ha^{-1} (lowest labeled rate), (3) 2 consecutive yr of summer burning, (4) first-year burn followed by a second-year clopyralid treatment (0.105 kg ha^{-1}), and (5) first-year clopyralid treatment (0.105 kg ha^{-1}) followed by a second-year burn. Burned plots were disked or sprayed along margins (3 to 4 m strip) to create a firebreak. Prescribed burns were conducted in collaboration with the California Department of Forestry and Fire Protection. All burns were conducted between June and July when plants were in the very early flowering stage, before viable seed production. Herbicide treatments were made in March or April when plants were in the rosette stage, before bolting. Clopyralid treatments were applied using an all-terrain vehicle (ATV; and a tractor at Siskiyou County) with a pull-behind sprayer set for 207 kPa. The spray boom carried 19, 80015 nozzles and applied a 9.6-m swath. Treatments were applied in 94 L ha^{-1} total spray solution.

In the third year of the project (2001), plots were not treated. Recovery of yellow starthistle, other vegetation, and biocontrol agents were monitored as described below.

Yellow Starthistle Control

Yellow starthistle seedling density was evaluated in late winter (February), before bolting. Seedlings were counted in randomly thrown 20-cm-diam rings in each sampling area (10 replicates per sampling area). Yellow starthistle vegetative cover was also estimated in spring and in early summer using the line-intercept technique described below.

Species Composition

During spring (April and May, the optimal identification timing for most plant species) and early summer (June and July, just before burning), the percentage of vegetative cover and plant diversity were estimated using a line-intercept technique. Plant species that intersected points at 30-cm intervals along a 15-m transect were recorded along three transects in each plot. Species richness was determined by comparing the total number of plant species in nested quadrats (0.25, 1, and 4 m^2).

Forage Quality and Quantity

Forage yield in each plot was measured in spring each year to estimate the amount of forage potentially available to grazing livestock. Aboveground plant biomass samples were harvested from three randomly tossed 0.25-m^2 quadrats per plot. Yellow starthistle stems were counted in each sample to give a density estimate. The samples were dried, weighed, and subsamples analyzed[1] for nutritive values (total nitrogen, crude protein, lignin, and acid detergent fiber (ADF 3%). Crude protein and total nitrogen were measured with a LECO FP-528 nitrogen gas analyzer[2] using an induction furnace and thermal conductivity detector. Lignin and ADF were measured with the reflux method using sulfuric acid and heat.

Seed-bank Dynamics

Of the three study sites, the San Benito County site had the densest infestation of yellow starthistle. At that site, the seedbank of yellow starthistle was determined after seed dispersal in fall (October). Five soil-sample cores (5 cm in diameter by 5 cm deep) per plot were collected. Seeds were removed from the soil-core sample through a water–air elutriation process (see DiTomaso et al. 1999a; Kyser and DiTomaso 2002). In brief, soil and seeds were separated by flushing water through a series of sieves with mesh sizes from 0.8 to 2 mm. Processed soil and seed samples were then dried at 60 to 66 C (140 to 151 F), and yellow starthistle seeds were sorted and identified. Each seed was ruptured using forceps, and seeds with moist endosperms were counted as viable parts of the seedbank.

Impact on Biological Control Agents

In the first year (1999), baseline data on biocontrol agents was collected by randomly bagging 90 seed heads immediately after full bloom in late July to early August in areas surrounding the plots. In 2002, 1 yr after the final treatment, treatment effects were monitored by bagging at least 125 seed heads from randomly selected plants in all treatment plots that contained yellow starthistle. After 3 to 4 wk, the bagged seed heads were collected. All bagged and collected seed heads were taken to the laboratory and dissected. Filled seeds were counted in each seed head, along with species, number, and life stage of bioagents, particularly hairy weevil (*Eustenopus villosus*) and false peacock fly (*Chaetorellia succinea*). These two introduced insects are the most effective of the introduced yellow starthistle biocontrol agents and are widespread in northern California.

Large-scale Study

Site Establishment

Two study sites were chosen at Fort Hunter Liggett (FHL) in Monterey County, CA, including a highly disturbed, military-use grassland (Training Area [TA] 15; 81 ha) and a disturbed wildland grassland surrounded by oaks (TA 27; 13 ha). Both treatment sites had a corresponding, adjacent, untreated site similarly evaluated for comparison. All untreated sites were much smaller than the treated areas (< 5 ha).

Transects were established at each study site to monitor yellow starthistle control and the vegetation community in 2000, 2001, and 2002. Twelve 100-m permanent transects were established in each treatment site in areas with high levels of yellow starthistle cover (20 to 70%). Transect starting and ending points were recorded using a global positioning system (GPS) receiver. Four 100-m permanent transects were established in each of the adjacent untreated sites.

Each treatment site received a first-year prescribed burn in 1999 and a second-year clopyralid treatment in 2000. In the third year, TA 15 received a second herbicide treatment, whereas TA 27 was again burned. Herbicide applications and prescribed fire were administered during spring and summer, respectively.

A fixed-wing biplane was used for clopyralid applications in the spring of 2000. In 2001, a helicopter equipped with ArcView Geographical Information Systems (GIS) Software[3] and on-aircraft Trimble GPS[4] was used at TA 15. The helicopter allowed for ease of mobility, and the advanced technology made for improved delivery of clopyralid to the treated sites. Prescription burning was conducted by the Fort Hunter Liggett Fire Department.

Various characteristics of yellow starthistle and the overall vegetation were quantified four times each year. These included measurements of late-winter yellow starthistle seedling density; total vegetation cover in the spring; summer-mature yellow starthistle frequency, density, and biomass; and fall yellow starthistle seedbank.

Seedling Density

In late February or early March each year, yellow starthistle seedling densities were estimated at each treated and untreated site. Pin flags were used to prevent bias that might occur from tossing rings that could bounce away from large yellow starthistle skeletons. The pin flags were randomly tossed, and at the point where the base of the flag contacted the soil, a 20-cm-diam ring was placed on the soil and each yellow starthistle seedling was counted and recorded. Forty rings were counted per treated area and 20 rings per untreated area. Average totals were represented as seedlings m^{-2}.

Spring Vegetation Cover

During April or May of each year (depending upon peak flowering time), vegetation frequency data were collected using a line-intercept method. Species were recorded at points every 2 m along 12, 100-m transects (50 points per transect) in the treated sites and four transects in the untreated control sites. All species contacting a meter stick perpendicular to the soil surface were recorded at each transect point. Cover values were grouped into vegetation classes and are reported here as legumes, annual grasses, forbs, and yellow starthistle. Forbs are defined as all other plants excluding grasses, legumes, and yellow starthistle.

Summer Yellow Starthistle Cover, Density and Biomass

During late June or early July, yellow starthistle cover, density, and biomass were monitored. Percentage of cover was obtained using the line-intercept method previously described. At three to five random locations along each transect, yellow starthistle plants in a 0.25-m^2 quadrat were counted, clipped, and bagged. Twelve transects were sampled per treated site, and four transects per untreated site. Each quadrat sample was dried in an oven at 60 C for 24 to 48 h and weighed. These sample values were used to determine yellow starthistle density and biomass.

Seed-bank Dynamics

In late October of 2000 and 2001, after most annual species had dispersed seed, soil samples were collected to estimate the quantity of yellow starthistle seeds in the seedbank. Two to four soil cores (5 cm diameter by 5 cm deep) were gathered from all sampling transects at each site, for a total of 16 samples in the untreated area and 48 samples in the treated area. Soil-core samples were elutriated as previously described. Average seed counts were represented as seeds m^{-2}.

Data Analysis

Multiple analysis of variance, followed by individual analysis of variance, was used to make across-treatment comparisons for vegetative cover of yellow starthistle, grasses, forbs, and native species; total biodiversity; and yellow star-

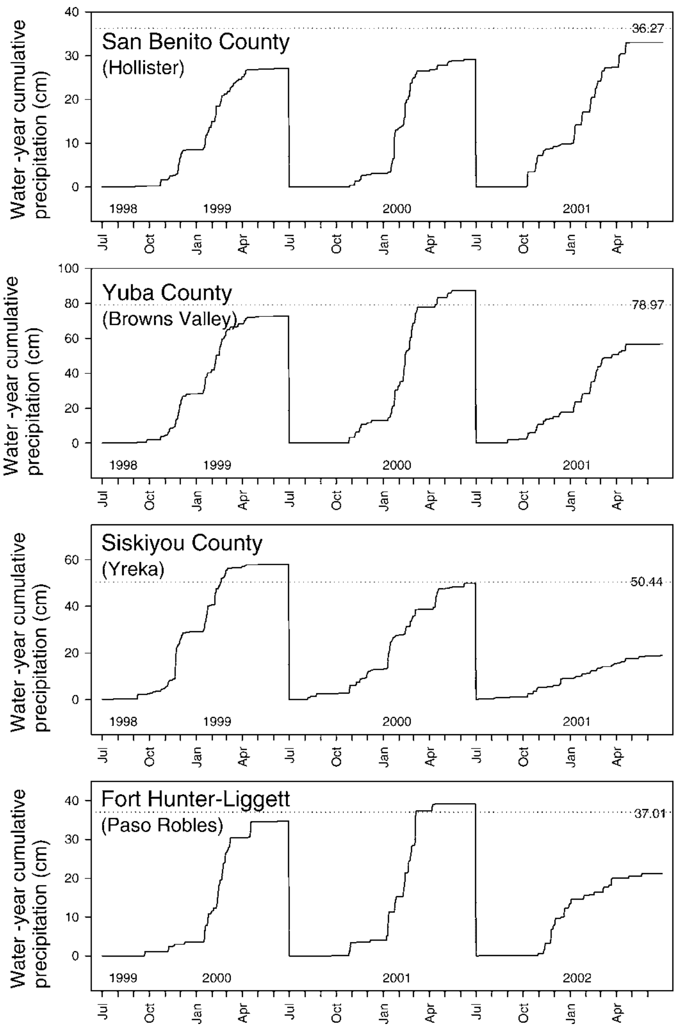

FIGURE 1. Cumulative annual precipitation for all field sites during trial years. Y-axis scale is different for different sites.

thistle seedbank and seedling density in both the small and large (Ft. Hunter Liggett) plot study areas. Quadrat species-richness values were plotted on a log-log scale, and the lines for each treatment compared statistically using multiresponse permutation procedures (MRPP). MRPP is a statistical technique that allows comparison of predetermined groups without relying on distributional assumptions (Mielke et al. 1981). Biological control agents were compared among treatments within locations by using Student–Newman–Keul's test.

Results and Discussion

Small-scale Study

Rainfall patterns at the three study sites differed dramatically over the 3-yr period of the study (1999 to 2001) (Figure 1). At the San Benito County site, all 3 yr experienced less than average rainfall (75, 80, and 91% of 30-yr mean in 1999, 2000, and 2001, respectively). At the Yuba County study site, rainfall was near average in 1999 (92% of mean), above average in 2000 (111% of mean), and far below average in 2001 (72% of mean). The most significant differences were seen in the rainfall patterns at the Siskiyou County study site. Although rainfall at that site was above average in 1999 (115% of mean) and exactly average in 2000 (100% of mean), the rainfall amount in 2001 was one of the lowest on record at only 38% of average. Because all three sites experienced drought in the year after the final treatment, 2001 seedling counts (except San Benito) and summer yellow starthistle plant density were lower than in 1999 and 2000 at all the experimental sites (Table 1), particularly in Yuba and Siskiyou counties. In Siskiyou County, no yellow starthistle plants survived beyond the rosette stage in 2001.

Based on the seedling density in the year following the treatments, the best overall strategy was a first-year prescribed burn followed by a second-year clopyralid application (Table 2). In San Benito County, burning followed by clopyralid gave complete control of winter seedlings, spring rosettes, and summer-mature yellow starthistle populations the following year, whereas 2 yr of clopyralid gave 95, 97, and 91% control of winter seedlings, spring rosettes, and summer-mature plants, respectively (although these treatment differences were not significant). Similar results were obtained in Yuba County for the 2 yr of clopyralid and the burn-and-clopyralid treatment, although the population of yellow starthistle was considerably less than San Benito County.

Both San Benito and Yuba county sites demonstrated that a first-year clopyralid treatment followed by a second-year prescribed burn is not an effective integrated approach for yellow starthistle management (Table 2). Although there was a statistical reduction in seedlings and late-spring vegetative cover in San Benito County, summer vegetative cover was similar to that of the untreated control plots, and the summer biomass of yellow starthistle in the clopyralid-and-burn plots was significantly greater than in the untreated plots. This difference was even more pronounced at the Yuba County study site where summer cover, density, and biomass

TABLE 1. Density of yellow starthistle plants in untreated control plots (plants m^{-2}), ± SD, and percentage of normal seasonal rainfall. Seedlings were counted in late spring, mature plants in midsummer.

	1999			2000			2001		
Site	Seedling	Mature (survival)	Normal rainfall	Seedling	Mature (survival)	Normal rainfall	Seedling	Mature (survival)	Normal rainfall
			%			%			%
San Benito	857 ± 195	205 ±171 (24%)	75	810 ± 224	345 ± 150 (43%)	80	1192 ± 357	174 ± 75 (15%)	91
Yuba	419 ± 217	55 ± 29 (13%)	92	170 ± 96	98 ± 51 (58%)	111	68 ± 33	3 ± 1 (4%)	72
Siskiyou	140 ± 38	28 ± 17 (20%)	115	214 ± 44	23 ± 12 (11%)	100	76 ± 30	0 (0%)	38

Table 2. Yellow starthistle measurements in 2001 following the final year of treatments (2000). Values within a column followed by the same letter are not different (Fisher's protected LSD test, $\alpha = 0.05$). Densities were highly variable at the Yuba site; therefore, differences were not significant. Spring drought at Siskiyou resulted in high mortality of starthistle plants.

Site treatment (1999/2000)	Early spring	Late spring	Summer		
	Density	Vegetative cover	Vegetative cover	Density[a]	Biomass
	seedlings m^{-2}	%	%	plants m^{-2}	g dry wt m^{-2}
San Benito County					
Control	1,192 b	73.8 a	22.4 a	174.2 ab	38.2 b
Burn/burn	1,792 a	60.7 b	9.3 b	105.8 b	32.0 bc
Burn/clopyralid	0 d	0.0 c	0.0 b	0 b	0.0 c
Clopyralid/burn	563 c	59.3 b	22.0 a	333.3 a	87.1 a
Clopyralid/clopyralid	55 d	2.4 c	2.0 b	1.8 b	1.3 c
Yuba County					
Control	68	11.6 ab	4.7 b	2.7	1.8 b
Burn/burn	0	0.2 b	0.9 b	1.8	2.2 b
Burn/clopyralid	0	0.2 b	0.0 b	0	0.0 b
Clopyralid/burn	90	20.0 a	25.3 a	106.2	77.3 a
Clopyralid/clopyralid	1	0.7 b	1.6 b	0.4	0.4 b
Siskiyou County					
Control	76 a	2.9	0	⟨n⟩	0
Burn/burn	27 b	0.0	0	⟨n⟩	0
Burn/clopyralid	5 b	0.0	0	⟨n⟩	0
Clopyralid/burn	15 b	0.4	0	⟨n⟩	0
Clopyralid/clopyralid	6 b	0.0	0	⟨n⟩	0

[a] Abbreviation: ⟨n⟩, insufficient numbers for analysis.

of yellow starthistle in the clopyralid-and-burn plots were 5, 39, and 43 times greater than in untreated control plots. We hypothesize that the poor control with a final year burn was because of stimulation in yellow starthistle germination after burning, followed by more vigorous growth in spring and early summer. With a first-year burn, germination would similarly be stimulated, but these seedlings would be controlled by the second-year herbicide treatment.

Interestingly, although 2 consecutive yr of burning provided excellent control of yellow starthistle in Yuba County, this sequence was not effective in San Benito County because of an incomplete burn in the second year at the San Benito site. The first-year burn removed all litter fuel. In the second year, because the initial population of yellow starthistle was so dense (205 plants m^{-2}) and the seedbank so well developed, the site was completely dominated by yellow starthistle at a mean density of 345 plants m^{-2}. As a result, there was little other vegetation available to provide dry fuel. Apparently, multiple years of burning are only effective when consumable fuel is available in later years. This is more likely when a good stand of annual grasses is also present, as was the case at the Yuba County study site.

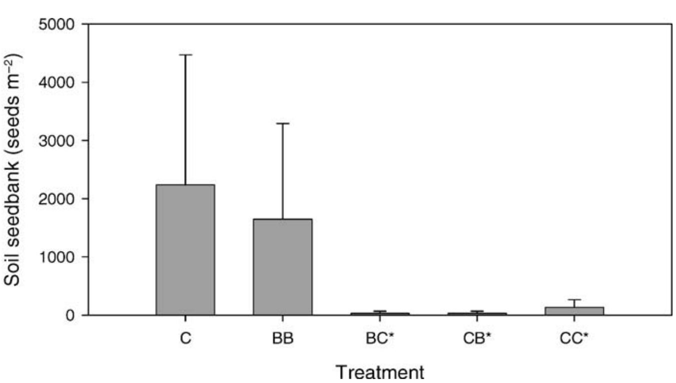

Figure 2. Soil seedbank in San Benito County plots in fall 2000, following final treatment. Abbreviations: C, untreated control; BB, burned 2 yr; BC, burned followed by clopyralid in the second year; CB, clopyralid followed by burn; and CC, clopyralid 2 yr. Error bars represent standard deviation. Asterisk indicates significant different from control (Fisher's protected LSD test, $\alpha = 0.05$).

Because yellow starthistle is an annual, successful management of the species depends upon reducing the soil seedbank. This requires multiple, consecutive years of control. In previous research (DiTomaso et al. 1999a), we have demonstrated that a single year of prescribed summer burning reduced yellow starthistle soil seedbank by 74%, and 3 consecutive yr of burning reduced the seedbank by more than 99%. Although the three treatments that integrated clopyralid nearly eliminated the seedbank of yellow starthistle by the fall of 2000 (Figure 2), the 2-yr burn treatment did not lead to a seed-bank reduction. The incomplete burn at San Benito in 2000 allowed the seedbank to recover in the following year.

At the Siskiyou County site, the severe drought in 2001 prevented yellow starthistle seedlings from progressing to maturation. However, seedling density data provide support for the findings at the other two sites. Although there were no statistical differences among the burn and clopyralid treatments, seedling density in the burn-and-clopyralid and clopyralid-and-clopyralid plots 1 yr following the final treatment was three times or greater that of the clopyralid-and-burn plots (Table 2). In all treatments, however, seedling densities were significantly reduced compared with the untreated control plots.

Although clopyralid is a growth-regulator herbicide, ef-

TABLE 3. Spring vegetative cover and forage weight of plants other than yellow starthistle in 2001, following final year of treatments. Values within a column followed by the same letter are not different (Fisher's protected LSD test, α = 0.05) for each vegetation type.

Site treatment (1999/2000)	Vegetative cover			Forage biomass
	All grasses	Legumes	Forbs[a]	
	%			g dry wt m^{-2}
San Benito County				
Control	81.8 b	20.9 bc	7.1 b	147.1 bc
Burn/burn	48.9 c	32.4 ab	39.8 a	96.0 bc
Burn/clopyralid	90.4 ab	0.9 c	65.3 a	152.0 b
Clopyralid/burn	69.3 bc	43.3 a	36.9 ab	87.1 c
Clopyralid/clopyralid	106.2 a	0.9 c	39.3 a	262.2 a
Yuba County				
Control	116.4 a	14.9 b	24.7 bc	296.9 a
Burn/burn	32.4 b	19.3 b	114.7 a	138.2 c
Burn/clopyralid	112.2 a	16.4 b	62.2 b	248.0 ab
Clopyralid/burn	55.1 b	53.1 a	105.1 a	197.3 bc
Clopyralid/clopyralid	127.3 a	6.2 b	20.0 c	295.6 ab
Siskiyou County				
Control	31.1 b	0.2	4.0	9.7
Burn/burn	37.3 ab	0.0	2.7	10.5
Burn/clopyralid	32.9 ab	0.0	1.1	12.4
Clopyralid/burn	32.0 ab	0.0	3.1	9.1
Clopyralid/clopyralid	41.1 a	0.2	3.1	14.1

[a] Plants, other than grasses, not including yellow starthistle or legumes.

fective on broadleaf species, it is considered to be fairly selective, even among dicots (DiTomaso et al. 1999b). It is particularly active on members of the legume (Fabaceae) and sunflower (Asteraceae) families. In contrast, grassland fires are well recognized to cause a transitory increase in legumes and other broadleaf species (e.g., *Erodium* spp.) (DiTomaso et al. 1999a; Kyser and DiTomaso 2002). In this study, all treatments, regardless of the application sequence or whether they were combined, increased nonleguminous forb cover (excluding yellow starthistle) in the year after the final treatment at the San Benito site (Table 3). A similar result was obtained in the Yuba site, except for the 2 yr of clopyralid treatment.

The percentage of vegetative cover of legumes showed a different response between the San Benito and Yuba sites. At San Benito, legume cover was lowest in plots with a final-year clopyralid treatment and highest in plots with a final-year burn treatment. Untreated control plots were intermediate; although not statistically significant, the control plots had 23 times more legume cover than the final-year clopyralid-treated plots. In contrast, legume cover in the treated plots at the Yuba site was not lower than in the untreated plots. At this site, the clopyralid-and-burn plots had more legumes than all other treatments. The predominant legumes at the San Benito site were hairy vetch (*Vicia villosa* Roth) and California burclover (*Medicago polymorpha* L.), both of which, we have observed to be very sensitive to clopyralid. By comparison, the predominant legume at the Yuba site was rose clover (*Trifolium hirtum* All.), which is less sensitive.

The continuous use of clopyralid was expected to have a negative impact on legume populations but to increase the composition of annual grasses. This was supported by results from all three study sites (Table 3). In all cases, the greatest grass cover in spring was in the plots treated 2 consecutive yr with clopyralid. At the San Benito and Yuba sites, this was not different from the burn-and-clopyralid (first-year burn and second-year clopyralid) treatment. Few perennial grasses were present at any of the three sites; thus, total grass cover was primarily annual grasses.

Forage biomass at the San Benito site was highest in the 2-yr clopyralid-treated plots (Table 3). This was because of the increase in annual grass production that replaced yellow starthistle. The lowest forage levels were in the clopyralid-and-burn and burn-and-burn plots. In Yuba County, the clopyralid-and-clopyralid plots also had high forage biomass, along with the burn-and-clopyralid and the untreated control plots. The lowest forage biomass was again in the two treatments where a burn was conducted in the final year. Because of the drought in Siskiyou County, the forage biomass was very low and not statistically different among treatments. In general, the clopyralid treatments resulted in the highest forage biomass, primarily composed of annual grasses. Burning treatments in the final year produced the lowest yields, but this appears to be a transient response. For example, when the first-year burn was followed by a second-year clopyralid treatment at San Benito, forage yield was statistically higher than in the reverse treatment. Likewise, in Yuba County, the burn-and-clopyralid treatment was not significantly different from the 2 yr of clopyralid treatment.

Results of forage nutritive quality analysis showed no statistical differences among treatments at each site (data not shown). Thus, regardless of the combination of treatments, analytical techniques indicated no impact on forage quality at this spring timing. However, forage quality in terms of palatability may be greatly improved with the elimination of starthistle spines following control of yellow starthistle.

Plant species richness was also affected by the different treatments. At the San Benito site, 2 consecutive yr of clopyralid gave statistically lower species richness compared with either clopyralid-and-burn or 2 yr of burning (Figure 3). Similar results were obtained at the Yuba site, but in that

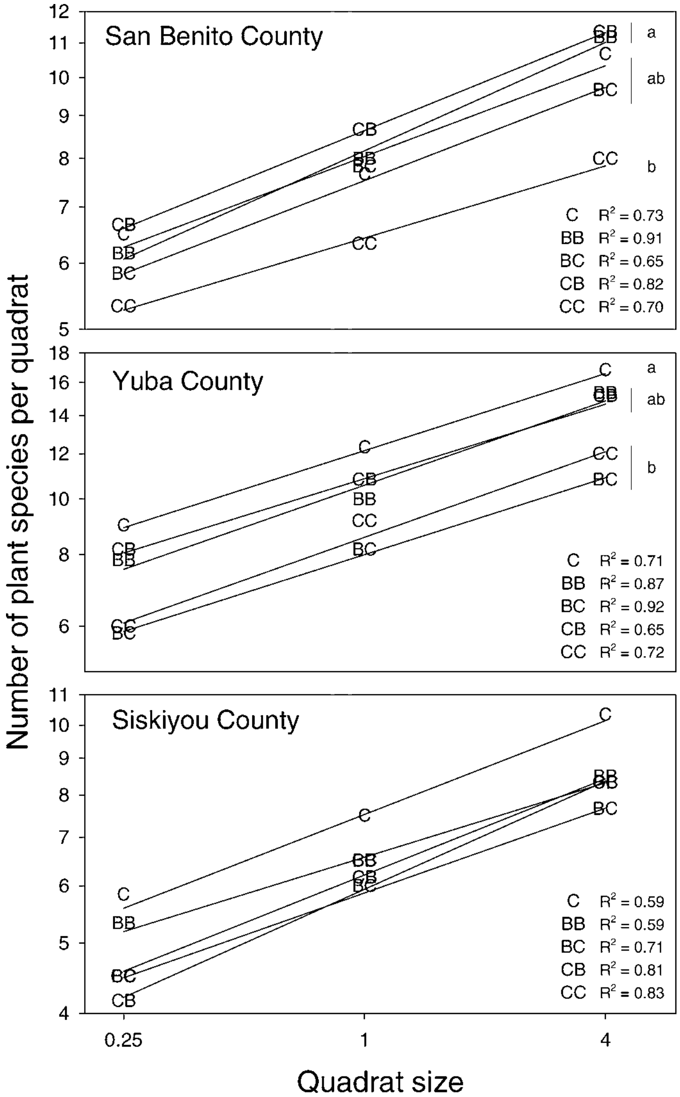

FIGURE 3. Plant species richness in nested quadrats, spring 2001, 1 yr after final treatment (log–log plot). Abbreviations: C, untreated control; BB, burned 2 yr; BC, burned followed by clopyralid; CB, clopyralid followed by burn; and CC, clopyralid 2 yr. Points are means of three replications; regressions are based on all data. Point sets followed by the same letter are not different at $\alpha = 0.05$, determined by multiresponse permutation procedures. There were no statistical differences at Siskiyou County site.

case, both treatments that included a final year clopyralid had significantly fewer species than either the control or final-year burn treatments. There were no significant differences at the Siskiyou County study site.

Among the more common species co-occurring with yellow starthistle at the Yuba site were the two noxious annual grasses, medusahead and ripgut brome. In 1999, 2000, and 2001, spring cover of medusahead in the untreated plots averaged 40, 21, and 13%, respectively, whereas ripgut brome cover averaged 5, 5, and 22%, respectively. In spring, following the last year of treatment, medusahead cover and ripgut brome cover were 49 and 30% higher in the 2-yr clopyralid-treated plots compared with the untreated control, respectively (Figure 4). Although this was not statistically higher, the trend supported our hypothesis that continuous clopyralid would increase the proportion of invasive grasses relative to the untreated site. In contrast, burning

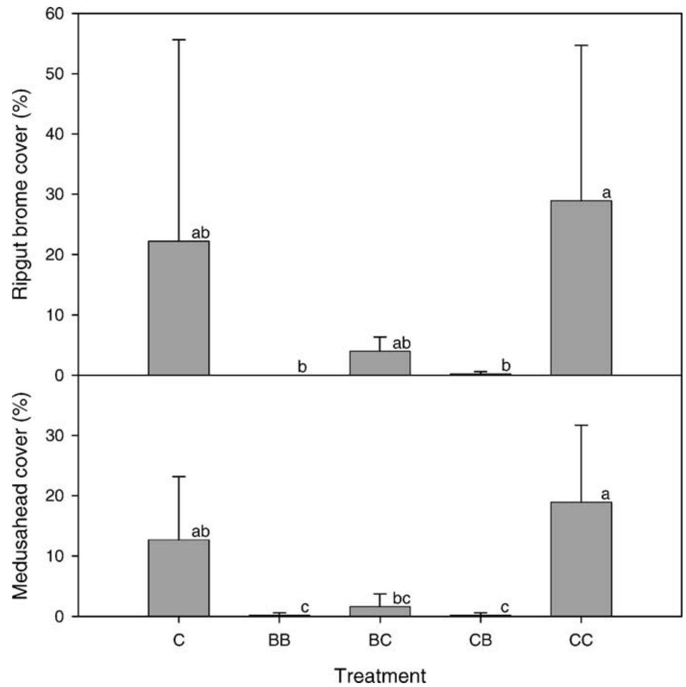

FIGURE 4. Cover of noxious annual grasses (ripgut brome and medusahead) at Yuba County site. Abbreviations: C, untreated control; BB, burned 2 yr; BC, burned followed by clopyralid; CB, clopyralid followed by burn; and CC, clopyralid 2 yr. Error bars represent standard deviation. Within each graph, values labeled with the same letter are not significantly different (Fisher's protected LSD test, $\alpha = 0.05$).

was very effective for the control of both medusahead and ripgut brome. Previous studies have similarly shown prescribed burning to be an effective tool for the management of ripgut brome (Kyser and DiTomaso 2002) and medusahead (George 1992; McKell et al. 1962).

There is some concern that either prescribed burning or clopyralid may negatively impact the presence and activity of yellow starthistle biological control insects. In 2001, the year following the final treatment, attack rates of the two most effective biocontrol agents (hairy weevil and false peacock fly), were measured in a subset of flower heads within each treatment plot at the San Benito and Yuba sites. In all treatments where yellow starthistle was present, there was no significant reduction in the attack rates of false peacock fly (Table 4). For hairy weevil, attack rates were high in all measured plots, but were highest in the plots incorporating a burn in San Benito County. Thus, despite the likely death of larvae within the seed heads of yellow starthistle in the burned site the previous year, new recruitment of bioagents the following year was rapid.

Based on these results, effective management of yellow starthistle can be achieved by using multiple approaches. Although 2 consecutive yr of early summer burning were very effective in areas where fuel was available due to senesced competing vegetation, burning was not possible where yellow starthistle populations were so dense that little consumable fuel was available in the second year. Furthermore, 2 yr of burning gave reduced forage yields in the year following the second burn. Consecutive years of clopyralid treatment also provided good control of yellow starthistle and increased total forage. However, that approach can reduce total species richness and can increase the density of

TABLE 4. Biocontrol agent infestation rates of yellow starthistle seed heads, in summer 2001, following completion of treatments. Columns with different letters represent statistically significant difference (α = 0.05) using Student-Newman-Keul's test for each site. When not indicated, differences are not significant.[a]

	Heads infested with biocontrol agents		Seed heads collected and evaluated
	Eustenopus villosus	*Chaetorellia succinea*	
	%	%	No.
San Benito County			
Control	90.9 b	6.4	137
Burn/burn	99.1 a	12.7	125
Burn/clopyralid	⟨n⟩	⟨n⟩	⟨n⟩
Clopyralid/burn	96.2 a	5.5	170
Clopyralid/clopyralid	⟨n⟩	⟨n⟩	⟨n⟩
Yuba County			
Control	65.7	12.9	206
Burn/burn	59.1	21.7	175
Burn/clopyralid	⟨n⟩	⟨n⟩	⟨n⟩
Clopyralid/burn	73.3	12.7	222
Clopyralid/clopyralid	70.3	18.0	146

[a] Abbreviation: ⟨n⟩, insufficient numbers for analysis.

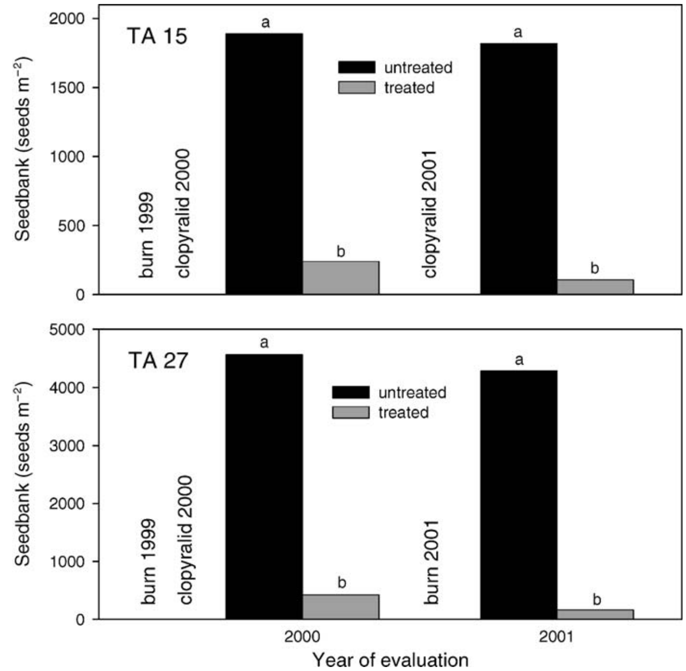

FIGURE 5. Yellow starthistle seed-bank densities at Fort Hunter Liggett. Timing of treatments is indicated. Bars labeled with the same letter are not significantly different (P ≤ 0.05) within sites.

noxious annual grasses. Generally, the most effective approach for yellow starthistle management is an integrated strategy using prescribed burning in the first year, followed by clopyralid the following winter or spring. This combination not only gave the best control of yellow starthistle but also resulted in excellent forage levels in the year following treatment. In addition, the integrated approach reduced the starthistle seedbank to very low levels in 2 yr, stimulated broadleaf cover without concurrently reducing annual grass cover, and provided effective control of noxious annual grasses. In some cases, the integrated approach reduced total species richness and legume cover, but these effects were likely transient.

Large-scale Study

Rainfall patterns in both 2000 and 2001 were close to normal (Figure 1), but in the year after the final treatment (2002), the area experienced a significant drought, receiving only 57% of average annual precipitation.

In 2001, following a first-year burn and a second-year clopyralid treatment, summer vegetative cover of yellow starthistle at TA 27 was only 3%, compared with 41% in an adjacent untreated control site; in the treated site at TA 15, yellow starthistle was completely absent, compared with 31% cover in the untreated control. In the small-scale study, this same integrated approach gave 100% control at both San Benito and Yuba counties.

Yellow starthistle seedbanks were measured in fall (2001) following the final treatment at both TA 15 and 27 (Figure 5). Results were very similar, regardless of whether the final treatment was a second clopyralid treatment (TA 15) or prescribed burn (TA 27). The 2001 estimates show a 94 and 96% reduction in the yellow starthistle soil seedbank in TA 15 and 27, respectively. This is similar to that found in the small-scale plot study (Figure 2), as well as the values reported for 2 consecutive yr of burning in a study conducted in Sonoma County (DiTomaso et al. 1999a).

Starthistle seedling densities supported the hypothesis that burning stimulates germination of much of the remaining residual seedbank in the subsequent rainy season. At TA 15, yellow starthistle seedling density in late winter 2000 increased 2.3-fold following the 1999 burn, compared with the adjacent untreated control site (Figure 6). Although not

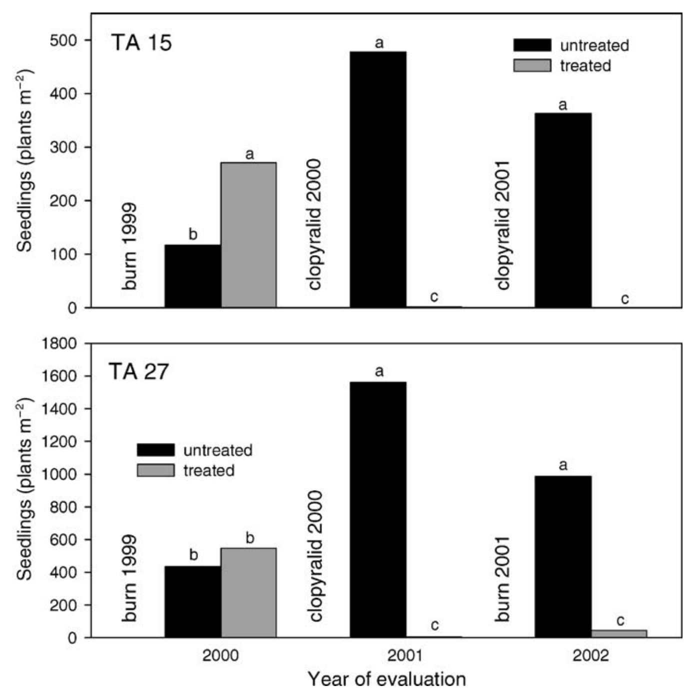

FIGURE 6. Yellow starthistle seedling densities in spring. Timing of treatments is indicated. Bars labeled with the same letter are not significantly different (P ≤ 0.05) within sites.

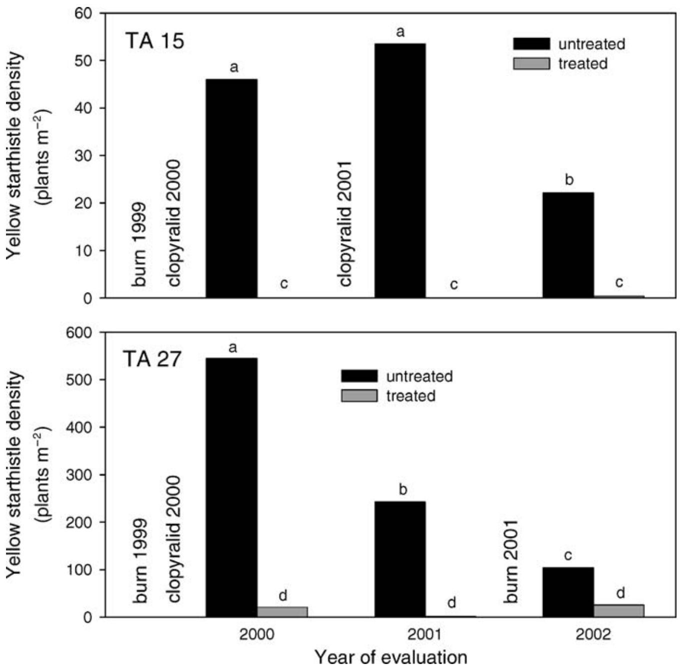

FIGURE 7. Yellow starthistle mature-plant densities in summer. Timing of treatments is indicated. Bars labeled with the same letter are not significantly different (P ≤ 0.05) within sites.

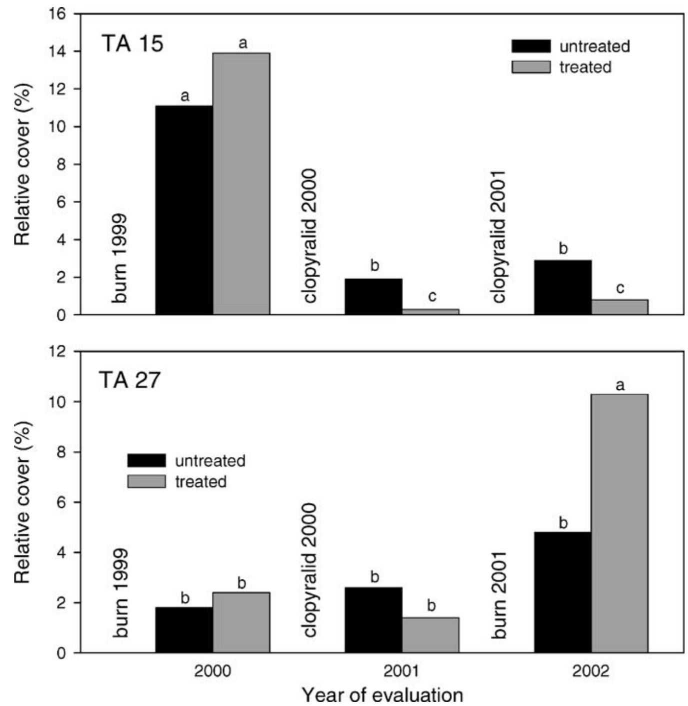

FIGURE 8. Relative cover of legume species. Timing of treatments is indicated. Bars labeled with the same letter are not significantly different (P ≤ 0.05) within sites.

statistically significant, seedling density at TA 27 also increased by 26% compared with the untreated site. The density of seedlings in late winter 2001, after the second-year clopyralid treatment in spring 2000, was dramatically reduced by 99.6% in both TA 15 and 27. These results are in close agreement with the small-scale plot study (Table 2), which showed a 100% reduction in seedlings after a similar control combination. A third-year clopyralid treatment at TA 15 gave a bit more seedling suppression, resulting in a 99.8% reduction compared with untreated control plots. By comparison, when a third-year burn was conducted at TA 27, the relative suppression of yellow starthistle seedlings decreased. In this case, the seedling reduction was only 95.4%. Although this is not significantly different from the previous year, it again supports the presumption that burning stimulates yellow starthistle germination.

The density of mature yellow starthistle plants was measured in midsummer of 2000, 2001, and 2002 (Figure 7). At TA 15, the level of control after a single burn (1999) and clopyralid treatment (2000) was 100%. A second clopyralid treatment in 2001 continued to provide 100% control of yellow starthistle. Based on the extremely effective control achieved by a single burn-and-clopyralid treatment, this second clopyralid treatment is probably unnecessary. In the year following the last clopyralid treatment, the site experienced a severe drought that significantly reduced the population of yellow starthistle even in the untreated control plots. Starthistle density in the treated plots remained less than 2% of the starthistle in control plots.

Mature plant density at TA 27 showed a similar response in the first 2 yr. The initial density of yellow starthistle was around an order of magnitude greater at this site compared with TA 15 (Figure 7). In summer of 2000, the density of yellow starthistle in the untreated site at TA 15 averaged 45 plants m^{-2}, whereas at TA 27 it was about 540 plants m^{-2}. After a first-year prescription burn followed by a clopyralid treatment the second year, the density of yellow starthistle had declined by 96.2%. In 2001, before the second burn, the density of yellow starthistle in the treated plots was 99.1% less than the adjacent untreated site. The drought of 2002 again caused a significant decline in the infestation of yellow starthistle in the untreated plots. Following a second burn at TA 27 (2001), the level of control decreased in 2002. Although the burn–clopyralid–clopyralid treatment at TA 15 gave a 98.3% reduction in yellow starthistle density a year following the last treatment, the burn–clopyralid–burn areas showed only a 75.4% decrease. Although these two levels of control were not statistically different between the two sites, the results support our contention that burning should not be used in the last year of an integrated management strategy.

In small-plot studies at the San Benito and Yuba sites, clopyralid had mixed effects on spring legume cover. At San Benito, there was a reduction in the total legume cover, but at Yuba there was no significant effect. Similar differences were noted between the two sites at FHL, although legume populations showed significant year-to-year variation even in untreated areas. At TA 15, 1 yr of clopyralid (2000) resulted in an 84.2% reduction in legumes compared with the untreated area (Figure 8). A second-year clopyralid treatment continued to suppress legumes (72.4% reduction). In contrast, there was a modest, although not significant, reduction (46.2%) in spring legume cover after a single year of clopyralid treatment at TA 27. The legume population increased significantly following the second burn in the third year (2001), resulting in a greater than twofold increase in legumes in 2002. The difference between the two sites was primarily because of the presence of lupines (*Lupinus* spp.) at TA 27. We have observed that members of this genus are less sensitive to clopyralid compared with other legume species.

Conclusions

Although multiple years of prescribed burning can be effective for the management of yellow starthistle and noxious annual grasses, it is unlikely that ranchers or land managers will be able to obtain permits and use local fire departments to conduct repeated burnings over multiple years. Continuous use of chemical management, particularly clopyralid, can also lead to undesirable results by increasing undesirable annual grasses, reducing species richness and plant diversity, and suppressing legume populations. The results of both the small- and large-scale studies indicate that an integrated management strategy may be the most effective approach for the control of yellow starthistle, as well as for noxious annual grasses susceptible to burning, such as medusahead and ripgut brome. However, the effect of integrating burning and herbicides depends on the treatment order. In a 2- or 3-yr program, the final-year treatment should not be a prescribed burn. The most effective approach for the management of yellow starthistle is an integrated strategy using a first-year summer prescribed burn followed by a second-year late winter to early spring clopyralid treatment. Because the first-year burn stimulates germination of yellow starthistle plants that are subsequently controlled by the second-year herbicide treatment, the starthistle seedbank is rapidly depleted so that it is possible to reduce the length of the management program by about a year. Unlike a multiple-year burn program, this approach also provides adequate forage production in the year following the final treatment. In some cases there may be an impact on legumes, but this is likely to be a transient response. Legumes are known to have long-lived seedbanks that will allow populations to recover over time. Regardless of the control methods employed, for long-term management of yellow starthistle, it is critical to incorporate a follow-up mechanical, cultural, or chemical maintenance program to prevent new seed recruitment and reestablishment.

Sources of Materials

[1] Sample analysis, Department of Agriculture and Natural Resources (DANR) Analytical Laboratory, North Region, Hopkins Road, Davis, CA 95616-8565.

[2] LECO FP-528 nitrogen gas analyzer, LECO Corporation, 3000 Lakeview Avenue, St. Joseph, MI 49085-2396.

[3] ArcView Version 3.0, ESRI Corporation, 380 New York Street, Redlands, CA 92373-8100.

[4] On-aircraft GPS, Trimble Navigation Limited, 935 Stewart Drive, Sunnyvale, CA 94085.

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Literature Cited

Benefield, C. B., J. M. DiTomaso, G. B. Kyser, S. B. Orloff, K. R. Churches, D. B. Marcum, and G. A. Nader. 1999. Success of mowing to control yellow starthistle depends on timing and plant's branching form. Calif. Agric. 53(2):17–21.

Callihan, R. H. and R. O. Schirman. 1991. Effects of five hormone-type herbicides on the survival of yellow starthistle seedlings from a known susceptible population and a suspected picloram resistant population. Pages 40–42 *in* Research Progress Report, Newark, CA: Western Society of Weed Science.

DiTomaso, J. M., G. B. Kyser, and M. S. Hastings. 1999a. Prescribed burning for control of yellow starthistle (*Centaurea solstitialis*) and enhanced native plant diversity. Weed Sci. 47:233–242.

DiTomaso, J. M., G. B. Kyser, S. B. Orloff, S. F. Enloe, and G. A. Nader. 1999b. New growth regulator herbicide provides excellent control of yellow starthistle. Calif. Agric. 53(2):12–16.

Duncan, C. L. and J. K. Clark. 2005. Invasive plants of range and wildlands and their environmental, economic, and societal impacts. Lawrence, KS: Weed Science Society of America. 222 p.

Enloe, S. F., J. M. DiTomaso, and S. Orloff. 2005. Perennial grass establishment integrated with clopyralid treatment for yellow starthistle management on annual range. Weed Technol. 19(1):94–101.

George, M. R. 1992. Ecology and management of medusahead. Range Science Report. Davis, CA: Department of Agronomy and Range Science, Agricultural Experiment Station Series 32. 3 p.

Gerlach, J. D., Jr. 1997. The introduction, dynamics of geographic range expansion, and ecosystem effects of yellow starthistle (*Centaurea solstitialis*). Proc. Calif. Weed Sci. Soc. 49:136–141.

Kyser, G. B. and J. M. DiTomaso. 2002. Instability in a grassland community following control of yellow starthistle (*Centaurea solstitialis* L.) with prescribed burning. Weed Sci. 50:648–657.

Maddox, D. M. 1981. Introduction, phenology, and density of yellow starthistle in coastal, intercoastal, and central valley situations in California. Oakland, CA: U.S. Department of Agriculture Agricultural Research Service, Agriculture Research Results ARR-W-20. 33 p.

Maddox, D. M. and A. Mayfield. 1985. Yellow starthistle infestations are on the increase. Calif. Agric. 39(11–12):10–12.

McKell, C. C., A. M. Wilson, and B. L. Kay. 1962. Effective burning of rangelands infested with medusahead. Weeds 10:125–131.

Mielke, P. W., K. J. Berry, P. J. Brockwell, and J. S. Williams. 1981. A class of nonparametric techniques based on multiresponse permutation procedures. Biometrika 68:720–724.

Miller, J. R. 2003. Integrated Management of Yellow Starthistle (*Centaurea solstitialis*) at Fort Hunter Liggett, Monterey County, California. M.S. thesis. University of California, Davis. 89 p.

Miller, T. W., S. L. Shinn, and D. C. Thill. 2001. Cross-resistance in and chemical control of auxinic herbicide-resistant yellow starthistle (*Centaurea solstitialis*). Weed Technol. 15:293–299.

Pitcairn, M. J., E. M. Coombs, and G. L. Piper. 2004. Yellow starthistle. Pages 421–435 *in* E. M. Coombs, J. K. Clark, G. L. Piper, and A. F. Cofrancesco, Jr., eds. Biological Control of Invasive Plants in the United States. Corvallis, OR: Oregon State University Press.

Pitcairn, M. J., R. A. O'Connell, and J. M. Gendron. 1997. Yellow starthistle: survey of statewide distribution. Pages 53–56 *in* D. M. Woods, ed. Biological Control Program Annual Summary, 1996. Sacramento, CA: California Department Food, Agriculture Division Plant.

Thomsen, C. D., M. P. Vayssieres, and W. A. Williams. 1997. Mowing and subclover plantings suppress yellow starthistle. Calif. Agric. 51(6): 15–20.

Thomsen, C. D., W. A. Williams, W. Olkowski, and D. W. Pratt. 1996. Grazing, mowing and clover plantings control yellow starthistle. Integr. Pest Manag. Pract. 18:1–4.

Thomsen, C. D., W. A. Williams, M. Vayssieres, F. L. Bell, and M. R. George. 1993. Controlled grazing on annual grassland decreases yellow starthistle. Calif. Agric. 47(6):36–40.
Turner, C. E. and L. Fornasari. 1992. Biological control of yellow starthistle (*Centaurea solstitialis* L.) in North America. Page XX *in* E. S. Delfosse and R. R. Scott, eds. Proceedings of the VIII International Symposium on Biological Control of Weeds. Melbourne, Australia: Department of Scientific and Industrial Research/Commonwealth Scientific and Industrial Research Organization (DSIR/CSIRO).
Vogl, R. J. 1974. Effects of fire on grasslands. Pages 139–144 *in* T. T. Kozlowski and C. E. Ahlgren, eds. Fire and Ecosystems. New York: Academic.

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