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Effect of Timing on Chemical Control of Dalmatian Toadflax (*Linaria dalmatica*) in California

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Dalmatian toadflax is listed as a noxious weed in most of the western United States, but control of this species has not been extensively studied in California. Studies in other states show effective control of Dalmatian toadflax with picloram, but this herbicide is not registered for use in California. In addition, reports vary as to the optimal timing for herbicide applications. In this study we evaluated several herbicides with combined foliar and soil-residual activity at two times of application: postsenescence (fall) and rosette (winter to early spring). We applied two series of treatments (2008 and 2009 to 2010) on adjacent sites in high desert scrub of southern California. In the year of treatment and the following year, we evaluated Dalmatian toadflax cover and presence/absence of associated dominant species (≥ 5% cover). Although time of application, treatment, and timing by treatment interaction all produced significant differences in Dalmatian toadflax cover in the 2008 trial, only the high rate of aminocyclopyrachlor (280 g ae ha^{-1}) applied to dormant plants in fall consistently reduced cover through the second year. No treatments at the rosette stage consistently produced 2 yr of control. In 2009 to 2010, treatments were more effective, probably owing to higher precipitation in spring. In both dormant and rosette applications made in 2009 to 2010, aminocyclopyrachlor (140 and 280 g ae ha^{-1}) and aminocyclopyrachlor + chlorsulfuron (140 g ae ha^{-1} + 53 g ai ha^{-1}) gave second year control; chlorsulfuron at the dormant stage (105 and 158 g ai ha^{-1}) and aminopyralid at the rosette stage (245 g ae ha^{-1}) also gave 2 yr of control. The treatments had only minor effects on grass species. The response of broadleaf species varied among treatments, with aminocyclopyrachlor at the high rate increasing *Eriogonum* spp., but greatly reducing Asteraceae species. These results provide options for the management of Dalmatian toadflax in California and other western states.

Nomenclature: Aminocyclopyrachlor; aminopyralid; chlorsulfuron; picloram; Dalmatian toadflax, *Linaria dalmatica* (L.) Mill. subsp. *dalmatica* LINDA; *Eriogonum* spp.

Key words: Herbicide, invasive, phenology, weed control.

Dalmatian toadflax [*Linaria dalmatica* (L.) Mill. subsp. *dalmatica*; Plantaginaceae, formerly Scrophulariaceae] is a short-lived herbaceous perennial native to the eastern Mediterranean region of Europe (Alex 1962). Like the closely related yellow toadflax (*Linaria vulgaris* Miller), it arrived in North America as an ornamental plant and subsequently escaped cultivation. At present, Dalmatian toadflax is distributed throughout the contiguous United States (except for the southeast) and southern Canada. In both its native and introduced ranges, Dalmatian toadflax prefers coarse, well-drained soils (Alex 1962). In North America, it generally occurs in cooler, semiarid climates, and is particularly well adapted to the western Great Plains, the Intermountain West, and higher elevations of the Southwest. All of the contiguous western states list Dalmatian toadflax as a noxious weed.

Like most of the *Linaria* species, Dalmatian toadflax is self-incompatible (Docherty 1982), which undoubtedly contributes to a high level of genetic variability within the species. Dalmatian toadflax also readily hybridizes with other *Linaria* species, again resulting in a great deal of variability that has caused many years of taxonomic confusion (Alex 1962; Ward et al. 2009).

Dalmatian toadflax grows to 1 m (3.3 ft) tall, producing showy yellow snapdragon-like flowers from late spring through summer, followed by abundant seeds with an estimated 10-yr soil life (Robocker 1970). Plants also reproduce vegetatively, developing an extensive root system with lateral roots that produce vegetative stems. The shoots

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Management Implications

Dalmatian toadflax is usually controlled with picloram in most areas of the western United States. However, results can vary owing to application timing or to environmental factors. Furthermore, picloram is not registered for use in California, and thus is not an option for controlling this plant in California's high deserts. In this study we evaluated several herbicides with combined foliar and soil-residual activity at two times of application: postsenescence (fall) and rosette (winter to early spring). The trial was conducted twice. The primary chemicals tested included aminocyclopyrachlor, aminopyralid, chlorsulfuron, dicamba, imazapic, imazapyr, metsulfuron, picloram, and 2,4-D, but only aminocyclopyrachlor, aminopyralid, and chlorsulfuron were effective. Aminocyclopyrachlor (280 g ae ha^{-1}), applied to dormant plants in fall, gave the most consistent long-term control, providing > 90% reduction in Dalmatian toadflax cover in both trials in the second season after treatment. This rate also increased native species in the genus *Eriogonum*, but reduced the presence of members of the Asteraceae. Applications at the rosette stage were less consistent between trials, probably because of differences in spring rainfall between the two trial years. In the first trial, with very low spring rainfall, none of the rosette-stage treatments produced 2 yr of control. However, in the second trial, with considerably more spring rainfall, both dormant and rosette applications of aminocyclopyrachlor (2 and 4 oz ae ac^{-1}) and aminocyclopyrachlor + chlorsulfuron (2 oz ae ac^{-1} + 0.75 oz ai ac^{-1}) gave 2 yr of control; chlorsulfuron at the dormant stage (1.5 and 2.25 oz ai ac^{-1}) and aminopyralid at the rosette stage (3.5 oz ae ac^{-1}) also gave 2 yr of control. Our results show that other herbicides besides picloram can be used for the control of Dalmatian toadflax, and the most effective timings in California are in the dormant to rosette stages. Effective control at the rosette stage appears dependent on adequate spring rainfall following application, as this enhances soil incorporation and uptake of the herbicide.

die back in fall and regrow from the rootstock in spring. Root carbohydrate reserves are highest in fall, as the plant approaches senescence, and are depleted in early summer as the plant begins to flower (Robocker et al. 1972).

Dense stands of Dalmatian toadflax competitively exclude native and forage plants, reducing wildlife habitat (Lajeunesse 1999) and livestock carrying capacity (Jacobs and Sing 2006; Lacey and Olson 1991). Although Dalmatian toadflax seedlings establish poorly in vegetated areas, this species readily colonizes bare or disturbed ground. In the western United States, Dalmatian toadflax is particularly invasive in sparsely vegetated, high-elevation semiarid shrublands. Once established, the species is intensely competitive for moisture and can spread vegetatively into undisturbed areas (Robocker 1974).

As with many resprouting perennial weeds, burning is ineffective in controlling Dalmatian toadflax and can result in increased biomass and seed production (Dodge et al. 2008; Jacobs and Sheley 2003). Likewise, hand-pulling or grubbing does not provide effective control unless continued over a period of several years (Jacobs and Sing 2006; Lajeunesse et al. 1993). Mowing and tillage are not considered feasible control methods, as plant fragments as short as 1 cm (0.4 in) can resprout from a node (Wilson et al. 2005). Furthermore, Dalmatian toadflax is often found in rough terrain, which precludes the use of most mechanical control options.

Because Dalmatian toadflax seedlings are not strong competitors, a healthy perennial plant community or a revegetation program with perennial grasses can be an effective approach for preventing its establishment or reinvasion (Gates and Robocker 1960; Rose et al. 2001). However, revegetation plantings often establish poorly in the semiarid shrublands typically invaded by Dalmatian toadflax in California. Furthermore, this strategy fails to address the necessity of controlling established stands of toadflax.

Efforts to find suitable biocontrol insects for Dalmatian toadflax have been underway since the 1960s in both the United States and Canada. Seven species of beetles and moths, with various attack strategies, have been released in North America for control of Dalmatian toadflax (Wilson et al. 2005). However, Dalmatian toadflax occupies a broad range of environmental conditions, resulting in differential survival and success of biocontrol species (Jacobs and Sing 2006). In addition, genetic variability among toadflax populations, particularly with respect to foliar glycoside compounds, may result in differences in success of biocontrol agents from site to site (Jamieson and Bowers 2010). Thus, in many situations biocontrol agents have not yet produced long-term, large-scale stand reductions.

Reviews of efforts to control Dalmatian toadflax using herbicides suggest that the thick, waxy cuticle on the leaf surface may interfere with herbicide uptake (Jacobs and Sing 2006; Lajeunesse et al. 1993). This may account for repeated failures to control this weed with selective foliar-uptake herbicides such as 2,4-D, triclopyr, and fluroxypyr (Ferrell and Whitson 1989; Hanson et al. 1989; Lange 1958).

The most successful chemical treatments for control of Dalmatian toadflax are likely to be selective herbicides with both foliar and soil-residual activity. For example, in early work on this weed, Robocker (1968) demonstrated effective control using silvex or picloram. More recently, researchers have tested aminocyclopyrachlor, aminopyralid, chlorsulfuron, metsulfuron, and picloram on Dalmatian toadflax (e.g., Duncan et al. 1999; Jacobs and Sheley 2005; Sebastian et al. 2012; Wallace and Prather 2009) and yellow toadflax (e.g., Sebastian and Beck 2010a,b; Wallace and Prather 2012). These studies generally report good control of both species with picloram, chlorsulfuron, and aminocyclopyrachlor.

Nearly all studies on Dalmatian toadflax control have been conducted in the Great Plains, Rocky Mountain foothills, or intermountain regions outside of California.

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For two main reasons, we felt it was important to study control of Dalmatian toadflax in California high desert. The first issue was herbicide application timing. In previous reports, optimal times of application have varied. For example, some studies report better control with picloram applied in fall (Robocker 1968), whereas others report better control with applications to rosettes or flowering plants in spring (Duncan et al. 1999; Jacobs and Sheley 2005). In addition, the phenology of Dalmatian toadflax populations in California is somewhat different from populations farther east. Little or no rain falls during summer in the California high desert, and Dalmatian toadflax appears to go completely dormant by early fall. New green leaves begin to emerge in December or January, a month or so into the rainy season, followed by bolting in mid spring. In the Great Plains, by contrast, summer precipitation enables development of new leaves in fall, and this new growth may overwinter under snow (S. F. Enloe, personal communication). This difference in life cycle timing may affect optimal application timing or efficacy of different herbicides.

A second issue is the availability of registered herbicides. In general, picloram, which is not registered for use in California, has been the most widely recommended herbicide for Dalmatian toadflax control. In addition to picloram, Sebastian et al. (2012) reported control of Dalmatian toadflax with aminocyclopyrachlor, a new chemical that shows promise for use on California rangelands but is not yet registered in this state.

In order to address the need for effective control options for Dalmatian toadflax in California, we evaluated the efficacy of several herbicides at different application timings in a heavily infested high desert ecosystem. We emphasized herbicides with combined foliar and soil-residual activity, applied at fall (postsenescence) and early spring (rosette) timings.

Materials and Methods

Location Description. The study was conducted in high desert scrub in the Hungry Valley State Vehicular Recreation Area, northeastern Ventura County, CA (34°47′N, 118°54′W; elevation 1,450 m). Dalmatian toadflax was first recorded in this vicinity in 1962. Although this species was collected at other locations in southern California during the early 1900s, this stand of several thousand acres appears to be the only large, persistent population, as well as the densest infestation, in the state. Dominant vegetation at this location includes *Artemisia* spp., *Ericameria nauseosa* (Pall.) G.L. Nesom & G.I Baird, *Eriogonum fasciculatum* Benth., and *Hesperoyucca whipplei* (Torr.) Trel. The area also has a sparse population of native perennial grasses, including *Stipa* spp. and *Elymus elymoides* (Raf.) Swezey; the nonnative perennial grass *Poa bulbosa* L.; and non-native annual grasses such as *Bromus tectorum* L., *Bromus diandrus* Roth, and *Avena barbata* Link. Other species include several native herbaceous Asteraceae (*Eriophyllum* spp. and others), Boraginaceae (*Cryptantha* and *Phacelia* spp.), and Polygonaceae (*Eriogonum* spp.). Soil at this location is Oak Glen loam, a well-drained sandy soil (sand : silt : clay in the top 30 cm = 45 : 42 : 13; organic matter = 2.5%; pH = 6.7) on 2 to 9% slopes.

Average annual precipitation is 30 cm, with 86% falling from November through March. During the years of this study (2007 to 2011), July through June precipitation was 24, 27, 25, and 33 cm, respectively. However, rainfall during the spring growth period (February through June) was very different in the 2 yr during which treatments were applied, totaling 3 cm in 2008 and 12 cm in 2010. Monthly average temperatures during February through June were 2 to 3 C (4 to 5 F) warmer in 2008 than 2010.

Treatments. We applied two series of treatments (2008 and 2009 to 2010) on adjacent sites at the same location. In the first trial, we treated at the rosette (January 16, 2008), bolting (April 22, 2008), and dormant stages (November 18, 2008) of Dalmatian toadflax. Because bolting treatments did not show any significant differences from the untreated control, we did not repeat this treatment timing in the second trial to minimize potential damage to sensitive native vegetation. As such, the results of the bolting treatment are not presented. In the second trial we made applications only at dormant (November 18, 2009) and rosette stages (March 5, 2010).

Each application timing trial was conducted as an independent unit, and all units were adjacent. Within each treatment timing, treatments were arranged in a randomized complete block design with four replications. Plots were 3 m by 9 m. All treatments (product formulations and sources are listed in Table 1) were applied in 234 L ha^{-1} (25 gal ac^{-1}) spray solution with a CO_2 backpack sprayer and 3-m boom with six nozzles (TeeJet XR8002, Spraying Systems Co., www.teejet.com). Treatments applied after emergence of foliage in spring (early rosette and early bolting stages) included 0.25% v/v nonionic surfactant. In the first year of the study (2008), 2,4-D-amine, dicamba, dicamba + 2,4-D, imazapic, imazapyr, and metsulfuron showed no significant difference in control compared to the untreated plot and, thus, the data are not presented. In addition, picloram, which is generally the standard treatment for Dalmatian toadflax control outside of California, gave no significant control; nor did picloram + 2,4-D, and these treatments are not included in the data presentation. In the second year (2009 to 2010), the newly registered rangeland product, rimsulfuron, was evaluated for Dalmatian toadflax control, but the results were not significantly different from untreated control and thus the data are not presented. The most successful treatments,

Table 1. Commercial sources of chemicals used in Dalmatian toadflax treatments.

Common name	Commercial product	Product concentration	Source
Aminocyclopyrachlor	DPX-MAT28	50% soluble granule	DuPont Crop Protection, Wilmington, DE (http://www2.dupont.com/Prod_Agriculture/en-us/content/crop-protection.html)
Aminocyclopyrachlor + chlorsulfuron	Perspective®	39.5% + 15.8% dry flowable	DuPont Crop Protection, Wilmington, DE (http://www2.dupont.com/Prod_Agriculture/en-us/content/crop-protection.html)
Aminopyralid	Milestone®	240 g ae L^{-1}	Dow AgroSciences LLC, Indianapolis, IN (http://www.dowagro.com)
Chlorsulfuron	Telar® DF	75% dry flowable	DuPont Crop Protection, Wilmington, DE (http://www2.dupont.com/Prod_Agriculture/en-us/content/crop-protection.html)
2,4-D amine	Weedar 64®	455 g ae L^{-1}	Nufarm Inc., Burr Ridge, IL (http://www.nufarm.com/US/Home)
Dicamba	Clarity®	479 g ae L^{-1}	BASF Corporation, Research Triangle Park, NC (http://www.basf.com/group/corporate/en)
Imazapic	Plateau®	240 g ae L^{-1}	BASF Corporation, Research Triangle Park, NC (http://www.basf.com/group/corporate/en)
Imazapyr	Arsenal®	240 g ae L^{-1}	BASF Corporation, Research Triangle Park, NC (http://www.basf.com/group/corporate/en)
Metsulfuron	Escort®	60% dry flowable	DuPont Crop Protection, Wilmington, DE (http://www2.dupont.com/Prod_Agriculture/en-us/content/crop-protection.html)
Picloram	Tordon®	240 g ae L^{-1}	Dow AgroSciences LLC, Indianapolis, IN (http://www.dowagro.com)
Rimsulfuron	Matrix® SG	25% soluble granule	DuPont Crop Protection, Wilmington, DE (http://www2.dupont.com/Prod_Agriculture/en-us/content/crop-protection.html)

including aminocyclopyrachlor, aminopyralid, and chlorsulfuron, were repeated over the two studies and results are presented in the tables.

Evaluations. Following the first trial, plots were evaluated June 4, 2009, at peak flower of Dalmatian toadflax (16, 14, and 7 mo after treatment [MAT] of the rosette, bolting, and dormant stages, respectively), and June 18, 2010 (29, 26, and 19 MAT). After the second trial, plots were evaluated June 18, 2010 (7 and 3 MAT of the dormant and rosette stages) and July 8, 2011 (20 and 16 MAT). During evaluation, we made visual estimates of percentage of living canopy cover of Dalmatian toadflax within the entire plot and recorded presence or absence of all dominant plant species (species with $\geq$ 5% cover in any treatment). It was not possible to estimate the density of Dalmatian toadflax stems owing to its basal branching pattern and the number of senesced stems from previous years. Thus, whole-plot living canopy cover was the most efficient method for evaluating treatment effects.

Analysis. All analyses were performed using JMP 8.0 (SAS Institute Inc., Cary, NC). Within each year of application, we compared Dalmatian toadflax cover using two-way ANOVA with timing, treatment, and timing by treatment as independent factors. We followed this analysis with one-way ANOVA of Dalmatian toadflax cover to compare treatment effects within each time of application, and separated means using the Tukey-Kramer test ($\alpha = 0.05$). These analyses were performed on data from both the first and second evaluations.

The first treatment series was applied from January through November 2008 and evaluated in 2009 and 2010 (7 to 17 MAT and 19 to 29 MAT), whereas the second series was applied from November 2009 to March 2010 and evaluated in 2010 and 2011 (3 to 7 MAT and 16 to 20 MAT). Because of the evaluation gaps and varying treatments, it was not feasible to compare the two trials in a full factorial analysis. For a final comparison, therefore, we compared across years using only the treatments applied in both years (chlorsulfuron, aminocyclopyrachlor, and aminopyralid at dormant and rosette stages), and using only ratings from 16 to 20 MAT. In this analysis we performed a three-way ANOVA with year, timing, and treatment as independent factors.

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Table 2. P-values from two-way ANOVAs of Dalmatian toadflax cover. Values in bold indicate significant differences ($P < 0.05$). The first trial uses evaluations 16 to 19 mo after treatment (16–19 MAT analysis), i.e., it compares the 2009 evaluation for the rosette application with the 2010 evaluation for the dormant application.

			Probability > *F*			
Trial	Data type	Evaluation	Whole model	Timing	Treatment	Timing × treatment
2008	Cover	Year 1 (2009)	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
		Year 2 (2010)	**< 0.0001**	**0.0108**	**< 0.0001**	**0.0017**
		16–19 MAT	**< 0.0001**	0.7983	**< 0.0001**	**0.0033**
	Cover indexed to untreated plots	Year 1 (2009)	**< 0.0001**	**0.0007**	**< 0.0001**	**0.0002**
		Year 2 (2010)	**< 0.0001**	**0.0021**	**< 0.0001**	**0.0015**
		16–19 MAT	**< 0.0001**	**0.0045**	**< 0.0001**	**0.0014**
2009–2010	Cover	Year 1 (2010)	**< 0.0001**	0.6176	**< 0.0001**	0.3213
		Year 2 (2011)	**< 0.0001**	0.1351	**< 0.0001**	**0.0022**
	Cover indexed to untreated plots	Year 1 (2010)	**< 0.0001**	**0.0031**	**< 0.0001**	0.2485
		Year 2 (2011)	**< 0.0001**	0.2475	**< 0.0001**	**0.0003**

We configured cover data two ways for analysis. First, we performed all ANOVAs on the values for percentage of cover, arcsine transformed [$x' = \arcsin(x^{0.5})$] in order to meet requirements for variance and normality (Zar 1999). Variations in Dalmatian toadflax cover from year to year and among sites complicated our efforts to compare results, s o in a second analysis we performed ANOVAs on indexed cover values. Indexed values were derived by expressing the cover in each plot as a percentage relative to the cover of the untreated plot in the same block. These values required a square root transformation [$x' = (x + 3/8)^{0.5}$] (Zar 1999).

Presence/absence data for other dominant species with cover values $\geq 5\%$ were grouped into annual grasses, perennial grasses, and broadleaf plants. These data were compared using contingency analysis (chi-square tests). Annual and perennial grass cover showed no differences, and these data are not presented. Broadleaf species showed significant differences, and we subdivided this category into *Eriogonum* spp., Asteraceae spp., and Boraginaceae spp. for contingency analysis.

Results and Discussion

Dalmatian Toadflax Cover. In the 2008 trial, time of application, treatment, and timing by treatment interaction all produced significant differences in Dalmatian toadflax cover. This was true both for cover data and cover indexed to untreated plots, for both evaluation timings (Table 2). Because the rosette treatment was applied early in 2008 and the dormant treatment was applied late in 2008, the time until evaluation was much shorter for the dormant treatment; therefore we also compared results from the 2009 evaluations for the rosette treatment (16 MAT) with the 2010 evaluation for the dormant treatment (19 MAT). This is reported as 16 to 19 MAT and all tested factors were still significant (with the exception of timing alone, for raw cover data).

In the 2008 trial, the high rate of aminocyclopyrachlor (280 g ae ha^{-1}), applied to dormant plants in fall, was the only treatment to significantly reduce Dalmatian toadflax cover, relative to untreated plots, through the 16 to 19 MAT evaluations (Table 3). No treatments at the rosette stage produced significant reductions in cover. It should be noted, however, that due to variability in cover, even plots with a 73% reduction in Dalmatian toadflax relative to untreated plots were not significantly different. In the first evaluation after the 2008 treatments (7 MAT after the dormant application), several dormant treatments reduced Dalmatian toadflax cover, including aminocyclopyrachlor (140 and 280 g ae ha^{-1}), aminopyralid (245 g ae ha^{-1}), and chlorsulfuron (105 g ai ha^{-1}) (data not shown). However, significant cover reductions with aminopyralid and chlorsulfuron did not persist to the second evaluation 19 MAT (Table 3).

In the 2009 to 2010 trial, herbicide treatment was significant in both evaluations, including evaluations for Dalmatian toadflax cover and for cover indexed to untreated plots. However, the factors of application timing and timing by treatment were not consistently significant (Table 2). In dormant applications, both rates of aminocyclopyrachlor, aminocyclopyrachlor + chlorsulfuron, and both rates of chlorsulfuron (105 and 158 g ai ha^{-1}) reduced cover significantly through the 16 to 20 MAT evaluations (Table 3). In rosette applications, both rates of aminocyclopyrachlor, aminocyclopyrachlor + chlorsulfuron, and the high rate of aminopyralid reduced cover through the second season.

In the 2008 trial, dormant applications of the most effective herbicides gave better control of Dalmatian toadflax than rosette applications. However, in the 2009 to 2010 trial, dormant and rosette applications appeared to give similar control. In addition, chlorsulfuron was much more effective in the 2009 to 2010 trial. We attribute the

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Table 3. Results of 2008 and 2009 to 2010 trials: Dalmatian toadflax cover as a percentage relative to untreated plots. The last column represents combined data for timing and year of study at the 16 to 20 mo after treatment (16–20 MAT) evaluation. One-way ANOVAs were performed within each application timing; P-values are shown at the bottom of each column. Data were square-root transformed [$x' = (x + 3/8)^{0.5}$] for analysis (actual values are presented).

		Toadflax cover, % relative to untreated plots (months after treatment)				
		2008 trial		2009–2010 trial		
Active ingredient	Rate	Rosette (16 MAT)	Dormant (19 MAT)	Rosette (16 MAT)	Dormant (20 MAT)	Both trials and timings combined
	g ai or ae ha^{-1}					
Aminocyclopyrachlor	140	48	43 ab[a]	24 ab	34 bc	37 bc
Aminocyclopyrachlor	280	27	9 a	4 a	9 ab	11 a
Aminocyclopyrachlor + chlorsulfuron	140 + 53	not tested	not tested	18 ab	12 ab	15 ab[b]
Aminopyralid	123	71	162 b	41 b	90 cd	86 de
Aminopyralid	245	68	43 ab	29 ab	76 cd	54 cd
Chlorsulfuron	105	not tested	67 ab	41 b	9 ab	25 abc[b]
Chlorsulfuron	158	40	not tested	47 bc	5 a	26 abc[b]
Untreated	—	100	100 b	100 c	100 d	100 e
		P = 0.062	P = 0.0031	P < 0.0001	P < 0.0001	P < 0.0001
Actual cover in untreated plots (%)		31.3	17.0	21.3	14.8	21.1

[a] Means were separated using the Tukey-Kramer test; values followed by the same letter within each column are not different at $\alpha = 0.05$.

[b] Mean includes only results from 2009–2010 trial.

different results to differences in spring rainfall. February through June precipitation in 2008 was only 3 cm, but in 2010 rainfall during this period was 12 cm. Low rainfall in 2008 probably reduced herbicide efficacy by reducing solubilization, soil penetration, and root uptake of soil-applied chemicals, particularly chlorsulfuron (see, e.g., Nalewaja and Woznica 1985). As another mechanism, low rainfall may have resulted in drought stress, thereby reducing uptake, translocation, or both, as reported for other perennial weeds, including mesquite (*Prosopis* spp.) (Davis et al. 1968), johnsongrass [*Sorghum halepense* (L.) Pers.] (McWhorter and Azlin 1978), Canada thistle [*Cirsium arvense* (L.) Scop.] (Lauridson et al. 1983), broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britt. & Rusby] (Sterling and Lownds 1992), and Russian knapweed [*Acroptilon repens* (L.) DC.] (Morrison et al. 1995). Dormant applications in fall, at the beginning of the rainy season, were less influenced by the variance in spring rainfall.

When the data were combined over both studies and both times of application, all treatments except the low rate of aminopyralid reduced Dalmatian toadflax cover compared to untreated plots (Table 3). Aminocyclopyrachlor at 280 g ae ha^{-1} gave an average 89% reduction in Dalmatian toadflax cover in the second season after treatment. Although this level of control was not statistically different from aminocyclopyrachlor + chlorsulfuron or chlorsulfuron alone, this treatment tended to control Dalmatian toadflax most consistently across both studies and times of application.

Presence/Absence of Other Species. The diversity or overall presence of dominant perennial grasses was not significantly different in any treatment or timing in either trial, likely due to their sparse overall cover (data not shown). In the 2008 trial, imazapyr reduced the occurrence of annual grasses in the first evaluation following treatment, but this effect did not hold through the next evaluation (data not shown). No other treatments resulted in significant reductions in the presence of dominant annual grasses. In the 2008 trial, dominant broadleaf species diversity and presence showed no overall significant differences at the dormant or rosette stage, although the low rate of aminocyclopyrachlor at the rosette stage, the high rate of aminopyralid at the dormant stage, and the low rate of chlorsulfuron at the dormant stage tended to increase the presence and diversity of dominant broadleaf species (Table 4).

In the 2009 to 2010 trial, none of the treatments affected dominance or presence of grass species (data not shown) and the overall effect on broadleaf species was also not significant among treatments (Table 4). In both dormant-stage and rosette treatments, the high rate of

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Table 4. Treatment differences in abundance of dominant native broadleaf species (species with mean cover ≥ 5% in any treatment). Values are based on contingency analysis for presence/absence, within each time of application in each trial, for evaluations 16 to 20 mo after treatment (MAT). Symbols are a qualitative representation of the contribution of respective cells to the chi-square total (followed by respective chi-square values in parentheses): +, greater than expected; −, less than expected; =, similar to expected; na, not applicable. Note that overall chi-square values are not significant; symbols indicate trends.

		Abundance of dominant broadleaf species			
		2008 trial		2009–2010 trial	
Active ingredient	Rate	Rosette (16 MAT)	Dormant (19 MAT)	Rosette (16 MAT)	Dormant (20 MAT)
	g ai or ae ha^{-1}				
Aminocyclopyrachlor	140	+ (2.23)	= (0.64)	= (0.85)	= (0.60)
Aminocyclopyrachlor	280	= (0.51)	= (0.64)	= (0.85)	= (0.60)
Aminocyclopyrachlor + chlorsulfuron	140 + 53	na	na	+ (2.50)	= (1.60)
Aminopyralid	123	= (1.27)	= (0.70)	= (0.34)	= (1.60)
Aminopyralid	245	= (0.79)	+ (4.24)	− (5.85)	− (5.60)
Chlorsulfuron	105	na	+ (6.21)	+ (4.24)	= (1.60)
Chlorsulfuron	158	= (1.03)	na	= (0.85)	= (1.80)
Untreated		= (1.27)	= (0.70)	− (2.01)	= (0.60)
Pearson chi-square ratio (significance)		0.72	0.59	0.23	0.23
Chi-square total		7.11	13.14	17.48	17.60

aminopyralid tended to reduce overall broadleaf species presence. In rosette-stage applications, aminocyclopyrachlor + chlorsulfuron and the low rate of chlorsulfuron resulted in slight increases in overall broadleaf species. We separated dominant broadleaf species into groups (*Eriogonum* spp., Asteraceae spp., and Boraginaceae spp.) and compared the groups over all treatments in both trials and at both application times (Table 5). *Eriogonum* increased following treatment with the high rate of aminocyclopyrachlor, but decreased with aminopyralid and in untreated plots. Asteraceae spp. increased with chlorsulfuron and in untreated plots, but decreased with the high rate of aminocyclopyrachlor. Boraginaceae spp. increased with the low rate of aminocyclopyrachlor.

Table 5. Treatment differences in abundance of main groups of native broadleaf species. Values are based on contingency analysis for presence/absence, combined over both trials and both times of application, for evaluations 16 to 20 mo after treatment. Symbols represent the contribution of respective cells to the chi-square total (followed by respective chi-square values in parentheses). Qualitatively, the number of symbols indicates the degree of difference: +, greater than expected; −, less than expected; =, similar to expected.

		Eriogonum spp.	Asteraceae spp.	Boraginaceae spp.
Active ingredient	Rate	Difference from expected (χ^2 values)		
	g ai or ae ha^{-1}			
Aminocyclopyrachlor	140	= (0.37)	= (0.21)	+ + +[a] (4.65)
Aminocyclopyrachlor	280	+ + + (4.68)	− (6.92)	= (0.29)
Aminopyralid	123	− (2.17)	= (0.01)	= (0)
Aminopyralid	245	− (0.91)	= (0.21)	− (1.16)
Chlorsulfuron	105 and 158[b]	+ (1.27)	+ + (2.97)	= (0.29)
Untreated		− (2.17)	+ + (2.97)	− (1.16)
Pearson chi-square ratio (significance)		0.041	0.021	0.18
Chi-square total		11.56	13.29	7.56

[a] Qualitatively, the number of symbols indicates the degree of difference.

[b] Analysis also included 105 g ai ha^{-1} for dormant application in first trial with 158 g ai ha^{-1} for rosette and dormant applications in second trial and rosette application in the first trial.

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Overall Management Perspective. The high rate of aminocyclopyrachlor (280 g ae ha^{-1}) most consistently reduced Dalmatian toadflax cover over 2 yr in this set of studies. This treatment provided better control than picloram (data not shown), which is the herbicide most often recommended for Dalmatian toadflax in the Great Plains and intermountain regions. Alms et al. (2012), Jenks (2012), and Sebastian and Beck (2010a,b) reported similar results in comparing aminocyclopyrachlor with picloram for yellow toadflax control in South Dakota, North Dakota, and Colorado, respectively.

In our study, aminocyclopyrachlor was effective applied in fall (postsenescence) in both trials, and in midwinter or early spring (early rosette) in 2009 to 2010. However, in 2008 it was less effective applied in the rosette stage, suggesting that its efficacy was impacted by the lack of spring rainfall. By contrast, researchers in the Great Plains and intermountain regions generally report successful control of Dalmatian and yellow toadflax with spring or summer applications of aminocyclopyrachlor (Sebastian and Beck 2010b; Sebastian et al. 2012; Wallace and Prather 2012). This probably reflects the availability of summer precipitation, and active growth in summer, in these regions, although the effect of seasonal drought needs to be evaluated further.

Chlorsulfuron appeared to be even more dependent than aminocyclopyrachlor on adequate precipitation. This chemical was very effective applied in fall in the second trial but was less effective in spring applications and in a fall application during a year with poor spring rainfall. Jacobs and Sheley (2005) demonstrated good control of Dalmatian toadflax with chlorsulfuron in both spring and fall applications in Montana, in an area with predominately summer precipitation. Daniel et al. (2010) successfully controlled Dalmatian and yellow toadflax with fall applications of chlorsulfuron in Wyoming and Colorado.

In our study, aminocyclopyrachlor had a negative impact on cover of native Asteraceae species (although not on *Eriogonum* or Boraginaceae species), and this effect should be taken into consideration when using this chemical. By comparison, chlorsulfuron was relatively safe on nontarget broadleaf species at this site.

We are unaware of any reports on interactions between aminocyclopyrachlor or chlorsulfuron and insect biological control agents for Dalmatian toadflax. However, one report found that although chlorsulfuron was not directly toxic to the leaf-eating beetle *Gastrophysa polygoni*, when applied to wild buckwheat (*Polygonum convolvulus* L.) the herbicide induced the plant to produce defense compounds toxic to the beetle (Kjær and Elmegaard 1996).

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