Weed Technology 2007 21:000–000

Control of Medusahead (*Taeniatherum caput-medusae*) and Other Annual Grasses with Imazapic

Guy B. Kyser, Joseph M. Ditomaso, Morgan P. Doran, Steven B. Orloff, Robert G. Wilson, Donald L. Lancaster, David F. Lile, and Marni L. Porath*

1 Invasive annual grasses, such as medusahead, can reduce forage production capacity and interfere with revegetation projects in California rangelands. Because of the taxonomic similarity to other more desirable grasses, achieving selective control of invasive annual grasses can be difficult. In selectivity trials conducted in Yolo and Siskiyou counties, CA, the herbicide imazapic gave control of many nonnative annual grasses yet provided some level of selectivity to specific perennial grasses used in revegetation projects throughout the western United States. The selectivity difference between newly seeded perennial and annual grasses was greater with PRE applications than with POST treatments. Both perennial and annual grasses within the tribe Hordeae were more tolerant to imazapic than other grass species. In addition, field experiments were conducted at three sites in northern California (Yuba, Yolo, and Lassen counties) and one in southern Oregon (Lake County) to test the response of imazapic to varying management conditions. Imazapic was applied PRE in fall (and also spring in Lake County) at rates from 35 to 210 g/ha on undisturbed rangeland, in comparison with rangeland cleared of standing plant material and thatch by either tillage, mowing and raking, or burning. Imazapic generally showed enhanced weed control when applied following disturbance. Rates as low as 70 g/ha, if combined with thatch removal, provided significant suppression of medusahead. In addition, disturbance alone generally reduced medusahead cover in the following year. Although imazapic showed potential for control of medusahead and other annual grasses, its selectivity window was relatively narrow.

Nomenclature: Imazapic; medusahead, *Taeniatherum caput-medusae* (L.) Nevski, ELYCM.
Key words: Grassland, integrated weed management, invasive weed, native species, rangeland, restoration, selectivity.

In restoring rangeland and grassland infested with noxious weeds, it may be necessary to incorporate revegetation efforts along with weed control strategies. Revegetation is critical for both reestablishing rangeland utility and for preventing weeds from quickly reinvading. Concurrently, some form of weed control is necessary to ensure success of revegetation plantings.

In California's Mediterranean climate, with most precipitation occurring from October to April, revegetation plantings are most successful when made in fall or late winter, depending on the location. However, invasive plants, such as yellow starthistle (*Centaurea solstitialis* L. CENSO) and many noxious annual grasses, germinate over an extended period during the rainy season, thus limiting the effectiveness of POST herbicides used at the time of planting. Because no herbicide currently registered for use in California rangelands selectively controls annual grasses, PRE or POST, without injuring perennial grass seedlings, grass weeds are the greatest obstacle to perennial grass revegetation efforts.

One of the most problematic annual grass weeds in
13 California and the western United States is medusahead, which is estimated to infest about 1 million ha in the 17 western states (Duncan and Clark 2005). Medusahead is a winter annual native to the Mediterranean region. It matures after most other annual vegetation has senesced. Thus, during its seed production phase, in late spring to early summer, medusahead can access soil moisture and sunlight without competition from other annual grasses. In addition, medusahead produces a thick, silica-rich thatch that decomposes slowly, suppressing germination and establishment of desirable plants (Young 1992). Because medusahead is adapted to germinate through thatch (Harris 1977; Young et al. 1971a), it can form dense stands, excluding nearly all competitors. Additionally, medusahead is considered to be a poor forage plant owing to its high-silica content ($> 10\%$ of dry weight), low-nutrient value, and rough unpalatable texture (George 1992; Lusk et al. 1961).

Management of medusahead has proven difficult. Control can be achieved by burning in some locations (Furbush 1953; Murphy and Lusk 1961), but not others (Young et al. 1971b), or by a combination of tillage, herbicide treatment, and perennial grass reseeding (Young et al. 1969).

Imazapic[1] is a PRE or POST herbicide that has been used in native-plant restoration projects in many parts of the western and midwestern United States (Barnes 2004; Masters et al. 2001). Its average persistence in soil is about 120 d (Vencill 2002), so it has the potential to control weeds throughout the initial establishment of a revegetation planting. Imazapic is most effective against annual grasses. For example, both fall and spring applications of imazapic at 70 g/ha controlled downy brome (*Bromus tectorum* L.) (Dewey et al. 2003; Sebastian and Beck 2004). A higher rate of 140 g/ha gave good control of medusahead in other studies (Monaco et al. 2005; Shinn and Thill 2002).

DOI: 10.1614/WT-06-027.1

* Staff Research Associate and Extension Specialist, Department of Plant Sciences, University of California, One Shields Avenue, Davis, CA 95616; third author: Farm Advisor, Cooperative Extension Solano County, 501 Texas Street, Fairfield CA 94533-4498; fourth author: Farm Advisor, Cooperative Extension Siskiyou County, 1655 South Main Street, Yreka, CA 96097; fifth and seventh authors: Farm Advisors, Cooperative Extension Lassen County, 707 Nevada Street, Susanville, CA 96130; sixth author: Farm Advisor, Cooperative Extension Modoc County, 202 West 4th Street, Alturas, CA 96101; eighth author: Farm Advisor, Cooperative Extension Malheur County, 710 Southwest 5th Avenue, Ontario, OR 97914. Corresponding author's E-mail: jmditomaso@ucdavis.edu.

Imazapic shows some selectivity among perennial grasses, e.g., it is relatively safe on several wheatgrass (*Agropyron* [2] Gaertn. sp.) species (Shinn and Thill 2004). Because of this reported selectivity, imazapic is of particular interest as a tool for controlling annual grasses during grassland restoration and establishment of perennial forage grasses (e.g., Barnes 2004; Beran et al. 2000; Shinn and Thill 2004).

The objectives of this study were to determine the effectiveness of imazapic on invasive annual grasses in semiarid northwestern rangeland and to examine the tolerance of important perennial grasses and broadleaf species used in rangeland revegetation programs. In addition, rate responses to imazapic were evaluated under a variety of field conditions, including several disturbance types, with the goal of understanding the parameters that maximize its effectiveness.

Materials and Methods

Selectivity Trials. *Yolo County.* Imazapic selectivity trials were conducted during 1998 to 1999 and 1999 to 2000 at the University of California, Davis, field station on well-drained, nearly level, Yolo silty-clay loam soil. Three rates of imazapic (70, 140, and 280 g/ha) were applied PRE and POST to 30 species of invasive annuals and native grassland annuals and perennials (Table 1). During December, species were seeded by hand in individual rows on 1.5-m beds (four rows per bed). Treatments were applied across the beds in four randomized complete blocks, either within a week after seeding (PRE treatments) or early the following March (POST treatments). Plots were 1.5 m wide by 13.7 m long in 1998 to 1999 and 2 m by 12.2 m in 1999 to 2000. Treatments were applied using a CO_2 backpack sprayer delivering 112 L/ha (12 gallons per acre [gpa]) at 172 kPa (25 pounds/in^2 [psi]) through three or four 8002 nozzles on a 1.5-m or 2-m boom. POST treatments included 0.1% v/v silicone polyether surfactant.

In June, visual evaluations for vigor were made for all species in each plot. The healthiest, most dense stand of each species, regardless of treatment, was assigned a vigor rating of 100%, and all other plots were compared with the 100% plots. A vigor rating of 0% indicated complete mortality of seeded plants. Treatments were compared using multiple analysis of variance (MANOVA) for each year, using vigor ratings for each species as responses. Wilks' lambda was used [3] for the probability value in all MANOVA results. This analysis was followed by compiling the 2 yr data, for a total of eight replications, and comparing treatment factors using two-way ANOVA (rate of imazapic by time of application, $\alpha = 0.05$) for each species. Finally, a single-factor ANOVA, concatenating all timing and rate combinations, was conducted for each species, and means were separated using the Student–Newman–Keuls test.

Siskiyou County. Imazapic was tested at several rates, PRE and POST, on three perennial grass species in the Shasta Valley Wildlife Area, near Montague, CA. The site was rangeland infested with medusahead (71% cover) and downy brome (2% cover), on a Salisbury cobbly loam. Intermediate wheatgrass [*Thinopyrum intermedium* (Host) Nevski var. *intermedium* 'Oahe', = *Agropyron intermedium* (Host) Beauv], pubescent wheatgrass [*Thinopyrum intermedium* (Host) Nevski var. *intermedium* 'Luna', = *Agropyron trichophorum* (Link) Richt.], and squirreltail [*Elymus elymoides* (Rafin.) Swezey] were drill-seeded November 1, 2001, at 1.3 cm deep. Plots were 3 m by 6 m, and treatments were replicated four times. PRE applications of imazapic (45, 53, 70, 105, and 140 g/ha) were made on November 6, 2001, and POST applications (45, 70 and 105 g/ha) were made on April 8, 2002, when the wheatgrass had four leaves, and most of the grassy weeds were in the early tillering stage, approximately 5 to 12 cm in diameter. A nontreated control was also included for comparison. Applications were made using a CO_2 backpack sprayer delivering 187 L/ha (20 gpa) at 207 kPa (30 psi) through 8002XR nozzles, with 0.25% v/v nonionic surfactant.

Visual evaluations were made on June 6, 2002, for control of medusahead and downy brome and for vigor of seeded perennial grasses. Treatments were compared using MANOVA twice, once in a two-factor analysis (timing and rate, for imazapic at 45, 70, and 105 g/ha), and once in a single-factor analysis concatenating all nine timing and rate combinations. Subsequently, protected ANOVAs were performed for control of medusahead and downy brome and for vigor of perennial grasses.

Imazapic Rate Trials With and Without Disturbance. [4] Disturbance and imazapic rate trials were established at four locations. At each location, disturbance treatments were applied in strips 9 m wide by 63 m long. Shortly after making the disturbance treatment, imazapic treatments were applied across the disturbance strips and adjacent undisturbed ground to form split plots. Subplots were 3 m wide by 9 m long. Imazapic was applied at seven rates (0 to 210 g/ha in 35-g increments) in three replications in randomized complete blocks. Treatments were applied using CO_2 backpack sprayers with six-nozzle booms, at spray volumes of 112 L/ha in Yuba and Yolo counties, CA, and 187 L/ha in Lassen County, CA, and Lake County, OR.

Plots were evaluated in the spring following treatment, at peak flowering of winter annuals. Percentage of cover for all plant species and bare ground and thatch was visually estimated in 1-m^2 quadrats (three per subplot in Yuba and Yolo, CA, counties and two per subplot in Lassen and Lake counties). Cover values were compiled into cover classes (e.g., bare ground, medusahead, annual grasses, broadleaf annuals), depending on the plant species present. Cover classes were used as dependent variables in a factorial MANOVA with rate of imazapic and soil disturbance as factors. This was followed by protected ANOVAs (Scheiner 1993) for each cover class. ANOVAs were used to decide whether data from different disturbance treatments should be grouped or plotted separately. ANOVA was also performed for total species richness (defined as number of species/1-m quadrat, based on species identified during the cover survey). Nonlinear regressions were performed on cover vs. rate of imazapic using curve-fitting software.[2] Values for different disturbance treatments were combined if ANOVA indicated no difference between treatments. Rate responses under different distur-

Table 1. Vigor of individual species following imazapic treatments in a controlled field setting at University of California, Davis.[a]

		PRE				POST			
			Vigor				Vigor		
	Vigor[b] untreated	Tolerance rank[c]	70	140	280	Tolerance rank	70	140	280
			g/ha				g/ha		
Native perennial grasses									
Spike bentgrass	95 a	L	3 c	0 c	0 c	M	55 b	21 c	18 c
California brome	98 a	M	52 b	4 c	9 c	L	31 bc	34 bc	13 c
Tufted hairgrass[d]	100 a	L	4 b	0 c	0 c	L	0 c	1 c	0 c
Slender hairgrass[d]	96 a	L	7 b	0 b	0 b	L	14 b	15 b	9 b
Squirreltail[e]	100 a	M	57 b	14 cd	9 d	M	56 b	48 b	29 c
Blue wildrye	100 a	L	17 c	0 d	0 d	M	55 b	21 c	14 c
Slender wheatgrass	100 a	M	41 d	6 e	9 e	H	79 b	55 c	31 d
Idaho fescue	98 a	H	95 a	6 cd	0 d	L	20 bc	31 b	18 bcd
Meadow barley	100 a	H	73 b	2 d	0 d	H	72 b	52 c	14 d
California barley	100 a	H	89 a	38 c	8 d	M	66 b	63 b	35 c
Beardless wildrye	82 a	M	49 b	17 b	22 b	L	7 b	19 b	10 b
California melicgrass	100 a	L	0 b	0 b	0 b	L	2 b	9 b	12 b
Nodding needlegrass	100 a	L	0 b	0 b	0 b	L	17 b	3 b	7 b
Foothill needlegrass	96 a	L	1 c	0 c	0 c	L	37 b	15 c	4 c
Purple needlegrass	98 a	L	6 c	0 c	0 c	M	52 b	13 c	4 c
Native broadleaf plants									
California poppy	100 a	H	93 a	3 c	4 c	H	95 a	96 a	60 b
Gumweed	91 a	H	88 a	17 b	4 b	H	68 a	75 a	58 a
Spanish clover	90 ab	H	100 a	74 ab	61 b	H	100 a	98 a	91 ab
Hollowleaf annual lupine	100 a	H	100 a	66 ab	33 b	M	41 ab	50 ab	19 b
Nonnative grasses									
Barb goatgrass[d]	98 a	M	45 b	5 d	0 d	L	33 c	14 d	8 d
Wild oat[d]	100 a	L	31 b	5 c	11 c	L	18 c	6 c	4 c
Rip gut brome	100 a	L	20 cd	7 d	17 cd	H	91 a	68 b	43 bc
Soft brome	100 a	L	9 e	1 e	0 e	H	80 b	49 c	33 d
Red brome	100 a	L	13 c	2 c	0 c	H	100 a	65 b	52 b
Wild barley[d]	94 a	M	45 b	26 bcd	0 d	L	37 bc	24 bcd	7 cd
Italian ryegrass	100 a	L	13 bc	0 c	0 c	L	26 b	19 bc	7 bc
Hood canarygrass	100 a	L	0 c	6 bc	0 c	H	98 a	28 b	11 bc
Medusahead[d]	100 a	M	66 b	5 cd	0 d	M	59 b	23 c	13 cd
Rattail fescue	97 a	L	39 c	3 d	0 d	M	67 b	39 c	29 c
Nonnative broadleaf									
Yellow starthistle	100 a	H	85 a	7 d	0 d	M	64 b	40 c	29 c

[a] Values are means from two trials (1998 to 1999 and 1999 to 2000) for a total of eight replications. Within each species (across the table), values followed by the same letter are not different (Student–Newman–Keuls test, $\alpha = 0.05$). Except where noted, PRE and POST applications produced different results according to a two-way factorial analysis.

[b] 100 = no injury, 0 = complete mortality.

[c] Abbreviations: H, high tolerance (vigor > 70%) at 70 g/ha; M, moderate tolerance (vigor between 40 and 70%) at 70 g/ha; L, low tolerance (vigor < 40%) at 70 g/ha.

[d] Two-way factorial analysis found no differences between PRE and POST applications.

[e] *Elymus elymoides.*

bance treatments were compared using multiple response permutation procedure (MRPP) (Mielke and Berry 1982).

Yuba County. At the Sierra Foothills Research and Extension Center in California, disking (tillage) was used for the disturbance treatment. The soil was a well-drained Auburn loam on a slope of ~ 5%, with vegetative cover of 64% exotic annual grasses, 17% nongrasses (mostly *Erodium* spp. [filarees] and exotic *Trifolium* spp. [clovers]), 2% perennial grasses, and 2% native forbs. The site was disked October 22, 2001; applications were made October 29, 2001, and the site received 3 cm of rainfall the following day (70 cm total from July 2001 through June 2002). No seedlings were present at the time of application. Plots were evaluated May 2, 2002. Cover data were grouped into three vegetative cover classes (annual grasses, broadleaf annuals, and bare ground).

Yolo County. At the Bobcat Ranch in the foothills near Winters, CA, the disturbance treatment consisted of mowing followed by raking to remove thatch. The soil was Corning gravelly loam (light-brown gravelly loam and loam about 11 inches thick, over clay subsoil) on a slope of < 2%, heavily 5 infested with medusahead (28% cover in early spring, increasing to 63% in late spring). Early spring cover also included 46% other exotic annual grasses and 7% forbs, half of them native. PRE applications were made November 12, 2002, within 1 wk after 4 cm of rainfall and followed by 34 cm of rainfall over the next 45 d (68 cm total for July

2002 through June 2003). Few seedlings were present at the time of application, except filarees.

Plots were evaluated April 23, 2003, at peak flowering of most winter annuals, and again in late spring (May 29, 2003), when medusahead was fully mature. Cover data were grouped into cover classes including medusahead, all grasses, broadleaf forage (legumes plus filarees), other broadleaf plants, and bare ground and thatch.

Lassen County. Two disturbance treatments (burning and tilling) were established on parallel strips in medusahead-6 infested rangeland near Likely, CA. Besides medusahead (40% cover), vegetation consisted primarily of Japanese brome (*Bromus japonicus* Thunb. ex Murr. BROJA) (13%), prickly lettuce (*Lactuca serriola* L.), native winter annual mustards, a few *Lupinus* spp., perennial *Poa* spp., bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh.) A. Löve], and low sagebrush (*Artemisia arbuscula* Nutt.). The soil was a Bieber cobbly loam to 15 cm and clay loam/clay from 15 to 46 cm, with a 2 to 5 cm thatch layer covering 60% of the ground. Strips were tilled with a spike-tooth harrow or burned with a propane torch on November 3, 2001. Herbicide treatments were applied across the strips on November 5, 2001. No seedlings had germinated in the plots before application. Plots were seeded with a mix of western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Löve] and squirreltail at 11 kg/ha on the day of application. Seeds were broadcast-applied without incorporation. Because of poor establishment in the first year, plots were seeded again in spring 2003 with the same mix, but with an additional 3.3 kg/ha crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.]. Precipitation was 13 cm from November 2001 to July 2002 and 27 cm from August 2002 to July 2003, with 18 cm of it from March through May.

In late June 2002 and 2003, estimates were made of medusahead density, bare ground (including thatch), and cover from all plant species.

Lake County, OR. On rangeland in southern Oregon a trial was established similar to the Lassen County, CA, study (burned and tilled treatments), but disturbance and herbicide application were conducted at two timings (fall and spring). The site was heavily infested with medusahead (74% cover); other vegetation consisted primarily of native and introduced 7 winter annual mustards (*Sinapis* L. sp.) and low sagebrush. The soil was a Pait cobbly loam. Fall plots were burned or tilled November 10, 2001, and treated November 15, 2001, before any seedlings had emerged. Spring plots were burned or tilled April 6, 2002, and treated April 12, 2002, with methylated seed oil surfactant (1,170 ml/ha) in the spray solution. Many medusahead seedlings ($\leq$ 6 cm tall) were present in the undisturbed plots at the time of spring application. Precipitation was 21 cm from November 2001 to July 2002 and 26 cm from August 2002 to July 2003, with 12 cm of it from March through May.

Plots were seeded in fall with 11 kg/ha of a mix of basin wildrye [*Leymus cinereus* (Scribn. & Merr.) A. Löve], bluebunch wheatgrass, and Idaho fescue (*Festuca idahoensis* Elmer), and in spring with 11 kg/ha of a mix of squirreltail, sheep fescue (*Festuca ovina* L. var. *ovina*), bluebunch wheatgrass, and crested wheatgrass. Seeds were broadcast-sown, without incorporation, the same day herbicides were applied. The same mixes were reseeded in fall 2002 and spring 2003 because of poor establishment in 2002. In late June 2002 and 2003, visual estimates were made of medusahead density and cover, other vegetative cover, and bare ground. Cover values were compared using a three-factor MANOVA (disturbance type by rate of imazapic by application timing), followed by protected ANOVAs for each cover type. Data were subsequently analyzed using regression and MRPP as described for Yuba County, CA.

Results and Discussion

Selectivity Trials. *Yolo County.* MANOVA over all species in both years indicated highly significant differences between treatments (Table 1). Individual ANOVAs showed that higher rates of imazapic decreased vigor in all species. In most species, PRE applications resulted in decreased vigor (greater injury) relative to POST applications; this trend was most clear at higher rates (140 to 280 g/ha). Relative tolerance for each species was designated high, moderate, or low, based on the response to imazapic at 70 g/ha applied PRE or POST. Highly tolerant plants showed vigor of greater than 70%, moderately tolerant species demonstrated vigor between 40 and 70%, and species with low tolerance to imazapic had vigor less than 40%.

Three grass species, all native perennials, were highly tolerant to PRE treatment (Table 1). In contrast, six grasses were highly tolerant to a POST application of imazapic, but only two were native perennials, and the rest were nonnative annuals. All broadleaf species, including natives and the nonnative yellow starthistle, were moderately or highly tolerant to 70 g/ha imazapic applied either PRE or POST. At rates higher than 70 g/ha, all grasses were susceptible to imazapic PRE, and only a few grasses were moderately tolerant to POST treatments.

Among native perennial grasses, members of the grass tribe Hordeae [slender wheatgrass, *Elymus trachycaulus* (Link) Shinn.; beardless wildrye, *Leymus triticoides* (Buckley) Pilger; meadow barley, *Hordeum brachyantherum* Nevski; California barley *Hordeum californicum* Covas & Stebbins; and squirreltail]; California brome (*Bromus carinatus* Hook. & Arn.), and Idaho fescue (*Festuca idahoensis* Elmer) generally retained 8 higher vigor after PRE imazapic treatments compared with other grasses. Other perennial grasses used in restoration efforts, including spike bentgrass (*Agrostis exarata* Trin.), tufted hairgrass [*Deschampsia caespitosa* (L.) Beauv.], slender hairgrass [*Deschampsia elongata* (Hook.) Benth.], blue wildrye [*Elymus glaucus* Buckl.], California melicgrass (*Melica californica* Scribn.), nodding needlegrass [*Nassella cernua* (Stebb. & Löve) Barkworth], foothill needlegrass [*Nassella lepida* (A. Hitchc.) Barkworth], and purple needlegrass [*Nassella pulchra* (A. Hitchc.) Barkworth], demonstrated low levels of tolerance 9 at 70 g/ha imazapic applied PRE.

Among the weedy grasses, *Bromus* species (ripgut brome, *Bromus diandrus* Roth BRODI; soft brome, *Bromus hordeaceus* L. BROMO; and red brome, *Bromus rubens* L. BRORU) were very susceptible to PRE imazapic treatments but were

Table 2. Effect of PRE and POST applications of imazapic on medusahead and downy brome control and perennial grass vigor in Siskiyou County.[a]

		Control[b]		Perennial grass injury[b]		
Imazapic	Timing	medusahead	downy brome	intermediate wheatgrass	pubescent wheatgrass	squirreltail
g/ha		%				
0 (control)	—	0 d	0 c	50 ab	35 abc	63 a
45	PRE	94 a	98 a	15 b	5 c	10 ab
53	PRE	94 a	100 a	10 b	8 c	5 b
70	PRE	99 a	100 a	30 ab	30 bc	23 ab
105	PRE	100 a	100 a	60 a	50 ab	35 ab
140	PRE	100 a	100 a	65 a	63 a	65 a
45	POST	63 c	73 b	35 ab	30 abc	63 a
70	POST	74 bc	81 ab	43 ab	38 abc	40 ab
105	POST	85 ab	85 ab	30 ab	30 abc	38 ab

[a] Within each species (within columns), values followed by the same letter are not different (single-factor ANOVA followed by Student–Newman–Keuls test, $\alpha = 0.05$).

[b] 0, no control or injury; 100, complete mortality. 10

relatively tolerant to POST applications (Table 1). Other species sensitive to 70 g/ha imazapic applied PRE included wild oat (*Avena fatua* L. AVEFA), Italian ryegrass (*Lolium multiflorum* Lam. LOLMU), hood canarygrass (*Phalaris paradoxa* L. PHAPA), and rattail fescue [*Vulpia myuros* (L.) C. Gmel. VLPMY]. As with the native perennial grasses, all three invasive annual grasses belonging to the tribe Hordeae (barb goatgrass, *Aegilops triuncialis* L. AEGTR; wild barley, *Hordeum murinum* L. HORMC; and medusahead) were the least sensitive to PRE imazapic, showing moderate tolerance.

In general, the perennial grasses were slightly more tolerant to PRE application of 70 g/ha imazapic than the annual grasses. However, the margin of differential tolerance was relatively narrow, suggesting that even slight overapplication could cause damage to desirable perennial grass species.

Most native forb species showed high tolerance to imazapic, including legumes (Spanish clover, *Lotus purshianus* (Benth.) Clements & E.G. Clements; and hollowleaf annual lupine, 11 *Lupinus succulentus* Koch), California poppy (*Eschscholzia californica* Cham.), and gumweed (*Grindelia camporum* E. Greene).

Siskiyou County. Two-factor MANOVA for treatments, which were duplicated PRE and POST, indicated differences by rate ($P = 0.021$) and timing ($P = 0.005$), but the rate-by-timing interaction was not significant ($P = 0.071$). Single-factor MANOVA of the concatenated variables found a strong difference among treatments ($P < 0.0001$); results from subsequent ANOVAs and means separations are shown in Table 2. At all rates, PRE applications produced greater control of medusahead and downy brome than POST applications. Medusahead was effectively controlled at lower rates (< 70 g/ha) in this trial than in the Yolo County, CA, study (Table 1) or in reports by Monaco et al. (2005) or Shinn and Thill (2002). Downy brome control was also excellent at low rates of imazapic applied PRE. Other studies have shown downy brome to be highly susceptible to PRE treatments with imazapic (Sebastian and Beck 2004; Dewey et al. 2003).

Results for perennial grass injury were variable for higher rates of imazapic, but imazapic applied PRE at 70 g/ha produced acceptable control of medusahead with tolerable levels of injury (30% or less) to perennial grasses. Perennial grass vigor in untreated control plots was lower than in many treated plots because of competition with annual grasses and broadleaf species.

Imazapic Rate Trials With and Without Disturbance. *Yuba County.* The MANOVA model for differences in vegetative cover was significant for rate of imazapic ($P < 0.0001$), disturbance ($P = 0.0172$), and rate-by-disturbance interaction ($P = 0.0002$). Bare ground increased with rate of imazapic (Figure 1a) and was higher in disked plots. Conversely, both grass cover (Figure 1b) and broadleaf cover (Figure 1c) decreased with increasing rate of imazapic. Grass cover was higher in undisturbed plots. Based on the regressions for bare ground and grass cover, imazapic at 210 g/ha on undisturbed soil with thatch produced similar results to imazapic at 70 g/ha on disked, bare soil. This suggests that imazapic was tied up in the thatch and litter layer and not available for plant uptake.

In contrast to the annual grasses, broadleaf cover did not change significantly with disturbance. Of the three most common broadleaf species present, broadleaf filaree [*Erodium botrys* (Cav.) Bertol. EROBO] and rose clover (*Trifolium hirtum* All.) were unaffected by disking, and blessed milkthistle [*Silybum marianum* (L.) Gaertn. SLYMA] tended to establish better in disturbed plots (data not shown). Species richness (overall mean of 10.8 species/m^2) was not affected by rate of imazapic or disturbance treatment.

Yolo County. For early spring cover data, the MANOVA model was significant for rate of imazapic ($P < 0.0001$) and disturbance ($P = 0.0005$) but not for the rate-by-disturbance interaction ($P = 0.0611$). For late spring medusahead cover, the MANOVA model was significant for rate ($P < 0.0001$), disturbance ($P < 0.0001$), and for the interaction ($P = 0.0262$).

In early spring evaluations, bare ground increased with rate of imazapic (Figure 2a) and, unlike the Yuba County trial, 12 was higher in undisturbed plots, especially at 140 to 210 g/ha of imazapic. This resulted from a large, extant population of smooth catsear (*Hypochaeris glabra* L. HRYGL), which is highly tolerant to imazapic. Overall, forb cover increased with rate of imazapic in the cleared plots, again, because of the

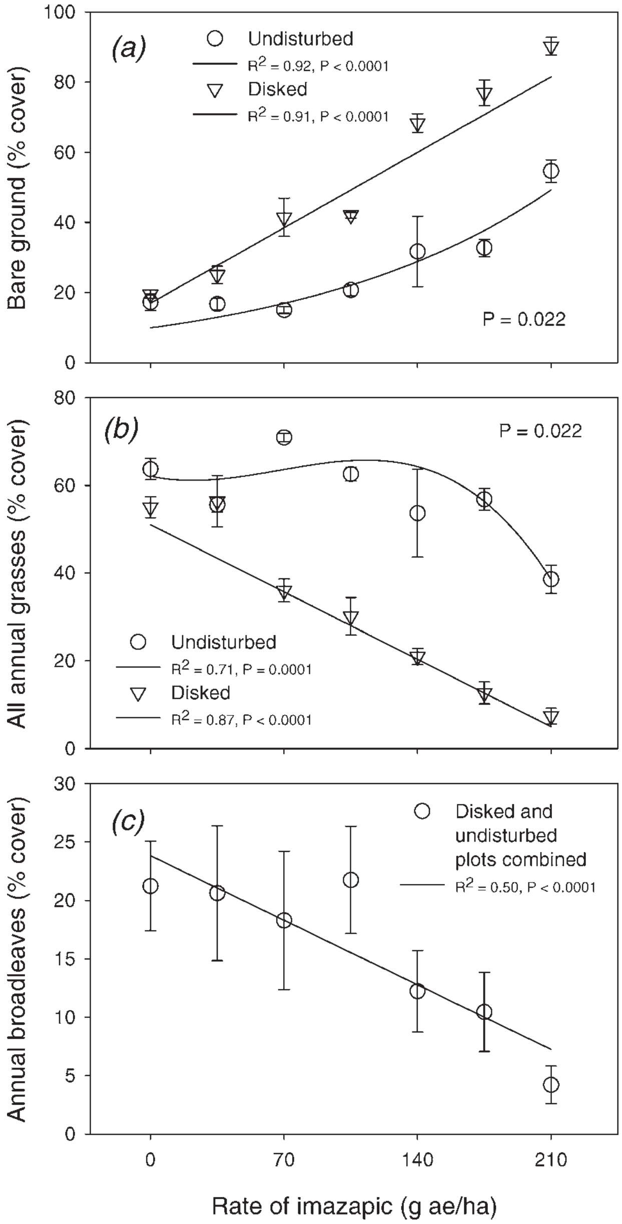

Figure 1. Rate response to imazapic (treated in fall 2001, evaluated spring 2002) on (a) bare ground, (b) annual grass cover, and (c) annual broadleaf cover in Yuba County. Regressions are calculated on all data, but only means are plotted. Error bars are standard error. Probability value (P) indicates significance of difference between disturbance treatments as determined by multiple response permutation procedure (MRPP).

presence of smooth catsear and selective suppression of grasses. However, broadleaf forage plants, such as *Erodium* and legumes, decreased with increasing imazapic rate in the cleared plots but not in the undisturbed plots (Figure 2c). Overall species richness was higher in disturbed than undisturbed plots (10.0 vs. 7.3 species/m^2, $P < 0.0001$) and tended to be lower, although not significantly, at the highest rates of imazapic.

Total annual grass cover and early spring medusahead cover decreased with increasing rate of imazapic. Interestingly, medusahead cover was statistically lower in mowed and raked

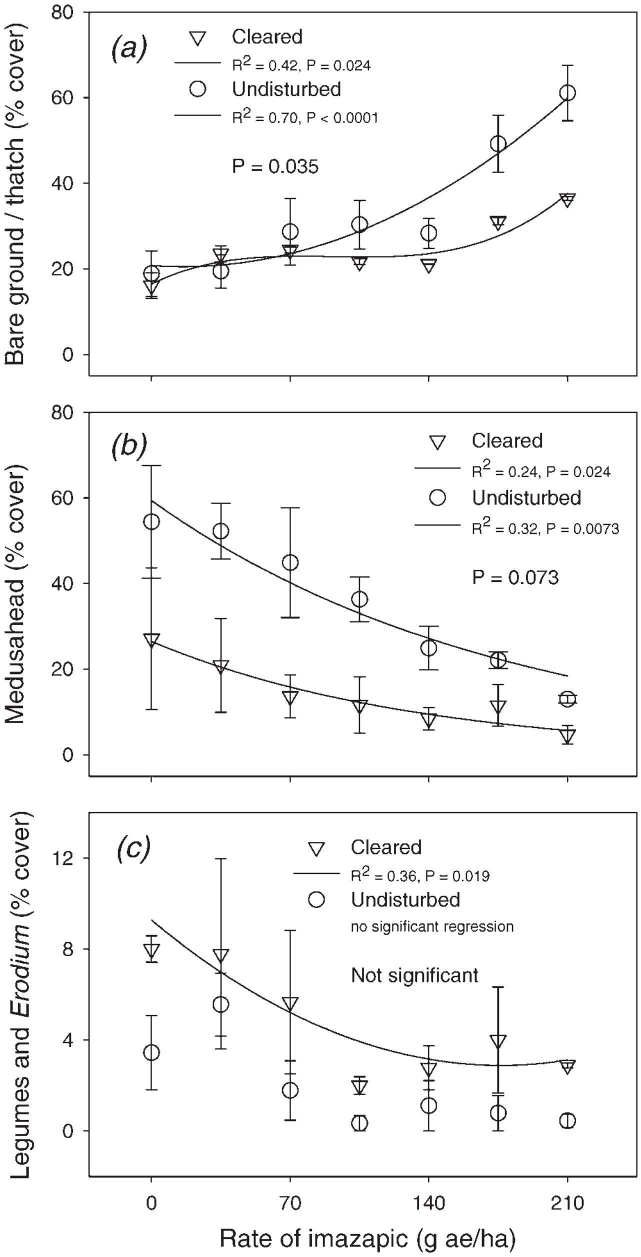

Figure 2. Yolo County rate response to imazapic (treated in fall 2002, evaluated spring 2003) on (a) bare ground, (b) medusahead cover, and (c) cover of legumes and *Erodium*. Cover data for (a) and (c) were taken in early spring and for (b) in late spring. Regressions are calculated on all data, but only means are plotted. Error bars are standard error. Probability value (P) indicates significance of difference between disturbance treatments as determined by multiple response permutation procedure (MRPP).

plots, but total grass cover was not different (data not shown). Although not statistically different, medusahead cover in nontreated, mowed and raked plots was nearly 80% lower than in nontreated, undisturbed plots in early spring (data not shown), and nearly 60% lower in late spring (Figure 2b, imazapic rate = 0). These data support the hypothesis that the competitiveness of medusahead is enhanced by its thatch layer, which can suppress the germination and establishment of competing species (Young 1992).

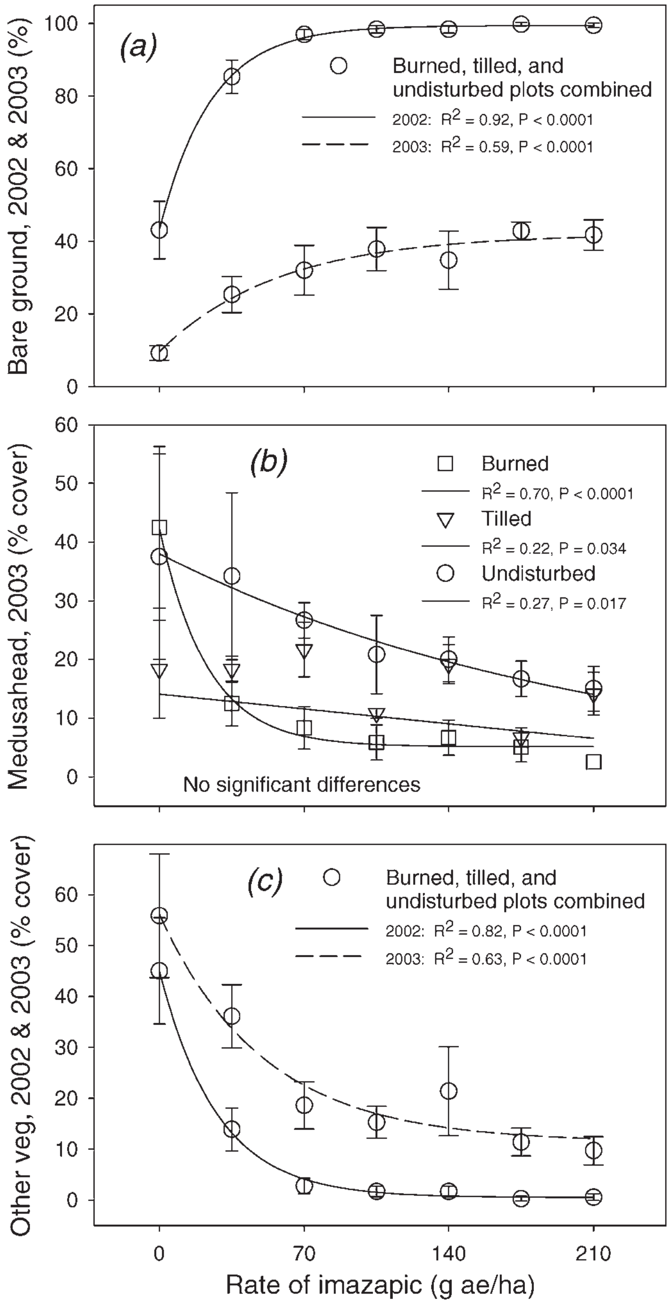

Figure 3. Lassen County rate response to imazapic (evaluated spring 2002 and spring 2003) on (a) bare ground, (b) medusahead, and (c) other vegetation. "Other vegetation" is predominantly Japanese brome and prickly lettuce. Regressions are calculated on all data, but only means are plotted. Error bars are standard error.

Late-spring medusahead cover continued to show a decrease with increasing rates of imazapic, but MRPP indicated that differences between cleared and undisturbed ground were no longer significant (Figure 2b) because of late-season compensatory growth of medusahead. Between the early and late evaluations (5 weeks), medusahead cover approximately doubled in undisturbed plots but increased nearly eightfold in the cleared plots.

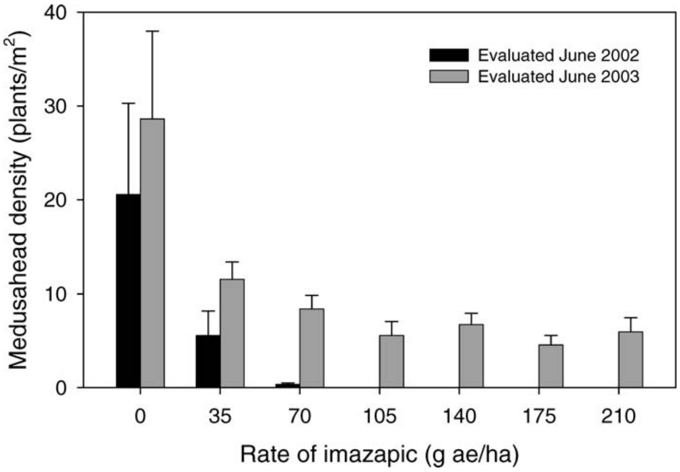

Figure 4. Lassen County medusahead density response to rates of imazapic. Imazapic applied in November 2001; evaluations were made in June 2002 and June 2003. Values are means for all disturbance treatments. Error bars are standard error (n = 9).

Lassen County. Results from MANOVA indicate that the rate of imazapic had a highly significant ($P < 0.0001$) effect on vegetative cover. However, disturbance type and rate-by-disturbance interaction were not significant ($P = 0.15$ and 0.41, respectively). Data were combined over disturbance types for plotting bare ground in 2002 and 2003 (Figure 3a) and other vegetation in 2002 and 2003 (Figure 3c). Although the effect of disturbance was not significant overall, tillage tended to result in reduced cover of medusahead in 2003, and cover remained lower with increasing imazapic rates (Figure 3b). Interestingly, burning alone did not reduce medusahead in the second season after treatment, but low rates of imazapic were much more effective in reducing medusahead cover in burned plots than in unburned plots. This again suggests that imazapic may be bound to the litter layer, thus reducing its activity. Monaco et al. (2005) reported similar results, showing that medusahead control with imazapic was significantly greater following a complete burn.

Medusahead density, measured in 2002, showed a significant reduction with increasing rates of imazapic. At rates of 70 g/ha and above, the control of medusahead was nearly complete (Figure 4). In the second season after treatment (2003), medusahead density recovered somewhat, but not to the level of the nontreated control plots.

In Lassen County, as in the selectivity trial in Siskiyou County, medusahead was more sensitive to imazapic than in either Yuba or Yolo counties. Because soil textures were essentially similar among the sites, it is speculated that microbial breakdown of imazapic may be slower in the cooler soils of the intermountain counties.

Perennial grasses seeded in fall 2002 failed to establish and were reseeded in spring 2003. The failure of the 2002 planting was likely a result of winter-frost heaving and lack of late-winter moisture. Rains during spring 2003 provided enough moisture for the more drought-hardy perennials to establish from the second seeding. However, no perennial grasses established in the untreated control plots, and establishment was sporadic or marginal in all imazapic-treated plots. Of all

Table 3. Effect of PRE applications of imazapic on the establishment (density) of perennial grasses in Lassen County, CA, and Lake County, OR in June 2003.[a]

	Perennial grass		
	Lassen County, CA	Lake County, OR	
Imazapic	Applied fall 2001	Applied fall 2001[b]	Applied spring 2002
g/ha	plants/m^2		
0	0 c	1.28	0.17 b
35	0.44 bc	0.28	0.50 ab
70	0.44 bc	0.78	1.28 ab
105	0.28 bc	0.33	2.17 a
140	0.33 bc	0.61	1.28 ab
175	0.78 ab	1.22	2.00 a
210	1.11 a	0.22	1.78 ab

[a] Values are means for all disturbance types. Within columns, values followed by the same letter are not different (Student–Newman–Keuls test, $\alpha = 0.05$).

[b] No significant differences.

the seeded species, more than 90% of the seedlings were crested wheatgrass; of the seeded native perennials, squirreltail established most successfully. These grasses established most densely at the two highest imazapic rates (Table 3), probably because of reduced weed competition. This supports the previous finding that squirreltail and wheatgrass have a high tolerance to imazapic. Neither tillage nor burning had an effect on perennial grass establishment.

Lake County, OR. The MANOVA model for vegetative cover was significant for rate ($P < 0.0001$), time of application ($P = 0.0131$), and rate-by-timing interaction ($P < 0.0001$). Disturbance type and disturbance interactions were not significant in the MANOVA model, so data from different disturbance treatments were combined for regression analysis in most of the response variables. Protected ANOVA results indicate time of application did not significantly affect bare ground in 2002 (Figure 5a), but the timing-by-rate interaction was significant for 2003 (Figure 5b).

In 2002, medusahead cover in spring-treated plots was not different than cover in fall-treated plots (Figure 5c), but in

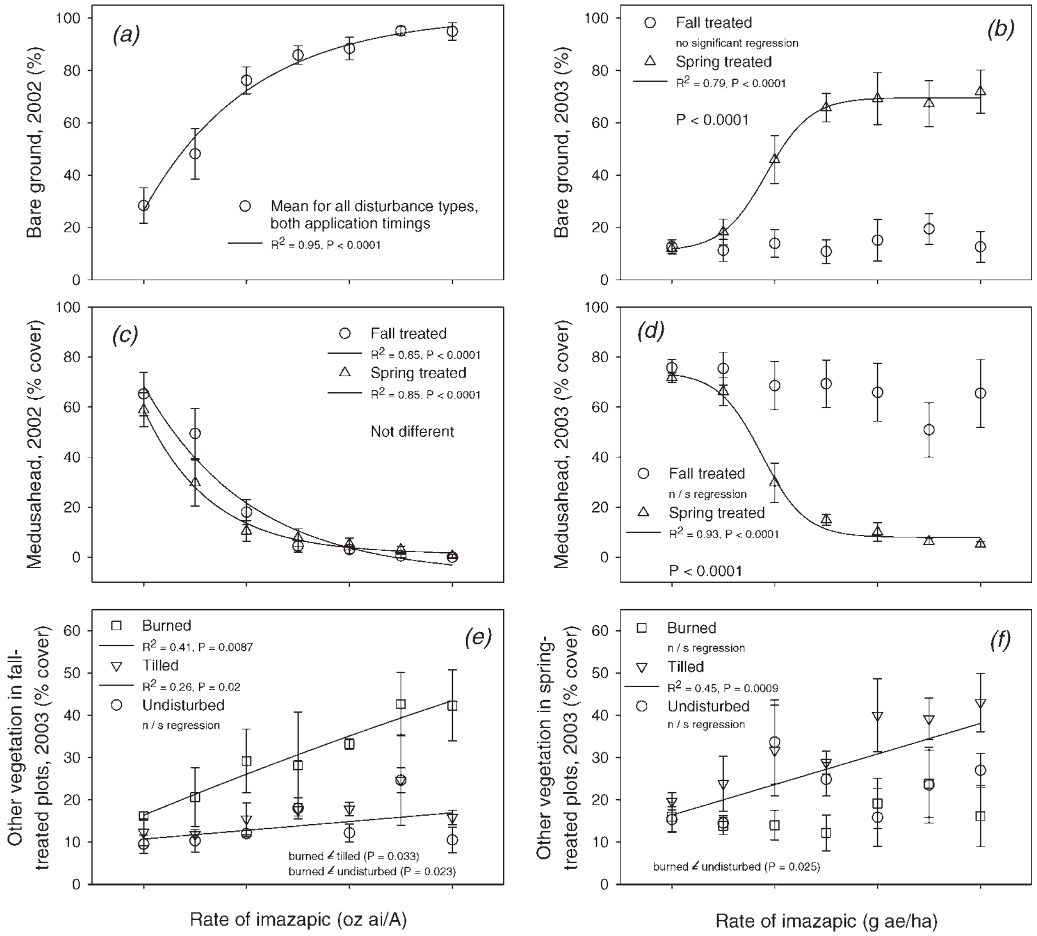

Figure 5. Lake County, OR, rate response to imazapic (evaluated spring 2002 and spring 2003) on bare ground in (a) 2002 and (b) 2003, medusahead in (c) 2002 and (d) 2003, and other vegetation in 2003 in (e) fall-treated plots and (f) spring-treated plots. "Other vegetation" is predominantly Japanese brome, prickly lettuce, and alfalfa (*Medicago sativa* L.). Regressions are calculated on all data, but only means are plotted. Error bars are standard error. Probability value (P) at the bottom of the legend (b and d) indicates significance of difference between application timings as determined by multiple response permutation procedure (MRPP). Where MRPP indicated no differences among disturbance treatments, all disturbance treatments are combined (a–d); otherwise, differences between disturbance treatments (e and f) are indicated.

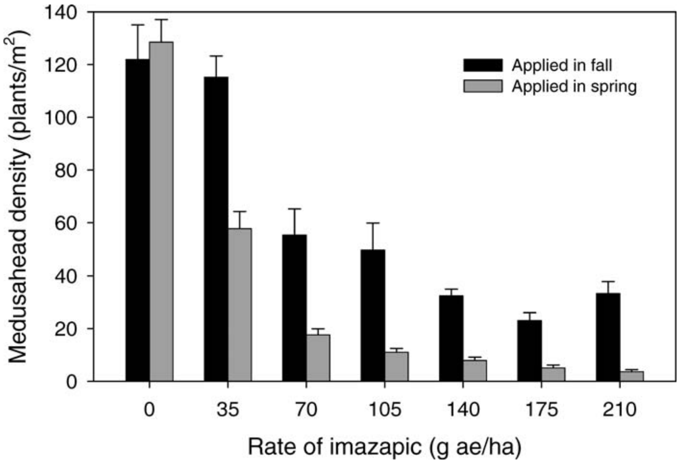

Figure 6. Lake County, OR, medusahead density response to rates of imazapic. Fall applications were made in November 2001; spring applications were in April 2002. Evaluations were made in June 2003. Values are means for all disturbance treatments. Error bars are standard error (n = 9).

2003, medusahead cover was significantly lower in spring-treated plots than in fall-treated plots (Figure 5d). This was probably due, in part, to differences in soil residual imazapic. At the time of the 2003 June evaluations, the fall treatments had been made 19 mo before the evaluation, whereas the spring treatments were applied only 14 mo earlier. Medusahead density in 2003 also indicated an enhanced response to spring applications (Figure 6). Although fall treatments provided some density reduction, that did not translate into a reduction in medusahead cover in 2003 (Figure 5d), probably because of compensatory growth of the plants remaining in the fall-treated plots. Most medusahead plants in fall-treated plots were taller and had more tillers compared with medusahead plants growing in the untreated plots (personal observation).

Cover of other vegetation differed by time of application during 2002, although not in a consistent manner. In 2003, in the second season after treatment, cover of other vegetation showed a significant three-way interaction effect (rate by timing by disturbance) in an ‘‘unprotected’’ ANOVA. The burn treatment gave an advantage to other vegetation in the first year following a fall treatment (Figure 5e), but the tilled plots had significantly higher cover by other vegetation in the spring-treated plots (Figure 5f).

As in Lassen County, perennial grasses seeded in fall 2001 and spring 2002 were unsuccessful because of weather conditions. After seeding again in fall 2002 and spring 2003, perennial grasses established sparsely. There were no statistical differences in the fall planting, and perennial grasses established in all plots. However, the spring planting showed a consistent increase in perennial grasses at higher imazapic rates (Table 3). This increase is likely due to the reduction in competition with annual species because these plots also had the most bare ground. As in Lassen County, the dominant perennial grasses included squirreltail and crested wheatgrass.

All Trials. Over all trials, several species of perennial grasses showed good tolerance to low rates of imazapic, particularly members of the tribe Hordeae (i.e., wheatgrasses and species in the genera *Hordeum*, *Leymus*, and *Elymus*). Shinn and Thill (2004) reported similar imazapic tolerance in wheatgrasses. Several native broadleaf species also showed high tolerance to imazapic, particularly species within the families Asteraceae and Fabaceae. Other studies have also shown that native Asteraceae or Fabaceae species could be seeded and established when competing grasses were controlled with imazapic (Beran et al. 1999; Masters et al. 2001).

Among nonnative annual grasses, species within the tribe Hordeae again showed the greatest tolerance, including barb goatgrass and medusahead. However, this level of tolerance did not appear to be as great as many of the perennial Hordeae. Overall, medusahead and other annual grasses were most effectively suppressed by low rates of imazapic (≤ 70 g/ha) in situations where the litter layer was removed by tillage, mowing and raking, or burning. Thatch and litter removal alone provided some suppression of medusahead in the following year, supporting the idea that the competitiveness of medusahead is at least partially due to its high-silica thatch layer.

At increasing imazapic rates, plant cover decreased, especially annual grasses. This shifted the plant community toward broadleaf species, particularly species in the Asteraceae. In some cases, this outcome may be desirable, e.g., in preparation for revegetation or in communities with important native composites. However, if the goal is to selectively remove medusahead in a rangeland system with other more desirable annual forage grasses, such as wild oat and ryegrass, imazapic is not likely to provide the desired results.

The rate of imazapic generally showed a significant interaction with disturbance, suggesting that the herbicide ties up in the thatch and litter component. For example, in Yuba County, 70 g/ha of imazapic applied to bare soil following tillage gave similar control of annual grasses as 210 g/ha imazapic applied to undisturbed ground. Imazapic efficacy also was related to timing of application. Medusahead was controlled more effectively with PRE applications in Yolo and Siskiyou counties but was most effective as a POST application in Lake County, OR, where a methylated seed-oil surfactant was included in the spray solution.

Although imazapic does show promise for use in perennial grass restoration efforts, the margin of safety for desirable species is fairly narrow. As found in this study, application rates that will control medusahead, while selecting for desirables, depend on a number of variables, including timing and the amount of soil surface organic material. In turn, the amount of surface litter and organic material is closely related to the recent disturbance history of a particular site. Deciding whether to use imazapic and determining optimal parameters for application may require site-specific evaluation.

Sources of Materials

[1] Plateau®, 2 lb ae/gallon, BASF Corporation, 26 Davis Dr., Research Triangle Park, NC 27709.

[2] SigmaPlot 2002 for Windows Version 8.0, SPSS Inc., 233 S. Wacker Drive, 11th floor, Chicago, IL 60606-6307.

Acknowledgments

We are grateful to Glenn Nader, UCCE Farm Advisor, Sutter, Yuba, and Butte counties; Mike Connor and Dave Labadie of the Sierra Foothills Research and Extension Center; and Joe and Jennifer Vollmer, BASF, Laramie, WY, for their logistical support in this project and to BASF for their financial support. We also thank Dr. John Anderson of Hedgerow Farms, Yolo County, for providing native plant seed for the preliminary screening trials.

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Received February 6, 2006, and approved April 19, 2006.

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