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Effects of Imazapic on Target and Nontarget Vegetation during Revegetation

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Medusahead is an introduced, winter-annual grass covering millions of hectares of the semiarid West. It forms exclusive stands and has a dense thatch cover that resists the establishment of desirable species. Prescribed fire can remove medusahead litter and improve plant establishment. Medusahead control is fundamental to establishing desirable species that will, in turn, resist further invasion. Imazapic is an effective herbicide for control of medusahead, but more information is needed on its effects on desirable species. Our objectives were to test how imazapic application rate and timing affected medusahead, seeded desirable species, and other nontarget vegetation on burned and unburned rangeland in southeast Oregon. We burned existing medusahead infestations at two different sites in June 2003. Following the burn, imazapic was applied at rates of 0, 35, 70, 105, 140, 175, and 210 g ai/ha between July and October of 2003 in a randomized strip-plot design. In November 2003, monocultures of seven desirable species were drill-seeded across the imazapic treated areas. Data on cover and density of medusahead and seeded species were collected in 2004 and 2005. Cover data of nontarget species were collected in the summer of 2005. Medusahead cover was highest in control plots and lowest in plots that received the highest herbicide application rates. Medusahead cover was lower in burned plots. The effect of imazapic on nontarget vegetation was less clear. Seeded species established in the study plots, but their response to herbicide rate showed few consistent patterns; some of the seeded species showed little response to herbicide, whereas others appeared to establish best at different herbicide rates, depending on site and whether the plots were burned or unburned. Site and burn treatment also affected how imazapic rate or application month influenced cover of perennial or annual grasses or forbs.

Nomenclature: Imazapic; medusahead, *Taeniatherum caput-medusae* (L.) Nevski ELYCM.

Key words: Invasive species, prescribed burn, prescribed fire, revegetation.

Medusahead is an aggressive, invasive, winter-annual grass native to Eurasia that is currently a great threat to plant communities in the Great Basin (Young 1992). This invasive weed grows in a variety of environments but is restricted to regions with 250 to 1,000 mm of annual precipitation with hot dry summers and cool wet winters (Miller et al. 1999). Medusahead requires soil moisture availability through late spring to complete its life cycle (George 1992). Dakheel et al. (1994) found that medusahead had its highest photosynthesis rates in areas with a moderate temperature regime. Medusahead commonly occupies clay soils that maintain soil moisture late into the growing season, in arid environments, and in well-developed loam soils where soil moisture is sufficient for maturation (George 1992). In many cases, medusahead invasion occurs after prolonged domination by cheatgrass (*Bromus tectorum* L.) (Bovey et al. 1961). However, it may be more persistent on clay soils, even though it has the capacity to encroach on native shrub–steppe plant communities on loam soils (Miller 1996).

Its range covers nearly a million hectares of land in 17 western states and is expanding at an average rate of 12% per year (Duncan et al. 2004). Medusahead is capable of forming monoculture stands that burn readily and resist reestablishment of native species (Young and Evans 1970). Medusahead is also largely unpalatable by livestock, thus medusahead invasion results in economic losses to rural communities, and it has been reported that medusahead-dominated ranges have suffered a 40 to 75% reduction in grazing capacity (Major et al. 1960).

Medusahead litter is very slow to break down because it has a high silica content, and that causes a dense thatch in medusahead-infested areas (Young 1992). Fire can be either beneficial or detrimental in medusahead-infested areas. If the frequency or intensity of fire is high, it may damage desired perennial plant species. Medusahead emerging from the seed bank following these sorts of wildfires may face little competition from a perennial plant community damaged by fire. However, in the absence of fire, the build-up of medusahead litter may impede natural or artificial establishment of desirable plant species from seed.

Prescribed burns may be used in medusahead populations for several purposes. Use of fire may increase the effectiveness of herbicide treatments because the removal of thatch may allow better contact between herbicide and growing plants (DiTomaso et al. 2006). Fire can be used to remove thatch, increasing the establishment of seeded revegetation species; or fire can be used for a combination of these purposes. It may be used for control of medusahead via destruction of seeds, but researchers disagree over whether this is an effective treatment or not. Recent work argues that the timing of prescribed burns is critical (DiTomaso et al. 2006). Pollak and Kan (1996) found a significant reduction in cover and thatch of exotic annual grasses, including medusahead, in response to a late-June prescribed burn at Jepson Prairie, CA. On the other hand, burns conducted near Alturas, CA, in August resulted in an increase in medusahead cover because medusahead seeds

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in the soil and litter were still able to germinate (Young et al. 1972). After seeds mature and litter dries, the medusahead thatch layer can burn rapidly, whereas the seeds on the soil surface may largely escape fire damage.

Herbicides have also had some success in controlling medusahead populations, but there has been very little published research on the effectiveness of imazapic at controlling medusahead. One study tested the effectiveness of two different rates of sulfometuron and imazapic applied to medusahead (70 and 140 g ai/ha) applied at two different times (spring and fall) at a site that was previously burned to reduce medusahead litter. Results indicated that greater control of medusahead was achieved at the higher rate of each herbicide; in addition, fall herbicide applications provided greater control than spring applications (Monaco et al. 2005). More research is needed to understand how medusahead will respond to different rates of imazapic and different herbicide application timings and whether those patterns are the same in burned and unburned fields.

An integrative management strategy that combines herbicides, fire, and reseeding of competitive species can create a diverse plant community that will resist future invasions (Masters et al. 1996). Perennial grass plantings may provide a plant community better able to resist further invasion of annual weeds such as medusahead, but these plantings may fail if competition from annual invaders is not controlled during perennial establishment (Borman et al. 1991). The initial growth of medusahead may exceed the initial growth of perennial grasses planted to help resist it (Goebel et al. 1988; Sheley et al. 1993). Thus, control of medusahead is critical for successful revegetation.

Use of imazapic herbicide to control medusahead can potentially have a negative impact on the ability of species seeded to compete with medusahead. Monaco et al. (2005) found that perennial grass cover was significantly higher in plots that received a low rate of imazapic (70 g ai/ha) than in plots that received a high rate of imazapic (140 g ai/ha). They did not note any significant difference in the two rates of imazapic on the cover of annual or perennial forbs. This suggests that one challenge of managing medusahead with plantings of competitive species is to find the rate of imazapic that will offer control of medusahead without damaging nontarget species. In addition, changing the timing of application may result in better or worse control of medusahead and may affect how nontarget plants respond to the herbicide.

In this study, we evaluated the effects of imazapic rate and timing of application on various grass species and forbs in burned and nonburned pastures. We hypothesized that a moderate rate of imazapic would offer a better trade-off between maximum medusahead control and minimum impact on nontarget vegetation. We also hypothesized that late summer or fall applications of imazapic would offer better control of medusahead because the herbicide would be applied closer to the germination of medusahead seeds. Finally, we hypothesized that less imazapic would be needed to control medusahead on the burned sites because the removal of thatch via burning would allow better contact of the herbicide with the soil.

Materials and Methods

Study Sites. The study was conducted at two sites in eastern Oregon from 2003 to 2005. The first site, Mullin Ranch, is located near John Day, OR, and receives an average of 353 mm of annual precipitation (Grant County; 118°56′18.29″W, 44°26′5.05″N; elevation 1,000 m). The soils at the Mullin Ranch, OR, are Waterbury series soils (clayey-skeletal, smectitic, mesic Lithic Argixerolls). The second site, Lamb Ranch, is located near Drewsey, OR, and receives an average of 278 mm of annual precipitation (Harney County; 118°26′43.94″W, 43°26′54.98″N; elevation 1,250 m). The soils at Lamb Ranch are Virtue series soils (fine-silty, mixed, superactive, mesic Xeric Argidurids). Both sites are located in the Snake River Plain and eastern Idaho plant-growth region (Thornburg 1982).

Experimental Procedures. Treatments were assigned in a randomized strip-plot design. At each site, a 2-ha portion of an existing medusahead infestation was burned in June 2003. Another 2-ha portion was left as an unburned control. On both the burned and unburned areas at each site, imazapic was applied at one of four times at one of seven herbicide application rates. Herbicide treatment rates consisted of imazapic applied at 0, 35, 70, 105, 140, 175, and 210 g ai/ha. A 0.625% v/v methylated seed oil was added to the herbicide mixture. Herbicide treatments were applied using an all-terrain vehicle (ATV)-mounted sprayer with a 3.05-m spray boom with five flat-fan nozzles. The system was calibrated to deliver 355 L/ha at 276 kPa. The herbicide-application plots were 6.1 m wide and 87.7 m long, and each herbicide application rate was replicated four times. The timing of herbicide application was late-July, late-August, late-September, and late-October 2003, and each application month was replicated seven times.

We removed the data for the August herbicide application of 140 g ai/ha at the Mullin Ranch site from the analyses because of misapplication. Hence, all data for the August application at the 140 g ai/ha rate at the Mullin Ranch site was replaced with a missing value indicator to avoid inaccuracies in the analysis results.

In November 2003, monocultures of seven species commonly used in revegetation were drill-seeded perpendicularly across the imazapic treated areas, resulting in three replications of the seeding treatment. One row in each of the three replications was left unseeded as a control. The seeding rows were 3.7 m by 170.6 m, which were created using two passes of a 1.83-m range drill. The species used were thickspike wheatgrass 'Critana' [*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould ssp. *lanceolatus*], Siberian wheatgrass 'Vavilov' [*Agropyron fragile* (Roth) P. Candargy], bluebunch wheatgrass var. 'P-7' [*Pseudoroegneria spicata* (Pursh) A. Löve], squirreltail 'Sand Hollow' [*Elymus elymoides* (Raf.) Swezey], Sandberg bluegrass (*Poa secunda* J. Presl), winterfat [*Krascheninnikovia lanata* (Pursh.) A.D.J. Meeuse & Smit], and forage kochia [*Kochia prostrata* (L.) Schrad.]. We will describe these seeded species with the following abbreviations in the results: ELLA, thickspike wheatgrass; AGFR, Siberian wheatgrass; PSSP, bluebunch wheatgrass; ELEL, squirreltail; POSE, Sandberg bluegrass; KRLA, winterfat; KOPR, forage kochia; and Control, unseeded control.

Sampling. During the summer of 2004 and 2005, we randomly placed 20 by 50-cm Daubenmire frames (0.10 m^2) within each plot to visually estimate the percentage of cover for plants growing within the frames. In 2004, two frames were sampled in each plot, whereas in 2005, the number of frames sampled increased to three or five, depending on location. We estimated percentage of cover for medusahead and for the seeded species as well as for the other species within the plots. The percentage of cover data for the other species was combined to give percentage of cover for four plant functional groups: annual grasses, perennial grasses, annual forbs, and perennial forbs. In 2005, we also recorded the density of seeded species within the frames; grass density was recorded as the number of tillers, whereas forb density was recorded as the number of plants.

Analytical Methods. All data was analyzed using SAS PROC MIXED and a randomized strip-plot design (SAS 1990). Strip-plot designs are used when some treatments must be applied across large experimental units (the whole-plot factors), whereas others are applied across subunits within that unit (the subplot factor) (Littell et al. 1996). Different error terms are used to test whole-plot factors vs. subplot factors. In these designs, the subplot factor is typically detected with greater precision than the whole-plot factor (Petersen 1994). Response variables were log-transformed to reduce problems with deviance from the assumptions of normality and equality of variance. Some response variables continued to exhibit moderate deviations from normality even after log-transformation, in particular, plant cover for nonmedusahead annual grass and seeded-species cover. Individual plants from these groups were rare in the plots. We conducted a separate analysis of these groups using the SAS GLIMMIX macro and specifying a Poisson distribution (Littell et al. 1996). However, the results of these analyses often offered anomalous results, most notably significant three-way interactions in which no other term was significant, so in this article, we will report the results found with the original PROC MIXED analysis. In addition, data for "other species" were inconsistent and nonconclusive in 2004. These data probably represent a transition period as a response to treatments. To improve the readability of this manuscript, data collected for "other species" in 2004 were omitted from the Results and Discussion.

Results and Discussion

Medusahead Cover. Medusahead cover overall tended to be highest in the plots that received no imazapic and lowest in plots that received the higher herbicide application rates (140 to 210 g ai/ha), though this pattern was less clear in the second year of the study (Figures 1 and 2). In addition, medusahead cover tended to be higher in the unburned plots than in the burned plots, though this pattern was less visible during the second year after burning, especially at the Lamb Ranch site (Figures 1 and 2).

Lamb Ranch. There was a significant effect of herbicide application rate on cover of medusahead ($P < 0.001$ for all treatment combinations) (Table 1), and medusahead cover was typically highest when no imazapic was applied (Figure 1A–D). In 2004, medusahead cover was near zero for imazapic rates of 70 g ai/ha or more in the burned plots and for rates of 140 g ai/ha or more in the unburned plots (Figures 1A and 1B). In 2005, medusahead cover was above zero in all the treatments but was at its lowest in the 175 and 210 g ai/ha plots, with the exception of the unburned plots that received herbicide in July (Figures 1C and 1D). There was also a significant effect of application month, with later applications typically resulting in stronger medusahead control, the exception being the 2004 burned plots at Lamb Ranch (Figure 1A–D). Similarly, the interaction between herbicide rate and month was significant in the unburned plots (Table 1). Later applications may have minimized herbicidal decomposition before fall emergence of medusahead.

There were also significant interactions between herbicide rate and species planted in the burned plots at Lamb Ranch in both years (Table 1). In 2004, there was an effect of seeded species on medusahead cover at high imazapic rates; in plots that received no imazapic, medusahead cover was greater in unseeded control plots than in plots seeded with Siberian wheatgrass or Sandberg bluegrass (Figure 3A). In 2005, there was greater medusahead cover in plots seeded with squirreltail that received an application of imazapic at 140 g ai/ha than in plots seeded with other species or in unseeded controls (Figure 3B). This significantly greater medusahead cover seen in the burned plots at Lamb Ranch in 2005 that were seeded with squirreltail was an unexpected finding. It implies that increasing cover of the perennial grass favored increased establishment of medusahead. However, the mean cover of squirreltail, although greater than that of any of the other seeded species in these plots, was still low at only 2.97 ± 0.40% overall. Indeed, the plots that had high medusahead cover were generally those that had no or little establishment of squirreltail after the seeding, whereas the plots with higher establishment of squirreltail had low medusahead cover (data not shown). The seeded species will likely need a few more years to establish before we can evaluate their effectiveness at withstanding medusahead invasion.

Mullin Ranch. The effect of herbicide application rate on medusahead cover was significant in both years and in burned and unburned plots as was the interaction between herbicide rate and application month ($P < 0.001$ for all treatment combinations, Table 1). Once again, in 2004, the lowest cover of medusahead was seen in plots receiving higher concentrations of herbicide—70 g ai/ha or more in the burned plots, 140 g ai/ha or more in the unburned plots (Figures 2A and 2B). In 2005, the lowest medusahead cover in the burned plots was seen for the July application of 70 g ai/ha imazapic and the 140 to 210 g ai/ha applications in all months, with the exception of the August application of 210 g ai/ha herbicide (Figure 2C). In the unburned plots, the lowest cover was seen for the 140 to 210 g ai/ha application rates, although it was higher for the July applications at those rates (Figure 2D). Applications made in July tended to be slightly less effective than applications made in the later months at many of the imazapic rates (Figure 2A–D),

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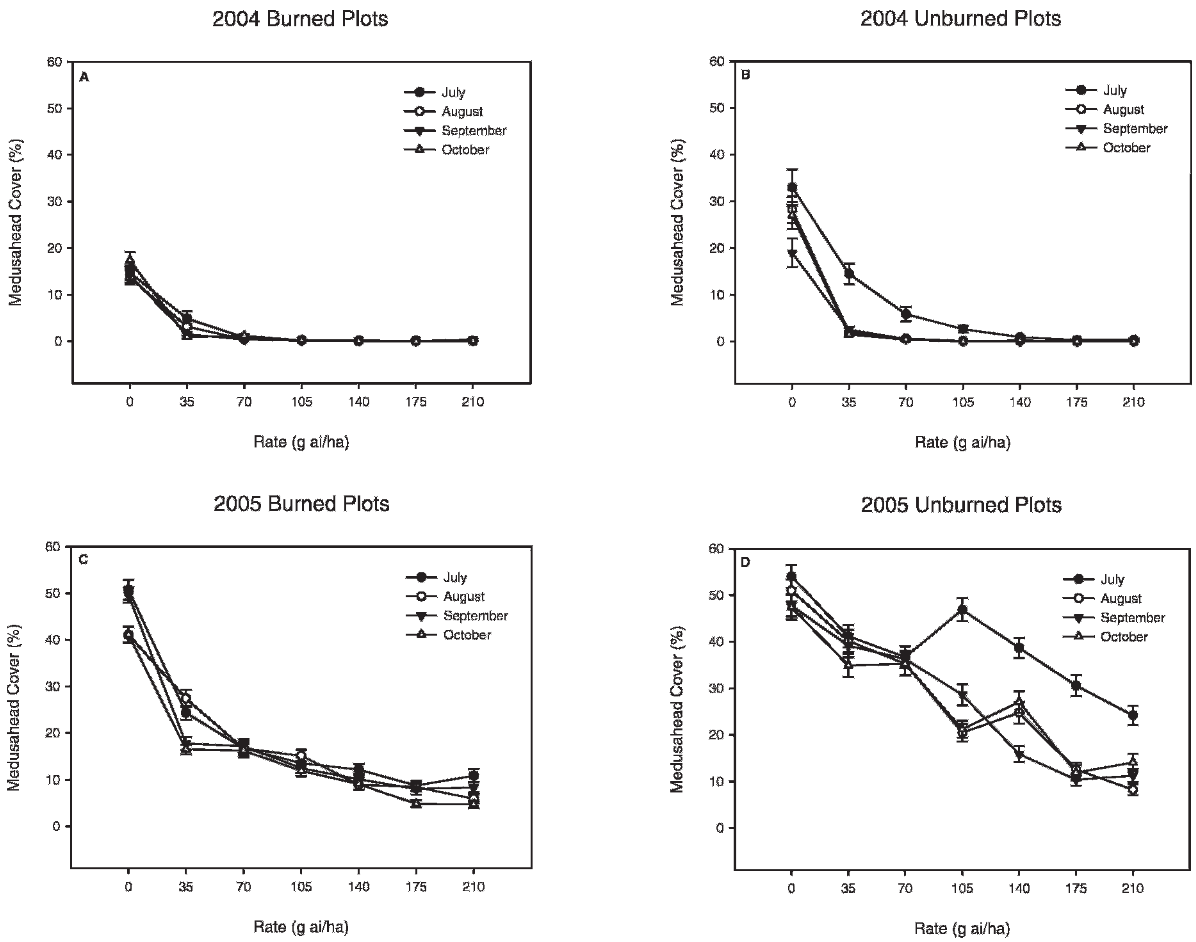

Figure 1. Lamb Ranch (Drewsey, OR) medusahead cover in response to herbicide rate and application month. Values are means ± SE. (A) 2004 burned plots, (B) 2004 unburned plots, (C) 2005 burned plots, and (D) 2005 unburned plots.

possibly because of less time for decomposition before medusahead emergence in fall.

Although we could not test, statistically, the effect of burning used in conjunction with herbicides because of the lack of burning treatment replication, the medusahead cover was much lower in the burned plots than in the unburned plots in the first year (Figures 1 and 2). By the second year after burning (2005), there appeared to be no difference in medusahead cover between the burned and unburned plots at Lamb Ranch (Figure 1), but at Mullin Ranch, medusahead cover was still lower in the burned plots than in the unburned plots (Figure 2). If this lower cover in the burned plots, especially in the first year after burning, was the result of a reduction in medusahead cover in response to the June 2003 burn, then our results support other studies that showed a reduction in medusahead in response to early summer burns (Pollak and Kan 1996).

Although imazapic reduced medusahead cover in both years, even the highest concentrations of imazapic did not reduce medusahead cover to zero, especially in the second year (Figures 1 and 2). A similar study showed medusahead control by imazapic ranging from 26 to 90% depending on year, application rate, timing, and the amount of litter at the site (Monaco et al. 2005). These results suggest that imazapic alone can control medusahead in the initial year; however, in subsequent years, medusahead is likely to again infest the area. Other herbicides can also be used to control medusahead, such as glyphosate, atrazine, bromacil, siduron with picloram, and dalapon. Careful selection and application of these herbicides can allow control of medusahead with minimal damage to desired species (Miller et al. 1999).

In our study, application timing had a small effect on herbicide effectiveness; July applications were often slightly less effective than applications in the other 3 mo. Other researchers have found that fall application of imazapic controlled medusahead more effectively than spring application, although that result was not seen in the second year of the study (Monaco et al. 2005). Mean medusahead cover was lower in burned plots than in unburned plots, and that difference in cover was especially noticeable in plots that received no imazapic or low imazapic concentrations (Figures 1 and 2). Also, the concentration of imazapic needed to reduce medusahead cover to zero appeared to be lower in the burned plots than in the unburned plots (Figures 1 and 2). These findings suggest that an integrated management strategy that uses prescribed burns in conjunction with

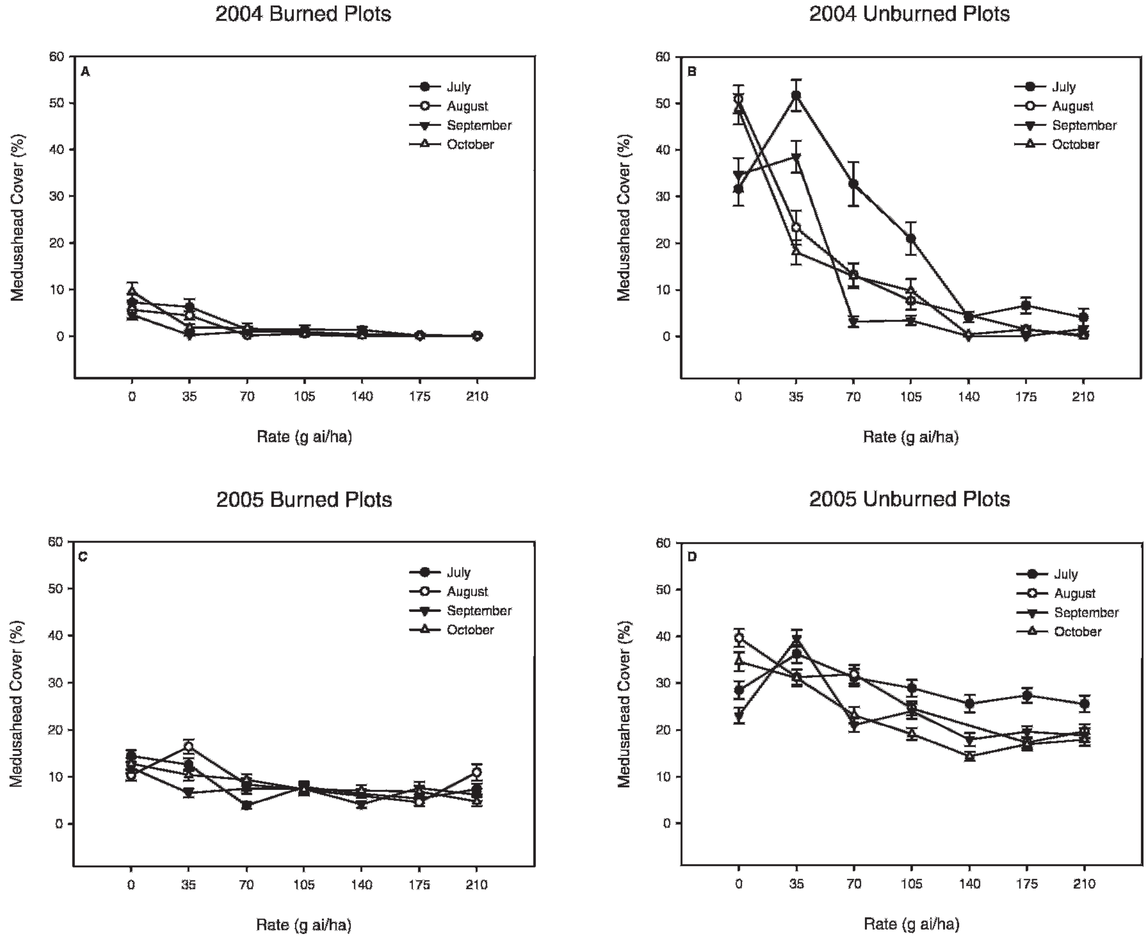

Figure 2. Mullin Ranch (John Day, OR) medusahead cover in response to herbicide rate and application month. Values are means ± SE. (A) 2004 burned plots, (B) 2004 unburned plots, (C) 2005 burned plots, and (D) 2005 unburned plots.

imazapic application can potentially result in better control at lower herbicide concentrations, although that control may be of short duration.

The different response of medusahead between the two sites may be because of differences in soil depth or texture. The soils at the Mullin Ranch site are an extremely stony, silty clay loam with a depth of 0.31 to 0.51 m to bedrock, whereas at the Lamb Ranch site, soils are more of a silt loam with a duripan at 0.51 to 1.02 m. These differences in soil depth and texture may have influenced the effect and duration of the different treatments. The shallower soils and higher clay content of the Mullin Ranch site may have resulted in better destruction of medusahead seeds in the burned field.

Seeded Species Cover and Density. Cover by seeded species was low throughout this study; mean cover was below 3% at Lamb Ranch and below 9% at Mullin Ranch. However, the seeded species were established at these two sites. Density of species showed similar patterns to those seen for cover, as would be expected for young, establishing perennial plants. Siberian wheatgrass density was as high as 82 ± 30 tillers/m^2 at the Lamb Ranch site and 398 ± 97 tillers/m^2 at the Mullin Ranch site.

There was a significant interaction between herbicide application rate and the species planted in all but two of the comparisons (Table 2). This interaction reflects both species success (some of the seeded species established better than others did) and establishment across different herbicide rates and different burn treatments (species establishment was not uniform across rate or burn treatment) (Figures 4 and 5). In fact, the effect of herbicide rate on seeded species cover showed few consistent patterns (Figures 4 and 5). Many species showed little response to herbicide, whereas others appeared to establish best at different herbicide levels depending on site and whether the plots were burned or unburned. There was no linear relationship between cover of medusahead and cover of the seeded species, with the exception of a negative relationship between medusahead cover and seeded cover seen only in the burned field at the Mullin site in 2005, although the distributions were widely scattered ($R^2 = 0.008$, $n = 3{,}127$, $P < 0.0001$).

Lamb Ranch. Cover. In 2005, the cover of seeded species increased slightly. Squirreltail, Siberian wheatgrass, and bluebunch wheatgrass had the greatest coverage, though bluebunch wheatgrass cover was only high in the unburned

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Table 1. Analysis results for medusahead cover for the Lamb Ranch (Drewsey, OR) and Mullin Ranch (John Day, OR) sites in 2004 and 2005.[a]

		2004				2005			
		Burned		Unburned		Burned		Unburned	
Effect	df	*F*	Pr > *F*	*F*	Pr > *F*	*F*	Pr > *F*	*F*	Pr > *F*
Lamb Ranch									
Month	3	1.39	0.2547	21.45	< **0.0001**	7.51	**0.0003**	14.17	< **0.0001**
Rate	6	202.98	< **0.0001**	135.08	< **0.0001**	85.98	< **0.0001**	23.53	< **0.0001**
Month × rate	18	1.78	0.0528	2.08	**0.0196**	1.16	0.3236	7.28	< **0.0001**
Species	7	1.01	0.4620	1.40	0.2794	0.82	0.5832	0.50	0.8204
Month × species	21	1.23	0.2216	0.86	0.6379	0.67	0.8639	1.51	0.0699
Rate × species	42	1.56	**0.0176**	0.90	0.6473	1.71	**0.0054**	1.19	0.2047
Month × rate × species	126	1.29	**0.0340**	1.23	0.0675	0.75	0.9717	0.86	0.8379
Mullin Ranch									
Month	3	3.09	**0.0350**	15.31	< **0.0001**	1.61	0.1977	9.02	< **0.0001**
Rate	6	34.41	< **0.0001**	79.06	< **0.0001**	12.27	< **0.0001**	18.22	< **0.0001**
Month × rate	17	2.27	**0.0122**	2.64	**0.0037**	2.36	**0.0090**	2.51	**0.0056**
Species	7	1.20	0.3621	0.36	0.9096	0.51	0.8128	0.78	0.6180
Month × species	21	1.12	0.3240	0.63	0.8941	0.92	0.5699	1.00	0.4674
Rate × species	42	1.24	0.1546	1.20	0.1877	0.85	0.7352	0.73	0.8888
Month × rate × species	119	1.04	0.3763	0.56	0.9999	0.93	0.6757	0.94	0.6545

[a] df, numerator degrees of freedom. Numbers in bold are significant at P < 0.001.

plots (Table 3). In the burned plots, squirreltail and Siberian wheatgrass cover were lowest at the 0 g ai/ha herbicide rate and highest at the 210 g ai/ha herbicide rate (Figure 4A). In the unburned plots, the relationship between herbicide rate and cover was less clear, though it appeared that squirreltail cover was similar at all herbicide rates, whereas Siberian wheatgrass cover was highest at a moderate (105 g ai/ha) imazapic application rate (Figure 4D). Some species, such as squirreltail, had higher mean percentage of cover in the burned plots, whereas other species, such as Siberian wheatgrass, bluebunch wheatgrass, and the two forb species, had slightly greater cover in the unburned plots (Table 3).

Density. The patterns seen for seeded species density at Lamb Ranch in 2005 were very similar to those seen for seeded species cover in 2005, and few patterns between density and herbicide rate were visible (data not shown). Squirreltail density in the burned plots ranged from a low of 29 ± 12 tillers/m^2 at the 35 g ai/ha to a high of 61 ± 19 tillers/m^2 at the 210 g ai/ha rate, whereas in the unburned plots, it ranged from 8 ± 6 tillers/m^2 (105 g ai/ha) to 54 ± 22 tillers/m^2 (70 g ai/ha). Siberian wheatgrass density in the burned plots ranged from 0 tillers/m^2 (0 g ai/ha) to 41 ± 10 tillers/m^2 (210 g ai/ha), whereas in the unburned plots, it ranged from 23 ± 8 tillers/m^2 (175 g ai/ha) to 82 ± 30 tillers/m^2 (105 g ai/ha). Bluebunch wheatgrass also established fairly well at Lamb Ranch but only in the unburned plots; bluebunch wheatgrass density ranged from 16 ± 8 tillers/m^2 (0 g ai/ha) to 58 ± 25 tillers/m^2 (105 g ai/ha) in the unburned plots and from 0 tillers/m^2 (35, 70, 175, and 210 g ai/ha rates) to 3 ± 3 tillers/m^2 (0 g ai/ha) in the burned plots. As for the forbs, density of

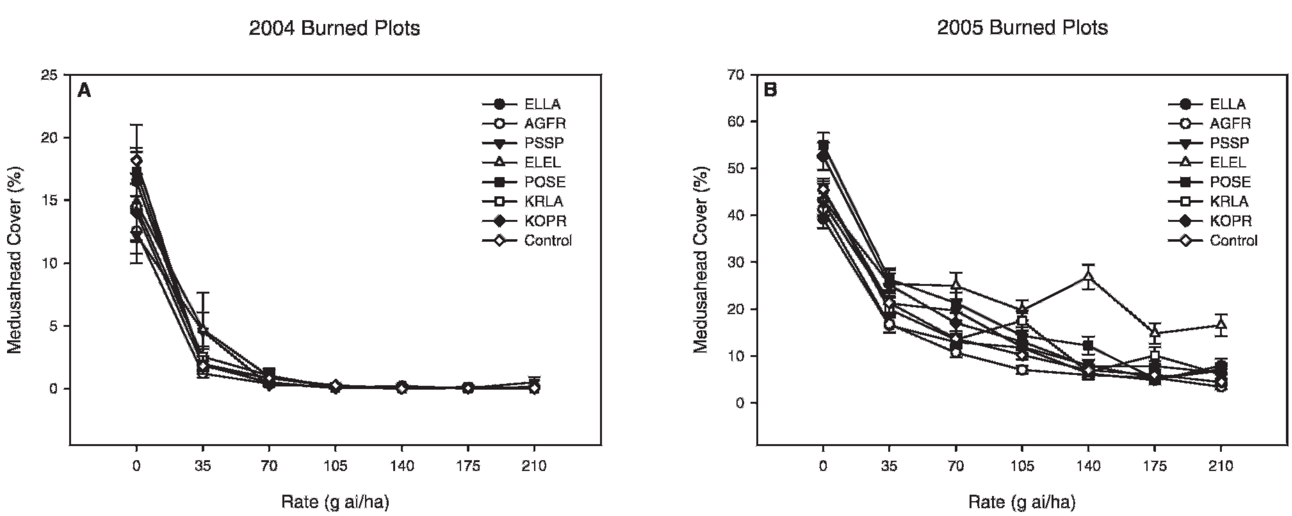

Figure 3. Lamb Ranch (Drewsey, OR) medusahead cover in response to herbicide rate and seeded species in burned plots only in (A) 2004 and (B) 2005. Values are means ± SE.

Table 2. Analysis results for seeded species cover for the Lamb Ranch (Drewsey, OR) and Mullin Ranch (John Day, OR) sites in 2004 and 2005.[a]

		2004				2005			
		Burned		Unburned		Burned		Unburned	
Effect	df	*F*	Pr > *F*	*F*	Pr > *F*	*F*	Pr > *F*	*F*	Pr > *F*
Lamb Ranch									
Month	3	1.85	0.1483	0.69	0.5599	1.51	0.2218	0.28	0.8391
Rate	6	1.89	0.0997	3.32	**0.0075**	3.20	**0.0092**	1.90	0.0977
Month × rate	18	1.04	0.4347	0.76	0.7390	0.70	0.7923	1.86	**0.0407**
Species	7	1.01	0.4634	10.00	**0.0002**	4.33	**0.0095**	2.84	**0.0460**
Month × species	21	1.16	0.2796	0.57	0.9361	1.94	**0.0082**	0.99	0.4756
Rate × species	42	1.32	0.0959	2.19	< **0.0001**	1.44	**0.0447**	1.53	**0.0226**
Month × rate × species	126	0.99	0.5133	0.72	0.9847	1.08	0.2852	1.10	0.2520
Mullin Ranch									
Month	3	0.28	0.8430	0.85	0.4708	0.91	0.4429	2.21	0.0977
Rate	6	6.17	< **0.0001**	2.81	**0.0192**	4.16	**0.0017**	5.26	**0.0003**
Month × rate	17	0.75	0.7345	0.90	0.5810	0.55	0.9110	2.51	**0.0056**
Species	7	13.12	< **0.0001**	6.35	**0.0017**	5.97	**0.0023**	9.39	**0.0002**
Month × species	21	0.76	0.7646	0.56	0.9424	0.54	0.9533	1.53	0.0634
Rate × species	42	1.98	**0.0005**	2.47	< **0.0001**	1.14	0.2646	2.26	< **0.0001**
Month × rate × species	119	0.70	0.9898	0.79	0.9350	0.85	0.8462	1.21	0.0915

[a] df, numerator degrees of freedom. Numbers in bold are significant at P < 0.001.

winterfat was zero in the burned plots, but in the unburned plots, it ranged from 0.2 ± 0.2 plants/m^2 (140 g ai/ha) to 22 ± 18 tillers/m^2 (70 g ai/ha). Forage kochia only established in a few of the unburned plots with densities of 11 ± 8 plants/m^2 (0 g ai/ha rate) and 15 ± 11 tillers/m^2 (175 g ai/ha rate).

Mullin Ranch. Cover. In 2005, cover of seeded species increased for most species (Table 3). Siberian wheatgrass established best in the burned plots (8.65 ± 0.85%), followed by squirreltail (2.75 ± 0.36%), and neither species showed a clear relationship between cover and herbicide application rate (Figure 5C). In the unburned plots, the best cover was seen for Sandberg bluegrass (1.01 ± 0.14%) followed by bluebunch wheatgrass (0.28 ± 0.11%), and Sandberg bluegrass appeared to establish best in the 0 g ai/ha imazapic (control) plots, whereas bluebunch wheatgrass showed no consistent pattern between herbicide rate and cover (Figure 5D).

Density. As was seen for Lamb Ranch, the patterns seen for seeded species density at Mullin Ranch in 2005 were similar to those seen for seeded species cover, with no clear pattern between herbicide rate and density (data not shown). Differences between the burned and unburned plots were quite pronounced. The highest density was seen for Siberian wheatgrass, followed by squirreltail, in the burned plots, whereas in the unburned plots, the highest density was seen for Sandberg bluegrass. Siberian wheatgrass density ranged from 145 ± 40 tillers/m^2 (175 g ai/ha) to 398 ± 97 tillers/m^2 (35 g ai/ha) in the burned plots, but it failed to establish in the unburned plots. Squirreltail density in the burned plots ranged from 14 ± 6 tillers/m^2 (70 g ai/ha rate) to 97 ± 29 tillers/m^2 (140 g ai/ha rate), whereas in the unburned plots, it ranged from 0.8 ± 0.8 tillers/m^2 (105 g ai/ha rate) to 11 ± 5 tillers/m^2 (0 g ai/ha) rate. Sandberg bluegrass density in the burned plots ranged from 5 ± 4 tillers/m^2 (175 g ai/ha rate) to 77 ± 25 tillers/m^2 (35 g ai/ha rate), whereas in the unburned plots, it ranged from 0.7 ± 0.7 tillers/m^2 (35 g ai/ha) to 63 ± 15 tillers/m^2 (0 g ai/ha). Bluebunch wheatgrass density ranged from 5 ± 5 tillers/m^2 (140 g ai/ha) to 24 ± 7 tillers/m^2 (35 g ai/ha). As for the forbs, winterfat failed to establish at Mullin Ranch, and forage kochia only established in a few burned plots at the 60 g ai/ha rate with a density of 3 ± 3 plants/m^2.

Seeded perennial grasses appear to have established more successfully than seeded forb during this study (Figure 4). There was a large difference in forb establishment between sites and in response to burning, with winterfat only establishing in the unburned plots at Lamb Ranch and not at all at Mullin Ranch, and forage kochia only establishing in a few unburned plots at Lamb Ranch and a few burned plots at Mullin Ranch. These results suggest that forbs may be more difficult to establish during medusahead control and revegetation. Establishment of all five perennial grass species was higher than forb establishment, and some, such as Siberian wheatgrass and squirreltail, did well in many plots. Other studies have shown that squirreltail may be one of the few perennial grasses that can be successfully seeded into even intact medusahead stands, suggesting that it can be an important grass for revegetation of areas in which it is native (Hironaka and Sindelar 1975).

Perennial Grass Cover. Perennial grass cover did not show a clear pattern with regard to herbicide rate or herbicide application month in this study. Instead, the effect of herbicide rate on perennial grass was dependent on site and whether or not the plot had been burned. In some plots, perennial grass was higher in plots that received no imazapic, whereas in others, perennial grass cover was higher in plots that received up to 140 g ai/ha herbicide.

Lamb Ranch. In 2005, the effect of herbicide rate on perennial grass cover was highly significant in the burned field and significant in the unburned field, and there was a significant

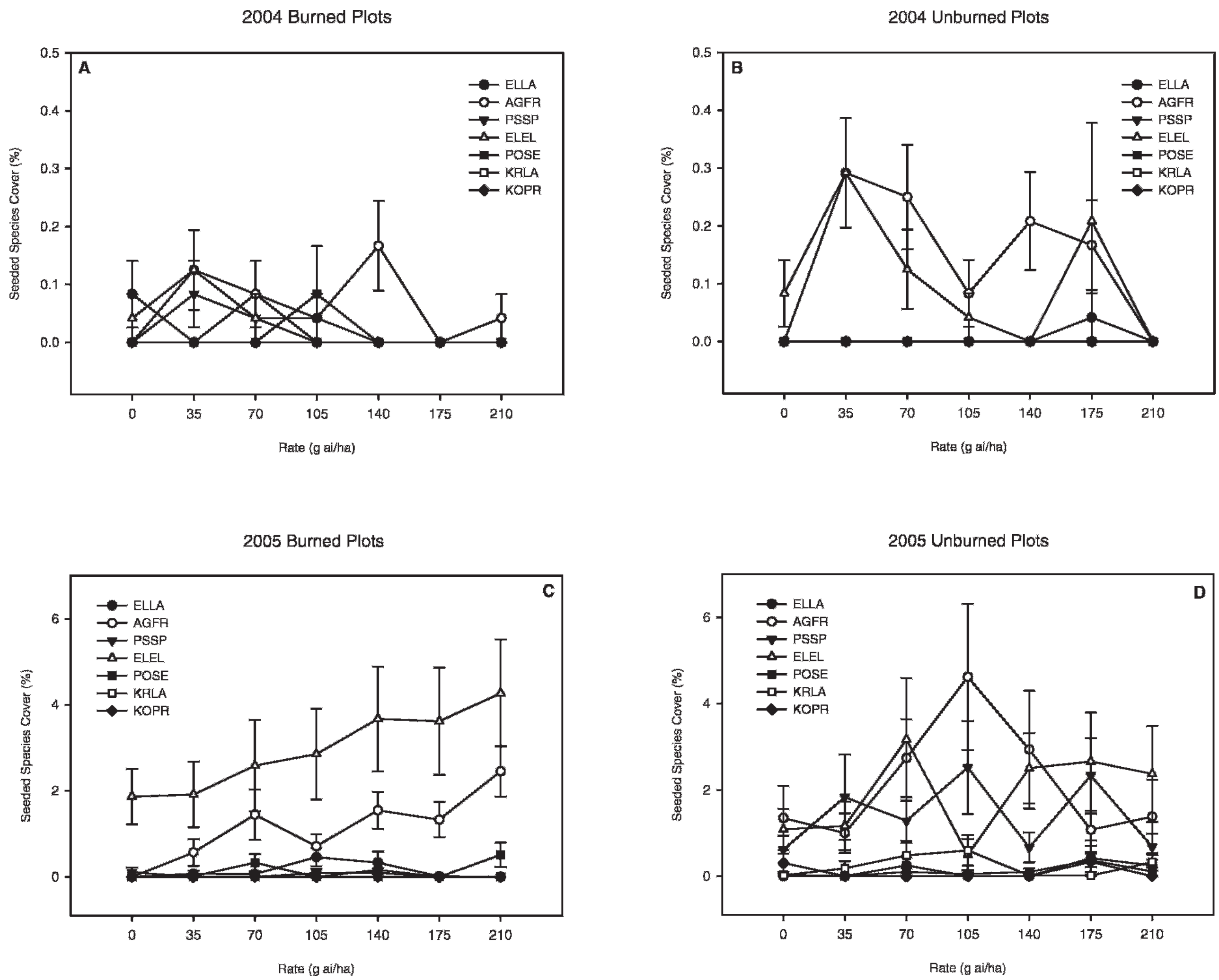

Figure 4. Lamb Ranch (Drewsey, OR) seeded species cover in response to herbicide rate and seeded species. Note: y-axis scales are different for 2004 and 2005 data. Values are means ± SE. (A) 2004 burned plots, (B) 2004 unburned plots, (C) 2005 burned plots, and (D) 2005 unburned plots.

three-way interaction in the burned field only (Table 4). Perennial grass cover was lowest in plots that received no herbicide and highest in plots that received a moderate rate of herbicide (105 to 140 g ai/ha) for both the burned and unburned plots in 2005 (data not shown).

Mullin Ranch. In 2005, in the burned field, there were significant responses of perennial grass cover to herbicide rate, herbicide application month, and species (Table 4). The highest percentage of cover by perennial grasses in the burned plots was seen for the September plots with no herbicide treatment, whereas plots that had herbicide applied in July and October had the highest percentage of cover at moderate herbicide rates (105 g ai/ha for October, 70 g ai/ha for July). Once again, one of the seeded perennial grass species had much better coverage than the others (data not shown). In the unburned plots, perennial grass cover showed a highly significant response to the interaction of herbicide application month and rate, as well as to herbicide rate alone (Table 4). There was a tendency for higher perennial grass cover at the 70 g ai/ha imazapic and lower rates, and that tendency was more pronounced for the August and October herbicide applications than for the July and September herbicide applications (data not shown).

Other researchers have found that perennial grass cover was significantly higher in plots that received a low rate of imazapic (70 g ai/ha) than in plots that received a high rate of imazapic (140 g ai/ha) (Monaco et al. 2005). However, we only saw higher cover of perennial grasses in response to lower imazapic rates in burned plots during the initial year of sampling, and that pattern did not carry over to the following year. Thus, we cannot say that perennial grass will establish better in plots treated with a low rate of imazapic, but rather, that the response of perennial grasses to imazapic will depend on species and site conditions.

Annual Grass Cover. Cover of annual grasses other than medusahead tended to be higher at the lower imazapic application rates, especially in the first year of the study. In the second year of the study, that pattern was less clear; in some plots the cover of annual grass was as high at the higher imazapic rates (170 to 210 g ai/ha) as at the low to moderate

#589

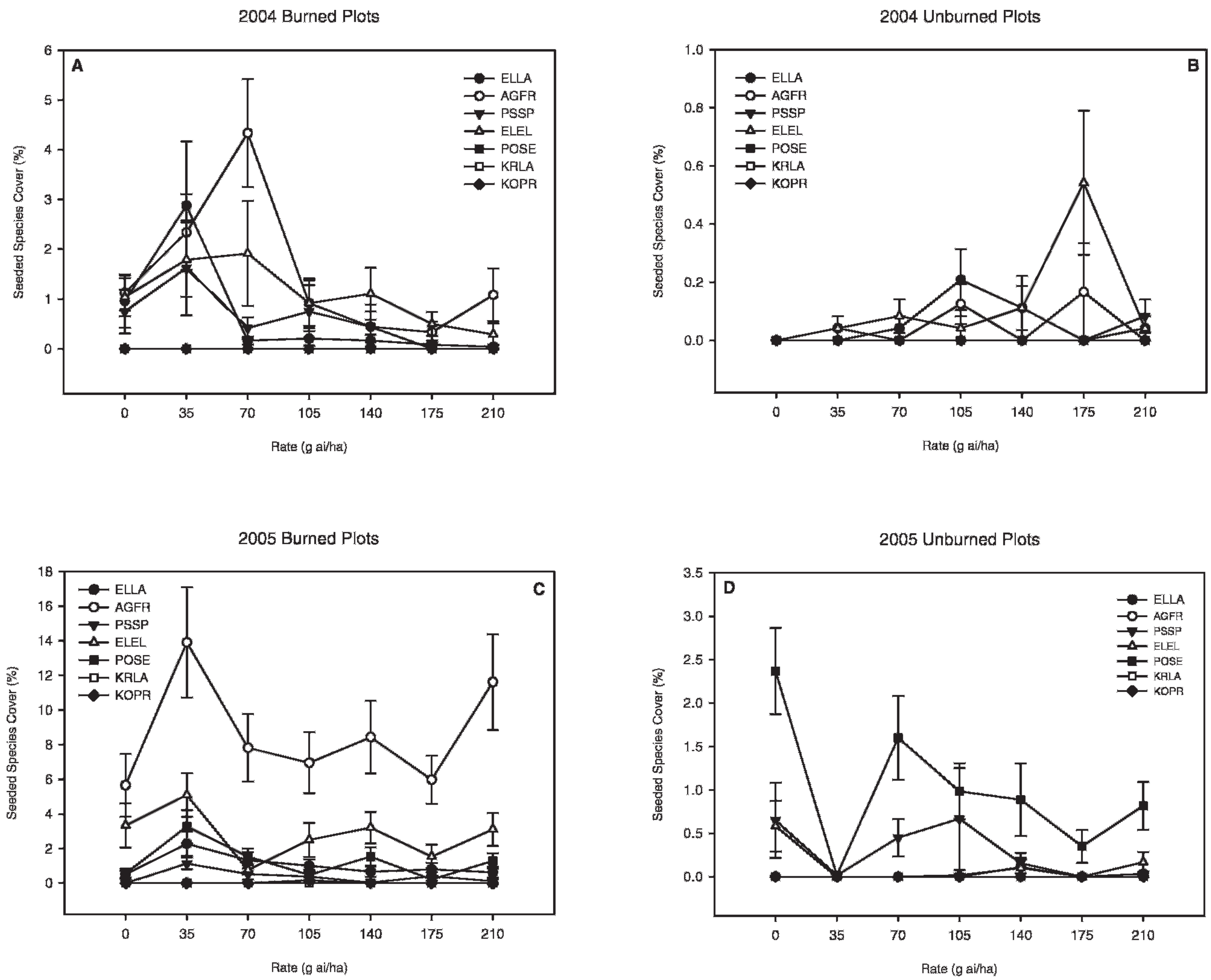

Figure 5. Mullin Ranch (John Day, OR) seeded species cover in response to herbicide rate and seeded species. Note: y-axis scales differ for all four graphs. Values are means ± SE. (A) 2004 burned plots, (B) 2004 unburned plots, (C) 2005 burned plots, and (D) 2005 unburned plots.

rates (0 to 70 g ai/ha). It appears that, 1 yr after spraying, coverage by annual grasses was lowest in burned fields in plots receiving 70 to 210 g ai/ha and in unburned fields in plots receiving 175 to 210 g ai/ha, but by 2 yr after spraying, annual grass cover could recover to higher levels even in plots treated with a high imazapic rate.

Lamb Ranch. In 2005, annual grass showed no significant response to any of the treatments. Annual grass cover was below 1% in both burned and unburned fields and showed no clear patterns in response to herbicide application.

Mullin Ranch. In 2005, in the burned plots, there were significant responses of annual grass cover to herbicide application rate, to the interaction between application rate and month, and to the interaction between rate and species (Table 4). Annual grass coverage was highest in August plots that received no imazapic or received 175 g ai/ha and in October plots that received 105 g ai/ha (data not shown). In the unburned plots, there were significant responses of annual grass cover to the interaction between application rate and month (Table 4). Annual grass cover was highest in the October plots that received 70 and 140 g ai/ha rates and was lowest for all months in the plots that received the highest application rate of 210 g ai/ha (data not shown).

Our results suggest that imazapic can control annual grasses other than medusahead during the first year after application, though that control may only be of short duration as those grasses can sprout readily from seed the year after management. Other studies have found effective control of annual grasses with imazapic. A study in Nebraska found that imazapic offered 96% control of the problematic annual grass, smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.], while allowing native legume species to establish (Beran et al. 1999).

Perennial Forb Cover. No consistent pattern of response by perennial forbs to imazapic application rate was seen, with the exception of a few unburned plots that showed higher coverage by perennial forbs at higher imazapic rates.

Lamb Ranch. In 2005, in the burned plots, there was no coverage response by perennial forb to any of the treatments (Table 4). In the unburned plots, there was a significant

Table 3. Mean percentage of cover by seeded species recorded at Lamb Ranch (Drewsey, OR) and Mullin Ranch (John Day, OR) sites in 2004 and 2005.[a,b]

	ELLA	AGFR	PSSP	ELEL	POSE	KRLA	KOPR
	%						
Lamb Ranch							
2004							
Burned	0.02 ± 0.01	0.07 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.01	0.00 ± 0.00	0.00 ± 0.00
Unburned	0.01 ± 0.01	0.14 ± 0.03	0.00 ± 0.00	0.11 ± 0.03	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
2005							
Burned	0.13 ± 0.05	1.13 ± 0.16	0.04 ± 0.02	2.97 ± 0.40	0.15 ± 0.06	0.00 ± 0.00	0.00 ± 0.00
Unburned	0.13 ± 0.07	2.11 ± 0.37	1.41 ± 0.26	1.95 ± 0.35	0.11 ± 0.03	0.23 ± 0.08	0.09 ± 0.05
Mullin Ranch							
2004							
Burned	0.66 ± 0.22	1.55 ± 0.25	0.57 ± 0.18	1.08 ± 0.22	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Unburned	0.06 ± 0.02	0.05 ± 0.03	0.01 ± 0.01	0.12 ± 0.04	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
2005							
Burned	1.04 ± 0.16	8.65 ± 0.85	0.39 ± 0.09	2.75 ± 0.36	1.26 ± 0.20	0.00 ± 0.00	0.02 ± 0.02
Unburned	0.02 ± 0.01	0.00 ± 0.00	0.28 ± 0.11	0.12 ± 0.05	1.01 ± 0.14	0.00 ± 0.00	0.00 ± 0.00

[a] Values are mean percentage cover ± SE.

[b] Abbreviations: ELLA, thickspike wheatgrass; AGFR, Siberian wheatgrass; PSSP, bluebunch wheatgrass; ELEL, squirreltail; POSE, Sandberg bluegrass; KRLA, winterfat; KOPR, forage kochia.

response of perennial forb coverage to herbicide application rate (Table 4), with the highest perennial forb cover seen at higher rates (140 g ai/ha or greater) of imazapic (data not shown).

Mullin Ranch. In 2005, in the burned plots, we saw no response of perennial forb cover to any of the treatments (Table 4). In the unburned plots, there was a significant response of perennial forb cover to interaction between herbicide rate and month, with the highest perennial forb cover seen in the plots that received an October application of 175 g ai/ha of imazapic (data not shown).

Annual Forb Cover. The relationship between annual forb cover and herbicide rate varied greatly between years and showed few consistent patterns. In some of the plots, the relationship of annual forb cover to imazapic rate switched between years; in the first year of the study, annual forb cover was lowest in the plots that received the highest rates of imazapic, but by the second year of the study, annual forb cover was lowest in plots that received the lowest rate of imazapic.

Lamb Ranch. In 2005, there was a significant response of annual forb cover to the month of herbicide application and to the rate in both the burned and unburned plots, and there was a significant interaction between rate and species in the burned plots (Table 4). In the burned plots, the lowest annual forb cover was seen for plots that received no imazapic, with the exception of the September plots, and the highest annual

Table 4. Analysis results for the cover of perennial and annual grasses and forbs at the Lamb Ranch (Drewsey, OR) and Mullin Ranch (John Day, OR) sites in 2005.[a]

	Perennial grass		Annual grass		Perennial forb		Annual forb	
Parameters	B	UB	B	UB	B	UB	B	UB
Lamb Ranch								
Month	NS	NS	NS	NS	NS	NS	*	*
Rate	***	*	NS	NS	NS	*	*	***
Month × rate	NS	NS	NS	NS	NS	NS	NS	NS
Species	NS	NS	NS	NS	NS	NS	NS	NS
Month × species	NS	NS	NS	NS	NS	NS	NS	NS
Rate × species	NS	NS	NS	NS	NS	NS	*	NS
Month × rate × species	*	NS	NS	NS	NS	NS	NS	NS
Mullin Ranch								
Month	**	NS	NS	NS	NS	NS	NS	NS
Rate	**	**	***	NS	NS	NS	*	NS
Month × rate	NS	***	**	**	NS	**	NS	NS
Species	*	NS	NS	NS	NS	NS	NS	NS
Month × species	NS	NS	NS	NS	NS	NS	NS	NS
Rate × species	NS	NS	*	NS	NS	NS	NS	NS
Month × rate × species	NS	NS	NS	NS	NS	NS	NS	NS

[a] Abbreviations: B, burned; UB, unburned; NS, not significant.

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

forb cover was seen for plots that received 70–175 g ai/ha (data not shown). In the unburned plots, the lowest annual forb coverage was seen in plots that received no imazapic, and the plots that received herbicide application in July had a lower percentage of cover than plots that received herbicide application in other months (data not shown).

Mullin Ranch. In 2005, we found a significant response of annual forb cover to herbicide application rate in the burned plots, and we found no response of annual forb cover to any of the treatments in the unburned plots (Table 4). In the burned plots, the cover of annual forbs was highest at the 105 g ai/ha rate and lowest at the 0 and 210 g ai/ha rate (data not shown).

In conclusion, imazapic application offers effective control of medusahead, and that control is more effective in plots that have been burned to remove medusahead thatch. This supports our hypothesis that less imazapic may be needed to control medusahead on burned sites because burning removes thatch and allows better contact of the herbicide with the soil. The earliest application of imazapic in July appeared to be less effective than later applications, supporting our hypothesis that late summer or fall applications of imazapic may offer better control of medusahead than earlier ones. We did not see consistent patterns in the effect of herbicide application rate or time relative to the impact of imazapic on nontarget vegetation, thus we were unable to support our hypothesis that moderate rates of imazapic would offer a better trade-off between maximum medusahead control and minimum impact on nontarget vegetation. Seeded species did establish in plots treated with imazapic, and our results suggest that imazapic can be used to control medusahead before seeding with desirable species. The relationship between the rate of imazapic and coverage by each functional group often differed between the two sites, or between the burned and unburned plots, or even between years. Thus, we cannot offer any conclusions about whether higher or lower imazapic rates or different application months favored the seeded species, the perennial or annual grasses, or the perennial or annual forbs. As was seen in the study by Monaco et al. (2005), our study found few consistent patterns relating the rate of imazapic to the cover of annual or perennial forbs.

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Literature Cited

Beran, D. D., R. A. Masters, and R. E. Gaussoin. 1999. Grassland legume establishment with imazethapyr and imazapic. Agron. J. 91:592–596.

Borman, M. M., W. C. Krueger, and D. E. Johnson. 1991. Effects of established perennial grasses on yields of associated annual weeds. J. Range Manag. 44:318–326.

Dakheel, A. J., S. R. Radosevich, and M. G. Barbour. 1994. Effect of temperature and moisture on growth interference and photosynthesis of *Bromus tectorum* and *Teaniatherum asperum*. Weed Res. 34:11–22.

DiTomaso, J. M., M. L. Brooks, E. B. Allen, R. Minnich, P. M. Rice, and G. B. Kyser. 2006. Control of invasive weeds with prescribed burning. Weed Technol. 20:535–548.

Duncan, C. A., J. J. Jachetta, and M. L. Brown, et al. (2004). Assessing the economic, environmental, and societal losses from invasive plants on rangeland and wildlands. Weed Technol. 18:1411–1416.

George, M. R. 1992. Ecology and Management of Medusahead. Davis, CA: University of California. Range Sci. Rep. 32, 1–3.

Goebel, C. J., M. Tazi, and G. A. Harris. 1988. Secar bluebunch wheatgrass as a competitor to medusahead. J. Range Manag. 41:88–89.

Hironaka, M. and B. W. Sindelar. 1975. Growth characteristics of squirreltail seedlings in competition with medusahead. J. Range Manag. 28:283–285.

Littell, R. C., G. Milliken, W. W. Stroup, and R. D. Wolfinger. 1996. SAS System for Mixed Models. Cary, NC: SAS Institute. 633 p.

Major, J., C. M. McKell, and L. J. Berry. 1960. Improvement of Medusahead Infested Rangeland. California Agricultural Experiment Station and Extension Service Leaflet 123. 3 p.

Masters, R. A., S. J. Nissen, R. E. Gaussoin, D. D. Beran, and R. N. Stougaard. 1996. Imidazolinone herbicides improve restoration of Great Plains grasslands. Weed Technol. 10:392–403.

Miller, H. C., D. Clausnitzer, and M. M. Borman. 1999. Medusahead. Pages 271–281 *in* R. L. Sheley and J. K. Petroff, eds. Biology and Management of Noxious Range Weeds. Corvallis, OR: Oregon State University Press.

Monaco, T. A., T. M. Osmond, and S. A. Dewey. 2005. Medusahead control with fall- and spring-applied herbicides on Northern Utah foothills. Weed Technol. 19:653–658.

Petersen, R. G. 1994. Agricultural Field Experiments: Design and Analysis. New York: Marcel Dekker. 409 p.

Pollak, O. and T. Kan. 1996. The use of prescribed fire to control invasive exotic weeds at Jepson Prairie Preserve. Pages 241–249 *in* C. W. Witham, E. T. Bauder, D. Belk, W. R. Ferren and R. Ornduff, eds. Proceedings, Ecology, Conservation, and Management of Vernal Pool Ecosystems. Sacramento, CA: California Native Plant Society.

SAS. 1990. SAS/STAT User's Guide, Version 6, 4th ed. Volume 2. Cary, NC: SAS Institute.

Sheley, R. L., L. L. Larson, and D. E. Johnson. 1993. Germination and root dynamics of range weeds and forage species. Weed Technol. 7:234–237.

Thornburg, A. A. 1982. Plant Materials for Use on Surface-Mined Lands in Arid and Semiarid Regions. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service SCS-TP-157. 88 p.

Young, J. A. 1992. Ecology and management of medusahead [*Taeniatherum caput-medusae* ssp. *asperum* (Simk.) Melderis]. Great Basin Nat. 52:245–252.

Young, J. A. and R. A. Evans. 1970. Invasion of medusahead into the Great Basin. Weed Sci. 18:89–97.

Young, J. A., R. A. Evans, and J. Robison. 1972. Influence of repeated annual burning on a medusahead community. J. Range Manag. 25:372–375.

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