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Effects of Integrating Mowing and Imazapyr Application on African Rue (*Peganum harmala*) and Native Perennial Grasses

Dustin D. Johnson and Kirk W. Davies*

African rue is a poisonous, perennial forb that readily invades salt-desert shrub and sagebrush-steppe rangelands. Information detailing options for integrated management of African rue is lacking. To date, a few studies have researched the efficacy of different herbicides for controlling African rue, but none have investigated integrated approaches to its management. Broadcast applications of imazapyr at three rates (0.275, 0.55, and 0.85 kg ae ha^{-1}) were made, with and without a prior mowing treatment, to African rue when it was in full bloom. Imazapyr resulted in significant reductions in both the cover and density of African rue, regardless of application rate or mowing treatment ($P < 0.05$). Mowing had no effect on African rue cover or density ($P > 0.05$). Higher rates of imazapyr resulted in significant reductions in the cover of native perennial bunchgrasses ($P < 0.05$), whereas the low rate did not affect perennial grass cover, regardless of mowing treatment ($P > 0.05$). Integrating a mowing treatment with imazapyr applications was less effective for controlling African rue than applying herbicide alone. Mowing before imazapyr application did not increase survival of perennial grasses. Our results suggest that the recommended rate of imazapyr for controlling African rue (0.85 kg ae ha^{-1}) could be reduced by as much as one-third on dry floodplain ecological sites within the northern Great Basin without comprising its effectiveness for controlling African rue. This lower rate would reduce nontarget damage to native perennial grasses, which are the dominant functional group in the herbaceous understory. Less damage to native perennial grasses would probably accelerate understory recovery and help prevent invasion by other invasive species.

Nomenclature: Imazapyr; African rue, *Peganum harmala* L.

Key words: Invasive plants, sagebrush steppe, weeds.

African rue (*Peganum harmala* L.) is a poisonous, exotic, perennial desert forb that has the potential to cause extensive ecological and economic losses in the western United States. It is native to the steppes and deserts of the Mediterranean region from Spain, northern Africa, and Arabia through southern Russia to Tibet (Eichler 1986). African rue was introduced into the United States in 1928 near Deming, NM (Roché 1991), for the production of red dye. In the United States, it has since escaped cultivation and spread to western Texas, Arizona, California, Nevada, Idaho, Oregon, Washington, and New Mexico and is currently listed as a noxious weed in six western states (USDA-NRCS 2013a). Information is lacking on how African rue spread to the Intermountain West. The species has the potential to move both by seed and vegetatively (Michelmore 1997) and, because of its competitive ability in drought conditions and early spring growth, it readily displaces native saltbushes and grasses in the salt-desert shrub lands of the western United States. The success of African rue in arid environments is due, in part, to the ability of seedlings to tolerate and recover from water deficit (Abbott et al. 2008).

Control of this invasive plant is necessary because established populations are persistent and tend to dominate invaded sites (Michelmore 1997), and the species is toxic to livestock (Faskhutdinov et al. 2000; Sperry et al. 1964). To date, a few studies have focused on determining the efficacy of different herbicides and their combinations for controlling African rue in the southwest deserts (e.g., Abbott et al. 2008). This species has extensive lateral roots and deep taproots (Michelmore 1997) that have been mapped to depths of at least 4 m (13 ft) (Abbott et al. 2008); consequently, only herbicides that are moved deep into the plant's root system have been shown to effectively control African rue (Abbott and Sterling 2006; McDaniel and

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Management Implications

African rue (*Peganum harmala* L.) is a poisonous, exotic, perennial desert forb that has the potential to cause extensive ecological and economic losses in the western United States. Broadcast applications of imazapyr at three rates (0.275, 0.55, and 0.85 kg ae ha^{-1}) were made, with and without a prior mowing treatment, to African rue during full bloom. The current rate recommended for control of African rue using broadcast applications of imazapyr is 0.85 kg ae ha^{-1}. Results of this study suggest that this rate can be reduced by as much as one-third on sagebrush–steppe rangeland without comprising the short-term effectiveness of imazapyr for controlling African rue; however, follow-up treatments or restorative actions may be required to sustain long-term control of African rue and to prevent invasion by exotic annual species. In addition, our results indicate that perennial bunchgrasses readily recover from imazapyr application rates of 0.55 kg ae ha^{-1} or less, whereas rates of 0.85 kg ae ha^{-1} resulted in suppression of desirable perennial grasses for 2 yr or more. Limiting damage to native perennial grasses is important because this functional group dominates the understory in noninvaded plant communities and, therefore, is critically important for preventing invasions by exotic plants in sagebrush–steppe rangelands.

Duncan 2006). Treatments of the nonselective herbicide imazapyr, applied at a 0.85 kg ae ha^{-1} (0.76 lb ac^{-1}) rate have provided the best control in New Mexico (McDaniel and Duncan 2006). However, the efficacy of imazapyr for control of African rue in the Intermountain West is unknown, and information detailing options for integrated management of this invasive plant is lacking. Information on the effects of imazapyr on native vegetation in the Intermountain West is also limited.

Integrated pest management has often increased the control of exotic plants (e.g., Bottoms and Whitson 1998; Davies 2010; Ferrell et al. 1998; Lym and Messersmith 1993; Lym et al. 1997; Masters and Nissen 1998; Whitson and Kock 1998). Mowing has been shown to be effective when integrated with other control methods (e.g., herbicide treatments) on other difficult-to-control, perennial, exotic species, such as perennial pepperweed (*Lepidium latifolium* L.) (Allen et al. 2001) and Canada thistle [*Cirsium arvense* (L.) Scop.] (Beck and Sebastian 2000). Mowing before applying a systemic herbicide may improve effectiveness for control of perennial invasive plants because such preparation changes the canopy architecture of the infestation, improving herbicide contact on lower leaves (Hunter 1996). That, combined with fewer active meristems present aboveground, can lead to increased herbicide translocation and accumulation in belowground vegetative reproductive structures (Renz and DiTomaso 2006). Therefore, the objectives of this study were to determine (1) whether mowing before application of imazapyr increased control of African rue, (2) appropriate applications of imazapyr for control of African rue in the Intermountain West, and (3) effects of mowing, imazapyr application, and their combination on desirable native vegetation. Maintaining desirable native vegetation in sagebrush-steppe plant communities is critically important for providing forage production for livestock and wildlife habitat for sagebrush-obligate and -facultative species (Davies et al. 2011).

Material and Methods

Study Area. This study was conducted in African rue–invaded sagebrush-steppe plant communities approximately 16 km (9.94 mi) east of Burns, OR (43.53°N, 118.88°W). Although documentation of the initial introduction of African rue is lacking, the landowner cooperating in the study indicated a presence of the noxious weed since the late 1990s. It was not until 2008 that the infestation was formally documented during a vegetation survey of adjacent tribal lands commissioned by the Burns Paiute Tribe (B. Rasmussen, personal communication). The nearly 1,100-ha (2,718 ac) infestation was subsequently mapped by the Oregon Department of Agriculture the same year (ODA 2013). Most of the infestation was characterized by small ($<$ 0.1 ha), disparate patches of African rue. We elected to conduct the study within a 65-ha, privately owned and managed pasture near the center of the infestation because it was the most heavily infested area and to minimize plot variation in vegetation characteristics within blocks before treatment. The study area occurred at an average elevation of 1,250 m on 0 to 2% slopes with variable aspects. The soils at the site were moderately deep and well drained, with surface textures ranging from clayey loam to silty loam (USDA-NRCS 2013b). Long-term annual precipitation averaged approximately 275 mm (10.8 in) with most falling as rain or snow from October through March (Western Region Climate Center 2013). Crop–year (October 1–September 30) precipitation was 99, 100, and 133% of the long-term average in 2009, 2010, and 2011, respectively (Western Region Climate Center 2013). Livestock were excluded from the study during the trial. Before treatment, the study area (treated plots and untreated controls) was dominated by an overstory of primarily large ($\sim$ 0.25 to $>$ 1-m-diam), mature, and multistemmed African rue plants with a suppressed understory of native perennial grasses, exotic annual grasses, and native and nonnative perennial and annual forbs. Potential natural plant communities (noninvaded) would have had an overstory dominated by basin big sagebrush (*Artemisia tridentata* Nutt. ssp. *tridentata*), gray rabbitbrush [*Ericameria nauseosa* (Pallas ex Pursh) Nesom & Baird], and greasewood [*Sarcobatus vermiculatus* (Hook.) Torr.], and an herbaceous understory dominated by basin wildrye [*Leymus cinereus* (Scribn. & Merr.) Á. Löve] and beardless wildrye [*Leymus triticoides* (Buckley) Pilg.] (USDA-NRCS

2013b). Common forbs would have included common yarrow (*Achillea millefolium* L.), hawksbeards (*Crepis* spp.), milkvetchs (*Astragalus* spp.), lupines (*Lupinus* spp.), docks (*Rumex* spp.), and scarlet globemallow [*Sphaeralcea coccinea* (Nutt.) Rydb] (USDA-NRCS 2013B).

Procedures and Experimental Design. The influence of mowing and imazapyr (Habitat, BASF Corporation, Research Triangle Park, NC) application on African rue and other vegetation was evaluated using a randomized complete-block design with five blocks within a 65-ha pasture. Blocks were located, on average, 131 m from one another and within a dry floodplain ecological site (USDA-NRCS 2013B). Blocks varied in aspect from east-facing to west-facing. The pretreatment plant communities also varied among blocks, as measured by the cover of perennial grasses and forbs and annual grasses and forbs ($P < 0.05$). Treatments were as follows: (1) control: no mowing and no herbicide (C); (2) mowing but no herbicide (M); (3) mowing and imazapyr at 0.275 kg ae ha^{-1} (ML); (4) mowing and imazapyr at 0.55 kg ae ha^{-1} (MM); (5) mowing and imazapyr at 0.85 kg ae ha^{-1} (MH); (6) no mowing and imazapyr at 0.275 kg ae ha^{-1} (NML); (7) no mowing and imazapyr at 0.55 kg ae ha^{-1} (NMM); and (8) no mowing and imazapyr at 0.85 kg ae ha^{-1} (NMH). Each treatment was applied to a 5-m by 10-m plot in each block with a 1-m buffer between plots. Treatments were applied in July 2009.

Herbicide treatments were accomplished with a ground-operated, boomless sprayer that delivered 234 L ha^{-1} of total spray volume (imazapyr at each of the tested rates combined with 0.25% methylated seed oil plus organosilicone surfactant in water) in mid-July when African rue was in full bloom. Temperature and relative humidity ranged between 23 and 26 C and 27 and 37%, respectively, during herbicide applications. In plots assigned a mowing treatment, mowing was conducted with a walk-behind, gas-powered rotary mower to a height of 8 cm. Mowing was conducted 1 wk before all herbicide applications. Vegetation characteristics were measured before treatment (2009) and for 2 yr after treatment (2010 and 2011) in late June. Herbaceous cover and density were measured by species in fifteen 50- by 50-cm frames (0.25 m^2) per plot. Annual grass and forb, perennial grass and forb, and African rue densities were determined by counting all individual plants at least half-rooted within the frame. African rue shoots were considered different individual plants if separated by 4 cm or more. Canopy cover by species was visually estimated to the nearest 1% inside the frames. Frames were divided into 1, 5, 10, 25, and 50% segments to improve accuracy and efficiency of cover estimates. The 50- by 50-cm frames were located at 2-m intervals on three 10-m transects (starting at 1 m and ending at 9 m), resulting in five frames per transect. The 10-m transects were deployed at 1.5-m spacing in each plot.

Data Analysis. African rue, perennial grass, and annual grass density and cover data were analyzed with ANOVAs for a randomized complete-block design in Tibco Spotfire S-Plus 8.1 software (Insightful Corp., Seattle, WA). The model included fixed effects for treatment and a random block effect. Because of the strong effect differences between the first and second year after treatment, years were analyzed separately to simplify presentation and better illustrate treatment effects on response variables. Treatment effects on African rue, perennial bunchgrass, and annual grass cover and density were also compared between years using ANOVA tests to evaluate implications for longer-term control and recovery. Treatment means were separated using Fisher's protected LSD test ($P < 0.05$) and were reported with standard errors (mean ± SE). For all analyses, plant cover and density were grouped into five functional groups (Davies et al. 2007; Lauenroth et al. 1978): perennial grass (native), annual grass (downy brome [*Bromus tectorum* L.]), perennial forbs (combination of native and introduced forbs, excluding African rue), African rue, and annual forbs (combination of native and exotic forbs).

Results

Cover. Pretreatment cover of African rue, perennial grass, and annual grass was not different among treatments in 2009 ($P > 0.05$; Figure 1) nor was pretreatment cover of perennial and annual forbs different among treatments ($P > 0.05$; data not shown).

African rue cover was less in plots treated with imazapyr than it was in the untreated control in the 2 yr after treatment, regardless of mowing treatment ($P < 0.05$; Figure 1A). Mowing did not influence African rue cover in either posttreatment year ($P > 0.05$; Figure 1A). African rue cover was reduced to between 0.05 ± 0.04 to 7.6 ± 5.03 and 0.24 ± 0.14 to 6.4% ± 4.1 SE in plots receiving an imazapyr application compared with 23.5 ± 4.38 and 24.9% ± 4.04 SE in the untreated control the first and second years posttreatment, respectively. We found no evidence that African rue cover varied by imazapyr application rate in either posttreatment year ($P > 0.05$). African rue cover did not vary between the first and second year posttreatment for any of the treatments tested ($P > 0.05$). In contrast, the density of African rue significantly increased from year one to year two posttreatment in plots receiving the low and moderate application rates of imazapyr ($P < 0.05$), regardless of mowing treatment, an increase in density not observed in plots left untreated, nor plots receiving a mow only or high application rate of imazapyr ($P > 0.05$).

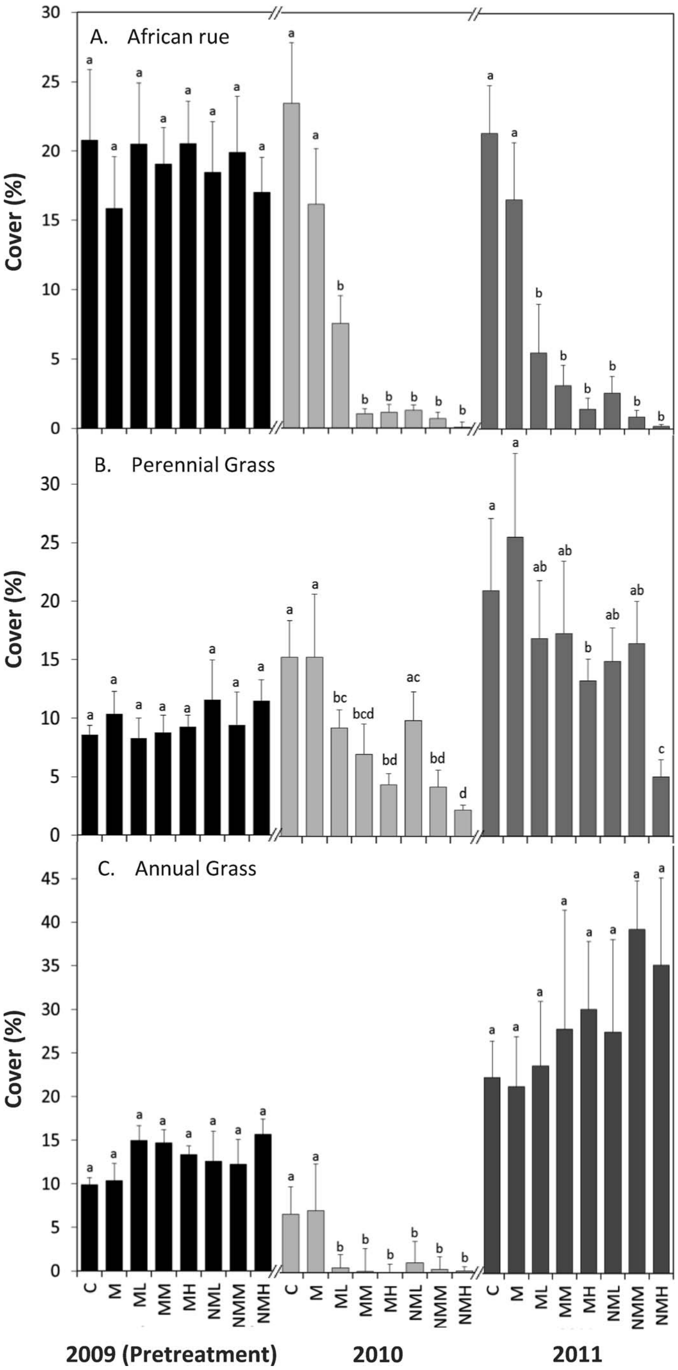

Figure 1. (A) African rue, (B) perennial grass, and (C) annual grass cover values (mean ± SE) in the various African rue control treatments in 2009 (pretreatment year), 2010, and 2011. Treatments: C, control; M, mowing to a height of 8 cm in early July; MH, mowing and imazapyr application of 0.85 kg ae ha^{-1}; MM, mowing and imazapyr application of 0.55 kg ae ha^{-1}; ML, mowing and imazapyr application of 0.275 kg ae ha^{-1}; NMH, no mowing and imazapyr application of 0.85 kg ae ha^{-1}; NMM, no mowing and imazapyr application of 0.55 kg ae ha^{-1}; and NML, no mowing and imazapyr application of 0.275 kg ae ha^{-1}. Different lowercase letters indicate differences between treatments in that year ($P < 0.05$).

Perennial grass cover was less in imazapyr-treated plots than it was in the untreated control the first year after treatment ($P < 0.05$; Figure 1B). The M and NML treatments had no effect on perennial grass cover ($P > 0.05$; Figure 1B). Perennial grass cover in plots treated with the moderate and low rates of imazapyr was not different from the untreated control by the second year after treatment, regardless of mowing treatment ($P > 0.05$; Figure 1B), whereas cover of perennial grasses remained less in plots treated with the high rate of imazapyr than it did in the untreated control, regardless of mowing treatment ($P < 0.05$; Figure 1B). Perennial grass cover in plots that were not mowed before receiving the high imazapyr rate had not recovered and remained less than all other treatments through the second year after treatment ($P < 0.05$; Figure 1B), whereas perennial grass cover in plots that were mowed before receiving the high imazapyr rate was not different from other plots receiving herbicide, regardless of mowing treatment ($P > 0.05$; Figure 1B), excluding the NMH treatment ($P < 0.05$; Figure 1B). Perennial bunchgrass density did not vary between the first and second year posttreatment for any of the treatments tested ($P > 0.05$). In contrast, the cover of perennial bunchgrasses significantly increased from the first to the second year posttreatment in treated plots ($P < 0.05$), excluding plots that were mowed and then treated with a low application rate of imazapyr ($P > 0.05$), whereas an increase in perennial grass cover was not observed during the 2-yr period in plots left untreated ($P > 0.05$).

Annual grass cover was less in plots receiving imazapyr treatments than it was in the untreated control during the first year after treatment, regardless of mowing treatment ($P < 0.05$; Figure 1C). Mowing alone did not influence the cover of annual grasses in either posttreatment year ($P > 0.05$; Figure 1C). Cover of annual grasses was not different among any of the treatments by the second year after treatment ($P > 0.05$; Figure 1C). Annual grass cover increased from the first year to the second year after treatment in all plots, including plots left untreated ($P < 0.05$). Annual grass density increased during the 2-yr period in treated plots ($P < 0.05$), excluding plots that were mowed before receiving a low application rate of imazapyr and plots that were only mowed ($P > 0.05$). An increase in annual grass density was also not observed in plots that were left untreated during the 2-yr trial ($P > 0.05$).

Perennial forb cover, excluding African rue, in the treated plots was not different from the untreated control in the 2 yr posttreatment ($P > 0.05$, data not shown). Annual forb cover was less in the treated plots than it was in the untreated control in 2010 ($P < 0.05$, data not shown), excluding the M and NML plots ($P > 0.05$, data not shown). By the second year after treatment, annual forb cover in the treated plots was not different from the untreated control ($P > 0.05$, data not shown).

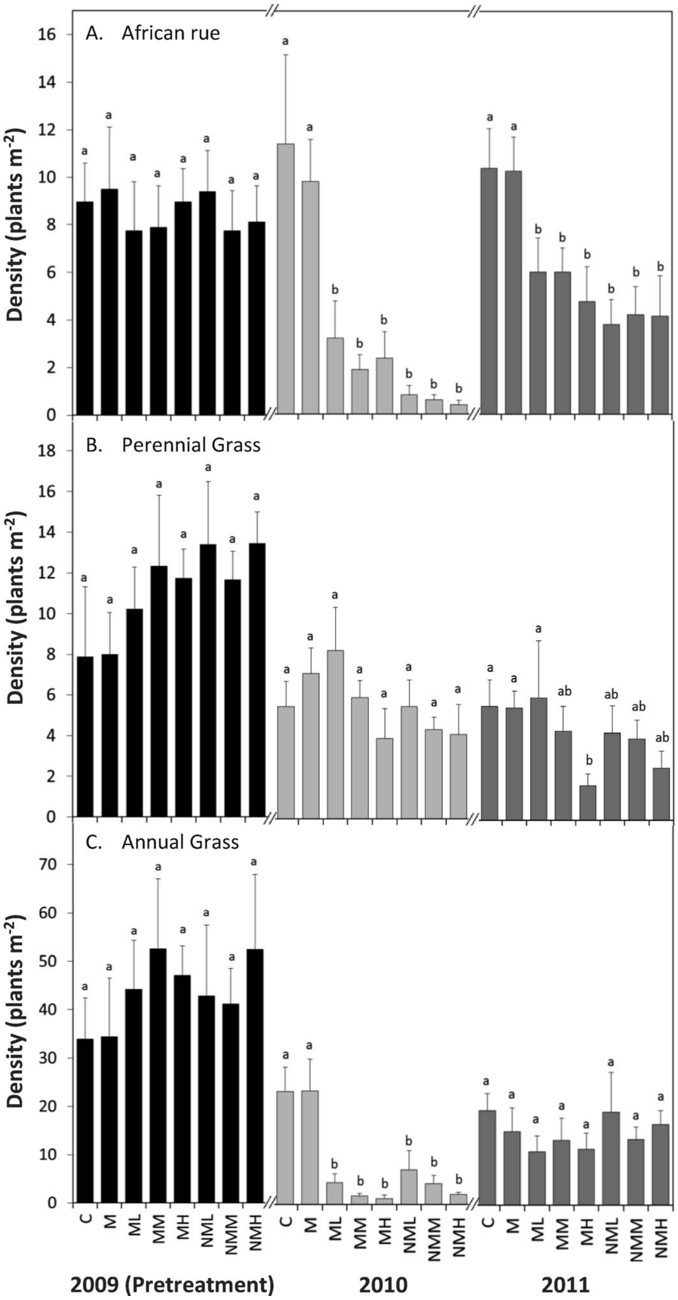

Figure 2. (A) African rue, (B) perennial grass, and (C) annual grass density values (mean ± SE) in the various African rue control treatments in 2009 (pretreatment year), 2010, and 2011. Treatments: C, control; M, mowing to a height of 8 cm in early July; MH, mowing and imazapyr application of 0.85 kg ae ha^{-1}; MM, mowing and imazapyr application of 0.55 kg ae ha^{-1}; ML, mowing and imazapyr application of 0.275 kg ae ha^{-1}; NMH, no mowing and imazapyr application of 0.85 kg ae ha^{-1}; NMM, no mowing and imazapyr application of 0.55 kg ae ha^{-1}; and NML, no mowing and imazapyr application of 0.275 kg ae ha^{-1}. Different lowercase letters indicate differences between treatments in that year ($P < 0.05$).

Density. Pretreatment density of African rue, perennial grass, and annual grass was not different among treatments in 2009 ($P > 0.05$; Figure 2) nor was pretreatment density of perennial and annual forbs different among treatments ($P > 0.05$, data not shown).

African rue density was less in plots treated with imazapyr than it was in the untreated control in the 2 yr posttreatment ($P < 0.05$; Figure 2A). African rue density was reduced to between 0.37 ± 0.75 to 3.2 ± 1.48 and 3.79 ± 0.51 to 6.8 ± 0.86 SE plants m^{-2} in plots receiving an imazapyr treatment compared with 11.4 ± 3.67 and 10.4 ± 1.87 SE plants m^{-2} in the untreated control during the first and second years posttreatment, respectively. We found no evidence that African rue density varied by imazapyr application rate in either posttreatment year ($P > 0.05$). Mowing did not influence African rue density in either posttreatment year ($P > 0.05$; Figure 2A).

There was no difference in perennial grass density among treatments 1 yr after treatment ($P > 0.05$; Figure 2B). However, by the second year after treatment, perennial grass density was less in plots receiving the high imazapyr rate (NMH and MH treatments) than it was in the untreated control ($P < 0.05$; Figure 2B). Perennial grass density in plots receiving lower imazapyr rates or a mowing treatment was not different from the untreated control in the second year posttreatment ($P > 0.05$; Figure 2B).

Annual grass density was less in plots that received imazapyr treatments than it was in the untreated control during the first year after treatment, regardless of mowing treatment ($P < 0.05$; Figure 2C). Mowing alone did not influence the density of annual grasses in either posttreatment year ($P > 0.05$; Figure 2C). Density of annual grasses was not different among any of the treatments by the second year after treatment ($P > 0.05$; Figure 2C).

Perennial forb density, excluding African rue, in the treated plots was not different from the untreated control in the 2 yr after treatment ($P > 0.05$, data not shown). Annual forb density was less in plots treated with imazapyr than it was in the untreated control in 2010 ($P < 0.05$, data not shown). Mowing alone did not influence the density of perennial or annual forbs in either posttreatment year ($P > 0.05$, data not shown). By the second year after treatment, annual forb cover in the treated plots was not different from the untreated control ($P > 0.05$, data not shown).

Discussion

Our results suggest summer applications of imazapyr are effective for gaining short-term control of African rue. Similar to findings of a trial conducted in Nevada by Davison et al. (2003), application of imazapyr in our study reduced the density of African rue by approximately 86%

compared with the untreated control the year following treatment. However, the density of African rue in plots receiving imazapyr applications was reduced only by approximately 54% compared with the untreated control by the second year after treatment, suggesting the reduction in the density of African rue may not persist into subsequent years without follow-up treatment or restorative action. Recovery in density was particularly evident in plots receiving the low and moderate rates of imazapyr, suggesting some efficacy for longer-term control of African rue may be sacrificed when using application rates of 0.55 kg ae ha^{-1} or less. We observed that most of the recovery in the density of African rue was in the form of resprouting shoots from plants that appeared dead the previous year, suggesting that one or more follow-up treatments may be necessary for longer-term control.

Applications of imazapyr substantially reduced both the cover and density of annual grasses (primarily downy brome) the year following treatment. However, by the second year after treatment the density and cover of annual grasses in herbicide-treated plots were not different from the untreated control, suggesting the preemergent suppression of annual grass by imazapyr had dissipated, allowing annual grasses to recolonize. These results are similar to those reported by Elseroad and Rudd (2011), who found that application of imazapic, a related imidazolinone herbicide with preemergent activity, resulted in only a short-term reduction in downy brome and failed to increase the abundance of native perennial plant species in a north-central Oregon sagebrush–steppe rangeland. The authors suggested that combining seeding of desired perennial plants with preemergent herbicide application may be a more-effective strategy for long-term suppression of downy brome. However, revegetation efforts should be postponed until after the residual phytotoxicity levels of the herbicide have subsided to prevent damage to the newly seeded species (Johnson and Davies 2012).

Mowing only once to a height of 8 cm, immediately before applying imazapyr in mid-July, did not significantly affect survival of desirable perennial bunchgrasses nor did it improve control of African rue. Contrary to our results, mowing before herbicide application has been effective for enhancing control of several other perennial, invasive plants (e.g., Mislevy et al. 1999; Monteiro et al. 1999). Beck and Sebastian (1993) demonstrated that mowing two or three times a year consistently enhanced control of Canada thistle following applications of herbicide. Therefore, repeated mowing treatments before herbicide application may have provided better control of African rue in our study than our single-mowing application. In addition, Renz and DiTomaso (2006) demonstrated that mowing to a height of 2 to 5 cm followed by an application of glyphosate to resprouting perennial pepperweed provided effective control, whereas applications of mowing or glyphosate alone were ineffective. Thus, the integration of mowing with herbicide may have been more effective for control of African rue if our mowing treatment had been conducted earlier in the growing season, thereby providing sufficient time and soil moisture for plants to begin active regrowth before herbicide applications were made.

Although we observed evidence of perennial grass recovery in plots receiving the high application rate of imazapyr, perennial grass cover remained significantly reduced in these plots through the second year after treatment compared with the untreated control. In contrast, perennial bunchgrass cover in plots receiving the low and moderate rates of imazapyr was not different from the untreated control by the second year after herbicide application, suggesting perennial bunchgrasses may be able to more readily recover from applications of 0.55 kg ae ha^{-1} or less of imazapyr under the environmental conditions that occurred during our study. Similarly, Bahm et al. (2011) reported an increase in native grass cover in the second and third growing seasons after imazapyr applications of 0.33 kg ae ha^{-1} in South Dakota. In comparison and similar to our findings, Stougaard et al. (1990) found that imazapyr applied at rates over 0.56 kg ai ha^{-1} severely suppressed perennial grasses in North Dakota. Our results suggest that lower imazapyr rates can be used to effectively achieve short-term control of African rue and limit nontarget herbicide damage to desirable plants in the Intermountain West. Limiting the damage to perennial grasses is important because this functional group dominates the understory in noninvaded plant communities (Davies et al. 2006; Davies and Bates 2010). Perennial grasses are also critically important in preventing other exotic plant invasion in these plant communities (Davies 2008; James et al. 2008). Additional research may be warranted to further evaluate combinations of mowing, conducted repeatedly or earlier during the growing season or both than tested in our study, with reduced rates of imazapyr for its effectiveness in controlling African rue and its effect to extant, desirable vegetation.

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