Invasive Plant Science and Management 2010 3:182–189

Managing Spotted Knapweed (*Centaurea stoebe*)–Infested Rangeland after Wildfire

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Invasive plants need to be managed after wildfire to suppress the invasive plant and to maintain or restore a desired plant community. Our study tested treatments that influence species availability and performance following a disturbance (wildfire). The overall objective was to determine the ability of herbicide and revegetation treatments to restore spotted knapweed–infested areas to desired plant communities after wildfire. The study consisted of a factorial combination of three herbicide application treatments (broadcast application, spot application, and no herbicide) and three seed mixture treatments (grass-only seed mix, a grass and forb seed mix, no seeding). Picloram was used for the herbicide. Both the broadcast and spot picloram application methods decreased spotted knapweed cover and density up to 80% while increasing desired grass cover and density up to 20% compared with the control. However, broadcast spraying picloram decreased species richness from 5.7 to 3.6 species 0.1 m^{-2} and decreased desired forb density and cover compared with spot-applied picloram treatment. Spot spraying resulted in an increase in other undesired forbs compared with broadcast spraying. Seeding with desired species had no effect on spotted knapweed cover or density. Spot spraying may help maintain desired species richness while managing spotted knapweed.

Nomenclature: Picloram; spotted knapweed, *Centaurea stoebe* L. CEST8.

Key words: Burn, invasive species, revegetation, spot-applied herbicide.

Disturbance is one contributing process leading to plant community change (Pickett et al. 1987). The size, severity, timing, and patchiness of the disturbance determine the characteristics of sites for recolonization. Recolonization following disturbance is further affected by species availability, namely, those species that survive in the propagule pool or disperse to the site. Once established on the site, a species' survival depends on its performance, including its ability to tolerate stress and acquire resources. Actively addressing the processes of plant community change—site availability, species availability, and species performance—is part of an ecologically based invasive plant management program (Krueger-Mangold et al. 2006; Sheley et al. 2006). By manipulating these processes, managers may better direct the recovery of a site to a desired state following disturbance.

DOI: 10.1614/IPSM-09-023.1

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Wildfire is a disturbance that often results in improved vegetative richness and productivity because conditions following a fire, including reduced aboveground biomass and increased light and nutrient availability (DeBano and Conrad 1978; Hulbert 1988, Whelan 1995), can be beneficial for seed germination and plant growth. However, the presence of invasive plants in a burned area may alter the community structure and function following fire. Some invasive plants are believed to have more rapid growth and reproductive rates than native species, which can be advantageous for weed productivity and spread following fire (Jacobs and Sheley 2003). In ponderosa pine (*Pinus ponderosa* C. Lawson) forests, areas experiencing high-severity fire have had short-term increases in nonnative plant species richness and abundance (Crawford et al. 2001). In northern Washington, a single low-intensity fire increased the cover and density of two nonnative invasive plants, diffuse knapweed (*Centaurea diffusa* Lam.) and spotted knapweed (*Centaurea stoebe* L., syn. *C. biebersteinii* and *C. maculosa*). However, studies on invasive plant response and spread following fire have had varied results (Johnson et al. 2006; Rice 2004).

Invasive plants need to be managed after fire to suppress invasive plants and to maintain or restore a desired plant community. Previous research suggests that establishing or maintaining plant diversity enhances resistance to invasion

(Tilman 1997; Tilman et al. 1997). Our research on native grasslands suggested that increased functional-group richness reduced invasion by spotted knapweed (Pokorny et al. 2005) and that after invasion occurs, maintaining overall production was important for suppressing the invader's growth (Rinella et al. 2007). A generalized objective for postfire invasive plant management should be to establish and maintain diverse plant communities.

Desired plant species richness and productivity can be maintained or improved with management using controlled herbicide-application methods and revegetation. Most herbicide is broadcast applied because this technique provides an even distribution and is relatively easy to implement compared with spot-applied herbicides. However, in studies where herbicides were spot-applied or the invasive plant was hand-removed, invasive plant biomass decreased and species richness was higher than where herbicide was broadcast applied (Krueger-Mangold et al. 2002; Sheley and Denny 2006).

Revegetating degraded lands using competitive native plants has become a priority for land managers (McArthur 2004; USFS 2008). Revegetation projects, with a species mix that includes different growth forms and sowing at high densities, may increase the establishment of desired species while providing control of invasive plants (Pyke and Archer 1991; Sheley et al. 2006). Most seed mixes are composed of grass species because native forb seed is expensive and supply is often limited (Richards et al. 1998). Incorporating forb species into seed mixes may improve the ability to maintain and increase species richness and resistance to invading species (Sheley and Half 2006).

Our study tested treatments that influence species availability and performance following a wildfire in an attempt to maintain and restore desired species. The overall objective was to determine the ability of herbicide application and revegetation treatments to restore spotted knapweed–infested areas to desired plant communities after wildfire. We hypothesized that (1) herbicide application plus revegetation would decrease spotted knapweed cover and density while increasing desired species cover, density, and species richness; (2) a broadcast or spot application of herbicide would decrease spotted knapweed cover and density compared with no herbicide application; (3) spot application or no application of herbicide would result in higher species richness than broadcast application; and (4) seeding a diverse seed mix of both grasses and forbs would result in higher species richness than seeding with a grass-only mix or no revegetation.

Materials and Methods

Study Site. The study area, located 13 km (8 mi) east of Lame Deer, MT (45°37′24″N, 106°39′58″W), is a rolling ponderosa pine and common chokecherry (*Prunus virginiana* L.) habitat type (Pfister et al. 1977). The area was burned by wildfire in June 1988 and in August 2003. Most of the ponderosa pines were removed by the fires, and the land is now dominated by shrubs, forbs, and grasses. Dominant species included chokecherry, bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve], Idaho fescue (*Festuca idahoensis* Elmer), and sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.]. A nonnative species, spotted knapweed, is present at the study site. Two research sites were located in the recent burn in patches of spotted knapweed. Site 1 has a west aspect, whereas site 2 has a northeast aspect, and both sites are on 5°-degree slopes. Soil classification surveys indicate the sites are a loamy-skeletal, mixed, frigid, Udic Ustochrept. These soils are greater than 1.5 m (5 ft) deep, well drained, and derived from colluvium (NRCS 1996). Soil pH ranges from 6.1 to 7.3. Average precipitation is 38 to 48 cm yr^{-1} (15 to 19 in yr^{-1}), and average temperature is 7 C (45 F). The study site was being managed for cattle grazing.

Experimental Design and Data Collection. The study consisted of a factorial combination of three herbicide-application treatments and three seed-mixture treatments. The three herbicide-application treatments were (1) broadcast application, (2) spot application, and (3) no herbicide. The three seed-mixture treatments were (1) grass-only seed mix (referred to as G seed mix), (2) a grass and forb seed mix (referred to as G&F seed mix), and (3) no seeding. Treatments were arranged in a randomized complete-block design with four replications at each site. Plots were 3 m by 2 m in size. Study sites were fenced to exclude cattle grazing.

Picloram[1] was used for the herbicide and was applied at a rate of 1.2 L ha^{-1} (0.13 gal ac^{-1})(0.28 kg ai ha^{-1}; 0.25 lb ai ac^{-1}) using a plot sprayer[2] for the broadcast-application treatment and a backpack sprayer[3] for the spot application treatment. For spot application, the backpack-sprayer wand was held close to the ground to treat individual and clumped spotted knapweed rosettes. Picloram was spot-applied to approximately half of each plot. Picloram application timing was based on realistic application times for each method following wildfire. The burned area emergency response plan called for broadcast spraying the entire burned area after the wildfire. Therefore, broadcast herbicide application treatment with picloram was applied in October 2003 after the fire to mimic the response-plan specifications. Spot spraying needs to occur when plants are visible. Because the fire had removed aboveground plant biomass, the spot-application treatment was applied in May 2004, when plants were resprouting and visible. Although the timing difference for the spot vs. broadcast picloram-application treatments was not ideal from an experimental-design standpoint, it was necessary for practical, on-the-ground considerations and represented how these treatments would be applied by land managers following a wildfire.

Seeded species were chosen for their site suitability, variation in phenology, life form (grass, forb), and growth form (bunch vs. sod grass). Seed-mixture treatments were broadcast at a rate of about 1,100 seeds m^{-2} using a hand-held broadcast seeder[4] in October 2003. Timing of the seeding was based on the burned-area response protocol, which called for seeding following the burn to prevent erosion and limit weed reinvasion. The G seed mix consisted of bluebunch wheatgrass (8.1 kg ha^{-1}), Idaho fescue (3.4 kg ha^{-1}), western wheatgrass [*Pascopyrum smithii* (Rydb.) A. Löve; 8.1 kg ha^{-1}), sideoats grama (4.7 kg ha^{-1}), and big bluestem (*Andropogon gerardii* Vitman; 6.1 kg ha^{-1}). The G&F seed mix consisted of bluebunch wheatgrass (4.1 kg ha^{-1}), Idaho fescue (1.7 kg ha^{-1}), western wheatgrass (4.1 kg ha^{-1}), sideoats grama (2.4 kg ha^{-1}), big bluestem (3.0 kg ha^{-1}), common yarrow (*Achillea millefolium* L.; 0.2 kg ha^{-1}), blanketflower (*Gaillardia aristata* Pursh, 2.7 kg ha^{-1}), prairie sage (*Artemisia ludoviciana* Nutt.; 0.1 kg ha^{-1}), purple coneflower (*Echinacea angustifolia* DC, 3.4 kg ha^{-1}), and blue flax (*Linum lewisii* Pursh; 1.4 kg ha^{-1}).

Data Collection and Statistical Analysis. Plots were sampled in July 2004 and 2005 for species richness, density, and canopy cover using two randomly located 20 by 50 cm frames $plot^{-1}$. The study could not be sampled additional years because of changes in land-management objectives by personnel managing the site. For ease of analysis, individual species were grouped according to growth form (grass, forb) and desirability (desired, undesired) of specific species to meet land-management objectives. The species targeted for control, spotted knapweed, occurred regularly throughout the plots and was analyzed independently. Species were grouped as desired grasses, desired forbs, and undesired forbs. Desired grasses consisted of the seeded species as well a forage grass (timothy; *Phleum pratense* L.) present on the site in low quantity. The desired forbs group consisted primarily of seeded forb species as well as American vetch (*Vicia americana* Muhl. ex Willd.), lupine (*Lupinus* sp.), and milkvetch (*Astragalus* sp.), and the undesired forbs group was primarily annual mustards (*Brassica* spp.), and Canada thistle [*Cirsium arvense* (L.) Scop.].

A PROC MIXED analysis[5] was used to detect treatment effects on vegetative canopy cover, density, and species richness. Fixed effects included herbicide-application method, seed-mixture treatment, and year. Random effects included site and replication. When a significant P value (≤ 0.05) was found, means were separated using Tukey's Honestly Significant Difference (HSD) test ($\alpha = 0.05$)(Ramsey and Schafer 2002).

Results and Discussion

Spotted Knapweed. Spotted knapweed cover was influenced by the interaction of herbicide application treatment and year ($P = 0.0012$). Spotted knapweed cover in 2004 was lowest when picloram was applied, regardless of application method (Table 1; Figure 1). By 2005, the broadcast picloram application resulted in less knapweed cover than the spot application (6.6 vs. 12.2%, respectively). Cover was highest (36.6%) in the nonsprayed plots in 2005.

Herbicide application method influenced the density of spotted knapweed ($P = 0.0023$). Similar to cover, density was lowest when picloram was either broadcast or spot applied (34 and 54 plants m^{-2}, respectively) vs. not sprayed (106 plants m^{-2}). We had hypothesized that a broadcast or spot application of herbicide would decrease spotted knapweed cover and density below that of no application of herbicide. Our results confirm previous results that picloram can provide control of spotted knapweed for 2 to 3 yr (Sheley and Jacobs 1997; Sheley et al. 2000).

However, contrary to our first hypothesis, seeding with desired species had no effect on spotted knapweed cover or density (Table 1). Other studies have suggested that establishment of desired species hinders the reestablishment of weedy species, including spotted knapweed (Mangold et al. 2007; Sheley and Carpinelli 2005, Sheley et al. 2005). Although we documented the establishment of our seeded species, they may not have been mature enough to affect spotted knapweed performance in the short-term. Although a fall-dormant seeding at the time of picloram application has been shown to provide successful grass establishment (Sheley et al. 2001), the picloram may have reduced seeded-grass vigor in the short term (Sheley et al. 2002).

Undesired Forbs. Cover of undesired forbs other than spotted knapweed was influenced by herbicide-application method ($P = 0.0043$) with the spot picloram application resulting in the highest, albeit low, cover of 2.7%. Broadcast picloram application and nonsprayed plots resulted in similar cover of 0.7 and 1.3%, respectively.

Herbicide application method and year interacted to influence undesired forbs density ($P = 0.0097$). A broadcast picloram application generally resulted in the lowest undesired forbs density (Figure 2), but by 2005, the broadcast and nonsprayed plots were similar at 7.3 and 21.7 plants m^{-2}, respectively. When picloram was spot-applied, undesired forbs density increased from 2004 to 2005 and resulted in the highest density 2 yr after treatment.

Targeting spotted knapweed with spot applications of picloram may have released nontarget, undesired forbs, which increased in cover and density compared with the

Table 1. P values and degrees of freedom (df) for main effects and interactions on cover and density of spotted knapweed, undesired forbs, desired forbs, and desired grasses.[a,b]

Source	df	Spotted knapweed	Undesired forbs	Desired forbs	Desired grasses
			Cover		
Herbicide	2	**<0.0001**	**0.0043**	**0.0009**	**0.0019**
Seed	2	0.3404	0.4739	0.8730	0.6627
H × S	4	0.3411	0.5022	0.9573	0.9165
Year	1	**<0.0001**	0.8130	**<0.0001**	**0.0224**
H × Y	2	**0.0012**	0.3524	0.1804	**0.0027**
S × Y	2	0.3350	0.3537	0.4228	0.3362
H × S × Y	4	0.3830	0.3120	0.3151	**0.0009**
			Density		
Herbicide	2	**0.0023**	**0.0108**	**<0.0001**	**0.0074**
Seed	2	0.6262	0.2863	0.6987	0.8623
H × S	4	0.2693	0.2734	0.7336	0.3331
Year	1	0.1743	0.6686	0.3916	0.9248
H × Y	2	0.1290	**0.0097**	0.3073	**0.0313**
S × Y	2	0.6925	0.8085	0.1491	0.5740
H × S × Y	4	0.4518	0.8489	0.4421	0.0957

[a] Abbreviations: H, herbicide; S, seed; Y, year.

[b] Values in bold are significant at $\alpha = 0.05$.

broadcast and nonsprayed plots. Targeted control of one weed may result in an increase in another weed if action is not taken to ensure desired species are available to fill open niches (DiTomaso 2000; Jacobs et al. 1999; Story et al. 2006). Additionally, the spring timing of the spot application may have injured desired plants more than the fall-broadcast application (Rice et al. 1997; Sheley et al. 2002), leading to increased site availability for undesired forbs. Carefully planned management should result in outcomes that meet objectives for all undesired and desired species alike. Alternatively, undesired forbs differ in their response to various herbicides (Whitson et al. 2000), and picloram may not have been as detrimental to some species of undesired forbs.

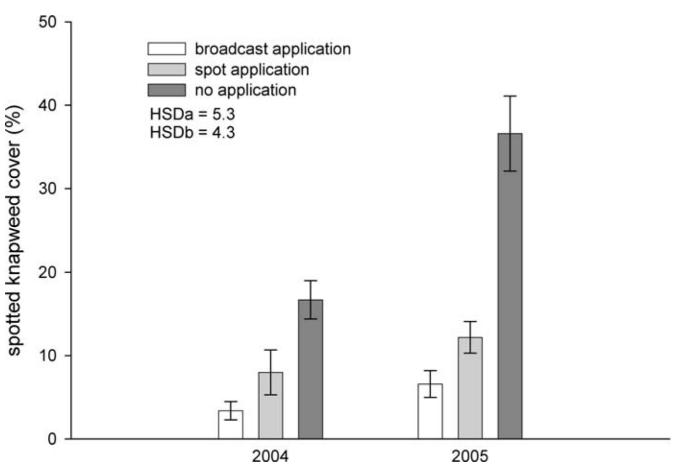

Figure 1. Spotted knapweed percentage of cover as affected by herbicide (picloram) application method and year. Error bars represent ± 1.0 SE. Honestly significant difference a (HSDa) separates means among herbicide application methods within a year. HSDb separates means within an herbicide application method across years.

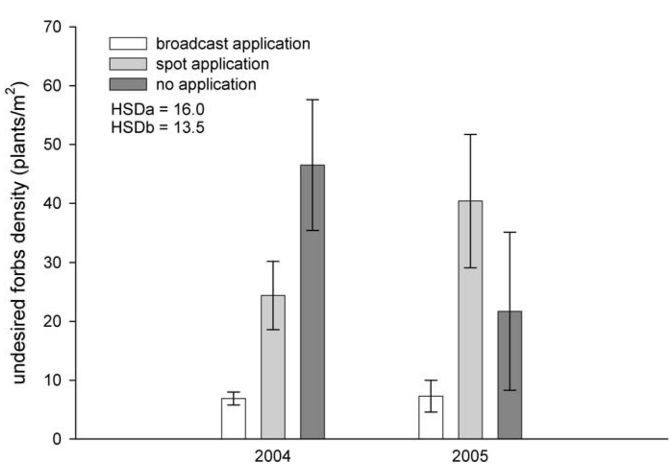

Figure 2. Undesired forbs density as affected by herbicide (picloram) application method and year. Error bars represent ± 1.0 SE. Honestly significant difference a (HSDa) separates means among herbicide application methods within a year. HSDb separates means within an herbicide application method across years.

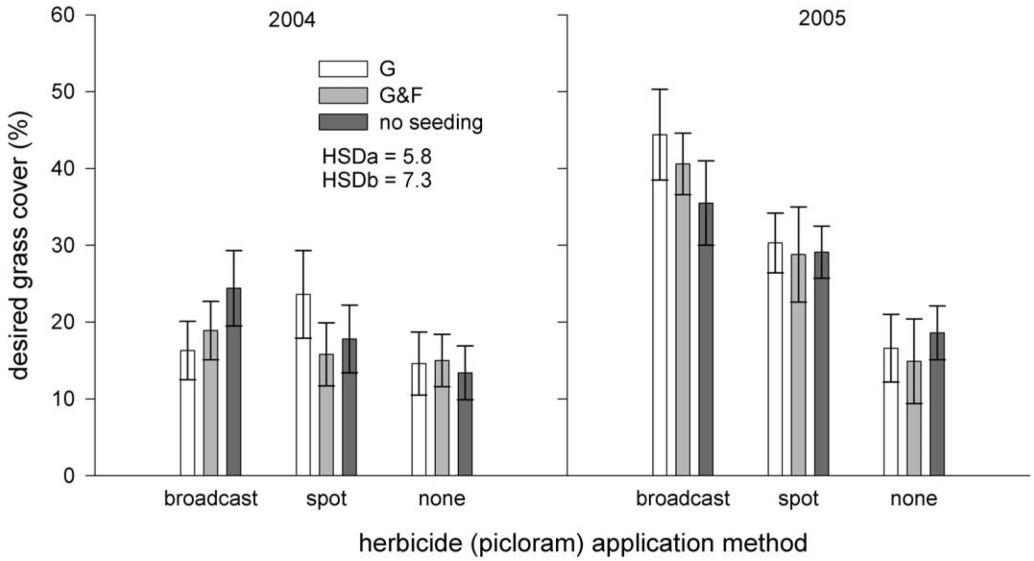

Figure 3. Percentage of cover by desired grasses as affected by herbicide (picloram) application method, seed mix, and year. Error bars represent ± 1.0 SE. Honestly significant difference a (HSDa) separates means across seed mixes within an herbicide application method and year. HSDb separates means within a treatment (seed mix by herbicide application method) across years. Abbreviations: G, grass-only seed mix; G&F, grass and forb seed mix.

Desired Forbs. Herbicide application method ($P = 0.0009$) and year ($P < 0.0001$) each affected the cover of desired forbs. Cover was lowest when picloram was broadcast (4.7%) compared with spot spraying and nonsprayed plots, which exhibited cover similar to each other (11.1 and 10.3%, respectively). Cover was higher in 2005 than 2004 (12.6 vs. 4.8%, respectively), suggesting desired forbs may increase over time.

Herbicide application method also affected desired forbs density ($P < 0.0001$). Similar to cover, density was lowest when picloram was broadcast applied with 15 plants m^{-2} vs. 73 and 87 plants m^{-2} for the spot application and nonsprayed treatments, respectively.

Even though spot application of picloram increased undesired forbs compared with broadcast application, it also had the beneficial effect of preserving desired forbs. Broadcast applications of picloram likely reduced the performance of nontarget, desired forbs (Sheley and Denny 2006). The presence of desired forbs has been found to decrease establishment by nonnative, invasive forbs (Mangold et al. 2007; Pokorny et al. 2005), so their preservation within a plant community is critical to effective, long-term weed management. Our data suggest spot-spraying spotted knapweed may be worth the effort if management goals include developing and maintaining a weed-resistant plant community.

Desired Grasses. Desired-grass cover was influenced by a three-way interaction between herbicide-application method, seed-mixture treatment, and year ($P = 0.0009$). Plots that were sprayed experienced an increase in desired grasses cover from 2004 to 2005, whereas the nonsprayed plots did not (Figure 3). Seeding in combination with herbicide application generally did not increase cover by desired grasses in 2004, but in 2005, the highest cover occurred when the G or G&F seed-mixture treatment was applied in combination with the broadcast picloram application (44.4 and 40.6%, respectively).

Density of desired grasses was affected by the interaction of herbicide-application method and year ($P = 0.0313$). Herbicide treatments increased desired grasses density in both years compared with the control. In 2004, broadcast and spot-spraying picloram increased desired-grass density similarly (1,173 and 1,113 tillers m^{-2}, respectively), whereas in 2005, broadcast picloram application increased the density of desired grasses significantly more than spot spraying (1,414 and1,064 tillers m^{-2}, respectively). In contrast, desired-grass density decreased from 814 to 590 plants m^{-2} between 2004 and 2005 in the nonsprayed plots.

Increased desired-grass cover and density with herbicide treatments suggests that picloram application released desired grasses from weed competition, similar to what was found in other studies (Sheley and Jacobs 1997; Sheley et al. 2000; Toly et al. 1992). In contrast, desired grasses decreased and spotted knapweed increased in plots that were not treated with herbicide.

The increase in desired-grass cover as a result of picloram application and seeding partially supports our first hypothesis that herbicide application plus revegetation will decrease spotted knapweed cover and density while increasing desired species cover and density and species

Table 2. P values and degrees of freedom (df) for main effects and interactions on species richness.[a,b]

Source	df	Species richness
Herbicide	2	**<0.0001**
Seed	2	0.1059
H × S	4	0.5444
Year	1	**<0.0001**
H × Y	2	**0.0080**
S × Y	2	**0.0397**
H × S × Y	4	0.8433

[a] Abbreviations: H, herbicide; S, seed; Y, year.

[b] Values in bold are significant at $\alpha = 0.05$

richness. We did not see this increase until 2 yr following seeding. Although seeding at the time of picloram application can result in decreased spotted knapweed densities and successful grass establishment (Sheley et al. 2001), some short-term injury to seeded grasses can occur. Seeded-grass injury may be more prevalent when picloram is applied in the spring (Sheley et al 2002). In our study, the timing of application for the spring-applied spot treatment vs. the fall-applied broadcast treatment may have led to the higher percentage of cover and density by desired grasses in the broadcast-applied picloram treatment. We are hopeful that desired grasses will continue to increase over time with appropriate management.

Species Richness. Species richness was influenced by the interaction of herbicide-application method and year (P = 0.0080; Table 2). Species richness was higher in the spot picloram application and nonsprayed treatments than in

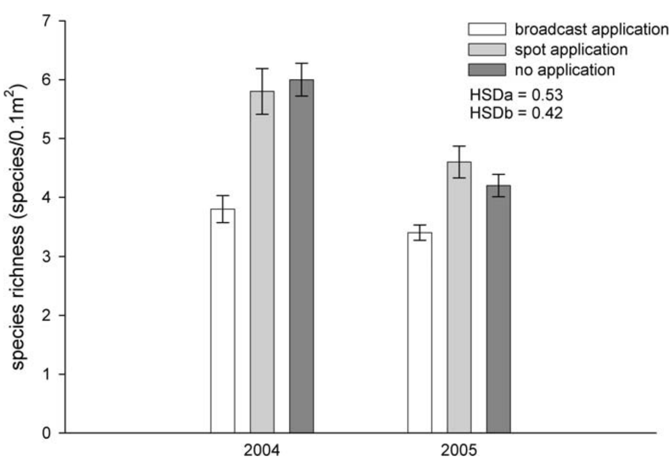

Figure 4. Species richness as affected by herbicide (picloram) application method and year. Error bars represent ± 1.0 SE. Honestly significant difference a (HSDa) separates means among herbicide application methods within a year. HSDb separates means within an herbicide application method across years.

the broadcast picloram application treatment in both years, but this difference was more pronounced in 2004 than in 2005 (Figure 4). These results support our hypothesis that species richness is higher when herbicide is spot applied or not applied at all, than when it is broadcast applied.

The decrease in species richness associated with the broadcast application of broadleaf herbicides has important implications for rangeland weed management. Fuhlendorf et al. (2002) found a decrease in forb dominance and forb species richness 1 yr after application of 2,4-D in Oklahoma. Native forb density and cover decreased when sprayed with various broadleaf herbicides at a site in southeastern Montana (Sheley and Denny 2006). Our results, in combination with other studies (Fuhlendorf et al.2002; Rinella et al. 2009; Sheley and Denny 2006, suggest that broadcast application of broadleaf herbicides on rangeland may make maintaining and restoring species richness difficult because key functional groups, such as forbs, appear to be at risk. At the same time, some research (Rice et al. 1997) suggests desired species diversity recovers within 3 yr of applying picloram. Forb species likely differ in their response to herbicide applications and further research is necessary to delineate these relationships.

A two-way interaction between seed-mixture treatments and year also affected species richness (P = 0.0397). Species richness decreased between 2004 and 2005 regardless of the seed-mixture treatment. In 2004, species richness was greatest in the G&F seed-mixture treatment at 5.8 species 0.1 m^{-2} compared with the G seed-mixture treatment and the unseeded treatment, which had a similar richness, 5.0 and 4.8 species 0.1 m^{-2}, respectively. These results support our hypothesis that a more diverse grass and forb seed mix would result in higher species richness compared with a grass-only seed mix or no revegetation. By 2005, however, all seeded plots resulted in similar species richness, suggesting that species availability was not ultimately enhanced by revegetation in this study. Instead, the on-site propagule pool and dispersal to the site following the fire may have been adequate. Alternatively, climate conditions may have been too poor for many seeded species to establish and persist at the sites.

In summary, both the broadcast and spot herbicide application methods decreased spotted knapweed performance (i.e., cover and density) while increasing desired-grass performance compared with the control. However, broadcast picloram spraying resulted in decreased species richness and decreased desired-forb density and cover compared with spot spraying. Spot spraying may help to maintain desired plant richness. Even though spot application had a beneficial effect on desired forbs, it also increased undesired forbs compared with broadcast application.

Our seeded species colonized the site but did not influence spotted knapweed performance in the short term.

Our results suggest that the plant community is on a path toward recovery, but continued management will be needed to ensure the plant community remains on the right trajectory. Follow-up spot-applied herbicide treatments may be needed to continue to suppress spotted knapweed performance while desired species, especially desired forbs, establish. It may also be beneficial to spot spray other undesired forbs or to use an herbicide that would affect a wider variety of undesired forb species. Longer-term investigations are needed to determine whether maintaining or restoring species richness affects spotted knapweed ability to spread or survive on the site.

Sources of Materials

[1] Picloram, Dow Chemical Company, P.O. Box 1706, Midland, MI 48640.

[2] R&D Sprayers, Bellspray, Inc., PO. Box 267, Opelousas, LA 70571.

[3] Solo 425 Backpack Sprayer, Solo, 5100 Chestnut Ave., Newport News,VA 23605.

[4] Earthway Hand-held Spreader, Earthway Products Inc., P.O. Box 547, Bristol, IN 46507.

[5] SAS Statistical software for Microsoft Windows, Version 2002–2003, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513.

Acknowledgments

We thank Dr. J. Jacobs for assisting in project design and B. McNamara for her enthusiastic field assistance. Thank you to reviewers whose comments improved this manuscript. Research was funded in part by the U.S. Department of Agriculture–Cooperative State Research, Education, and Extension Service Tribal Colleges Research Grant Program.

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Received March 30, 2009, and and approved February 26, 2010.