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Herbicide and Native Grass Seeding Effects on Sulfur Cinquefoil (*Potentilla recta*)-Infested Grasslands

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Sulfur cinquefoil is an exotic, perennial forb that invades a wide range of ecosystems in western North America. It forms dense populations and often threatens native plant species and communities. In this study, we address the following questions: (1) what herbicides, rates, and application times are most effective at reducing sulfur cinquefoil abundance while having the least impact on native plants; and (2) does postherbicide seeding with native grass species increase native plant abundance? In 2002, we experimentally examined the effects of five herbicides (dicamba + 2,4-D; metsulfuron-methyl; triclopyr; glyphosate; and picloram) at two rates of application (low and high), three application times (early summer, fall, and a combined early summer–fall treatment), and two postherbicide seed addition treatments (seeded or not seeded) on sulfur cinquefoil abundance, plant community composition, and species richness. Experimental plots were monitored through 2005. Picloram was the most effective herbicide at reducing sulfur cinquefoil density, the proportion of remaining adult plants, and seed production. The effects of picloram continued to be evident after 3 yr, with 80% reduction of sulfur cinquefoil in 2005. In addition, seeding of native grass seeds alone (no herbicide application) reduced the proportion of sulfur cinquefoil plants that were reproductively active. Despite reductions in sulfur cinquefoil abundance, all treatments remained dominated by exotic species because treated areas transitioned from exotic forb- to exotic grass-dominated communities. However, a one-time herbicide application controlled sulfur cinquefoil for at least 3 yr, and therefore might provide a foundation to begin ecological restoration. Herbicide applications alone likely are to be insufficient for long-term sulfur cinquefoil control without further modification of sites through native grass or forb seeding. Integrating herbicides with native plant seeding to promote the development of plant communities that are resistant to sulfur cinquefoil invasion is a promising management approach to ecological restoration.

Nomenclature: Dicamba; 3,6-dichloro-2-methoxybenzoic acid; Glyphosate; *N*-(phosphonomethyl)glycine; Metsulfuron-methyl; 2-[[[[94-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl]amino]sulfonyl]benzoic acid, Picloram; 4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid; Triclopyr; [(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid; Sulfur cinquefoil, *Potentilla recta* L.

Key words: Rangeland, restoration, species richness, plant community dynamics, sulfur cinquefoil, bunchgrass.

In the last several decades, the impact of exotic invasive plants on ecological patterns and processes has been recognized and invasive species are considered a significant threat to biodiversity and the structure and function of ecosystems (Mack et al. 2000; Vitousek et al. 1996). In the intermountain Pacific Northwest, one invasive species of concern is sulfur cinquefoil, a perennial forb that invades a wide range of grassland, shrub, steppe, and open-forest communities (Endress et al. 2007; Parks et al. 2005; Zouhar 2003).

Sulfur cinquefoil, a native of Eurasia, was introduced to North America prior to 1900 and has since spread across the continent (Rice 1999). In eastern North America, sulfur cinquefoil is considered a minor agricultural weed, but in the drier climates of western North America, sulfur cinquefoil forms dense populations, becomes a plant-community dominant, and threatens native species (End-

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Interpretive Summary

The development of cost-effective approaches to managing invasive plants and restoring native communities are key concerns for many land managers. Clearly it is important to know which herbicides are most effective at controlling the target species; but managers often want to know which herbicides have the least impact on desired native species and if postherbicide seeding of native species promotes native species establishment in degraded areas. In this study we address these issues in grasslands infested with sulfur cinquefoil in northeastern Oregon. Sulfur cinquefoil is an exotic, perennial forb that invades a wide range of grassland, shrub, steppe, and open-forest communities in the western United States. It forms dense populations and often threatens native plant species and communities. In 2002 we initiated an experiment to determine: (1) what herbicides, rates, and application times are most effective at reducing sulfur cinquefoil abundance, while having the least impact on native plants; and (2) if postherbicide seeding with native grasses promotes native plant establishment. We monitored sulfur cinquefoil abundance, plant community composition, species richness, and native grass establishment through 2005. Picloram was the most effective herbicide at reducing sulfur cinquefoil density, the proportion of remaining adult plants, and seed production. The effects of picloram continued to be evident after 3 yr, with 80% reduction of sulfur cinquefoil in 2005. Also, seeding of native grass seeds alone (no herbicide application) reduced the proportion of sulfur cinquefoil plants that were reproductively active. Despite the effectiveness in controlling sulfur cinquefoil of many of the herbicide treatments, all treatments remained dominated by exotic species because treated areas transitioned from exotic forb- to exotic grass-dominated communities. However, a one-time herbicide application controlled sulfur cinquefoil for at least 3 yr, and therefore might provide a foundation to begin ecological restoration. Herbicide applications alone are likely to unsuccessful for long-term sulfur cinquefoil control without further modification of sites through native grass or forb seeding.

ress et al. 2007; Rice 1999). Dominance by sulfur cinquefoil not only reduces the abundance of native plant species, but also reduces forage production for wildlife and livestock (C.G. Parks, unpublished data; Zouhar 2003). The high tannin content in sulfur cinquefoil might also negatively affect soil flora and fauna and associated ecological processes (Powell 1996; Werner and Soule 1976). As a result, land managers and policy makers are interested in eliminating sulfur cinquefoil from invaded communities and re-establishing desired species, such as native forbs and grasses.

A variety of methods have been suggested to control Sulfur cinquefoil including prescribed fire (Lesica and Martin 2003), hand-pulling (Sheley and Denny 2006), and herbicide application (Sheley and Denny 2006; Sheley et al. 2006). Herbicides are by far the most commonly used tool to manage sulfur cinquefoil, although little research exists on which herbicides, application rates, or application timings best control sulfur cinquefoil. Lesica and Martin (2003) report mixed results in a study that examined the recruitment of sulfur cinquefoil following combinations of treatments consisting of prescribed fire and picloram. In some cases, the herbicide was effective in eliminating sulfur cinquefoil, but sulfur cinquefoil density was greatest in plots that were first treated with picloram then burned (Lesica and Martin 2003). Thus, the effectiveness of herbicides on sulfur cinquefoil control remains unclear. Of additional concern is that although herbicides might succeed in reducing the abundance of target species such as sulfur cinquefoil, they also might negatively affect nontarget native species that are considered important to the ecology of the ecosystems (Carlson and Gorchov 2004; Laufenberg et al. 2005; Sheley and Denny 2006). Non-target native forbs appear to be most impacted by herbicide treatments (Sheley and Denny 2006), because most herbicides used to control wildland exotic species target broadleaf plants.

Our objectives were to examine the effectiveness of a range of herbicide applications on sulfur cinquefoil abundance and plant community structure and composition, with a focus on native species. Specifically, we addressed the following questions: (1) what herbicides, rates, and application times are most effective at reducing the abundance of sulfur cinquefoil, while having the least impact on native plant species; and (2) does postherbicide seeding with native grass species increase native species abundance and facilitate grassland restoration?

Materials and Methods

Study Site. Research was conducted in the Wenaha State Wildlife Area in northeastern Oregon. Elevation ranges from 900 to 1,150 m (2,953 to 3,773 ft), and annual precipitation averages 43 cm/yr (17 in/yr). Most precipitation occurs from October through May with the warm, drier summer months, characterized by periodic thunderstorms. The landscape ecology and land use history of this area is representative of the low elevation grasslands of the Blue Mountain Ecoregion (Parks et al. 2005). As with many areas of the region, intense land use began with the expansion of cattle and sheep ranching and the conversion of bunchgrass grasslands to agricultural fields in the mid- to late-nineteenth century (Galbraith and Anderson 1971; Jordan 1954). The rugged landscape and dry climate resulted in abandonment of most agricultural fields. Currently, the predominant land use activities are cattle ranching, recreation, and wildlife habitat management.

Species Description. Sulfur cinquefoil was first collected and reported in 1897 in southern Ontario (Werner and Soule 1976). It has since spread west across Canada and the United States, and currently poses a serious threat to ecosystems throughout western North America (Zouhar 2003). It is a long-lived perennial with a woody rootstock. Sulfur cinquefoil has four general life-history stages: seeds, seedlings, rosettes, and stemmed individuals. Stemmed plants (adults) are reproductively active, usually have 1 to 5 stems that range in height between 15 to 70 cm (6 to 28 in) (Perkins et al. 2006), and can reach densities > 100 stems/m^2 (9.3 stems/ft^2) (Naylor et al. 2005). In northeastern Oregon, sulfur cinquefoil flowers during mid-summer, and stemmed sulfur cinquefoil individuals can produce over 8,500 seeds/yr (Dwire et al. 2006). Seeds remain viable in the soil at least 3 yr (Rice 1993).

Experimental Design. In 2002, three sulfur cinquefoil-dominated meadows in the Wenaha State Wildlife Area were selected. These sites were once in agricultural production for forage and grain crops, but have been abandoned for at least 15 yr. The three areas were fenced to exclude cattle during the experiment.

The experiment consisted of five herbicides, two rates of application, three application times, and two postherbicide seed addition treatments (seeded and unseeded). The experiment was replicated once at each of the three sites. Treatments were arranged in a randomized complete block design, with a split-plot treatment structure. Blocks were placed in areas representing uniform sulfur cinquefoil density. Each block was 120 by 15 m (1800 m^2) (394 by 50 ft [19,375 ft^2]). The first three treatment factors (herbicide, rate, and timing) were included in the experiment in a complete factorial arrangement. In addition, a control treatment consisting of no herbicide application was included. This resulted in 31 treatment combinations: five herbicides by two rates by three timing of applications plus one untreated area, the control. Each block, therefore, consisted of 31 plots and each plot was 4 by 15 m (60 m^2) (13 by 50 ft [646 ft^2]). The 31 treatment combinations were then randomly assigned within each block. The native grass seeding treatment was the split-plot portion of the design, and was applied randomly to half of each plot (30 m^2 [323 ft^2]).

Herbicide application rates included ''high'' and ''low'' rates. The five herbicides and rates were: dicamba + 2,4-D (0.07 kg ai/ha [0.06 lb ai/ac]+ 0.07 kg ai/ha [0.06 lb ai/ac], 0.14 kg ai/ha [0.12 lb ai/ac] + 0.07 kg ai/ha [0.06 lb ai/ac]), glyphosate (0.07 kg ai/ha [0.06 lb ai/ac], 0.263 kg ai/ha [0.23 lb ai/ac]), metsulfuron methyl (0.006 kg ai/ha [0.005 lb ai/ac], 0.011 kg ai/ha [0.01 lb ai/ac]), picloram (0.28 kg ai/ha [0.62 lb ai/ac], 0.56 kg ai/ha [0.05 lb ai/ac]), and triclopyr (0.116 kg ae/ha [0.10 lb ai/ac], 0.232 kg ae/ha [0.21 lb ai/ac]). These rates were within the broad range of rate recommendations on the manufacturer's label, and were suggested by local professional weed managers. Although the herbicide rates tested did not exactly correspond to the maximum and minimum recommended rates for every product label, they are clearly within a range that is reasonable for rate efficacy test purposes. Herbicides were applied with a calibrated hand pumped sprayer. The sprayer pressure was approximately 220 kPa with a water volume approximately 358 L/ha (153 qt/ac). Herbicides were applied at moderate temperatures (12 to 16 C) as wind speeds ranged 2.5 to 6 km/h (1.5 to 3.7 mi/h).

The three application timing treatments were early summer application, fall application, and a combined early summer and fall application. Early summer application of herbicides occurred in early May 2002 and fall applications occurred in mid-October 2002. The combined early summer and fall application applied the full herbicide rate in both May and October of 2002. The seed addition mix was comprised of five native grass species at the following rates: Bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve; 4.0 kg/ha (3.6 lb/ac)], Mountain brome [*Bromus carinatus* Hook. & Arn.; 6.9 kg/ha (6.2 lb/ac)], Blue wildrye [*Elymus glaucus* Buckl.; 4.4 kg/ha (3.9 lb/ac)], Sandberg's bluegrass [*Poa secunda* J. Presl; 0.6 kg/ha (0.05 lb/ac)], and Idaho fescue [*Festuca idahoensis* Elmer; 1.2 kg/ha (1.1 lb/ac)]. These species are common components of the native bunchgrass grasslands in northeastern Oregon (Johnson and Swanson 2005). Seeding was done in late October 2002 and seeds were broadcast from the back of a four-wheel off-road vehicle that also trailed a harrow to increase soil-seed contact.

Data Collection and Analysis. Plant community composition, structure, and species richness were determined at 1 and 3 yr following treatment application (2003 and 2005). Sampling occurred over a 1-wk period in mid-July of each year. Percent canopy cover of all species was recorded in six 0.6 by 0.3 m (0.18 m^2) (2 by 1 ft [2 ft^2]) quadrats placed along the center of each plot. Thus, each split plot herbicide treatment contained three sampling quadrats. Quadrats were spaced at 2 m (7 ft) intervals and the first quadrat began 1.5 m (5 ft) from the edge of each plot to avoid potential edge effects. Percent canopy cover was recorded using the following scale: < 1, 1 to 5, 5 to 15, 15 to 25, 25 to 35, 35 to 45, 45 to 55, 55 to 65, 65 to 75, 75 to 85, 85 to 95, > 95%. Densities of sulfur cinquefoil rosettes and adults (stemmed) were recorded in two of the quadrats (one within each split-plot). Because seedlings in some cases exceeded 4,000 seedlings m^{-2} (372 seedlings/ft^2) and mortality rates are often well above 95% (Tuitele-Lewis 2004), they were not counted.

Canopy cover by species and life form (e.g., native grass, exotic forb, etc.) was averaged among quadrats for each treatment combination. Percent control of sulfur cinquefoil was determined by calculating the difference in sulfur cinquefoil cover between the control treatment (no herbicide) and each treatment combination. Reductions in sulfur cinquefoil control between 2003 and 2005 were evaluated by calculating the difference in sulfur cinquefoil control between the two dates and testing for mean differences among treatments. To evaluate treatment effects

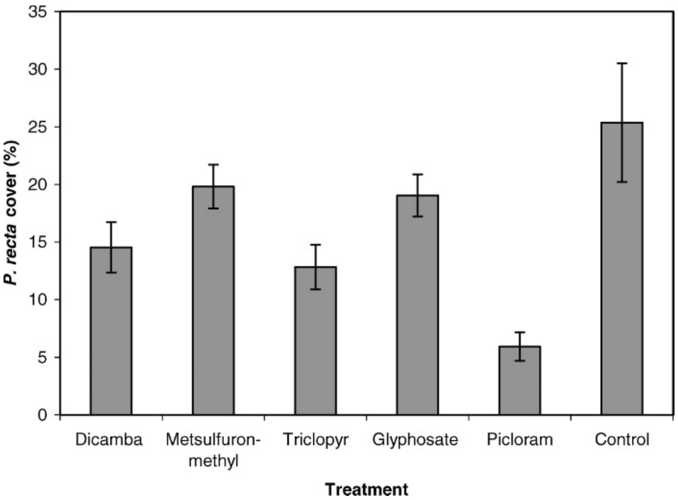

Figure 1. 2005 mean (± 95% CI) percent canopy cover of Sulfur cinquefoil among herbicide treatments, 3 yr after treatment application (2002).

on sulfur cinquefoil and community composition, data analysis was restricted to the 2005 dataset, because this allowed additional time to better evaluate any increase in native grass cover due to seedling establishment from our seeding treatments. Data met the assumptions for general linear models, and were analyzed using PROC GLM in SAS (SAS version 9.1). Response variables for the GLM models included: sulfur cinquefoil cover, percent sulfur cinquefoil control, sulfur cinquefoil density, total vegetation cover, native forb cover, exotic forb cover, native grass cover, exotic grass cover, and species richness. Comparisons between control and herbicide treatments were done using contrast statements in SAS; Contrasts were also used to evaluate seeding effects on the response variables.

To determine the effect of treatments on sulfur cinquefoil seed production 3 yr after treatment application, we multiplied the 2005 density adult individuals for each treatment combination with mean sulfur cinquefoil seed production rates (± 95% confidence intervals) collected from 85 adult sulfur cinquefoil individuals located adjacent to the experimental plots (average seed production = 1,791 seeds/adult; 95% confidence interval range = 1,512–2,065 seeds/adult; B. A. Endress, unpublished data).

Results and Discussion

Sulfur Cinquefoil Density and Cover. Herbicide application reduced sulfur cinquefoil density and cover. In 2005, the nonherbicide (control) treatment averaged 25.4% sulfur cinquefoil cover with a density of 100.1 plants/m^2 (9.3 plants/ft^2). Sulfur cinquefoil cover in the herbicide treatments was significantly lower than the control (df = 1,60; P = 0.016; Figure 1), and cover values ranged from 6% (picloram) to 19% (metsulfuron-methyl and glyphosate). Density mirrored cover responses, and we again found significant differences between herbicide and control treatments (df = 1,60; P = 0.0023; Table 1). Sulfur cinquefoil density was lowest in the picloram treatment (26.9 plants/m^2 [2.5 plants/ft^2]) and highest in the glyphosate treatment (63.9 plants/m^2 [6 plants/ft^2]). No time, rate, or seeding effects were observed on sulfur cinquefoil cover or sulfur cinquefoil density.

Differences were also found in 2005 in the percentage of sulfur cinquefoil control among the five herbicide treatments (df = 4, 60; P < 0.0001; Figure 2 and Table 1). In 2005, Picloram provided greatest control (80%), followed by triclopyr (52%), dicamba + 2,4-D (50%), metsulfuron-methyl (25%), and glyphosate (11%). Herbicide rate (low or high), application timing, and seeding treatments had no effect on sulfur cinquefoil control, and no interactions were found. Between 2003 and 2005, herbicides averaged a 9% reduction in sulfur cinquefoil control, with no significant differences found among treatments (df = 4, 60; P = 0.9648).

Sulfur Cinquefoil Population Size Structure and Seed Production. In 2005, 52% of sulfur cinquefoil individuals in no-herbicide (control) plots were adults and 48% were rosettes. Some herbicide and seeding treatments resulted in significantly different sulfur cinquefoil population stage (size) structures. A significant interaction among herbicide treatments and timing of application was found (df = 8, 60; P = 0.0101; Table 1; Figure 3); sulfur cinquefoil populations in plots treated in early summer with dicamba + 2,4-D, metsulfuron-methyl, and triclopyr had a much smaller proportion of adults (and therefore a greater proportion of nonreproductive rosettes) in 2005 than plots treated with the same herbicides in the fall. Picloram treatments showed the opposite trend, with fall application treatments having a smaller proportion of adults (3.5% compared to 16.6%). In addition, herbicide-treated plots had smaller proportions of adults, with significant differences found among herbicides (df = 4,60; P < 0.0001; Table 1). Picloram treatments had the smallest proportion of adults (10%; 3 adults/m^2 [0.3 adults/ft^2]), followed by triclopyr (26%; 11 adults/m^2 [1.0 adults/ft^2]), dicamba + 2,4-D (26%; 11 adults/m^2 [1.0 adults/ft^2]), metsulfuron-methyl (44%; 20 adults/m^2 [1.9 adults/ft^2]) and glyphosate (49%; 31 adults/m^2 [2.9 adults/ft^2]).

Seeding with native grass species also resulted in significant differences among treatments in the size structure of sulfur cinquefoil populations. Regardless of the herbicide type, rate, or timing, native grass seeding resulted in a smaller proportion of adults, and a greater proportion of rosettes (24% vs. 31% adults; df = 1,62, P = 0.0319; Table 1). This suggests that native grass seeding

Table 1. Summary of generalized linear models to evaluate the effects of five herbicides, two application rates, three application timings, and the addition of postherbicide seeding with native grass species at three sites on sulfur cinquefoil control and community composition, structure, and richness. Analysis is shown for data collected in 2005, 3 yr after treatment application.

	Sulfur cinquefoil			Species richness		2005 Canopy cover			
	Control (%)	Density	Proportion of adults	Native	Total	Native forb	Native grass	Exotic forb	Exotic grass
Control vs. Herbicide	*	**	*	_	_	_	_	*	_
Herbicide	***	**	***	**	_	_	_	***	**
Rate	_[a]	_	_	_	_	_	_	_	_
Herbicide by Rate	_	_	_	_	_	_	_	_	_
Time	_	_	**	_	_	_	_	_	_
Herbicide by Time	_	_	*	_	_	_	_	_	_
Rate by Time	_	_	_	_	_	_	_	_	_
Herbicide by Rate by Time	_	_	_	_	_	_	_	_	_
Seed	_	_	*	**	_	_	*	_	_
Control by Herbicide by Seed	_	_	_	_	_	_	_	_	_
Herbicide by Seed	_	_	_	_	_	_	_	_	_
Rate by Seed	_	_	_	_	_	_	_	_	_
Herbicide Rate by Seed	_	_	_	_	_	_	_	_	_
Time by Seed	_	_	_	_	_	_	_	_	_
Herbicide by Time by Seed	_	_	_	_	_	_	_	_	_
Rate by Time by Seed	_	_	_	_	_	_	_	_	_
Herbicide Rate by Time by Seed	_	_	_	_	_	_	_	_	_

[a] _ not significant.

*P < 0.05; **P < 0.01, ***P < 0.0001.

might increase competition for site resources resulting in sulfur cinquefoil individuals allocating more resources to growth at the expense of reproduction. More research in required to better understand competitive interactions between sulfur cinquefoil and seeded species.

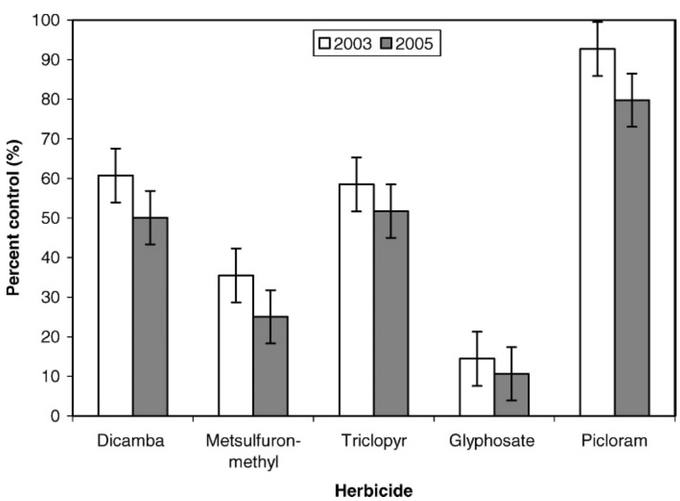

Figure 2. Percent sulfur cinquefoil control (mean ± SE) 1 and 3 yr after treatment applications. On average, there was a 9% reduction in control between 2003 and 2005.

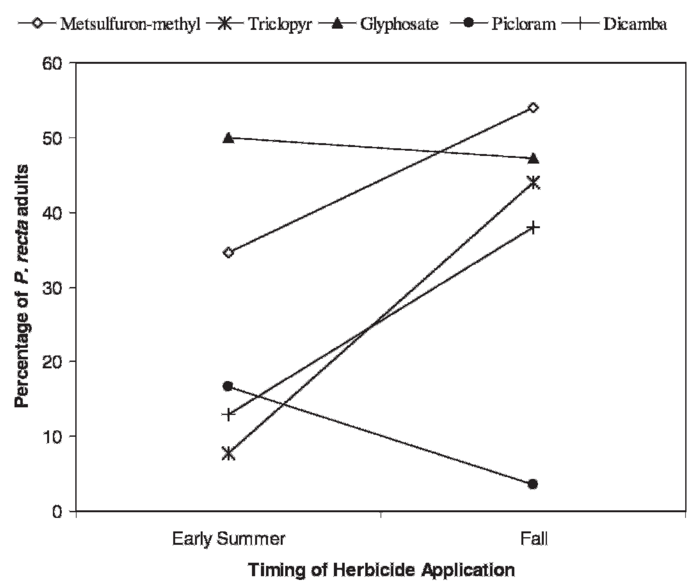

Figure 3. Interactions between timing of herbicide application and herbicide type on the proportion of living sulfur cinquefoil individuals that were adults (reproductively active) in 2005. Herbicides were applied in 2002 in May (early summer) and October (fall).

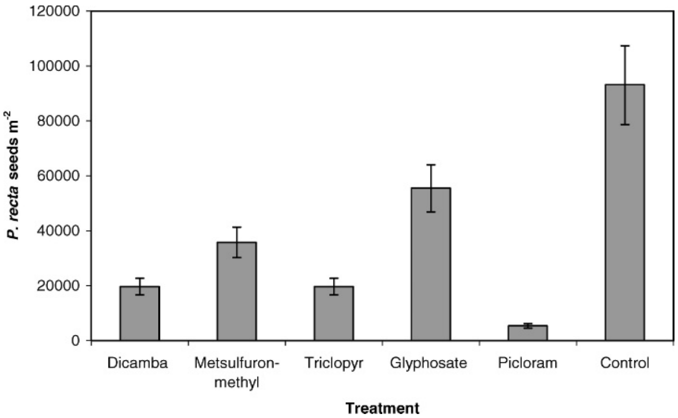

Figure 4. Mean sulfur cinquefoil seed production (seeds/m^2 ± 95% confidence intervals) based on 2005 sulfur cinquefoil density, the proportion of adults for the herbicide treatments, and a mean of 1,791 seeds/adult (95% CI = 1,512–2,065 seeds/adult).

Treatment effects on estimated sulfur cinquefoil seed production reflected treatment effects on sulfur cinquefoil density and the proportion of adults. These differences resulted in large differences in estimated seed production rates among the treatments (Figure 4). In 2005, the control treatment produced an average of 93,132 seeds/m^2 (8,652 seeds/ft^2) (95% CI: 78,624 to 107,380 seeds/m^2 [7,304 to 9,975 seeds/ft^2]), whereas seed production was lowest in picloram treatments (average 5,373 seeds/m^2 [499 seeds/ft^2] 95% CI: 4,536 to 6,195 seeds/m^2 [421 to 576 seeds/ft^2]). These results must be treated with caution however, because it might be possible that treatments affected the number of seeds per flower; however, no research has been conducted with sulfur cinquefoil to evaluate this possibility.

The choice of herbicide is clearly more important than the herbicide rate or timing of herbicide application to control sulfur cinquefoil. Picloram was the most effective herbicide at reducing sulfur cinquefoil cover, density, the proportion of remaining adult plants, and seed production. The effects were still evident after 3 yr, indicating that picloram provide at least a 3-yr window of time in which sulfur cinquefoil abundance and seed production can be reduced, during which native perennial plants can be reintroduced into the plant community. Overall, few differences were found among the other herbicides, with the exception of glyphosate, which did little to reduce sulfur cinquefoil infestations. Simply seeding native grass seeds reduced the reproduction of sulfur cinquefoil, by reducing the proportion of individuals in the adult (reproductive) stage. Although the effect of seeding was modest (7% reduction), the influence of seeding might increase through time as the newly establishing grass continues to grow and compete with sulfur cinquefoil for resources and space.

Effects on Community Composition. A total of 93 species were identified in our experimental plots (Table 2). Common species included: smooth brome (*Bromus inermis* L.), mountain tarweed (*Madia glomerata* Hook.), sulfur cinquefoil, bulbous bluegrass (*Poa bulbosa* L.), Canada bluegrass (*Poa compressa* L.), and phlox [*Phlox gracilis* ssp. *gracilis* (Hook.) Greene]. On average, vegetation cover was 50.5% and no differences were found in cover among treatments in 2003 or 2005. However, significant differences were found in the composition and structure of vegetation among the treatments. In 2005, total grass cover differed among herbicide treatments (df = 4, 60; MS = 1412.3, F = 6.657, P $<$ 0.0001), with triclopyr treatments having the greatest grass cover (36.5% ± 1.9 SE), followed by picloram (35.6% ± 1.9SE), dicamba + 2,4-D (29.6% ± 1.9 SE), metsulfuron-methyl (26.4% ± 1.9 SE), and glyphosate (21.6% ± 1.9 SE). Main effects of herbicide rate, timing, and seeding were not found, but there was a significant herbicide by seed interaction (df = 4, 60, MS = 202.4, F = 4.38, P = 0.0035). In this case, only the glyphosate treatment responded to seed additions with increased grass cover (17.4% ±3.5 SE vs. 25.9% ± 2.3 SE), whereas only small differences ($<$ 3% cover) were found among the other herbicide treatments.

Effects on Exotic Species. Differences in grass cover were primarily the result of changes in the abundance of exotic grass species. Significant differences in exotic grass cover were found among herbicide treatments (df = 4,60; P = 0.005; Table 1), with values lowest in the glyphosate treatment (16.5 ± 2.3 SE). Exotic grass cover values for the other herbicide treatments were similar, and ranged from 25.3 to 32.9%. Exotic forb cover differed among herbicide treatments (df = 4,60; P = 0.00002; Table 1). Treatments that were best at controlling sulfur cinquefoil had the lowest exotic forb cover because sulfur cinquefoil was the dominant forb at the site. Picloram resulted in the lowest exotic forb cover (9.7 ± 2.1 SE) followed by triclopyr (13.9 ± 2.1 SE), dicamba + 2,4-D (18.1 ± 2.1 SE), metsulfuron-methyl (21.4 ± 2.1 SE), glyphosate (23.0 ± 2.1 SE), and the untreated (control) treatment (24.6 ± 2.1 SE). No rate, timing, or seeding treatments, nor any interactions were found.

Despite considerable reductions in the abundance of sulfur cinquefoil in many of the herbicide treatments, no differences were found in total exotic plant canopy cover between the untreated and herbicide treatments (df = 1,60; P = 0.6129), and no differences were found among herbicide treatments (df = 4,60; P = 0.2286). Canopy cover of exotic plants ranged from 39.7% ± 2 SE (glyphosate) to 46.8 ± 2 SE (metsulfuron-methyl), whereas the control treatment averaged 46.5% ± 2 SE. Because total vegetation cover averaged 50.5%, all treatments were dominated by exotic species. In 2005,

Table 2. Species found in experimental areas (species that had > 5% cover in any plot). A total of 96 species were identified.

	Common Name	Life Form
Exotic Forb species		
Hypericum perforatum L.	St. John's wort	Perennial
Plantago lanceolata L.	buckhorn plantain	Annual
Potentilla recta L.	sulfur cinquefoil	Perennial
Sanguisorba minor Scop.	garden burnet	Perennial
Native Forb species		
Achillea millefolium L.	common yarrow	Perennial
Agoseris spp.	agoseris	Annual and Perennial
Apocynum androsaemifolium L.	spreading dogbane	Perennial
Asclepias speciosa Torr.	showy milkweed	Perennial
Collomia linearis Nutt.	tiny trumpet	Annual
Epilobium brachycarpum K. Presl	tall annual willow-herb	Annual
Lotus unifoliolatus (Hook.) Benth.	birds-foot trefoil	Annual
Lupinus sericeus ssp. *sericeus* Pursh	silky lupine	Perennial
Madia exigua (Sm.) Gray	little tarweed	Annual
Madia glomerata Hook.	mountain tarweed	Annual
Madia gracilis (Sm.) Keck & J. Clausen	grassy or slender tarweed	Annual
Phlox gracilis ssp. *gracilis* (Hock.) Greene	phlox	Annual
Ranunculus glaberrimus Hook.	sagebrush buttercup	Perennial
Sanguisorba occidentalis Nutt.	western burnett	Annual
Exotic Grass species		
Apera interrupta (L.) Beauv.	dense silkybent	Annual
Bromus inermis Leyss.	smooth brome	Perennial
Bromus japonicus Thunb. ex Murr.	Japanese brome	Annual
Bromus tectorum L.	cheatgrass, downy brome	Annual
Elymus repens (L.) Gould	quackgrass	Perennial
Phleum pratense L.	common timothy	Perennial

relative canopy cover of exotic plants, a measure of dominance, ranged from 72 to 85%.

Effects on Native Species. We found no herbicide, rate, and timing effects on canopy cover of native species in 2005 (native grass and forbs combined; df = 4,60, P = 0.08) and there were no significant interactions. Native species cover in 2005 ranged from 6% (control) to 14.3% (glyphosate). Native grass cover in 2005 ranged from 4 to 8% canopy cover, and showed a significant seeding effect (df = 1,60; P = 0.05; Table 1); seeded plots averaged greater native grass cover (6 ± 1.2 SE) than unseeded plots (3.4 ± 1.2 SE). Thus, broadcast seeding was somewhat effective in establishing native grass within the plots, although cover remained fairly low 3 yr after seeding. Because grass seedlings were small and difficult to identify, we used cover estimates rather than direct seedling counts to evaluate changes in native species cover. In 2008, plots will be revisited and counts of native grasses will be done to better evaluate seedling establishment 6 yr following treatments.

No treatment effects were found on native forb cover (Table 2), with values ranged from 4.8 to 9.2% cover among plots. Other studies have shown that native forbs are particularly at risk to herbicide applications. Rice et al. (1997) found that an initial postspray depression in nontarget forbs occurred but the nontarget native forbs recovered within several years after spraying (Sheley et al. 2006). A reason for the lack of response in our study was that the native forb community was primarily limited to wind-dispersed, fast growing annual species such as tall annual willow-herb (*Epilobium brachycarpum* K. Presl), mountain tarweed, tiny trumpet (*Collomia linearis* Nutt.), and birds-foot trefoil [*Lotus unifoliolatus* (Hook.) Benth] that could quickly reestablish in sprayed plots. The abundance of specific perennial forb species such as *Lupinus* spp. and slender cinquefoil (*Potentilla gracilis* Dougl. ex Hook.) was too low to evaluate their response to herbicide applications.

Effects on Species Richness. No treatment effects on total species richness were found; across treatments, species richness averaged 8.0 species/quadrat. However, differences were found in richness of native species among the herbicide treatments. Glyphosate, the herbicide that was least effective in reducing sulfur cinquefoil, resulted in the highest native species richness at 4.6 species/quadrat, followed by metsulfuron-methyl (3.7 species/quadrat), triclopyr (3.3 species/quadrat), picloram (3.3 species/quadrat), and dicamba + 2,4-D (3.1 species/quadrat; df = 4,60; P = 0.0056). Herbicide rate and timing had no effect on species richness. The control treatment averaged 3.5 native species/quadrat. The seeding treatment increased native species richness (df = 1,62; P = 0.0025). On average, seeded treatments had 4.1 native species/quadrat, whereas unseeded quadrats averaged 3.2 native - species/quadrat.

Weed Control and Ecological Restoration. One-time herbicide applications can reduce the abundance of sulfur cinquefoil on sites for at least 3 yr. However, if restoration of a site to a native plant community is desired, and there are few native species on-site or in the seed bank, herbicide applications alone appear insufficient to meet management goals. Herbicide application does not address the underlying ecological mechanisms and processes that caused sulfur cinquefoil dominance at our study sites, and all treatments continued to be dominated by exotic species. Thus, herbicides simply resulted in a transition from exotic forb- to exotic grass-dominated communities. It remains unclear if the exotic-grass community will be maintained over time, if sulfur cinquefoil will recolonize the treated areas of this experiment, or if seeded native grass species will continue to grow and eventually dominate the sites. Seeding treatments increased native grass cover and richness, although increases were small. Long-term management of sulfur cinquefoil should focus on integrating herbicide use with ecological restoration to promote the development of plant communities that are resistant to sulfur cinquefoil invasion.

These results highlight the difficulties in shifting exotic-dominated plant communities to one with a considerable native, perennial component. Perhaps ecological restoration is best viewed as an iterative process where various components and processes of the ecosystem are methodically repaired or replaced over time (Sheley et al. 2006). From such perspective, herbicide application and seeding of native grass species can be viewed as a first step in restoration. A further step in restoration would focus on reintroducing the native forb component.

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