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Research

Grassland Response to Herbicides and Seeding of Native Grasses 6 Years Posttreatment

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Herbicides are the primary method used to control exotic, invasive plants. This study evaluated restoration efforts applied to grasslands dominated by an invasive plant, sulfur cinquefoil, 6 yr after treatments. Of the five herbicides we evaluated, picloram continued to provide the best control of sulfur cinquefoil over 6 yr. We found the timing of picloram applications to be important to the native forb community. Plots with picloram applied in the fall had greater native forb cover. However, without the addition of native perennial grass seeds, the sites became dominated by exotic grasses. Seeding resulted in a 20% decrease in exotic grass cover. Successful establishment of native perennial grasses was not apparent until 6 yr after seeding. Our study found integrating herbicide application and the addition of native grass seed to be an effective grassland restoration strategy, at least in the case where livestock are excluded.

Nomenclature: Picloram; sulfur cinquefoil, *Potentilla recta* L.

Key words: *Potentilla recta* L., rangeland, sulfur cinquefoil, wildlife management.

Grasslands are highly valued for their ecosystem services including soil conservation, food and fiber production, and provision of recreation sites and unique wildlife habitat. Worldwide, invasive exotic plants have become one of the most pressing issues of grassland conservation and management (Vasquez et al. 2010). A variety of factors such as altered disturbance regimes, global climate change, land use patterns, and habitat fragmentation—alone and in concert—have facilitated invasive plant expansion in grasslands. Grasslands invaded by exotic plants often result in lower yield and quality of forage for wildlife and livestock, increased costs of land management, reduced wildlife habitat, altered fire frequencies, increased erosion, depleted soil moisture and nutrient levels, and threatened biodiversity (DiTomaso 2000).

Perennial bunchgrasses such as bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve], mountain brome (*Bromus carinatus* Hook. & Arn.), blue wildrye (*Elymus glaucus* Buckley), Sandberg's bluegrass (*Poa secunda* J. Presl), and Idaho fescue (*Festuca idahoensis* Elmer) were the primary species in grasslands of the interior Pacific Northwest of the United States and Canada prior to the introduction of exotic annual grasses and livestock (Franklin and Dyrness 1988). Chronic, intense livestock grazing in the region eliminated or resulted in large reductions in the abundance of native perennial grass species across large areas, resulting in overgrazed grasslands dominated by exotic grasses or more recently, by exotic forbs (Belsky and Gelbard 2000; Bunting et al. 2002; DiTomaso 2000).

In recent years, a variety of chemical, biological, and mechanical techniques have been utilized to control invasive plants, though herbicides remain one of most commonly used methods of invasive plant management in most grassland systems (Bussan and Dyer 1999; Hobbs and Humphries 1995; Ortega and Pearson 2011; Simmons et al. 2007). Long-term studies to determine the effects of

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Management Implications

- If the objective is simply to reduce abundance of an invasive plant for temporary control, one application of the proper herbicide may suffice. This study found that a one-time application of picloram effectively reduced sulfur cinquefoil for 6 yr.
- Although herbicide applications were successful at reducing sulfur cinquefoil abundance, they were was not successful at reducing overall exotic plant cover, as other exotics species, primarily annual grasses generally replaced sulfur cinquefoil.
- Simply seeding native perennial grasses into plots was effective at reducing sulfur cinquefoil abundance, and herbicide application combined with native grasses seeding provided best control of sulfur cinquefoil while at the same time increasing native species abundance.
- Seeding success appeared poor in the first 1 to 3 yr because of the slow growth and small size of native perennial grass species in the years immediately following seeding. Therefore, longer-term monitoring is needed to evaluate success of seeding efforts.

herbicides and seeding in grasslands are sparse because most herbicide research reports treatment results within a 2- or 3-yr period after treatment (but see Enloe et al. 2005; Ortega and Pearson 2011; Rinella et al. 2009). When used alone, herbicides seldom provide sustainable control of invasive plants because, although they may control existing invasive plants, a desirable plant community or seed bank of desirable plants may be lacking, which hinders natural recovery. The most commonly used herbicides in grasslands over the last decade are the auxin- or growth-regulator herbicides: picloram, 2,4-D, dicamba, triclopyr, and clopyralid (Bussan and Dyer 1999). However, it has been proposed that herbicidal control prescriptions that lower the abundance of undesirable and desirable forbs may cause losses in the ecological function of grasslands and may ultimately accelerate further degradation (Sheley and Krueger-Mangold 2003). The timing of herbicide application must also be considered as the effects of an herbicide on nontarget native species vary depending on the timing of application (Rice et al. 1997; Simmons et al. 2007). In the interior Pacific Northwest, late summer or autumn herbicide applications, when most native species are dormant, could minimize negative effects (Rice et al. 1997).

The exotic forb, sulfur cinquefoil (*Potentilla recta* L.) is a major grassland invader in the western United States, where it poses a serious threat to ecosystems (DiTomaso 2000; Zouhar 2003). It is a long-lived perennial with a woody rootstock. Adults produce one to five stems a year, range in height from 15 to 70 cm (Perkins et al. 2006), and reach densities > 100 stems m^{-2} (Endress et al. 2007; Naylor et al. 2005). Sulfur cinquefoil flowers during midsummer and adult plants can produce over 10,000 seeds yr^{-1} (Dwire et al. 2006; Lesica and Ellis 2010). Abandoned agriculture fields located within grassland ecosystems are particularly susceptible to early colonization and rapid dominance by sulfur cinquefoil, but sulfur cinquefoil can also invade low-disturbance bunchgrass communities and other associated plant communities, thus it is rapidly increasing its geographic distribution (Endress et al. 2007; Rice et al. 1999).

Few studies quantify the degree to which herbicide applications induce long-term changes in the structure and composition of plant communities. The objective of this study was to evaluate restoration efforts applied to sulfur cinquefoil–dominated grasslands 6 yr after treatments. Evaluations made 1 and 3 yr after herbicide applications and seeding with native species have been reported by Endress et al. (2008) and show the immediate effects of herbicide treatment on sulfur cinquefoil abundance. However, the long-term effect of treatments remained unclear. In particular, we were interested in understanding (1) the length of effective sulfur cinquefoil control of a one-time herbicide application, (2) if, over time, native seed additions reduce sulfur cinquefoil and exotic plant dominance, and (3) how the effects of herbicide and seed additions affect plant community composition and structure.

Materials and Methods

Study Site. The experiment was conducted in the Wenaha State Wildlife Area, located in Wallowa County in northeastern Oregon. Elevations range between 900 to 1150 m, and annual precipitation averages 43 cm yr^{-1}. The ecology and history of the area is representative of the low elevation grasslands of the Blue Mountain ecoregion (Parks et al. 2005). Intense land use began with the expansion of livestock ranching and the conversion of bunchgrass grasslands to agricultural fields in the mid- to late 19th century. The rugged landscape and arid climate resulted in poor yields and the subsequent abandonment of most agricultural fields. Currently, cattle (*Bos taurus*) grazing, recreation, and wildlife habitat management for deer (*Odocoileus heminous* and *Odocoileus virginianus*), elk (*Cervus elaphus*), bighorn sheep (*Ovis canadensis*), and upland birds are the primary land use activities in the Wenaha Wildlife Area, which is managed by the Oregon Department of Fish and Wildlife. The wildlife area is considered critical winter range habitat for deer, elk, and bighorn sheep.

Experimental Design. Three sulfur cinquefoil–dominated grasslands within the Wenaha Wildlife Area were selected in 2002. These sites were once in agricultural production for forage and grain crops, but had been abandoned for at least 25 yr. The areas were fenced to exclude cattle during the entire duration of the 6-yr experiment.

The experiment consisted of five herbicides, two application rates, three application times, and two postherbicide seed-addition treatments (seeded and unseeded), and was replicated once at each site. Treatments were arranged in a randomized complete block design, with a split-plot treatment structure. Blocks (120 by 15 m) were placed in areas with dense populations of sulfur cinquefoil. 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 timings of applications plus one untreated area, the control. Each block, therefore, consisted of 31 plots. Each plot was 4 by 15 m. 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).

Herbicide application rates included both "high" and "low" rates. The five herbicides and rates were: dicamba + 2,4-D (0.07 kg ae ha^{-1} + 0.07 kg ae ha^{-1} and 0.14 kg ae ha^{-1} + 0.07 kg ae ha^{-1}), glyphosate (0.07 kg ae ha^{-1}, 0.263 kg ae ha^{-1}), metsulfuron methyl (0.006 kg ai ha^{-1}, 0.011 kg ai ha^{-1}), picloram (0.28 kg ae ha^{-1}, 0.56 kg ae ha^{-1}), and triclopyr (0.116 kg ae ha^{-1}, 0.232 kg ae ha^{-1}). Specific details regarding the 2002 herbicide applications are reported by Endress et al. (2008).

The three application timing treatments were early summer application, fall application, and a combined early summer and fall application. Early summer application occurred in early May 2002 and fall applications occurred in mid-October 2002. The combined early and fall application applied the full herbicide rate in both May and October of 2002.

The seed mix comprised five native grass species from local sources at the following rates: bluebunch wheatgrass, 4.0 kg ha^{-1}; mountain brome, 6.9 kg ha^{-1}; blue wildrye, 4.4 kg ha^{-1}; Sandberg's bluegrass, 0.6 kg ha^{-1}; and Idaho fescue, 1.2 kg/ha. 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 distributed from a broadcast seeder mounted on the back of a four-wheel drive off-highway vehicle that also trailed a spike-tooth harrow to increase soil–seed contact.

Data Collection and Analysis. Previous data analysis (Endress et al. 2008) indicated that our seeding application failed in one of the three blocks. Therefore, in 2008, we restricted our sampling to two of the three original blocks.

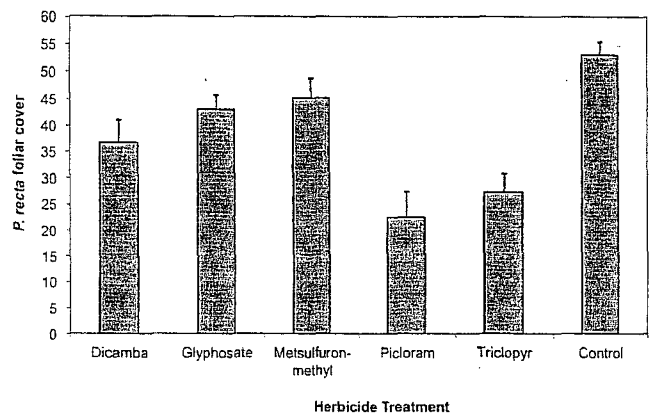

Figure 1. Percentage of foliar cover of sulfur cinquefoil 6 yr after application of five herbicides treatments (± SE). Analysis revealed significant differences among treatments (P = 0.0001).

Plots were sampled over a 1-wk period in mid-July 2008, 6 yr after treatments were initiated. We used line-point intercept sampling to measure plant foliar cover by species and functional group as well as to measure litter cover. Foliar cover was measured every 0.5 m along transects spaced 0.5-m apart across each plot. This resulted in 130 point measurements per plot. At each point, we recorded hits of sulfur cinquefoil as well as the five seeded grass species. Other plants were categorized into one of the following six functional groups: native forb, exotic forb, native grass, exotic grass, tree, and shrub.

Data were analyzed with a mixed model using PROC MIXED in SAS (SAS 9.1, Cary, NC) with the blocks considered as a random effect and the treatments fixed effects. Response variables for the models included the following: sulfur cinquefoil cover, native forb cover, exotic forb cover, native grass cover, and exotic grass cover. 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.

Results and Discussion

Herbicide Effects. The effects of herbicide treatments remained evident 6 yr after application with significant differences in sulfur cinquefoil foliar cover among herbicide treatments (df = 4, 31 F = 8.17 P = 0.0001; Figure 1). Plots treated with picloram had the lowest sulfur cinquefoil cover (22.6%), followed by those treated with triclopyr (27.3%), dicamba (36.9%), glyphosate (43.1%), and metsulfuron-methyl (45.3%). Foliar cover of sulfur cinquefoil in the control plots was 53.1%.

Although herbicides reduced cover of the sulfur cinquefoil, no difference was found in total exotic foliar cover among herbicide treatments (df = 4, 30 F = 0.65, P = 0.6329). Exotic cover estimates ranged from 58.5%

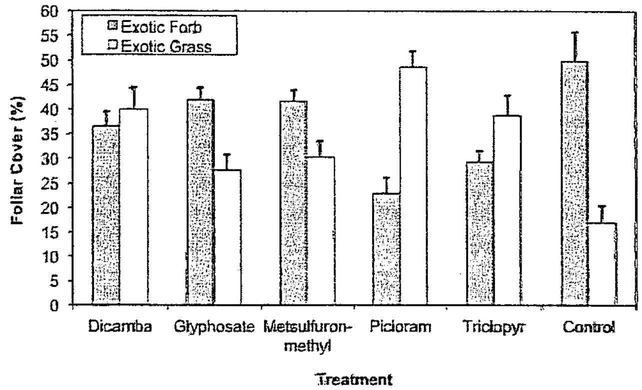

Figure 2. Percentage of foliar cover of exotic grass and forbs 6 yr after application of five herbicides treatments (± SE). Analysis revealed significant differences among treatments (P = 0.0383).

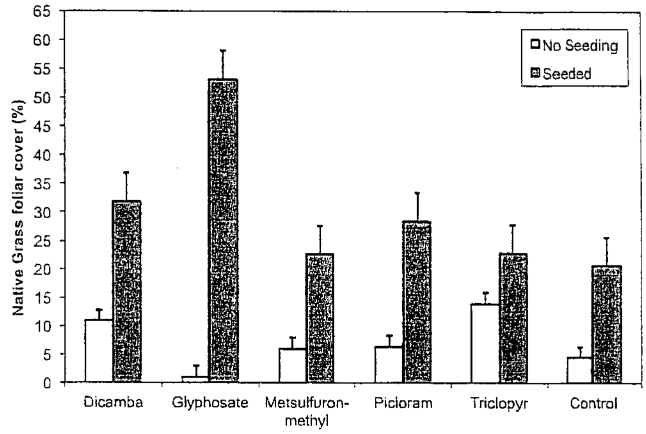

Figure 3. Percentage of native grass cover of herbicide-treated plots 6 yr posttreatment (± SE). Analysis indicated a significant herbicide by seeding interaction (P = 0.0014), with the greatest increase in cover of native grass in plots treated with glyphosate (from 1.0 to 53.3%).

(± 3.69 SE) in the triclopyr treatment to 65.4% (± 3.69 SE) in plots treated with dicamba. Exotic cover in control plots averaged 59.2% (± 8.93 SE). Thus, sulfur cinquefoil was simply replaced by other exotic species following control.

Despite similar exotic cover estimates among the treatments, herbicide treatments did alter the percentage of cover of exotic forbs and grass species (Figure 2). Because sulfur cinquefoil was the dominant forb in our study plots and there was a strong correlation between exotic forb cover and sulfur cinquefoil cover (r = 0.99; P < 0.0001), it was not surprising that we found significant differences in exotic forb cover among the herbicide treatments (df = 4, 31, F = 7.74, P = 0.0002). Picloram plots had the lowest exotic forb cover (23% ± 3.17 SE), followed by triclopyr (29.4% ± 2.17 SE), dicamba (36.6 ± 2.80 SE), and metsulfuron-methyl (41.7% ± 2.21 SE). Untreated plots averaged 50% (± 5.7 SE) cover of exotic forbs.

However, reductions in the cover of sulfur cinquefoil and other exotic forbs generally resulted in increased exotic grass cover (Figure 2). The picloram treatment, which provided the best sulfur cinquefoil control in 2005, continued to have the lowest sulfur cinquefoil cover in 2008. However, this treatment also had the highest foliar cover of exotic grasses. The control treatment had the lowest cover of exotic grasses (16.9% ± 3.50 SE), followed by glyphosate (27.7% ± 2.26 SE), metsulfuron-methyl (30.5% ± 3.18 SE), triclopyr (38.7% ± 4.34 SE), and picloram (48.7% ± 3.27 SE; df = 4, 31 F = 2.89 P = 0.0383; Figure 2).

A significant interaction between herbicide and timing of application was found for native forb foliar cover. Overall, native forb cover ranged from 4 to 28% among the herbicide by timing combinations, with the fall application of picloram having greater native forb cover (28.8% ± 3.1 SE) than other herbicide treatments.

Native Seeding Effects. Seeding with native grass species resulted in a significant reduction in exotic plant cover after 6 yr (df = 1,31 F = 10.25 P = 0.0032), with seeded plots averaging 58.1% (± 2.07 SE) cover of exotic species compared with 65.7% (± 2.07 SE) cover in plots not seeded. Moreover, seeding resulted in a 20% (± 2.43 SE) decrease in exotic grass cover (df = 1, 31 F = 12.96, P = 0.0011), regardless of herbicide type, rate, or timing of application. Seeded plots averaged 32.4% ± 2.43 SE exotic grass cover while unseeded plots averaged 40.5% ± 2.43 SE exotic grass cover. No other main effects or interactions were found. We found no effect of seeding on exotic forb cover.

Across herbicide treatments, seeding increased foliar cover of native grass species 6 yr posttreatment from 7.56% ± 3.74 SE (unseeded half-plots) to 31.5% ± 3.74 SE (seeded half-plots). Analysis indicated a significant herbicide by seeding interaction (P = 0.0014; Figure 3), with the greatest increase in cover of native grass in plots treated with glyphosate (from 1.0 to 53.3%), with the other treatments having lower native grass cover in seeded plots (ranging from 22.7 to 31.9% cover).

These results indicate that some herbicide applications (picloram, triclopyr, and dicamba) simply shifted the vegetation from an exotic forb–dominated system to an exotic grass–dominated system. The other herbicide treatments (metsulfuron-methyl and glyphosate) were still dominated by exotic forbs, but had a larger component of exotic grasses than the control treatment (Figure 2). We found no effects of herbicide timing or application rate on the abundance of exotic forb or grass species, and no significant interactions were found.

The shift in plant community composition from exotic forb–dominated to exotic grass–dominated was likely due to the application of broadleaf herbicides as well as a limited seed bank of native perennial species due to past cultivation in the area (Endress et al. 2007). Only six native perennial forbs species were identified in our comprehensive vegetation surveys in the plots, and they occurred at extremely low abundances (Endress et al. 2008). Past cultivation also likely limited native forb recruitment from the soil seed bank. Therefore, as the canopy opened following herbicide application, exotic grasses such as *Bromus tectorum* L. and *Bromus japonicus* Thunb., which were more abundant on the site, were able to colonize and establish quickly.

We found no herbicide treatment effects on native plant cover in years 1, 3, or 6 of this study. This may have been partially due to native species being negatively impacted by all herbicide treatments, which is a common concern with broadcast application of herbicides (Rinella et al. 2009; Sheley and Denny 2006). However, we suspect in our case, the primary cause for continued exotic dominance is native seed limitation coupled with large abundances of seeds from exotic species. Because our study sites were highly degraded with few native species on site or in the soil seed bank, native species were unable to take advantage of the resources (light, nutrients, space, etc.) available within the plant community to establish and increase abundance following herbicide treatments. On the other hand, exotic species, primarily annual grasses, were much more abundant and were quick to colonize and establish utilizing the resources made available through the herbicide treatments. Despite these limitations, our finding suggest that a one-time herbicide application can substantially reduce sulfur cinquefoil abundance, which may result in slowing its spread for a number of years, providing additional time for land managers to implement a comprehensive site-specific management plan to address the underlying causes of exotic plant dominance.

Results from this study support findings from other studies indicating broadleaf herbicides used to control exotic forbs promote an increase in exotic annual grass species (Ortega and Pearson 2010, 2011). For example, in our study, 6 yr after herbicide application nearly half of the vegetation cover in plots treated with picloram was due to annual exotic grass species, which was 2.5 times greater cover of exotic annual grass cover than in untreated plots. Seeding of native perennial grass species, alone or in concert with herbicide, reduced exotic grass cover. Likewise, seeding of native plant species has been shown to reduce dominance of exotic grass species following the control of exotic forbs in a number of other studies (Ortega and Pearson 2011; Pearson and Ortega 2009). Results also suggest postherbicide seeding of perennial native grass species may reduce the likelihood of reinvasion by the targeted exotic forb, a result also found by Enloe et al. 2005 for yellow starthistle (*Centaurea solstitialis* L.).

These findings also support the concept that establishing and maintaining a diversity of plant functional groups (e.g., native perennial grasses) may reduce exotic plant dominance and enhance resistance to invasion (Mangold et al. 2007; Pokorny et al. 2005). In this study, by adding a functional group that was virtually absent from the site (native perennial grasses) we were able to reduce exotic cover. Perhaps seeding with a mix of two functional groups, native perennial forbs and native perennial grass, would not only more directly target resource competition with the target exotic forb (*P. recta* in this case), but also reduce the growth of exotic grasses (e.g., *Bromus* spp.) following control.

Results of this study must be treated with caution, as our inference space is limited due to limited replication. However, few studies have reported herbicide and seeding effects after 6 yr, and this research adds to the growing literature indicating that short-term effects of herbicide and seeding treatments on the target species as well as plant community composition and structure may differ substantially from long-term effects (Enloe et al. 2005; Ortega and Pearson 2011; Rinella et al. 2009). More research is needed to more fully understand the implications of various invasive plant management approaches on long-term plant community dynamics. Applying ecological restoration to grasslands dominated by exotic plants is no simple task and grassland managers typically have multiple land management objectives. Our results found integrating herbicide application and the addition of native grass seed to be an effective grassland restoration strategy when combined with temporary livestock exclusion.

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