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Evaluating Restoration Methods across a Range of Plant Communities Dominated by Invasive Annual Grasses to Native Perennial Grasses

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Prairies are imperiled habitats, with remnants being generally small and often existing in isolation. Invasive plants have the potential to invade not just the edge of small remnants but also the interior because smaller remnants experience greater edge effects than do large, contiguous prairies. Additionally, invasive plants limit recruitment of native plants, which can arrest secondary succession. We proposed to assess techniques for restoration that included removing annual grasses and supplementing native species recruitment with seeding of native grass and forb species. We also assessed the effect of specific factors affecting recruitment: soil moisture and seed predation. Treatments included broadcast, spot, or no application of the herbicides imazapic and glyphosate and with or without seeding plus mulch. With treatments nested within each of three plant communities, ranging from annual- to perennial-dominated communities, in four blocks per community, plant characteristics (percentage of cover and plant density), soil moisture availability, and seed-predation losses were measured along a plant community gradient within one season at two locations. A combination of broadcast herbicide application and seeding with mulching was found to be more effective in reducing annual grasses and enhancing the establishment of native grass species in predominately annual and mixed communities (annuals and perennials). Spot herbicide application was effective in predominately perennial communities, whereas only seeding native species did not improve recruitment. Although seed predation reduced seedling recruitment, mulch provided seed protection and enhanced soil moisture retention. Plant community response to imposed treatments differed among communities, suggesting that a decision support tool would facilitate management decisions tailored for each plant community. The decision tool would be useful to ensure that appropriate treatments are applied and that specific factors affecting recruitment, such as seed predation and soil moisture, are addressed.

Nomenclature: Glyphosate; imazapic.

Key words: Invasive species, plant community, restoration, seed predation, soil moisture.

The Palouse Prairie and other grasslands are among the most imperiled habitats in North America (Cully et al. 2003). Many areas that were originally considered Palouse Prairie have been converted to agriculture, with less than 1% remaining (Strand et al. 1998). The remnant prairies are generally small and are under threat from invasive plants (Fitzpatrick 2004; Hanson et al. 2008; Seabloom et al. 2003a). Invasive plants can arrest ecosystem processes, such as succession, and reduce native plant diversity and habitat quality (Barnes 2007; Sheley et al. 1996; Stanley et al. 2008).

Increasing native perennial plants can reduce weedy species and reduce invasion to additional areas (Bakker and Wilson 2004; Blumenthal et al. 2003). Increases in native species have also been shown to reduce community invasibility (Ruijven et al. 2003; Stanley et al. 2008; Tilman 1997) by limiting space, nutrients and resisting reestablishment of weed populations (Carpinelli et al. 2004; Corbin and Carla 2004). For that reason, some studies have included seeding of native grasses and pioneer forbs that compete well against nonnatives (Seabloom et al. 2003b; Sheley and Melissa 2006). However,

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Interpretive Summary

Restoration of grasslands in the Pacific Northwest from annual, nonindigenous plant–dominated communities to native, perennial plant–dominated communities is impeded by loss of viable native perennial seed reserves and by competition from the nonindigenous annuals. Addressing those challenges within the framework of a decision mechanism that considers initial plant community composition would allow restoration strategies tailored to emphasize techniques appropriate to the challenges faced. Our study assessed techniques for restoration within Palouse Prairie that included removing annual grasses by broadcast and spot-herbicide applications and supplementing native species recruitment with seeding of native grass and forb species across a plant community gradient. We also assessed seed predation and soil moisture as specific factors affecting plant recruitment. The results showed that response to treatment differed for annual and perennial grasses and forbs among the plant communities. High seed predation, ranging from 40 and 85% was observed. Although seed predation was associated with the observed low recruitment of native perennial grasses, mulch seemed to provide seed protection and enhanced soil moisture retention. The results enabled us to develop a decision mechanism that suggests (1) predominately perennial plant communities do not benefit from added seed, but spot herbicide treatment can reduce annual grass cover; (2) broadcast herbicide applications are required in mixed plant communities, even when foliar cover of perennial grasses approaches 20%; and (3) predominately annual plant communities should be seeded along with the use of a broadcast herbicide application. Decision mechanisms focused on foliar cover and density of dominant plant species can inform restoration efforts within the Palouse Prairie and are likely useful within other Pacific Northwest grasslands as well.

for successful restoration, seeding may need to be accompanied by effective weed control (Blumenthal et al. 2003; Huddleston and Young 2005; Rice and Toney 1998). Whether herbicides are applied once or repeatedly, there is need to ensure the proper timing and use of low, efficacious rates to minimize effects on nontarget species (Ewing 2002; Tunnell et al. 2006).

In addition to the effects of invasive species, seed limitation and lack of suitable microsites have been identified as factors that affect native plant recruitment and recovery of the prairie ecosystem (Foster et al. 2007; Zeiter et al. 2006). Seed limitation has been attributed to seed loss resulting from predation by granivores, such as rodents (Rodentia) and ants (Formicidae), especially in arid and semiarid ecosystems (Anderson and MacMahon 2001; Hulme 1998; Orrock et al. 2003). Suitable microsites, including availability of soil water needed for seed germination, is a significant factor in the colonization process of a disturbed ecosystem (Bochet et al. 2007). Although the dynamics of availability and loss of soil moisture depends on a given plant community (Enloe et al. 2004; Seabloom et al. 2003b), use of mulch to reduce loss of water through evaporation and to provide seed protection has been shown to be effective in native grass establishment and survivorship (Bakker et al. 2003; Brown et al. 2008; Chambers 2000). Seed predation and soil moisture are thus important considerations because they not only have a direct effect on the recruitment of native plants but also can be manipulated by management to favor native plant establishment (Brown et al. 2008). As a result, providing seed protection as well as favorable growing conditions for seedling establishment has been emphasized as essential components of restoring native plant ecosystems (Chambers 2000; Daehler 2003).

Restoration of native prairies requires techniques that are not only site specific but also are based on ecological principles and concepts that provide for predictable outcomes (Fitzpatrick 2004; Sheley and Krueger-Mangold 2003). The understanding and use of a gradient of plant communities or succession as one such ecological concept in restoration can provide a framework for ecological processes to help managers achieve a desired plant community (Krueger-Mangold et al. 2006; Sheley et al. 1996, 2006). In predominately annual plant communities, techniques that enhance resource capture by native plants may be emphasized, whereas in predominately perennial plant communities, techniques that reduce negative effects on native plants may be a priority (Carpinelli et al. 2004). Additionally, Tunnell et al. (2006) point out that plant communities differ in response to restoration treatments along a secondary successional gradient and suggest that measurements based on indicators of successional status can inform treatment selection.

If plant community response to restoration treatments depends, in part, on plant assemblage, then prairie restoration should benefit from studies that use a plant assemblage framework. Most important, such a framework would be useful in developing a decision support tool for landowners and managers who evaluate restoration alternatives that encompass all objectives intended to restore degraded grasslands, including prairies. Given competing objectives and complex ecosystem requirements, such a tool would be useful in integrating information needed for making management decisions. Therefore, with the overall goal of shifting the plant communities toward perennial species, we proposed to assess techniques for restoration that included removing annual grasses and supplementing native plant recruitment with seeding of native grasses and forb species. The proposed assessment involves measuring the characteristics of the plant communities (percentage of cover and plant density), soil moisture availability, and seed predation losses. Specifically, the study was designed to (1) determine whether there are differences in native and nonnative (invasive annual grasses) plant response to restoration treatments as measured by vegetation cover and density across treatments and across annual, mixed, and perennial plant communities; (2) determine seed predation and soil moisture losses as two of the factors that can limit native plant establishment, across treatments and plant communities; and (3) identify what restoration technique or techniques would be more appropriate for a given plant community.

Materials and Methods

Study Area. The study was conducted on two prairie remnants located in Latah County, ID: Paradise Ridge (46°40′N, 116°58′W) and Gormsen Butte (46°38′N, 116°58′). The study sites are located approximately 3 km apart and range in elevation from 953 m (3,127 ft) at Gormsen Butte to 1,127 m (3697ft) at Paradise Ridge. Climate in the Palouse region is Mediterranean, with cool moist winters, warm dry summers, and a local annual average precipitation of 610 mm (24 in). The study area has an average annual maximum temperature of 14.4 C (58 F) and a minimum temperature of 2.2 C. Soils are silt loam formed from loess deposits. Both study sites are located within a bluebunch wheatgrass–Idaho fescue–arrowleaf balsamroot plant association. Plants species typically found in the Palouse Prairie include bunchgrasses, such as Idaho fescue (*Festuca idahoensis* Elmer), bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve], Sandberg bluegrass (*Poa secunda* J. Presl), prairie junegrass [*Koeleria macrantha* (Ledeb.) Schult], and a diverse set of native forbs, including Eaton penstemon (*Penstemon eatonii* Gray), arrowleaf balsamroot [*Balsamorhiza sagittata* (Pursh) Nutt.], and common yarrow (*Achillea millefolium* L.). Shrubs, such as common snowberry [*Symphoricarpos albus* (L.) Blake], Woods' rose (*Rosa woodsii* Lindl.), and dwarf rose (*Rosa gymnocarpa* Nutt.), are also common (Weddell and Lichthardt 2001). Palouse Prairie remnants are mainly threatened by two invasive annual grasses: downy brome (*Bromus tectorum* L.), a winter annual of Eurasian origin, and ventenata [*Ventenata dubia* (Leers) Coss. in Dur.], a winter annual that may have originated from Africa, Asia, or Europe.

Experimental Design. Each study site was visually evaluated to identify three communities dominated by annual grasses, perennial grasses, or mixed annual and perennial grasses, using the protocols described in Johnson and Simon (1987). *Predominately annual communities* were described as areas containing less than 10% native perennial grass. *Mixed communities* were described as areas containing between 15 and 25% native perennial grass, whereas *predominately perennial communities* were described as areas containing more than 25% native perennial grass. Within each of the three community types, five treatments and a control were established: (1) herbicide broadcast application, (2) herbicide spot application, (3) herbicide broadcast application with seeding and mulching, (4) herbicide spot application with seeding and mulching, and (5) seeding and mulching only.

The treatments were arranged in a randomized complete-block design and replicated four times in each plant community. Each treatment plot was 3 by 6 m, and depending on the treatment assigned to the plot, measurements for the vegetation, soil moisture, and seed predation were taken from those plots. All treatment plots were raked in the fall of 2007 to reduce litter and to improve herbicide efficacy. Herbicide application was timed to the one- to two-leaf stage (early postemergence) of ventenata and downy brome. This timing targeted the susceptible stage of development of both annual grasses and was aimed at minimizing nontarget effects by applying the herbicide when the perennial species were in a dormant stage; 0.988 L ha^{-1} (0.1056 gal ac^{-1}) of Journey[1] (0.358 L ha^{-1} [0.0383 gal ac^{-1}] imazapic plus 0.459 L ha^{-1} [0.0491 gal ac^{-1}] glyphosate) was applied on November 14, 2007. Herbicide broadcast treatments were applied with a CO_2-pressurized backpack sprayer and 3.05 m (10 ft) boom at a carrier rate of 153 L/ha across the whole plot. Herbicide spot-spray treatments were applied with a single offset nozzle at a carrier rate of 185 L ha^{-1}. Spot-spray applications targeted only areas with the invasive annual grasses in the treatment plots. Seeding treatments were applied in April 2008. Native species used for seeding treatments included three perennial grasses seeded at rates used for broadcast seedings—bluebunch wheatgrass (22.7 kg ha^{-1} [20.3 lb ac^{-1}]), Idaho fescue (13.5 kg ha^{-1}[12.1 lb ac^{-1}]), Sandberg bluegrass (8 kg ha^{-1})—and two native forbs: common yarrow (15 seeds m^{-2} [1.9 seeds ft^{-2}]) and Eaton penstemon (10 seeds m^{-2}). The above grasses were selected because they are dominant species within the Palouse Prairie. The two forb species were selected because common yarrow tends to increase with disturbance, and so, it was expected to survive in predominately annual communities, whereas Eaton penstemon is often associated with mixed and predominately perennial communities. Seeds were broadcast to mimic situations where rangeland drills cannot be used. Seeds of each species were obtained locally because the use of local seeds has been shown to be an important factor in seed establishment and survival (Brown et al. 2008; Humphrey and Schupp 2002; Montalvo et al. 2002). Immediately following seeding, compressed pellets of bluegrass straw mulch (Strawnet)[2] were also broadcast on the seeded plots at a rate of 1,953 kg ha^{-1}.

Following seeding, soil moisture was measured in the broadcast herbicide application and broadcast herbicide plus seeding and mulching treatment plots in the predominately annual community at both study sites. The ECH_2O Dielectric soil moisture probes[3] (sensors that measure the dielectric permittivity of the surrounding medium) were buried in the soil at 5 cm depths (oriented horizontally) in each of the two treatments, and readings were recorded into data loggers at hourly intervals. The predominately annual community was selected because it had the greatest amount of exposed ground following annual grass removal, thus providing the best treatment set to measure the effect of mulch. Raw moisture readings were downloaded from these probes weekly with a handheld computer installed with Echo-mobile utility software. The readings were then converted to volumetric water content (*VWC*) using the equation provided for the device:

$$VWC = 4.24 \times 10^{-4} \times RAW - 0.29 \quad [1]$$

where each moisture reading recorded was the *RAW* value in the equation. Prior experience in calibrating sensors indicated the equation was suitable for comparisons involving mulch experiments in the Palouse silt loam soils.

Seed predation measurements were taken from May 5, 2008, to July 12, 2008, at both study sites. Two feeding stations (9-cm-diam by 2-cm-high [3.55 by 0.788 in] petri dishes) per plot with 40 seeds (20 each of bluebunch wheatgrass and Idaho fescue) were placed in the broadcast spray only, the broadcast spray with seeding and mulching, and the control plots. To distinguish predation by vertebrates and invertebrates in each plot, 17- by 12- by 4-cm cages with 5- by 5-mm holes were used to cover one feeding station, whereas the second feeding station was left uncaged to allow both invertebrate and vertebrate access. Feeding stations were replaced at 2 wk intervals, and seeds remaining in each dish were counted. The feeding stations were painted a tan color to reduce glare and mimic the background, and in the mulched plots, two to three moist mulch pellets were mixed with seeds in the dish.

Plant response to treatments was measured using percentage of foliar cover and plant density. Data were collected in the summer and fall of 2008. Beginning at the middle of the 3-m side of each plot, sampling was done with a line transect oriented along the 6-m length of the plot and a 0.5- by 0.25-m rectangular metal frame. To capture variation within the plot and to avoid the edges, measurements were taken in four quadrats at 1.2-, 2.4-, 3.6-, and 4.8-m points along the transect while alternating left and right of the transect.

Analysis. Plant species sampled were grouped into perennial grass, annual grass, and native forb categories. ANOVA for a randomized complete-block design, pooled over plant communities, was used to examine overall differences among treatments within and across plant communities. An arcsine square-root transformation was performed on the percentage of cover data, and a log transformation was done on the density data to meet the assumptions of ANOVA. As a result, statistical inferences were based on the transformed data at the $P < 0.05$ level of significance. A test of significance for the site indicated the sites were different, with Paradise Ridge having greater perennial grass cover ($P = 0.02$) and perennial grass density ($P = 0.01$), so each site was reported separately. There was no significant interaction between site and other independent variables. All analysis for vegetation was done using SAS software[4] with six levels of restoration treatments and four blocks in each plant community.

The seed predation study was analyzed as a split-split block design with repeated measures in which plant community was the main plot, the two treatments (broadcast spray and broadcast spray with seeding and mulching) and the control were the subplots, and the feeding station was the sub-subplot. ANOVA was run on the data, including all the main effects of feeding station, treatment, plant community, and time as well as two-way and three-way interactions. An arcsine square-root transformation was performed on the percentage data to meet the assumptions of ANOVA. Statistical inferences were based on the transformed data at the $P < 0.05$ level of significance, whereas untransformed means were used to contrast predation levels among treatments. Because we expected that only invertebrates could gain access into the caged stations, the difference in predation between the uncaged and caged feeding stations was assumed to be the amount of predation caused by vertebrates.

Four periods that best represented moisture loss following a precipitation event during summer and fall data collection were selected at both sites for the soil moisture analysis. For each data set at each site, a linear model was fitted as:

$$y_i = \beta_0 + (\beta_1 \times \mathrm{d}) + e_i \quad [2]$$

where y_i was percentage moisture, β_0 was an intercept representing the initial moisture level, β_1 was the rate of change in moisture over days (d), and e_i was a random error term assumed to be normally distributed with a constant variance. After model fitting and assessment, the intercept and slope terms for each treatment within each site were compared using a dummy variable-regression procedure.

Results and Discussion

Vegetation. Overall, the effect of treatments differed between the treatments as well as across the three plant communities. Treatments involving herbicide showed a higher reduction in percentage of cover and density of the annual grasses (downy brome and ventenata) compared with treatments with no herbicide. Highest reduction in the annual grasses was observed in the predominately annual and mixed plant communities (Table 1). Analyzing the treatments separately, a higher reduction of annual grasses was observed for broadcast treatments (broadcast spray and broadcast spray with seeding and mulching) compared with the spot treatments (spot spray and spot spray with seeding and mulching) (Table 2) in the two plant communities. There were no consistent differences at the predominately perennial plant community. Higher perennial grass density was observed in the herbicide-treated plots at the predominately annual community at Paradise Ridge and in the mixed and predominately perennial communities at Gormsen Butte (Table 3), suggesting that perennial grass recruitment increased when seedlings were released from the competition of the annual grass that were removed. However,

Table 1. Mean annual grass cover and density across treatments (pooled) in three plant communities at two study sites.[a]

	Treatment[b]	Paradise Ridge Plant community[c] P. annual	Mixed	P. perennial	Gormsen Butte Plant community[c] P. annual	Mixed	P. perennial
Herbicide vs. no herbicide							
Annual grass cover (%)	Herbicides	6.61 a	4.74 a	5 a	8.39 a	9.41 a	6.02 a
	No herbicides	31.06 b	25.69 b	8.53 b	23.28 b	23.94 b	18.81 b
Annual grass density (plants m^{-2})	Herbicides	126.13 a	96.42 a	172.63 a	158.13 a	218 a	170.75 a
	No herbicides	468.25 b	469 b	299.75 b	462.25 b	595.75 b	533.75 b
Broadcast vs. spot spray							
Annual grass cover (%)	Broadcast	3.44 a	2.29 a	3.66 a	7.03 a	6.31 a	5.28 a
	Spot	9.78 b	7.19 a	6.34 b	9.75 a	12.5 b	6.75 a
Annual grass density (plants m^{-2})	Broadcast	63 a	46.08 a	107.25 a	125.25 a	186.25 a	145.75 a
	Spot	189.25 b	146.75 b	238 b	191 b	249.75 a	195.75 a

[a] Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[b] Treatments: herbicide, all treatments involving herbicide; no herbicides, all treatments without herbicide; broadcast, treatments involving broadcast herbicide application; spot, treatments involving spot herbicide application.

[c] Plant communities: P. annual, predominately annual; mixed, mixed annual and perennial; P. perennial, predominately perennial.

our ability to separate augmented seed recruitment from resident seed recruitment was limited to comparisons to the control plots. Among individual treatments, high perennial grass density was observed in the broadcast application with seeding and mulching in predominately annual community at Paradise Ridge and in both broadcast and spot application with seeding and mulching in both predominately annual and mixed communities at Gormsen Butte (Table 4).

Higher forb cover (5 to 10%) was observed in treatments where herbicide was used compared with the control in all plant communities at Gormsen Butte. Forb cover was particularly high in plots that received broadcast

Table 2. Mean annual grass cover and density across treatments (individual) in three plant communities at two study sites.[a]

	Treatment[b]	Paradise Ridge Plant community[c] P. annual	Mixed	P. perennial	Gormsen Butte Plant community[c] P. annual	Mixed	P. perennial
Annual grass cover (%)	BS	3.25 a	2.75 a	5.31 a	6.13 a	5.44 a	5 a
	BS + SM	3.63 a	1.83 a	2 a	7.94 a	7.19 a	5.56 ab
	SS	11.19 a	8.81 a	6.69 b	8.31 a	10.94 ac	9.13 b
	SS + SM	8.38 a	5.56 a	6 b	11.19 a	14.06 c	4.38 ae
	SM	24.94 b	25.69 b	5.5 ab	21.13 b	20.75 b	14.44 c
	CONT	37.19 b	25.69 b	11.56 b	25.44 b	27.13 b	23.19 d
Annual grass density (plants m^{-2})	BS	63 a	57.5 a	154 a	90.5 a	145 a	141.5 ac
	BS + SM	63 a	34.67 a	60.5 b	160 ab	227.5 ab	150 ac
	SS	189 b	164.5 b	246 ac	152.5 ab	232 ab	252 b
	SS + SM	189.5 b	129 b	230 ac	229.5 b	267.5 bc	139.5 c
	SM	403 c	517.5 c	246 ac	436 c	602.5 cd	454 d
	CONT	533.5 c	420.5 bc	353.5 c	488.5 cd	589 d	613.5 d

[a] Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[b] Treatments: BS, broadcast spray; BS + SM, broadcast spray with seeding and mulching; SS, spot spray; SS + SM, spot spray with seeding and mulching; SM, seeding and mulching; CONT, control.

[c] Plant communities: P. annual, predominately annual; mixed, mixed annual and perennial; P. perennial, predominately perennial.

Table 3. Mean perennial grass density across treatments (pooled) in three plant communities at two study sites.[a]

		Paradise Ridge			Gormsen Butte		
		Plant community[c]			Plant community[c]		
	Treatment[b]	P. annual	Mixed	P. perennial	P. annual	Mixed	P. perennial
Herbicide vs. no herbicide							
Perennial grass density (plants m^{-2})	Herbicide	15.38 a	12.65 a	36.63 a	31.5 a	47.63 a	53.25 a
	No herbicide	4 b	12.75 a	34.5 a	30 a	35.25 a	36.75 a
Broadcast vs. spot spray							
Perennial grass density (plants m^{-2})	Broadcast	19.75 a	13.04 a	37.5 a	25.75 a	44.5 a	54 a
	Spot	11.01 a	12.25 a	35.75 a	37.25 b	50.75 a	52.5 a

[a] Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[b] Treatments: herbicide, all treatments involving herbicide, no herbicides; all treatments without herbicide; broadcast, treatments involving broadcast herbicide application; spot, treatments involving spot herbicide application.

[c] Plant communities: P. annual, predominately annual; mixed, mixed annual and perennial; P. perennial, predominately perennial.

and spot herbicide plus seeding and mulching in the predominately annual community, as well those with broadcast herbicide in mixed community (Table 5). There were no consistent differences in forb response to treatments at the predominately perennial community or between seeding and mulching only and the control.

Prairie remnants are at significant risk to invasion by winter annual grasses, such as downy brome and ventenata, which displace native plant species (Hanson et al. 2008; Scheinost et al. 2009). Use of herbicide such as glyphosate in combination with a selective herbicide like imazapic has been reported to be more effective at reducing weeds and increasing native species (Fitzpatrick 2004). Proper timing is a major consideration, especially when using herbicides such as glyphosate, to minimize injury to desired plants (Cox 2003). Our fall application of glyphosate plus imazapic at a time when annual grasses had just emerged and native plants were dormant or semidormant resulted in significant reduction of the two annual grasses and no detectable negative impact on native grass species. Journey was our preferred herbicide for use in this study because it is labeled for, and has been used previously in prairie restoration. The two types of herbicide application (broadcast and spot) were considered to discern differences in effectiveness and potential nontarget effects by comparing the amount of herbicide applied at each plant community by spot against the reference broadcast amount (Table 6). The lower annual grass cover and density observed with herbicide treatments confirm that herbicide application was effective in reducing annual grasses. Higher reductions of annual grasses were observed in the predominately annual and mixed communities. We suspect

Table 4. Mean perennial grass density across treatments (individual) in three plant communities at two study sites.[a]

		Paradise Ridge			Gormsen Butte		
		Plant community[c]			Plant community[c]		
	Treatment[b]	P. annual	Mixed	P. perennial	P. annual	Mixed	P. perennial
Perennial grass density (plants m^{-2})	BS	12.5 a	14.75 a	37 a	15.5 a	27 a	50 a
	BS + SM	27 b	11.33 a	38 a	36 ab	62 b	58 a
	SS	11 ab	11 a	34.5 a	39.5 b	33 abd	51 a
	SS + SM	11 ab	13.5 a	37 a	35 b	68.5 bc	54 a
	SM	5.5 ab	15 a	36 a	32.5 ab	37.5 abe	44 a
	CONT	2.5 ab	10.5 a	33 a	27.5 ab	33 ade	29.5 a

[a] Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[b] Treatments: BS, broadcast spray; BS + SM, broadcast spray with seeding and mulching; SS, spot spray; SS + SM, spot spray with seeding and mulching; SM, seeding and mulching; CONT, control.

[c] Plant communities: P. annual, predominately annual; mixed, mixed annual and perennial; P. perennial, predominately perennial.

Table 5. Mean native forb cover across treatments (pooled and individual) in three plant communities at Gormsen Butte.[a]

	Treatment (pooled)[b]	Gormsen Butte — Plant community[c]: P. annual	Mixed	P. perennial
Herbicides vs. no herbicides				
Native forb cover (%)[d]	Herbicide	8.27 a	3.88 a	3.16 a
	No herbicide	4.16 b	1.19 b	2.13 a
Broadcast vs. spot				
Native forb cover (%)	BS	9.44 a	4.94 a	3.91 a
	SS	7.09 a	2.81 a	2.41 a
Native forb cover (%)[e]	BS	7.63 a	7.38 a	3.69 ab
	BS + SM	11.25 a	2.5 ab	4.13 a
	SS	5.19 ab	3.06 ab	1.5 ab
	SS + SM	9 a	2.56 ab	3.31 ab
	SM	1.25 b	2.31 b	3.38 ab
	CONT	7.06 ab	0.06 c	0.89 b

[a] Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[b] Treatments: herbicide, all treatments involving herbicide; no herbicides, all treatments without herbicide; BS, broadcast spray; BS + SM, broadcast spray with seeding and mulching; SS, spot spray; SS + SM, spot spray with seeding and mulching; SM, seeding and mulching; CONT, control.

[c] Plant communities: P. annual, predominately annual; mixed, mixed annual and perennial; P. perennial, predominately perennial.

[d] Pooled treatment.

[e] Individual treatment.

that this reflects the higher initial infestation levels in those communities than there were in the predominately perennial community, thus resulting in a measurable response to treatments. We suspect that high litter levels and greater standing biomass in the predominately perennial community (Dickson and Busby 2009) may have contributed to the observed, reduced effectiveness of herbicides in that community. The increase in perennial grass density can be attributed to the removal of annual grasses, which made resources available for capture by native plants, increasing recruitment and establishment. The higher perennial grass density and forb cover in the herbicide treatments compared with the no-herbicide treatments suggest that native plants increased through recruitment, and we detected no nontarget injuries attributed to the herbicide application.

In our study, the higher perennial grass density in the herbicide application with seeding and mulching treatments demonstrated that mulch potentially played a role in improving germination conditions for seedlings through moisture retention. Results from seeding alone were similar to those for the control, suggesting that seeding alone as a

Table 6. The average (SD) amount of active ingredient of herbicide product applied by spot spray per treatment plot[a] at two study sites (ML product/plot).[b,c]

Plant community	Paradise Ridge: SS	Paradise Ridge: SS + SM	Gormsen Butte: SS	Gormsen Butte: SS + SM
	mean (SD)			
P. annual	1.49 (0.06)	2.16 (0.07)	2.32 (0.73)	2.14 (0.15)
Mixed	1.42 (0.54)	1.71 (0.82)	1.53 (0.68)	2.3 (0.31)
P. perennial	0.9 (0.36)	0.59 (0.32)	1.68 (0.32)	1.89 (0.42)

[a] Reference: broadcast spray = 1.82 ml product $plot^{-1}$.

[b] Treatments: SS, spot spray; SS + SM, spot spray with seeding and mulching.

[c] Plant communities: P. annual, predominately annual; mixed, mixed annual and perennial; P. perennial, predominately perennial.

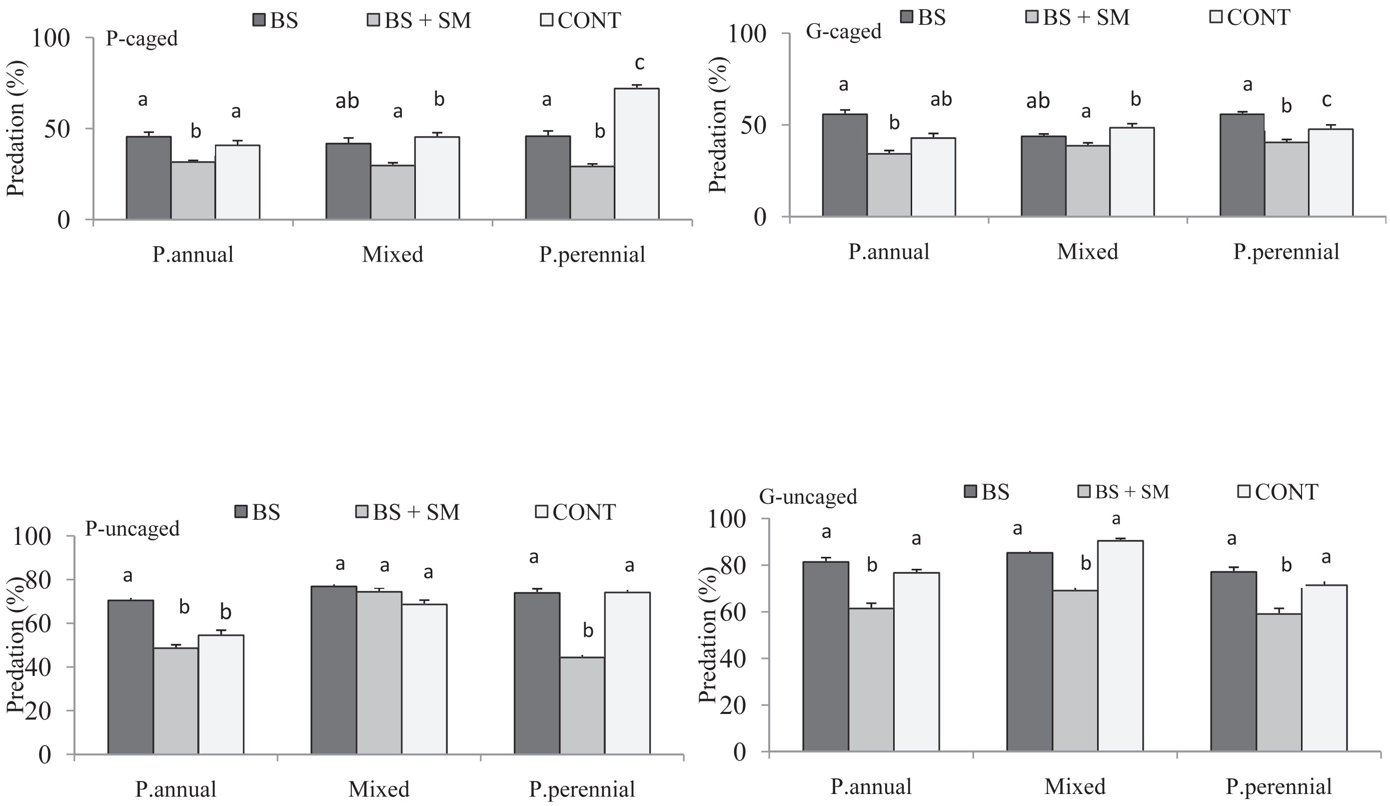

Figure 1. Seed predation in caged and uncaged feeding stations across three treatments (BS, BS + SM, and CONT) in three plant communities at two study sites: Paradise Ridge (P) and Gormsen Butte (G). Abbreviations: BS, broadcast spray; BS + SM, broadcast spray with seeding and mulching; CONT, control. Error bars represent standard errors. Means followed by the same letter in each plant community are not significantly different at $P < 0.05$.

restoration treatment may not be an effective strategy. Recruitment on our study sites was generally lower than expected, however, and there was no detectable increase in recruitment from the seeded forbs. However, one resident native forb species, woolly sunflower [*Eriophyllum lanatum* (Pursh) Forbes] increased significantly in the herbicide-treated plots, suggesting its potential for future restoration projects.

Seed Predation. As mentioned before, seed predation in the uncaged feeding stations was attributed to both vertebrates and invertebrates, whereas predation in the caged stations was attributed to only invertebrates; therefore, the difference in predation between the caged and uncaged was attributed to vertebrate feeding. Overall, high seed predation, ranging from 40 to 85% was observed in this study (Figure 1). Significant differences in seed predation were observed among the three treatments (broadcast spray, broadcast spray + seeding + mulching, and control; $P = 0.0017$) and between the caged or uncaged feeding stations ($P < 0.0001$). In both the caged and uncaged stations, seed predation was lower within the plots treated with broadcast herbicide plus seeding and mulching than it was in the broadcast herbicide only plot or the control. There was higher predation in the uncaged than in the caged feeding stations (Figure 1). Although the amount of predation differed among the three plant communities, those differences were not statistically significant in our study. However, when we looked at predation by vertebrates only, high predation of up to 45% was observed at the mixed plant community. No consistent differences in predation were found among treatments in the case of predation by vertebrates. No linear increasing trend in predation was found over the study period, suggesting that the granivores did not learn the feed locations and, therefore, did not cue in on the feeding stations.

Seed consumption has been found to reduce recruitment by 30 to 50% (Orrock et al. 2008). Ants and rodents have been found to be responsible for most of the predation (Predavec 1997). In a study by Anderson and McMahon (2001), predation attributed to vertebrates was higher than that by invertebrates, and mulch was found to have relatively less effect in preventing vertebrate predation. The results of our study are consistent with the those findings. Treatment effects were significant overall, but when separated, the treatments, especially the use of mulch, which was our main interest, did not seem to have had much effect on seed predation by vertebrates. As seen from the results of our study, seed predation can be considered a

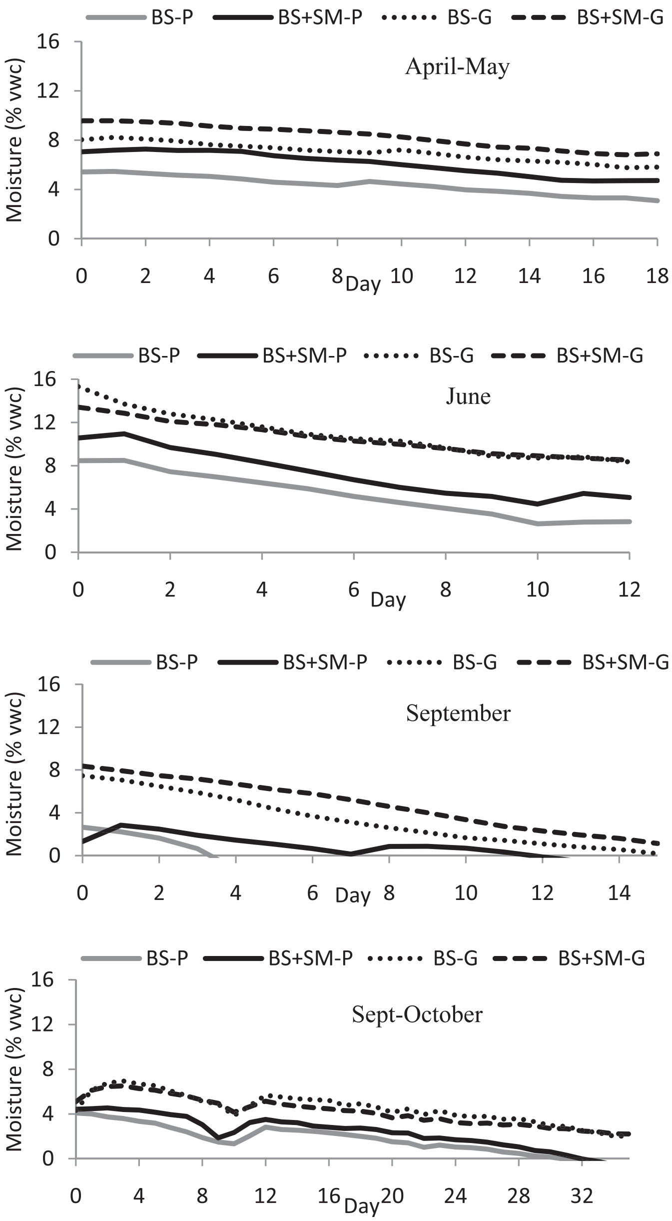

Figure 2. Soil moisture decline over time in April, June, and September and September to October between two treatments (BS and BS + SM) and two study sites: Paradise Ridge (P) and Gormsen Butte (G). Abbreviations: BS, broadcast spray; BS + SM, broadcast spray with seeding and mulching. April to May, April 24 to May 12; June, June 11 to June 23; September, September 2 to September 20; September to October, September 22 to October 27.

factor limiting establishment of native species at our study site. We suggest that in places where seed predation is suspected to be a potential limiting factor on native plant recruitment, the use of mulch can be helpful, although higher amounts may need to be used. The amounts used will depend on the type of seed-eating organisms on the site and on the costs. We also recommend the use of mulch with other techniques, for example, appropriate chemical repellants. Factors such as the size of the area to be restored and resource availability should be considered in the choice of seed-protection method.

Soil Moisture. There were no significant differences in the rates of soil moisture loss between the two treatments (broadcast herbicide application and broadcast herbicide application with seeding and mulching) at both study sites. However, total soil moisture was found to be generally higher in mulched plots at both sites (Figure 2). As expected, soil moisture was higher in spring than in fall. These results suggest that the use of mulch as a treatment may reduce the loss of moisture through evaporation and enhance moisture infiltration. We suggest that in situations where seeds cannot be drilled into the soil, the application of mulch may improve conditions for seedling establishment.

Decision-Support Tool and Management Implications. Invasion by nonnative plant species such as downy brome and ventenata poses a great threat to prairie ecosystems. Restoration efforts should consider strategies to control annual grasses to enhance native plant establishment. The effectiveness of selected restoration techniques will not only be different depending on the location of the community along a plant community gradient as has been seen in this study but also must involve addressing factors such as seed predation and loss of soil moisture. Restoration techniques appropriate for each plant community can be timed to arrest establishment of the invasive plant species while minimizing any potential negative effects on native species. In the Palouse Prairie, imazapic plus glyphosate applied in the fall reduced annual grasses and did not negatively affect native perennial grasses or forbs.

From this study, we developed a decision tool that included the following suggestions. Broadcast herbicide applications with seeding and mulching can be adequate in the predominately annual community, whereas spot applications with seeding and mulching can reduce annual grasses in a mixed-plant community. Within the predominately perennial community, spot treatment is as efficacious on annual grasses as broadcast treatment, suggesting that in situations where reduced risk of nontarget impacts is highly valued, spot treatment could be selected. Although seeding as a treatment is unlikely to benefit recruitment at predominately perennial communities, annual grass control may still be warranted. For seed predation and in situations where seeds must be broadcast, increasing the seeding rate by 40% may overcome some of the predation at the predominately annual community, in addition to use of mulch to enhance moisture retention and to deter invertebrates. Additionally, the high predation by vertebrates in the mixed plant community suggests other measures are needed, such as appropriate chemical repellants in addition to mulch, to reduce seed predation. Seed predation was not a major issue at the predominately perennial plant community and, therefore minimal to no seed protection measure may be warranted.

Assessment of plant community as well as evaluation of progress over time is important for adjusting management strategies for future work. The assessment process can also assist managers to determine whether any future intervention is needed. For example, from our study, if perennial grass cover increased to more than 20% after restoration in the predominately annual and mixed communities, then the community might be on a trajectory toward recovery, and additional treatment may not be needed. Finally, we emphasize that a decision-support tool, such as the one from this study, can assist landowners and managers to deal with the multiple factors involved in restoration of prairie ecosystems invaded by annual grasses.

Sources of Materials

[1] Journey herbicide, BASF Corporation, 100 Campus Drive, Florham Park, NJ 07932-1089.

[2] Strawnet, HydroStraw, LLC, 3676 W 9000N Road, Manteno, IL 60950.

[3] ECH_2O Dielectric probes, Decagon Devices Inc., 2365 NE Hopkins Court, Pullman WA 99163.

[4] SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513-2414.

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