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Integrated Management of Perennial Pepperweed (*Lepidium latifolium*)

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Perennial pepperweed is invasive throughout California. It thrives in a wide range of environments and is a common weed in floodplains, pastures, wetlands, and roadsides. In disturbed areas, perennial pepperweed rapidly forms monotypic stands with a thick litter layer. These infestations not only out-compete other vegetation, but prevent re-establishment of desirable species even after perennial pepperweed control. This experiment examined integrated management strategies with the goal of maximizing perennial pepperweed control and establishment of desirable native vegetation. The experiment was conducted at two sites in Lassen County, CA. Both sites were heavily infested with perennial pepperweed and lacked competing vegetation. The experimental design was a split-split-randomized block with four replications. Site preparation treatments included winter burning, summer and fall mowing, winter grazing, and fall disking. These treatments were designed to remove thatch to facilitate herbicide application and reseeding of desirable perennial grasses. Herbicide treatments included chlorsulfuron, 2,4-D, or glyphosate applied at the flower bud stage. Revegetation treatments included no seeding and no-till seeding of native perennial grasses. Most site preparation plus herbicide combinations reduced perennial pepperweed cover > 85% compared to the untreated control, although treatment efficacy was variable between sites and years. Burning, grazing, mowing, or disking in combination with herbicide treatment and no-till seeding was necessary for successful native perennial grass establishment. Burning or mowing with yearly 2,4-D applications for 3 yr gave the best combination of perennial pepperweed control and native grass establishment. Chlorsulfuron caused chlorosis and stunting to western wheatgrass, basin wildrye, and beardless wildrye at both sites when applied the spring before seeding. No treatment offered complete weed control, suggesting follow-up spot herbicide applications are needed for long-term perennial pepperweed suppression. These results provide several successful integrated strategies for control of perennial pepperweed and revegetation to a desired native perennial grass community.

Nomenclature: 2,4-D; chlorsulfuron; glyphosate; perennial pepperweed, *Lepidium latifolium* L.; basin wildrye, *Leymus cinereus* (Scribn. & Merr.) A. Löve; beardless wildrye, *Leymus triticoides* (Buckl.) Pilger; western wheatgrass, *Pascopyrum smithii* (Rydb.) A. Löve.

Key words: Burning, disking, grazing, mowing, native grass, reseeding, revegetation, soil, nutrient cycling.

Perennial pepperweed is a nonnative creeping perennial introduced to California from southeastern Eurasia (Young et al. 1995). Since its introduction, it has spread rapidly and invaded a wide range of environments, including floodplains, irrigation channels, rangeland, riparian areas, brackish marshes, and crop fields throughout the intermountain west (Miller et al. 1986; Renz 2001; Young et al. 1998). Perennial pepperweed develops an extensive creeping root system and produces numerous seeds (Young et al. 2002). Its rapid spread is associated with the ease with which its roots fragment and seeds move by water, humans, and wildlife (Blank and Young 1997).

Perennial pepperweed threatens the core functions of riparian areas and hay meadows throughout the intermountain west (Young et al. 2002). Once established, dense perennial pepperweed populations form monotypic stands that reduce plant diversity, decrease grazing and haying productivity, and alter element cycling (Blank and Young 1997, 2002; Young et al. 1995). In addition, dense infestations form a thick, persistent litter layer of senesced shoots that inhibit desirable vegetation growth and regeneration (Renz 2001; Renz and Blank 2004). Even

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Interpretive Summary

This study investigated integrated management strategies for controlling heavily infested perennial pepperweed sites and revegetating with native grasses. The experiment was conducted at two sites located within the Susan River floodplain in the high desert of northeastern California. Results demonstrated that herbicides are needed to control perennial pepperweed. Repeat yearly applications of 2,4-D, chlorsulfuron, or glyphosate (before seeding)/2,4-D (after seeding) provided > 80% control of perennial pepperweed when applied alone or in combination with grazing. 2,4-D and glyphosate/2,4-D applied in combination with burning, mowing, or disking also gave > 80% control at both sites.

Revegetation of native grasses in perennial pepperweed monotypic stands required burning, mowing, or disking in combination with herbicides and no-till seeding. Sowing seeds through cattle trampling yielded variable grass establishment compared to drill seeding. However, trampling might be a more practical seeding option in rough terrain. Herbicide treatment to control perennial pepperweed and annual broadleaf weeds before seeding and during perennial grass establishment was critical to revegetation success.

These results indicate that successful control and revegetation of perennial pepperweed monotypic stands required at least 3 yr of intensive integrated management using thatch removal, herbicide treatment, and reseeding. Spot herbicide treatments are likely needed for several years after revegetation for long-term perennial pepperweed suppression. Adequate winter and spring precipitation during the year of seeding were critical to the success of perennial grass establishment. For this reason, multiple reseedings and/or supplemental irrigation might need to be considered when developing management plans in areas prone to drought.

when perennial pepperweed is controlled in these dense stands, re-establishment of desirable vegetation is minimal when the litter layer remains intact.

Integrated management using a combination of cultural, mechanical, and chemical controls is likely the best sustainable approach to controlling dense, monotypic stands of perennial pepperweed (Krueger and Sheley 1999) and establishing desirable vegetation. In such stands, herbicides are typically needed to effectively suppress perennial pepperweed's extensive creeping root system (Wilson et al. 2004; Young et al. 2002), whereas mechanical or cultural techniques are needed to remove or incorporate the litter layer (Blank and Young 1997; Renz and Blank 2004) and allow reseeded perennial species to establish (Young et al. 2002). Although studies have evaluated cultural, mechanical, and chemical controls for perennial pepperweed, few studies have examined combining these strategies for both perennial pepperweed control and revegetation.

Our objective was to develop integrated management strategies that control perennial pepperweed and re-establish desirable, native vegetation. In this study, we evaluated site preparation methods, including winter burning, winter grazing, fall disking, or summer and fall mowing in combination with various herbicides and native perennial grass seeding. The goal was to determine the combination or combinations that not only gave acceptable perennial pepperweed control, but also resulted in the establishment of a native, perennial grass community.

Materials and Methods

The study was conducted from 2002 to 2006 on two sites near Wendel, CA. Sites were located at California Department of Fish and Game Honey Lake Wildlife Area (HLWA) and Mapes Ranch. The Mapes Ranch site is located in the delta of the Susan River as the river approaches Honey Lake. The site is a raised area within seasonally flooded pasture that had been used as a stack and feed yard before perennial pepperweed invasion. The Mapes site was first invaded by perennial pepperweed in the mid-1980s.

The HLWA site sits on leveled, agricultural land upland from the swales of the Susan River that historically was used for irrigated crop production. In 1987, the field was seeded to tall wheatgrass [*Elytrigia elongata* Host (Nevski)] and alfalfa (*Medicago sativa* L.) for wildlife habitat. In wet years, the field was flood irrigated in fall and early spring for waterfowl. The HLWA site was first invaded by perennial pepperweed in the mid-1990s. Only isolated tall wheatgrass plants were found within the site area at the time of experiment initiation.

Both sites were heavily infested with perennial pepperweed with significant litter accumulation. Perennial pepperweed live cover averaged 50% at Honey Lake Wildlife area and 71% at Mapes Ranch in July 2002 before treatments were initiated. Perennial pepperweed formed nearly monotypic stands at both sites with other vegetation cover averaging < 5%.

Soil at the Honeylake Wildlife area is Humboldt silty clay (fine, smectitic, calcareous, mesic Fluvaquentic Endoaquoll) and at Mapes Ranch is Truckee clay loam (fine-loamy, mixed, superactive, mesic Fluvaquentic Haploxeroll). Soils include the Standish series (fine, smectitic, mesic Xeric Natrargids) and the Bobert series (fine-loamy, mixed, superactive, mesic Aquic Natrargids). Climate at both sites is considered high desert with cold, somewhat moist winters and dry, hot summers. Average annual precipitation at both sites is 22 to 30 cm (9 to 12 in). The experiment was laid out in a split-split-randomized block design with four replications. Whole blocks were 37 by 18 m (120 by 60 ft), sub-blocks were 9 by 18 m (30 by 60 ft), and sub-sub-blocks were 9 by 9 m (30 by 30 ft).

Whole blocks consisted of five site preparation treatments: winter burning, winter grazing, fall disking, summer and fall mowing, and an untreated control. The primary purpose of site preparation treatments was to remove accumulated thatch to facilitate herbicide application, stimulate desirable vegetation recovery, and improve seedbed conditions for no-till seeding. The winter burn was conducted in March 2003 and January 2004 using drip torches. In 2003, the litter layer carried a hot fire with flame heights from 1 to 2 m (3 to 7 ft) at a wind speed below 8 km/h (5 mph) at both sites. The 2003 burn successfully removed all litter. In 2004, several burn blocks at both sites did not carry a fire due to a lack of fine fuels burned in 2003, so unburned portions were flamed with a propane torch to avoid variability within blocks.

Winter grazing was conducted in February 2003, March 2004, and March 2005. One hundred cows per whole block were contained with electric fencing, with supplemental alfalfa hay spread throughout the block for 1 d. The short duration and high stock rate grazing prescription was used to force the cattle to trample and break apart the litter layer. Plots were not grazed throughout the growing season to prevent cattle from grazing seeded perennial grasses.

Mowing was conducted using a flail mower during June 2003, November 2003, June 2004, November 2004, and June 2005. The June mowing was used to cut perennial pepperweed shoots and break apart the litter layer. The November mowing was used to break apart standing litter to facilitate spring drill seeding. Disk blocks were tilled using an offset stubble disk with 66-cm (26 in) blades during November 2002 and 2003 to incorporate litter into the soil and prepare a seedbed for drill seeding.

Sub-blocks consisted of four herbicide treatments: chlorsulfuron; 2,4-D ester; glyphosate/2,4-D; and an untreated control. Herbicides were applied with a CO_2-backpack sprayer delivering 190 L/ha (20 gal/ac) at 172 kPa (25 psi). A nonionic surfactant (NIS) was added to all spray solutions at 0.25% v/v. In the burn, graze, disk, and untreated whole blocks, herbicides were applied in June when perennial pepperweed was in the flower bud growth stage. This application timing has been shown to be the most effective in previous trials (Renz and DiTomaso 2006; Wilson 2005). In mow blocks, herbicides were applied in September after perennial pepperweed shoots regrew and again reached the flower bud stage following the June mowing. This application timing was chosen because spring mowing in combination with fall herbicide treatment can enhance the efficacy of some herbicides on perennial pepperweed (Renz and DiTomaso 1998, 2006).

In the 2,4-D ester-treated blocks, the herbicide was applied at 2.2 kg ae/ha (2 lb ae/ac) in 2003. In 2004 and 2005, 2,4-D ester was applied at a lower rate of 1.1 kg ae/ha (1 lb ae/ac) to minimize herbicide injury on young reseeded grasses. In the glyphosate/2,4-D blocks, glyphosate was applied at 3.4 kg ae/ha (3 lb ae/ac) in 2003, followed by 2,4-D ester at 1.1 kg ae/ha (1 lb ae/ac) in 2004 and 2005. In the chlorsulfuron treated sub-blocks, the herbicide was applied at 100 g ai/ha (1.5 oz ai/ac) in 2003 and at 50 g ai/ha (0.75 oz ai/ac) in 2004.

The 2004 and 2005 herbicide applications were used to suppress perennial pepperweed resprouts, and more importantly, control annual broadleaf weeds to prevent competition with seedling grasses planted in 2004 and 2005. In previous efficacy trials (Renz and DiTomaso 1998; Wilson 2005), one application of glyphosate or chlorsulfuron provided over 85% perennial pepperweed control 1 yr following application. Chlorsulfuron was not applied in 2005. Three consecutive applications of chlorsulfuron are generally cost-prohibitive in rangeland and noncrop situations, as well as unnecessary because of its soil residual activity.

Sub-sub-blocks consisted of two reseeding treatments, including a native perennial grass mix and an untreated control. Reseeded blocks were seeded with a mix of 'Rosana' western wheatgrass at 7 kg/ha (6 lb/ac) pure live seed (PLS), 'Shoshone' beardless wildrye at 10 kg/ha (9 lb/ac) PLS, 'Magnar' basin wildrye at 4 kg/ha (4 lb/ac) PLS, and 'Revenue' slender wheatgrass [*Elymus trachycaulus* (Link) Gould ex Shinners] at 2 kg/ha (2 lb/ac) PLS. Mow, burn, and disk blocks were seeded in March 2004 using a no-till range drill. Grazed blocks were broadcast seeded in March 2004 2 d before cattle grazing. Cattle trampled the seed into the soil. Untreated blocks were broadcast-seeded in March 2004, without incorporation owing to the prohibitively thick litter layer. Grass failed to establish in 2004 at both sites. Because precipitation in 2003 to 2004 was extremely low (7 cm [3 in] between October to September) compared to the historical average (27 cm [11 in]), all blocks were seeded again in March 2005. Precipitation during 2004 to 2005 (October to September) totaled 23 cm (9 in) at both sites.

Perennial pepperweed, other vegetation, bare ground, and litter cover were measured in July 2002; June 2003; August 2003; and June 2004, 2005, and 2006 in each sub-sub-block using three randomly placed 1 m^2 quadrats (2 m by 0.5 m rectangle). Seeded perennial grass cover was measured in each sub-sub-block in three randomly placed 1 m^2 quadrats in June and August 2004, 2005, and 2006. Soil was sampled in September 2002 by taking soil cores from 0 to −15 cm (0 to −6 in) at 12 random locations in each whole block. Soil was sampled again in May 2005 by taking similar soil cores at 12 random locations in each sub-block. Cores from each whole-block sampled in 2002 or each sub-block sampled in 2005 were mixed together in a bucket before analysis. Soils were air-dried, crushed, and passed through a 20 mesh screen. The following attributes were measured on each sample: pH (U.S. Salinity Lab 1954c); electrical conductivity (EC_e; Rhoades 1982); sodium adsorption ratio (SAR; U.S. Salinity Lab 1954b);

Table 1. Interaction of site preparation treatments plus herbicides on perennial pepperweed cover at the Honey Lake Wildlife Area and Mapes Ranch.

Treatment	August 2003		June 2004		June 2005		June 2006	
	HLWA[a]	Mapes[a]	HLWA	Mapes	HLWA	Mapes	HLWA	Mapes
	% cover							
No site preparation								
untreated	51	91	55	67	44	60	61	70
chlorsulfuron[b]	0	41	6	6	8	3	9	12
2,4-D[c]	2	41	10	7	13	1	2	4
glyphosate/2,4-D[d]	11	48	5	9	23	8	9	1
Burning								
untreated	48	73	47	88	45	72	59	66
chlorsulfuron	1	40	4	36	6	48	9	56
2,4-D	4	15	13	7	7	6	3	1
glyphosate/2,4-D	22	19	11	7	17	34	10	2
Mowing								
untreated	18	69	37	48	32	84	49	87
chlorsulfuron	19	57	5	16	4	33	10	48
2,4-D	18	55	30	8	7	4	3	3
glyphosate/2,4-D	20	57	14	4	10	1	5	4
Grazing								
untreated	48	75	43	77	37	72	48	85
chlorsulfuron	1	46	2	5	6	18	9	13
2,4-D	3	43	17	15	11	6	3	3
glyphosate/2,4-D	14	54	7	10	20	20	9	1
Disking								
untreated	28	61	39	57	45	85	72	89
chlorsulfuron	15	50	11	31	14	51	14	57
2,4-D	14	57	20	15	17	45	12	15
glyphosate/2,4-D	24	51	16	18	19	31	4	9
LSD ($P = 0.05$)	6	23	7	11	7	15	9	13

[a] Abbreviations: HLWA, Honeylake Wildlife Area site; Mapes, Mapes Ranch site.

[b] Chlorsulfuron was applied at 100 g ai/ha (1.5 oz ai/ac) in 2003 (before seeding) and at 50 g ai/ha (0.75 oz ai/ac) in 2004 (after seeding).

[c] 2,4-D ester was applied at 2.2 kg ae/ha (2 lb ae/ac) in 2003 (before seeding) and at 1.1 kg ae/ha (1 lb ae/ac) in 2004 and 2005 (after seeding).

[d] Glyphosate was applied at 3.4 kg ae/ha (3 lb ae/ac) in 2003 (before seeding) and 2,4-D ester was applied at 1.1 kg ae/ha (1 lb ae/ac) in 2004 and 2005 (after seeding).

extractable sodium, magnesium, and calcium (Knudsen et al. 1982); extractable bicarbonate and carbonate (U.S. Salinity Lab 1954a); extractable nitrate (Knepel 2003); bicarbonate extractable ortho-P (Olsen and Sommers 1982); total nitrogen and carbon (AOAC 1997); and oxidizable organic matter (Nelson and Sommers 1982).

Cover and soil data were analyzed as a split-split-block using a mixed model ANOVA. Fixed effects were considered significant if the F statistic was $P < 0.05$. Treatment mean comparisons were considered significant if the t statistic was $P < 0.05$.

Results and Discussion

Vegetation Cover. *Perennial Pepperweed.* In 2003, 2004, 2005, and 2006, a site preparation by herbicide interaction was significant for perennial pepperweed cover. Burning and disking without herbicide treatment did not reduce perennial pepperweed cover compared to untreated blocks (Table 1). Mowing and grazing reduced perennial pepperweed cover by 15 to 33% in 2004, 2005, and 2006, compared to blocks without site preparation at HLWA. At Mapes Ranch, perennial pepperweed cover was higher in all

Table 2. Soil attributes at study sites in 2002.

	HLWA[a]	Mapes[a]
pH (#)	7.6	7.8
OM[a] (%)	4	10
Total C (%)	2.6	8.2
Total N (%)	0.2	0.7
EC_e[a] (dS/m)	2	8
Ca^{+2} (meq/L)	2	21
CO_3 (meq/L)	< 0.1	< 0.1
HCO_3 (meq/L)	3.0	4.3
Mg^{+2} (meq/L)	2	14
Na^{+} (meq/L)	10	33
SAR[a] (#)	7	8
NO_3–N (ppm)	22	183
Olsen-P (ppm)	18	535

[a] Abbreviations: HLWA, Honeylake Wildlife Area site; Mapes, Mapes Ranch site; OM, organic matter; EC_e, electrical conductivity; SAR, sodium adsorption ratio.

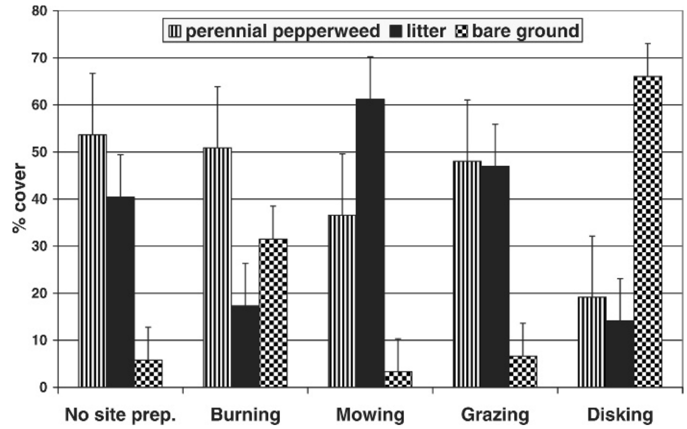

Figure 1. Influence of site preparation treatments on perennial pepperweed, litter, and bare ground cover in June 2003 immediately before the initial herbicide application. There were no site by treatment interactions, thus data were pooled for the two sites. Errors bars represent a 95% confidence interval.

site preparation treatments, except burning, compared to untreated controls by 2006 (Table 1).

Across years at HLWA, burning, grazing, mowing, and disking had little influence on herbicide efficacy compared to herbicide treatments without site preparation. Mowing and disking slightly decreased the efficacy of initial 2,4-D and glyphosate treatments 1 yr after application (2004), but this trend was not significant in 2005 and 2006 after 2,4-D was applied for consecutive years (Table 1). At HLWA in 2006, all site preparation plus herbicide combinations reduced perennial pepperweed cover by $> 80\%$ compared to untreated blocks.

At Mapes Ranch, burning, mowing, and disking reduced the efficacy of chlorsulfuron compared to chlorsulfuron applications without site preparation or to grazed blocks in 2004, 2005, and 2006 (Table 1). The Mapes Ranch site had 250% higher soil organic matter and 300% higher total carbon compared to the HLWA site (Table 2). Burning and disking, in particular, reduced the litter layer while increasing bare ground exposure in the year after the treatment (Figure 1). This difference was even more dramatic by 2006 (Figure 2). Burning, disking, and mowing also removed all standing litter, including the previous seasons' stems. Much of the standing litter remained in the grazing blocks and blocks without site preparation. Poor results with chlorsulfuron at the Mapes Ranch might be due to herbicide adsorption to the exposed high organic matter soil, whereas standing litter in the grazed and no site preparation treatments could have intercepted a significant proportion of the applied herbicide, funneling it down the stems following precipitation, where it could come into contact with the lower leaves or shallow roots.

When comparing herbicides in blocks without site preparation, 2,4-D; glyphosate (before seeding)/2,4-D (after seeding); and chlorsulfuron provided similar perennial pepperweed control in 2004, 2005, and 2006 (Table 1). In burn, mow, graze, and disk blocks at HLWA, chlorsulfuron provided better perennial pepperweed control compared to 2,4-D after the initial application, but chlorsulfuron, 2,4-D, and glyphosate/2,4-D gave similar perennial pepperweed control by 2006, after the herbicides had been applied for consecutive years (Table 1). In contrast, 2,4-D and glyphosate/2,4-D provided better control of perennial pepperweed compared to chlorsulfuron in burn, mow, and disk blocks at Mapes Ranch (Table 1).

Litter, Bare Ground, and Annual Vegetation Cover. Burning, mowing, and disking reduced standing thatch in 2003 before the initial herbicide application. This made herbicide applications considerably easier in these blocks. Burning and particularly disking also removed over 50% of the total litter and exposed more than five times as much bare ground compared to untreated blocks (Figures 1 and 2). All site preparation treatments had a higher percentage of annual grass cover, including downy brome (*Bromus tectorum* L.) and Japanese brome (*Bromus japonicus* Thunb.) compared to blocks without site preparation, but this was only statistically significant in the burned and grazed blocks (Figure 2). As has been shown in other prescribed burning studies, the burned blocks also had significantly higher annual broadleaf cover (Kyser and DiTomaso 2002; DiTomaso 2006), predominantly *Atriplex* spp., flixweed (*Descurainia sophia* L.), prickly lettuce (*Lactuca serriola* L.), and poverty sumpweed (*Iva axillaris*

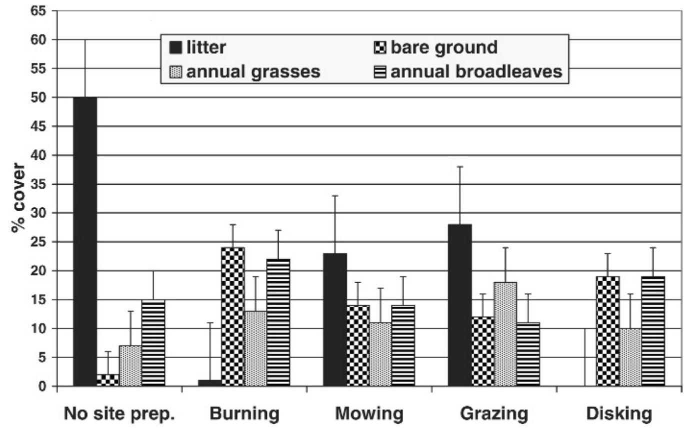

Figure 2. Influence of site preparation treatments on litter, bare ground, annual grass, and annual broadleaf cover in June 2006. Data were averaged across herbicide and reseeding treatments. There were no site by treatment interactions, thus data were pooled for the two sites. Error bars represent a 95% confidence interval.

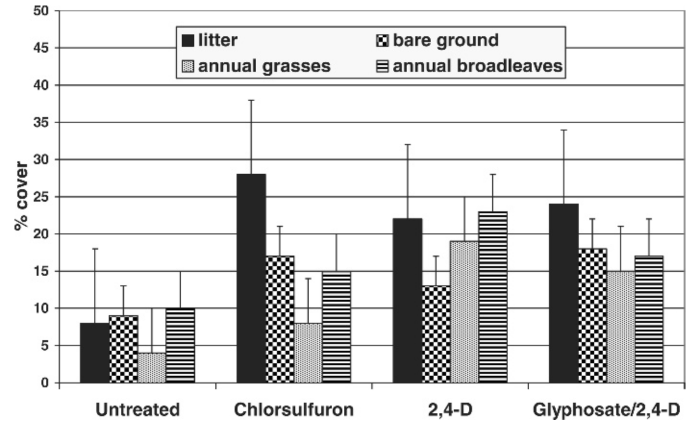

Figure 3. Influence of herbicides on litter, bare ground, annual grass, and annual broadleaf cover in June 2006. Data were averaged across site preparation and reseeding treatments. Glyphosate/2,4-D refers to the treatment glyphosate applied before seeding and 2,4-D applied after seeding. There were no site by treatment interactions, thus data were pooled for the two sites. Error bars represent a 95% confidence interval.

Pursh) compared to blocks without site preparation, or to mowed and grazed blocks.

All herbicide treatments increased annual broadleaf cover compared to untreated blocks (Figure 3). The 2,4-D and glyphosate/2,4-D blocks also had higher annual grass cover compared to untreated or chlorsulfuron blocks.

Seeded Perennial Grass Cover. Perennial grasses made up less than 1% of vegetation cover at both sites before treatments were applied. Perennial grasses seeded in March of 2004 did not establish at either site. Establishment failure was likely due to drought because both sites only received 7 cm (2.75 in) precipitation from October 2003 to September 2004 compared to the historical average of 27 cm (10.5 in). A second seeding in March 2005 was more successful at both sites, but grass growth was slow the year of seeding (typical of dryland, grass seedings in the high desert). Within 5 mo of the second seeding (August 2005 evaluation), perennial grass cover was above 10% in only a few treatments and was highest in the burn plus 2,4-D or glyphosate/2,4-D blocks (Table 3). Fortunately, many of the seeded grasses survived summer drought during 2005 and produced vigorous spring growth in 2006, stimulated by an abnormally wet winter and spring (31 cm [12 in] between December 2005 and June 2006).

The interaction of site preparation and herbicides had a significant effect on seeded grass cover in August 2005 (5 mo after seeding) and June 2006 (15 mo after seeding). Without perennial pepperweed control with herbicides, seeded grass cover was $< 4\%$ at both sites by June 2006, regardless of site preparation treatment (Table 3). This was presumed to be due to competition from perennial pepperweed. With herbicides, burn, mow, graze, and disk blocks typically had 15 to 50% seeded grass cover by June 2006. Treatments with the highest grass cover in 2006 were burning, mowing, or disking in combination with herbicides (Table 3). Disking in combination with glyphosate before seeding and 2,4-D after seeding at the Mapes Ranch had the highest seeded grass cover at 88%. Burning and disking in particular provided a seedbed for precise seeding depth and seed-to-soil contact with a no-till drill. Grasses successfully established in grazed plots (especially in low lying areas at Mapes Ranch), but seeded perennial grass cover was not as uniform or dense as in burned, mowed, and disked plots. Because of the uneven litter layer or standing litter in grazed and no site preparation blocks, these treatments were more difficult to seed. Lower grass cover in these plots might have resulted from irregular seeding depth and poor seed-to-soil contact.

Overall, perennial grasses established most consistently in plots treated with 2,4-D or glyphosate before seeding and 2,4-D after seeding (Table 3). At both sites in 2006, perennial grass cover was lower in chlorsulfuron blocks compared to 2,4-D blocks across site preparation treatments. Many seedling grasses in chlorsulfuron blocks were stunted and chlorotic in the first two months after emergence and did not grow large enough to survive subsequent summer drought.

The interaction between reseeding plus herbicides and herbicide-only blocks for perennial pepperweed cover indicated no significant differences in 2005 or 2006. This suggested that seeded perennial grasses did not have an additive effect on suppressing perennial pepperweed within

Table 3. Interaction of site preparation treatments and herbicides on total perennial grass cover in reseeded plots at the Honey Lake Wildlife Area and Mapes Ranch.

Treatment	August 2005		June 2006	
	HLWA[a]	Mapes[a]	HLWA	Mapes
	% cover			
No site preparation				
untreated	0	3	0	0
chlorsulfuron[b]	0	0	1	3
2,4-D[c]	1	9	4	24
glyphosate/2,4-D[d]	1	3	8	15
Burning				
untreated	1	0	1	1
chlorsulfuron	6	6	11	37
2,4-D	14	22	30	43
glyphosate/2,4-D	18	17	42	71
Mowing				
untreated	1	0	3	0
chlorsulfuron	5	7	21	21
2,4-D	8	11	34	52
glyphosate/2,4-D	6	10	24	41
Grazing				
untreated	0	0	2	1
chlorsulfuron	2	0	3	13
2,4-D	2	21	4	49
glyphosate/2,4-D	3	2	17	54
Disking				
untreated	1	0	1	0
chlorsulfuron	7	7	21	11
2,4-D	5	13	16	73
glyphosate/2,4-D	9	9	36	88
LSD ($P = 0.05$)	4	11	7	12

[a] Abbreviations: HLWA, Honeylake Wildlife Area site; Mapes, Mapes Ranch site.

[b] Chlorsulfuron was applied at 100 g ai/ha (1.5 oz ai/ac) in 2003 (before seeding) and at 50 g ai/ha (0.75 oz ai/ac) in 2004 (after seeding).

[c] 2,4-D ester was applied at 2.2 kg ae/ha (2 lb ae/ac) in 2003 (before seeding) and at 1.1 kg ae/ha (1 lb ae/ac) in 2004 and 2005 (after seeding).

[d] Glyphosate was applied at 3.4 kg ae/ha (3 lb ae/ac) in 2003 (before seeding) and 2,4-D ester was applied at 1.1 kg ae/ha (1 lb ae/ac) in 2004 and 2005 (after seeding).

the 15 mo of establishment compared to using herbicides alone.

Soil Attributes. Soil attributes were considerably different between HLWA and Mapes Ranch before study initiation in 2002 (Table 2). The Mapes Ranch site had higher percent organic matter; electrical conductivity (EC_e); bicarbonate-extractable P (Olsen-P); C : N ratio; nitrate (NO_3–N); and extractable Ca^{+2}, Mg^{+2}, and Na^{+} compared to the HLWA site (Table 2). Based on soil test results from surrounding farms near both sites, the HLWA soil attributes are more typical of the area and Mapes Ranch soil attributes are atypical (data not shown).

Given that soil types are fairly similar between sites, it is unusual that soil attributes at the Mapes Ranch site are so different. The reason for these soil differences between sites is unknown, but we propose two possibilities. One explanation is that Mapes Ranch was used as a winter feeding area in the 1970s and 1980s and the deposition of manure during these years might have altered soil attributes. Alternatively, perennial pepperweed has infested the Mapes Ranch site for a longer period compared to

Table 4. Effect of site preparation treatments on soil attributes (0 to −15 cm deep) in May 2005.

Soil attribute (unit)	Site	No site preparation	Burning	Disking	Grazing	Mowing	LSD P = 0.05
ECe[a]	HLWA[a]	1.2	0.9	2.5	1.6	1.3	0.6
(dS/m)	Mapes[a]	7.4	9.5	16.1	9.3	9.9	1.8
Ca^{+2}	HLWA	2	2	5	2	3	2
(meq/L)	Mapes	22	29	35	24	26	9
Mg^{+2}	HLWA	1	1	3	1	2	1
(meq/L)	Mapes	12	17	21	15	18	8
Na^{+}	HLWA	9	6	20	13	9	7
(meq/L)	Mapes	30	38	79	38	34	19
SAR[a]	HLWA	7.0	4.1	9.8	9.4	6.0	2.3
(#)	Mapes	7.7	7.5	15.0	8.5	8.8	2.4
NO_3-N	HLWA	20	26	24	17	19	5
(ppm)	Mapes	161	210	455	213	239	80

[a] Abbreviations: EC_e, electrical conductivity; HLWA, Honeylake Wildlife Area site; Mapes, Mapes Ranch site; SAR, sodium adsorption ratio.

other surrounding sites, and this might have resulted in a more dramatic alteration in nutrient cycling.

Blank and Young (2002) showed perennial pepperweed litter contained high concentrations of C, N, P, S, Ca, K, Mg, and Na, and over time, perennial pepperweed populations enrich the soil with these nutrients near the soil surface. They also found perennial pepperweed increases soil-solution Ca^{+2}, which lowers the SAR and may ameliorate sodic soils. Because a near-monotypic stand of perennial pepperweed existed at Mapes Ranch much earlier than at HLWA, high soil P, NO_3–N, Ca, Mg, and Na at Mapes Ranch are consistent with elevated nutrient cycling reported by Blank and Young (2002). Unfortunately, SAR is similar between the Mapes Ranch and HLWA site, suggesting perennial pepperweed has not ameliorated the sodic soil.

As would be expected over the short duration of the study, herbicides and their associated control of perennial pepperweed did not influence soil attributes. In contrast, site preparation did affect soil attributes, particularly in the disked blocks (Table 4). At both sites, disking increased soil EC_e compared to other site preparation treatments (Table 4). Disking also increased extractable Ca^{+2}, Mg^{+2}, and Na^{+2} along with the sodium adsorption ratio (SAR) at both sites (Table 4). At Mapes Ranch, soil NO_3-N also increased, but only in the disk treatment (Table 4).

These soil changes following disking have the potential to decrease plant growth and revegetation success, especially at the Mapes Ranch. Based on other published results (Ludwick et al. 1995), elevated soil EC_e (16.13) in the disk treatments at Mapes Ranch was expected to be high enough to severely limit seed germination and growth of most grass species. The increase in SAR would also be expected to promote soil dispersion, decreased permeability, and other negative physical changes (Ludwick 1995), and high NO_3–N could encourage the invasion of competitive annual grasses. In contrast to this expected result, we showed that reseeded disked blocks resulted in high native perennial grass cover at both sites, compared to other site preparation treatments (Table 3).

An explanation for the increase in EC_e, Ca^{+2}, Mg^{+2}, Na^{+2}, NO_3–N, and SAR in the disked treatments is unknown, but we speculate that it might be due to incorporation of the thatch layer because perennial pepperweed litter contains high elemental content (Blank and Young 1997, 2002). In addition, disking might have also enhanced the rate of organic matter mineralization at the Mapes Ranch. Because the percent organic matter was so high at this site, this could have led to an increase in NO_3-N.

Management Implications

Results of these trials demonstrated that repeated applications of herbicides are necessary to reduce perennial pepperweed cover below 5%. Burning, disking, or mowing alone are not effective for long-term control. Yearly applications of 2,4-D, chlorsulfuron, or glyphosate (before seeding)/2,4-D (after seeding) when applied alone or in combination with grazing reduced perennial pepperweed cover by 82 to 99% compared to untreated blocks. 2,4-D and glyphosate/2,4-D applied in combination with burning, mowing, or disking also gave good to excellent control, reducing perennial cover by 81 to 99%.

Successful establishment of native grasses in perennial pepperweed monotypic stands required burning, mowing, or disking in combination with herbicides and no-till drill seeding. Sowing seeds through cattle trampling resulted in variable grass establishment compared to drill seeding. However, trampling might be a more practical seeding option in rough terrain. None of the treatments provided complete control of perennial pepperweed at either study site, indicating that spot herbicide applications will likely be necessary for several years to prevent perennial pepperweed populations from rebounding after native grass restoration.

Along with aboveground changes, soil characteristics should also be accounted for when developing a weed control and revegetation program on perennial pepperweed sites. At both sites, disking increased soil EC_e and SAR compared to untreated blocks. An increase in total salts and sodium concentration could have a negative effect on perennial grass emergence and growth.

Soil attributes can also affect herbicide efficacy and selectivity. In this study and those of Young et al. (2002), chlorsulfuron applied to high pH, salt-affected soils before reseeding injured grass seedlings and decreased grass establishment. Chlorsulfuron efficacy at the Mapes Ranch in disked, mowed, and burned blocks was reduced, presumably due to chlorsulfuron adsorption to the high soil organic matter at the site.

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