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Two-Year Effects of Aminopyralid on an Invaded Meadow in the Washington Cascades

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Four rates of aminopyralid (30, 60, 90, and 120 g ae ha^{-1} [0.4, 0.9, 1.3, and 1.8 oz ae acre^{-1}]) were compared for their ability to reduce abundance of nonnative dicot species and favor native species in an invaded Cascade Mountain meadow near Trout Lake, WA. Treatments were applied in two replicated studies (June 2009 and 2010), and foliar cover and species richness were monitored for two years. First-year control of nonnative dicots from application of 30 g ae ha^{-1} of aminopyralid (69%) was greater than that of native dicots (29%); whereas, significant control of both species groups occurred at the higher rates. By the second year after treatment, absolute differences in cover between treated and non-treated plots averaged −17% and −21% for native and nonnative dicots, respectively, and +1% and +27% for native and nonnative monocots, respectively. First-year control of Canada thistle and oxeye daisy was greater after treatment in 2009 (88% and 90%, respectively) than after treatment in 2010 (56% and 55%, respectively), probably because lower spring temperatures in 2010 limited vegetation development and plant susceptibility to aminopyralid. Cover of Kentucky bluegrass and sheep fescue averaged 20% and 6% greater, respectively, in treated plots than in non-treated plots. Application of 30 g ae ha^{-1} of aminopyralid had no detectable effect on second-year richness of native and nonnative species relative to non-treated plots; however, higher rates caused 24% to 43% reductions in richness of each species group. Research results suggest that application of aminopyralid at 30 g ae ha^{-1} has the potential to reduce abundance of nonnative dicot species in similar meadow communities of the Pacific Northwest with little or no negative impacts to abundance and richness of native species. As a potential strategy to limit the subsequent spread of Kentucky bluegrass, a grass herbicide, such as fluazifop or sethoxydim, could be added to the treatment.

Nomenclature: Aminopyralid; Canada thistle, *Cirsium arvense* (L.) Scop.; Kentucky bluegrass, *Poa pratensis* L.; oxeye daisy, *Leucanthemum vulgare* Lam.; sheep fescue, *Festuca ovina* L.

Key words: Community restoration, mixed conifer, species richness.

Meadow ecosystems of the Pacific Northwest provide important habitat for native plant and animal species but increasingly are becoming threatened by disturbance (Kauffman and Krueger 1984) and nonnative plant invasion (Wallace et al. 2010). Herbicide treatments have been used successfully to selectively reduce or eliminate invasive plant species in arid grasslands of the Pacific Northwest (Dennehy et al. 2011), but meadow communities present unique challenges for herbicide use because of their temporally-dynamic hydrology. Given the management goal of restoring important features of a native plant community, selection of the appropriate herbicide and application rate can limit potential injury to nontarget species as well as increase cost-effectiveness of the treatment for controlling target species.

Aminopyralid is a dicot-specific herbicide that was recently registered for use in riparian areas because of its favorable environmental fate (Jachetta et al. 2005). It controls many broadleaf species, but unlike glyphosate and picloram, it is tolerated by a number of broadleaf families and genera (Halstvedt et al. 2010). Aminopyralid also is known to have little or no phytotoxic activity on perennial grasses and other monocots common to meadow communities (Carrithers et al. 2005). Therefore, if used at the appropriate rate, aminopyralid has the potential to control a variety of nonnative dicot species without severely damaging native species in monocot-dominated meadow communities.

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Management Implications

Herbicides can be used selectively to shift species composition of plant communities to favor native species over nonnative species. Such selectivity can be achieved through species' differences in herbicide tolerance, stature, and timing of development. Aminopyralid is an herbicide that provides selective control of dicot species with little or no injury to many monocot species. To test the feasibility of using aminopyralid to reduce abundance of nonnative dicots in an invaded meadow community in the Washington Cascade Mountains, we compared species abundance and richness one and two years after application of four rates of aminopyralid (30, 60, 90, and 120 g ae ha^{-1}) in separate replicated studies treated in June 2009 and 2010. At the lowest aminopyralid rate (30 g ae ha^{-1}), control of nonnative dicots was considerably greater than control of native dicots, and there was no detectable negative effect on richness of either native or nonnative species. Reductions in dicot abundance from the aminopyralid treatments stimulated a 27% increase in cover of nonnative monocots, primarily Kentucky bluegrass and sheep fescue. First-year control of Canada thistle and oxeye daisy was lower after treatment in 2010 than in 2009 because initial vegetation development had been limited by the cooler spring temperatures of 2010. These research results suggest that a low rate of aminopyralid can be used in similar meadow communities to control nonnative dicots with minimal injury to native dicots. A grass herbicide, such as fluazifop or sethoxydim, could be added to the treatment to control Kentucky bluegrass. Timing of treatment application for Pacific Northwest plant communities should be selected carefully to ensure that target species have reached a stage of development adequate to render them susceptible to aminopyralid, but before the onset of summer drought when many herbaceous species complete their life cycle or become dormant.

The objective of this study was to compare various rates of aminopyralid for their ability to restore characteristics of the native plant community of an invaded meadow in the Washington Cascade Mountains. Aminopyralid was an appropriate choice for the research because the study site was seasonally wet, requiring an herbicide labeled for riparian applications, and the meadow contained a high abundance of Canada thistle [*Cirsium arvense* (L.) Scop.] – a nonnative, invasive species of known susceptibility to the herbicide (Enloe et al. 2007). The research sought to identify appropriate rates of aminopyralid for controlling nonnative dicot species, thereby facilitating potential increases in abundance of native dicot and monocot species that tolerate the herbicide. A secondary objective was to determine whether aminopyralid could cause injury or loss of vigor to mountain blue-eyed grass (*Sisyrinchium sarmentosum* Suks. ex. Greene), a small native iris found on the study site that is listed as a threatened species in Washington.

Materials and Methods

Study Site. The study site is located in Cave Creek meadow (45.942°N, 121.613°W) on the Mount Adams Ranger District, Gifford Pinchot National Forest, near Trout Lake, WA. Elevation of the site is approximately 850 m and slope is less than or equal to 3%. The area surrounding the meadow had standing water during early spring of each year of the study; however, the actual study area was well drained for the duration of the research. Soil orders include seasonally wet spodosols (aquods), histosols (fibrists), and mollisols (aquolls) that are high in organic matter and occasionally anaerobic during seasonal flooding (USDA FS 2012; USDA NRCS 2012). Surface and subsurface layers include silty loam and clay loam textures, respectively. The site receives 1,392 mm (54.8 in.) of annual precipitation based on 20-yr (1989 to 2008) estimates, with only 17% (236 mm) occurring during the growing season (April to September) (PRISM Climate Group 2013) because of summer drought typical of the Mediterranean climate of the Pacific Northwest (Franklin and Dyrness 1973). Local temperature and precipitation data for the research period of 2009 to 2012 were obtained from the Mount Adams Ranger Station, Trout Lake, WA, located approximately 9 km (5.6 mi) from the study site.

Prior to forest harvesting in the 1960s, the site was dominated by widely-spaced, old-growth western redcedar (*Thuja plicata* Donn ex D. Don) in association with coast Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*], grand fir [*Abies grandis* (Douglas ex D. Don) Lindl.], lodgepole pine (*Pinus contorta* Douglas ex Loudon), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). Similar plant communities have been referred to as ''forested swamps'' (Franklin and Dyrness 1973), and attempts to reforest the site after harvest were thwarted by an elevated water table (A. Ruchty, personal communication). In surrounding areas where the forest has recovered since harvest, understory species include those capable of tolerating standing water such as *Carex* spp., redosier dogwood (*Cornus sericea* L.), sitka alder [*Alnus viridis* (Chaix) DC. ssp. *sinuata* (Regel) Á. Löve & D. Löve], and vine maple (*Acer circinatum* Pursh). Cave Creek meadow contains one of the few known populations of mountain blue-eyed grass (Ruchty 2011). Several nonnative dicot species common to the meadow are considered imminent threats to sustainability of mountain blue-eyed grass, including Canada thistle, tansy ragwort (*Senecio jacobaea* L.), and houndstongue (*Cynoglossum officinale* L.). A history of livestock grazing probably facilitated invasion and spread of these nonnative species in the meadow (Raven 2003).

Experimental Design. A total of 36 plots, 6 m by 6 m (19.7 ft × 19.7 ft) in dimension, were located on the study site in June 2009 within areas having a uniform abundance of a primary target species, Canada thistle (i.e., a minimum of 2 thistle stems m^{-2}). Twenty-four of the 36 plots were randomly assigned for treatment with aminopyralid in

2009 (Study 1), and 12 plots were randomly assigned for treatment in 2010 (Study 2). Each plot was split and one half (3 m by 6 m) was randomly assigned to be treated with aminopyralid and the other half was left non-treated to serve as an experimental check. On June 18, 2009, each of four rates of aminopyralid (30, 60, 90, and 120 g ae ha^{-1}), corresponding approximately to 25, 50, 75, and 100% of the maximum labeled rate for Milestone® (Dow AgroSciences LLC, Indianapolis, IN 46268), was applied to the randomly assigned halves of the 24 plots for treatment year 2009. Each aminopyralid treatment included addition of a nonionic surfactant (R11®, Wilbur-Ellis Agribusiness, Walnut Creek, CA 94596) at 0.5% volumetric concentration. On June 22, 2010, the experiment was repeated and each of the herbicide rates was applied to the randomly assigned halves of the remaining 12 plots. No measureable rainfall was recorded within three days after each aminopyralid treatment. For each study, the experimental design is completely randomized with a split-plot arrangement of treatments replicated six or three times for treatment years 2009 and 2010, respectively. Plots were assigned an aminopyralid rate and split-plots were assigned either to be treated with aminopyralid or to be left non-treated. This experimental approach, similar to that used by Almquist and Lym (2010), ensures the presence of a non-treated area in close proximity to each treated area to account for spatial variation in microsite characteristics and species' abundances. Herbicide treatments were applied with a calibrated CO_2 pressurized sprayer with four flat fan nozzles (8002VS) mounted on a 1.4-m boom (model GS, Bellspray, Inc., Opelousas LA 70570). A single pass of the sprayer was made over the central section of each assigned split-plot with the boom held approximately 1.2 m above ground, resulting in a 1.8-m spray swath. Spray volume was 187 L ha^{-1} applied with 200 kPa of pressure. A metronome (Seiko model DM50, Mahwah, NJ 07430) was used to time the application for precise coverage of each split-plot.

Data Collection and Analysis. In June, immediately prior to each herbicide application, and at one and two years after the treatments, projected foliar cover (%) was estimated visually by species and the number of Canada thistle stems was counted in each of two 1- by 1-m subplots centered at 2 and 4 m along the central axis of each split-plot. Note that each subplot was surrounded by a treated buffer strip at least 0.4 m in width, reducing the likelihood of vegetation encroachment from adjacent plots during the 2-yr period of each study. Vegetation responses for split-plots treated in 2009 (Study 1) were assessed in June 2010 and 2011, while those for split-plots treated in 2010 (Study 2) were assessed in June 2011 and 2012. Species' scientific names, common names, and nativity follow those given in the USDA Plants Database (USDA NRCS 2013). For each 1 m^2 subplot we calculated covers of native dicots, nonnative dicots, native monocots, and nonnative monocots, and values of species richness for native and nonnative species groups (i.e., the total number of higher vascular plant species m^{-2}).

All statistical analyses were conducted in SAS (SAS Institute, Inc., 2008) with a significance level of $\alpha = 0.05$. Data from each study were analyzed separately to provide independent assessments of aminopyralid efficacy that would corroborate our findings. Subplot values for each response variable were averaged by split-plot, and the data were subjected to repeated measures analysis of variance (ANOVA) using a mixed-model approach in PROC MIXED to test for significant effects of aminopyralid treatment, aminopyralid rate, measurement year, and their interactions. A first-order autoregressive covariance structure was used to adjust each repeated measures ANOVA for serial correlation. If the model failed to converge, an unstructured covariance structure was used (SAS Institute Inc. 2008). An angular transformation (arc-sine, square-root) was applied to proportionate values of individual-species' cover, and a logarithmic transformation was applied to thistle stem density (Y + 1) to homogenize the residual variances (Sokal and Rohlf, 1981). A total of 21 species were adequately represented among the treatment replications to enable ANOVA based on model convergence in PROC MIXED. Pretreatment cover could not be used as a covariate in the ANOVA because the slope of its relationship with post-treatment cover differed between treated and non-treated plots, violating the assumption of homogeneity of slopes (Quinn and Keough 2002). When the interaction of aminopyralid treatment and measurement year was significant, multiple comparisons of least-squares means were conducted using Tukey's HSD test with Bonferroni-adjusted probabilities to control the Type I error rate (Quinn and Keough 2002). Results were presented as back-transformed, least-squares means from the ANOVA. Control of a species or species group was expressed as percentage reduction in a given response variable relative to the non-treated check (Miller and Glover 1991); whereas, differences in plant cover between treated and non-treated plots were reported as absolute values. Potential linear and quadratic effects of aminopyralid rate were tested for each treatment year and measurement year using polynomial orthogonal contrasts (i.e., four contrasts) and Bonferroni-adjusted probabilities (Sokal and Rohlf 1981). When significant, effects of aminopyralid rate were illustrated graphically for individual species (i.e., those having an average cover $\geq$ 1%) and species groups.

A total of 19 plants of mountain blue-eyed grass present in the research plots were pin-flagged to monitor their status following the herbicide treatments, 9 and 10 of which were in treated and non-treated split-plots, respectively. In August 2009, approximately 10 wk after treatments were applied, each plant was re-located and its

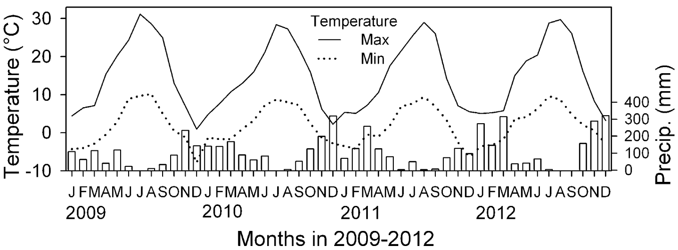

Figure 1. Maximum and minimum air temperatures and precipitation by month during 2009–2012 at the Mount Adams Ranger Station, Trout Lake, WA.

vigor and phenology described. In June 2011, the total number of flowers of mountain blue-eyed grass was counted on each split-plot to provide a measure of population vigor, and the data were subjected to ANOVA to test for potential treatment effects.

Results and Discussion

Temperature and Precipitation. Growing season (April to September) precipitation at Mount Adams Ranger Station was 222, 289, 264, and 148 mm (8.7, 11.4, 10.4, and 5.8 in.) during 2009, 2010, 2011, and 2012, respectively (Figure 1), or 94, 122, 112, and 63% of the estimated long-term average (PRISM Climate Group 2013). During June, when the treatments were applied and foliar cover by species was assessed, minimum temperatures averaged 8.9 C, 7.2 C, 6.8 C, and 6.2 C (48°, 45°, 44°, and 43° F) in 2009, 2010, 2011, and 2012, respectively. Daily maximum temperatures in April, May, and June averaged 3.3 C lower in 2010 than in 2009.

Abundance of Dicots and Monocots. A total of 67 higher-vascular plant species were identified on the study site, including 56 dicots and 11 monocots. Dicots included 34 native and 22 nonnative species, and monocots included six native and five nonnative species. Pretreatment foliar covers of dicots and monocots were lower in treatment year 2010 than in treatment year 2009 (Table 1) probably because vegetation development was limited by the cooler spring temperatures of 2010. First-year control of dicots after treatment in 2009 was greater for nonnative (82%) than for native species (45%), attributable to strong reductions in cover of nonnatives at all rates of aminopyralid but only gradual reductions in cover of natives with increasing rate (Figure 2). For example, first-year control following 30 g ae ha^{-1} of aminopyralid was 69% and 29% for nonnative and native dicots, respectively. As a result of these contrasting native and nonnative responses, total cover of dicots declined linearly with increasing rate of aminopyralid (R^2 = 0.21; Figure 2). Although no other linear or quadratic effects of aminopyralid rate were detected for the species groups, the same general trend was observed during each year after treatment in 2010: control following 30 g ae ha^{-1} of aminopyralid was consistently greater for nonnative dicots (67% to 70%) than for native dicots (22% to 23%).

Table 1. Average foliar cover by species group (with standard errors [SE]) at 0, 1, and 2 years after treatment in 2009 and 2010 with aminopyralid at Cave Creek meadow near Trout Lake, WA.

		Years after treatment						
		0	1		2			
Species group	Trmt. year	Avg.	Not treated	Treated	Not treated	Treated	SE	Significant effects[1]
		% foliar cover						
Native dicots	2009	43.5	34.1	18.8	30.2	18.6	3.0	T,R×Y
	2010	32.5	39.0	18.5	42.8	20.7	3.5	T,R
Nonnative dicots	2009	39.4	25.9	4.6	37.7	14.9	2.3	T,Y
	2010	22.6	37.9	16.0	34.9	15.1	3.5	T
Subtotal	2009	82.9	60.0	23.4	67.8	33.5	3.3	T×R×Y
	2010	55.1	77.0	34.5	77.7	35.8	5.6	T
Native monocots	2009	11.9	11.5	10.1	9.7	11.5	2.0	
	2010	10.0	8.3	8.9	9.8	10.4	2.5	
Nonnative monocots	2009	57.8	53.9	70.3	39.3	66.6	3.9	T×R,Y
	2010	43.7	40.7	68.0	44.7	70.5	6.8	T
Subtotal	2009	69.6	65.4	80.4	49.0	78.1	4.9	T,R×Y
	2010	53.7	48.9	76.9	54.6	80.9	7.2	T,Y
Total	2009	152.6	125.4	103.9	116.9	111.6	5.6	T
	2010	108.8	125.9	111.4	132.3	116.7	9.2	

[1] $P \leq 0.05$ from ANOVA; T = treated with aminopyralid, R = aminopyralid rate, and Y = yr after treatment.

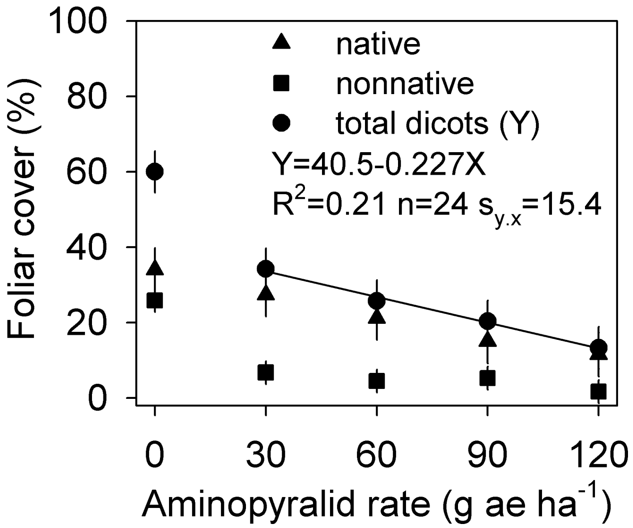

Figure 2. Foliar cover (± SE) of native dicots, nonnative dicots, and all dicot species combined (treatment year 2009, measurement year 1) in response to aminopyralid rate at Cave Creek meadow near Trout Lake, WA. Regression model shown is for the only species group, treatment year, and measurement year combination that had a significant ($P \leq 0.05$) linear effect of aminopyralid rate. Mean values for non-treated plots (aminopyralid rate = 0 g ae ha^{-1}) are shown for comparison purposes only.

Two years after treatment in both studies, absolute cover differed between treated and non-treated plots by averages of −17% and −21% for native and nonnative dicot species, respectively, and by averages of +1% and +27% for native and nonnative monocot species, respectively (Table 1). Increased cover of nonnative monocots in treated plots was attributed primarily to Kentucky bluegrass (*Poa pratensis* L.) and secondarily to sheep fescue (*Festuca ovina* L.). For the duration of the research, abundance of native monocots did not differ significantly among treatments for either study (Table 1).

Abundance by Species. A total of 11 native and 10 nonnative plant species were distributed adequately among treatment replications to enable ANOVA of their foliar cover responses (Table 2). Pretreatment cover of most species was lower in 2010 than in 2009, presumably because of differences in spring temperatures. Species' responses to the aminopyralid treatments were grouped below according to those that were controlled, not controlled, or released.

Species Controlled by Aminopyralid. Eleven species had significant reductions in their foliar cover by aminopyralid, five of which were nonnative (Table 2). Angular-transformed cover values of common yarrow (*Achillea millefolium* L.) decreased linearly ($R^2 = 0.31$) with aminopyralid rate in the first year after treatment in 2009 (Figure 3). Even at the lowest aminopyralid rate (30 g ae ha^{-1}), yarrow cover was only one third of that in non-treated plots. At higher rates (60 to 120 g ae ha^{-1}), control was close to 100% because of the species' high susceptibility to aminopyralid.

First-year control of Canada thistle cover was greater after treatment in 2009 (88%) than after treatment in 2010 (56%) (Table 2). Log_e-transformed stem density of Canada thistle had a negative linear relationship with aminopyralid rate in the first year after treatment in 2009 ($R^2 = 0.36$; Figure 4). As rate increased from 30 to 120 g ae ha^{-1}, predicted stem density decreased from 3.2 to 0.5 stems m^{-2}; whereas, stem density in non-treated plots averaged 10 stems m^{-2}. Significant linear or quadratic effects of aminopyralid rate on thistle density were not detected for other combinations of treatment year and measurement year. Second-year control of thistle density was 64% and 27% after treatment in 2009 and 2010, respectively (Table 3). September applications of aminopyralid at 120 g ae ha^{-1} to Canada-thistle-infested prairies in North Dakota and Minnesota resulted in 62% and 89% control of thistle density, respectively, in the second year after treatment (Samuel and Lym 2008, Almquist and Lym 2010).

Cool spring temperatures in 2010 probably limited control of Canada thistle because of delayed plant development prior to treatment. Estimates of average crown width of thistle plants from the cover and stem density measurements indicated differences at the time of treatment between 2009 (9.4 cm [3.7 in]) and 2010 (8.1 cm). A review of photographic records indicated that, in general, the developmental stage of thistle plants (i.e., leaf elongation and plant height) was more advanced at the time of treatment in 2009 than in 2010. No obvious signs of encroachment of thistle plants from adjacent split-plots were observed. Label specifications for Milestone® indicate that the herbicide achieves best control of Canada thistle when applied after all plants of the species have emerged and are at the prebud to early-bud growth stage (Dow AgroSciences LLC, Indianapolis, IN 46268). This stage of development was present in both treatment years at the Cave Creek study site, but differences in thistle plant morphology and stature between 2009 and 2010 probably affected herbicide uptake and efficacy. In studies conducted on 10 sites in the Great Plains, first-year control of Canada thistle did not differ between spring and fall applications of aminopyralid, suggesting that plant phenology does not affect aminopyralid efficacy in regions with summer rainfall (Enloe et al. 2007). However, summer drought, typical of the Mediterranean climate of the Pacific Northwest, would likely render Canada thistle plants less susceptible to control by aminopyralid. Hence, at Cave Creek meadow, appropriate timings for controlling Canada thistle with aminopyralid may be limited to the period between full

Table 2. Average foliar cover of 21 plant species (with standard errors [SE]) at 0, 1, and 2 yr after treatment in 2009 and 2010 with aminopyralid at Cave Creek meadow near Trout Lake, WA. For the interaction of aminopyralid treatment and years after treatment (T×Y), row means followed by the same letter do not differ significantly (P > 0.05).

				Years after treatment						
				0	1		2			
Life form	Nativity	Plant species	Trmt. year	Avg.	Not treated	Treated	Not treated	Treated	SE	Significant effects[1]
				% foliar cover						
Dicot	Native	*Achillea millefolium* Common yarrow	2009	9.3	5.3 a	0.3 c	1.0 b	0.4 bc	0.3	T×Y,R
			2010	4.4	2.2	0.1	2.4	0.1	0.3	T
		Collinsia parviflora Maiden blue-eyed Mary	2009	0.1	0.0 b	0.2 a	0.0 b	0.0 b	0.0	T×Y
			2010	0.1	0.0	0.0	0.0	0.0	0.0	R×Y
		Epilobium minutum Chaparral willowherb	2009	1.2	0.8 a	0.0 b	0.4 a	0.0 b	0.1	T×R,T×Y
			2010	1.4	0.4 a	0.0 b	0.1 b	0.0 b	0.0	T×Y
		Fragaria virginiana Wild strawberry	2009	4.7	0.9	0.2	1.3	0.5	0.5	R×Y
			2010	3.4	1.8	0.0	3.5	0.2	0.9	Y
		Microsteris gracilis Slender phlox	2009	1.9	0.2 ab	0.1 b	0.2 ab	0.2 a	0.1	T×R,T×Y
			2010	0.3	0.3 a	0.0 b	0.1 ab	0.1 ab	0.1	T×Y
		Prunella vulgaris Selfheal	2009	2.1	0.7	1.6	2.9	4.3	0.7	R×Y
			2010	1.1	1.9	6.4	3.8	8.7	2.1	Y
		Ranunculus uncinatus Woodland buttercup	2009	7.0	3.3	0.3	4.3	0.2	0.6	T
			2010	9.9	8.6	0.1	11.2	0.3	1.6	T
		Taraxacum officinale Common dandelion	2009	13.3	7.7	7.1	4.1	4.6	1.6	Y
			2010	8.9	7.2 a	3.9 a	4.6 a	4.4 a	1.7	T×Y
		Veronica serpyllifolia Thymeleaf speedwell	2009	0.2	0.3	1.0	0.2	0.4	0.1	T,Y
			2010	0.5	0.1 b	1.2 a	0.2 b	0.4 b	0.2	T×Y
		Vicia americana American vetch	2009	2.5	0.7	0.0	0.9	0.0	0.1	T
			2010	0.8	1.1	0.0	1.0	0.0	0.2	T
	Nonnative	*Cerastium fontanum* Mouseear chickweed	2009	0.4	0.0	0.0	0.1	0.0	0.0	T×R×Y
			2010	0.0	0.1	0.0	0.1	0.0	0.0	T
		Cirsium arvense Canada thistle	2009	11.7	5.2	0.6	9.7	4.3	0.8	T,Y
			2010	7.4	10.5	4.6	7.6	6.1	1.4	T×R×Y
		Leucanthemum vulgare Oxeye daisy	2009	6.6	5.0 a	0.5 c	5.3 a	1.9 b	0.8	T×Y
			2010	4.0	4.4	2.0	5.1	1.4	0.7	T×R×Y
		Plantago lanceolata Buckhorn plantain	2009	1.4	0.6	0.5	2.0	2.3	0.5	Y
			2010	1.3	1.3	3.8	1.7	3.2	1.0	
		Plantago major Broadleaf plantain	2009	0.5	0.1	0.0	0.2	0.2	0.1	Y
			2010	0.2	0.1 a	0.2 a	0.2 a	0.1 a	0.1	T×Y
		Rumex acetosella Red sorrel	2009	10.0	3.0 a	0.1 c	1.6 b	0.2 c	0.2	T×Y
			2010	2.1	0.7	0.1	0.4	0.0	0.1	T,R,Y

Table 2. Continued.

Life form	Nativity	Plant species	Trmt. year	Years after treatment: 0 Avg.	1 Not treated	1 Treated	2 Not treated	2 Treated	SE	Significant effects[1]
		Trifolium repens White clover	2009	7.7	4.9	0.0	8.1	0.0	0.7	T
			2010	7.0	12.0	0.0	9.7	0.0	1.4	T
		Veronica arvensis Corn speedwell	2009	0.4	0.0	0.1	0.1	0.5	0.1	T,R×Y
			2010	0.0	0.1	0.4	0.1	0.2	0.1	
Monocot	Native	*Carex hoodii* Hood's sedge	2009	11.8	10.1	7.9	7.2	9.1	1.7	
			2010	9.9	6.4	6.4	7.3	7.6	2.6	
	Nonnative	*Festuca ovina* Sheep fescue	2009	14.7	6.1 b	10.1 ab	4.3 b	13.3 a	2.9	T×Y
			2010	2.9	2.7	5.6	5.3	7.8	2.1	R,Y
		Poa pratensis Kentucky bluegrass	2009	39.9	39.3	49.9	25.9	42.6	4.4	T,R×Y
			2010	38.2	32.7	56.3	31.6	55.6	7.2	T

[1] P ≤ 0.05 from ANOVA; T = treated with aminopyralid, R=aminopyralid rate, and Y = yr after treatment.

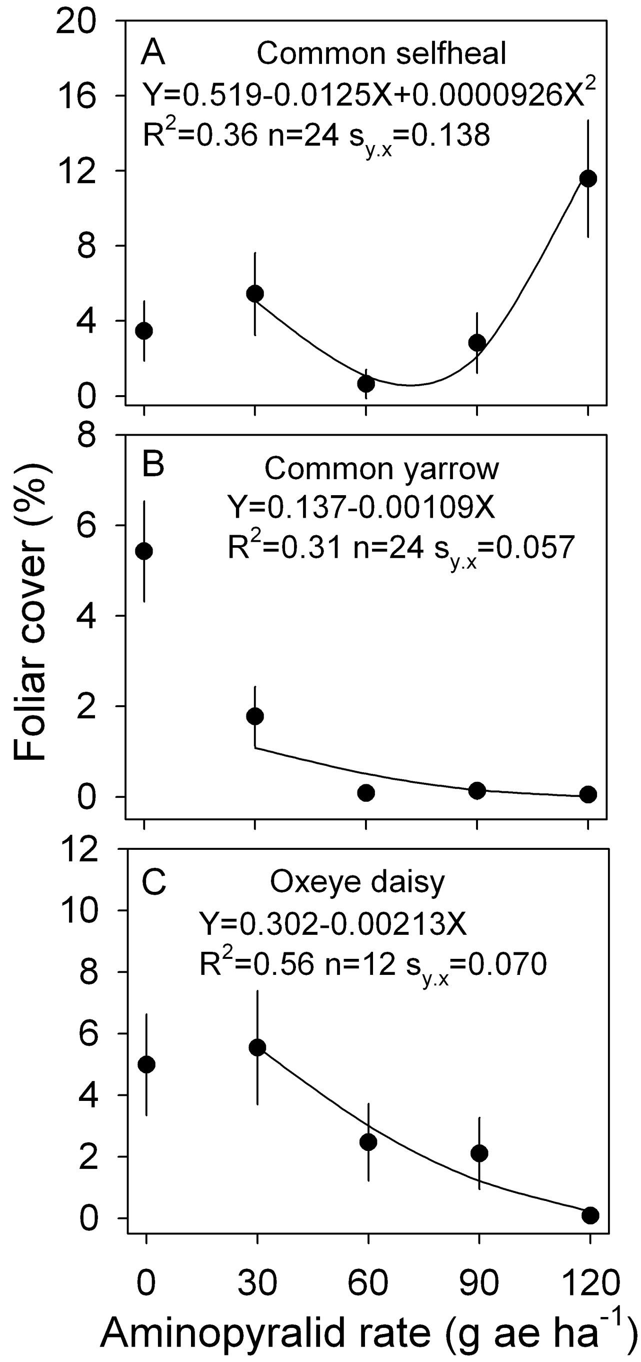

Figure 3. Regression relationships of foliar cover (± SE) of: (a) common selfheal (treatment year 2009, measurement year 2), (b) common yarrow (treatment year 2009, measurement year 1), and (c) oxeye daisy (treatment year 2010, measurement year 1) to aminopyralid rate at Cave Creek meadow near Trout Lake, WA. Models shown are for the species, treatment year, and measurement year combinations that had significant ($P \leq 0.05$) linear or quadratic effects of aminopyralid rate. Models predict angular-transformed values of foliar cover. Mean values for non-treated plots (aminopyralid rate = 0 g ae ha^{-1}) are shown for comparison purposes only.

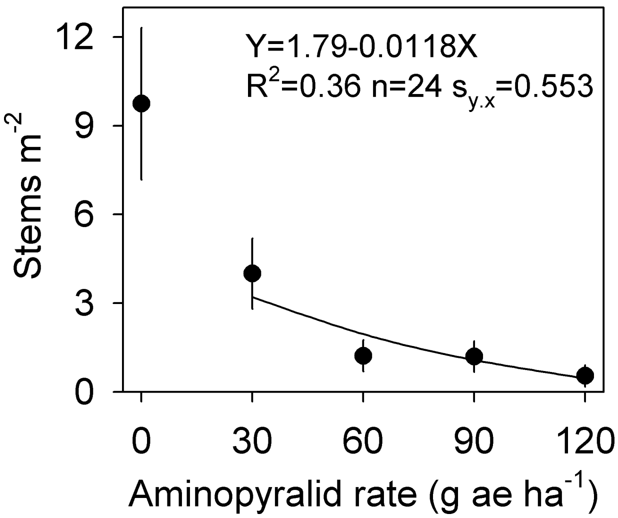

Figure 4. Regression relationship of Canada thistle stem density (± SE) to aminopyralid rate (treatment year 2009, measurement year 1) at Cave Creek meadow near Trout Lake, WA. Model shown is for the only treatment year and measurement year combination that had a significant ($P \leq 0.05$) linear effect of aminopyralid rate. The model predicts Log_e-transformed values of stem density (Y + 1). Mean values for non-treated plots (aminopyralid rate = 0 g ae ha^{-1}) are shown for comparison purposes only.

emergence and early development of stems (late June) and the onset of summer drought (mid-August).

As found for Canada thistle, first-year control of oxeye daisy (*Leucanthemum vulgare* Lam.) was greater after treatment in 2009 (90%) than after treatment in 2010 (55%) (Table 2). Angular-transformed values of oxeye daisy cover declined linearly ($R^2 = 0.56$) with increasing aminopyralid rate in the first year after treatment in 2010 (Figure 3). The highest rate of aminopyralid (120 g ae ha^{-1}) was required to achieve complete control of oxeye daisy.

For each treatment year, over 85% control was observed in years 1 and 2 for red sorrel (*Rumex acetosella* L.), white clover (*Trifolium repens* L.), and woodland buttercup (*Ranunculus uncinatus* D. Don ex G. Don) (Table 2). Four species controlled by aminopyralid had foliar covers that averaged less than 3% for the duration of the study, including American vetch (*Vicia americana* Muhl. ex Willd.), mouseear chickweed (*Cerastium fontanum* Baumg.), chaparral willowherb (*Epilobium minutum* Lindl. ex Lehm.), and slender phlox [*Microsteris gracilis* (Hook.) Greene].

Species Not Controlled by Aminopyralid. Five species demonstrated no clear response to the aminopyralid treatments: broadleaf plantain (*Plantago major* L.), buckhorn plantain (*Plantago lanceolata* L.), common dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), Hood's sedge, and maiden blue-eyed Mary (*Collinsia parviflora* Lindl.) (Table 2). Although a significant treatment-by-year interaction was detected for dandelion after treatment in 2010 ($P = 0.029$), multiple comparisons failed to detect a difference in foliar cover between treated and non-treated plots in either measurement year (Table 3). In previous research, only moderate control of dandelion was observed two years after treatment with aminopyralid at 120 g ae m^{-2} (Almquist and Lym 2010; Samuel and Lym 2008).

Although abundance of wild strawberry (*Fragaria virginiana* Duchesne) appeared to be reduced by treatment, multiple comparisons and polynomial contrasts failed to detect significant differences in cover because of aminopyralid treatment or rate. In a summary of results from studies at 10 locations in four western or midwestern U.S. states, Halvstedt et al. (2010) concluded that a variety of native forbs, such as slender phlox and wild strawberry, are tolerant to or capable of recovering from aminopyralid. Results from the Cave Creek study site are in general concurrence with the findings of Halvstedt et al. (2010).

Ten weeks after the treatment in 2009, each of the 19 pin-flagged plants of mountain blue-eyed grass showed no visual signs of injury from aminopyralid and had already flowered and shed seeds. Based on the inventory conducted in 2011, six of the 72 split-plots present on the study site had flowering plants of mountain blue-eyed grass, and all

Table 3. Average stem density of Canada thistle (with standard errors [SE]) at 0, 1, and 2 years after treatment in 2009 and 2010 with aminopyralid at Cave Creek meadow near Trout Lake, WA. For the interaction of aminopyralid treatment and years after treatment (T×Y), row means followed by the same letter do not differ significantly ($P > 0.05$).

	Years after treatment						
	0	1		2			
Trmt. year	Avg.	Not treated	Treated	Not treated	Treated	SE	Significant effects[1]
	thistle stems m^{-2}						
2009	17.0	9.7	1.5	14.2	5.1	0.4	T×R×Y
2010	14.4	22.8 a	8.2 b	14.5 b	10.6 b	1.2	T×Y

[1] $P \leq 0.05$ from ANOVA; T = treated with aminopyralid, R = aminopyralid rate, and Y = yr after treatment.

Table 4. Average native and nonnative species richness (with standard errors [SE]) at 0, 1, and 2 years after treatment in 2009 and 2010 with aminopyralid at Cave Creek meadow near Trout Lake, Washington. For the interaction of aminopyralid treatment and years after treatment (T×Y), row means followed by the same letter do not differ significantly ($P > 0.05$).

		Years after treatment						
		0	1		2			
Nativity	Trmt. year	Avg.	Not treated	Treated	Not treated	Treated	SE	Significant effects[1]
		species m^{-2}						
Native	2009	7.3	7.6	5.2	7.9	5.7	0.3	T,Y
	2010	8.0	8.4 a	5.0 b	7.6 a	5.5 b	0.4	T×Y
Nonnative	2009	7.3	7.1 b	4.8 c	8.1 a	6.9 b	0.3	T×Y
	2010	6.6	7.8	6.5	7.7	6.4	0.2	T×R

[1] $P \leq 0.05$ from ANOVA; T = treated with aminopyralid, R = aminopyralid rate, and Y = yr after treatment.

of them occurred within the 48 split-plots of treatment year 2009. The number of flowers per split-plot averaged 0.2 ± 0.7 SE and it did not vary with aminopyralid treatment, rate, or their interaction ($P \geq 0.307$). These results confirm that no adverse effects on survival or flowering of mountain blue-eyed grass resulted from the aminopyralid treatments.

Species Released by Aminopyralid. Five species were released by aminopyralid: corn speedwell (*Veronica arvensis* L.), Kentucky bluegrass, selfheal (*Prunella vulgaris* L.), sheep fescue, and thymeleaf speedwell (*Veronica serpyllifolia* L.). Overall, Kentucky bluegrass had the largest release response, with absolute increases in foliar cover that averaged 17% and 20% for measurement years 1 and 2 of the two studies, respectively (Table 2). After treatment in 2009, increases in cover of sheep fescue were significant in year 2 (9%) but not in year 1 (4%). These results suggest that Kentucky bluegrass and sheep fescue continued to increase their cover from measurement year 1 to 2 to fully occupy the additional growing space made available from control of the dicot species. Almquist and Lym (2010) observed a similar increase in foliar cover of grasses (22%), including an increase in Kentucky bluegrass cover of 3% approximately 2 year after a September application of aminopyralid at 120 g ae ha^{-1} to a Canada-thistle-infested prairie in Minnesota. Samuel and Lym (2008) reported a 4% increase in cover of several native grass species two years after a September application of the same aminopyralid rate to a Canada-thistle-infested prairie in North Dakota.

Angular-transformed values of common selfheal cover had a significant quadratic relationship with aminopyralid rate in the second year after treatment in 2009 (Figure 3). In this response, observed covers of selfheal for aminopyralid rates of 30 to 90 g ae ha^{-1} (0.6 to 5.4%) differed little from that of non-treated plots (3.5%), but cover increased substantially for the 120 g ae ha^{-1} rate (11.6%). Such a response suggests that selfheal increased its cover only where the greatest reductions in dicot cover occurred – at the rate of 120 g ae ha^{-1} – given the linear response of dicot cover to aminopyralid rate described previously. In addition, this release response took two years to develop to the point at which it was statistically detectable.

After treatment in 2009, corn speedwell and thymeleaf speedwell each had greater foliar cover in treated plots than in non-treated plots for years 1 and 2, although the increases did not exceed 0.7% cover (Table 2). After treatment in 2010, a release response was observed for thymeleaf speedwell in year 1 but no detectable effect of treatment was observed for corn speedwell.

Species Richness. In both the first and second years after treatment in 2010, linear or quadratic relationships were detected between richness of native or nonnative species and aminopyralid rate (Figure 5). In the relationships for measurement year 2, richness differed little between plots treated with aminopyralid at 30 g ae ha^{-1} (7.7 to 8.5 species m^{-2}) and non-treated plots (7.5 to 7.7 species m^{-2}). A threshold response was observed in which richness of either native or nonnative species decreased abruptly by about 3 species m^{-2} after application of 60 g ae ha^{-1} of aminopyralid and then changed little with further increases in herbicide rate. Decreases in species richness from aminopyralid resulted primarily from control of the native species, common yarrow, chaparral willowherb, woodland buttercup, and American vetch and the non-native species, common mouseear chickweed, sheep sorrel, and white clover (Table 2). Almquist and Lym (2010) reported reductions in richness of 2.4 to 2.8 species m^{-2} 2 yr after a September application of aminopyralid at 120 g ae ha^{-1} in two Minnesota prairies. Samuel and Lym (2008) observed little to no detectable change in species richness two years after a similar treatment in two North Dakota prairies.

Aminopyralid was effective at controlling several nonnative, invasive plant species in the Cascade Mountain

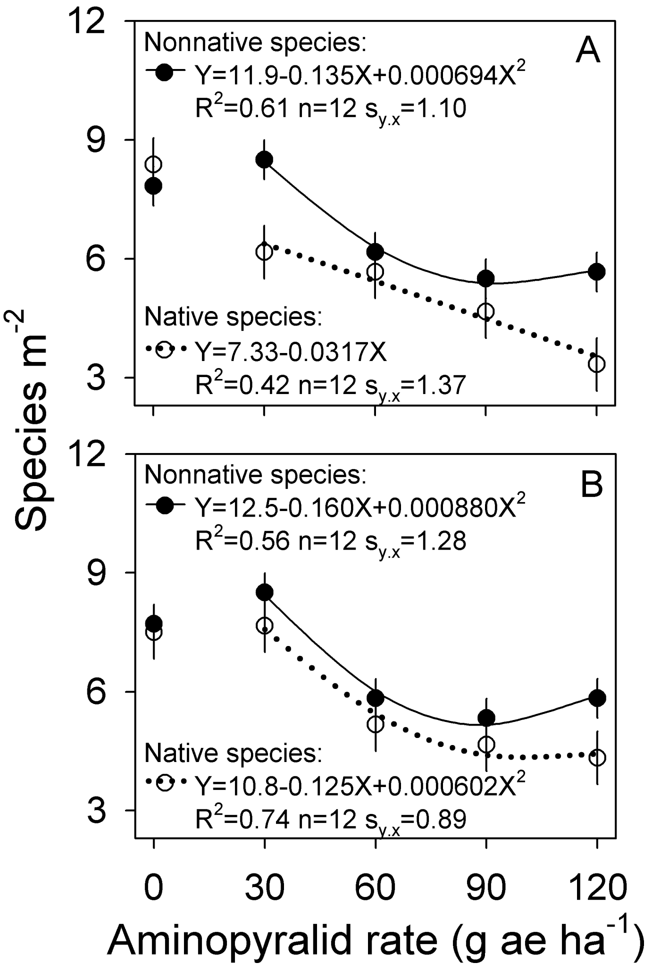

Figure 5. Regression relationships of species richness of native and nonnative plants (± SE) to aminopyralid rate at Cave Creek meadow near Trout Lake, WA for: (a) treatment year 2010, measurement year 1, and (b) treatment year 2010, measurement year 2. Models shown are for the only treatment year and measurement year combinations that had significant ($P \leq 0.05$) linear and quadratic effects of aminopyralid rate. Mean values for non-treated plots (aminopyralid rate = 0 g ae ha^{-1}) are shown for comparison purposes only.

meadow community at Cave Creek, including Canada thistle, oxeye daisy, sheep sorrel, and white clover, and thus, the herbicide demonstrated potential utility for restoring the native plant community. Control after an aminopyralid application of 30 g ae ha^{-1} was consistently greater for nonnative dicots than for native dicots; whereas, both species groups had significant control at the highest rates. In addition, richness of either native or nonnative species was not affected by an aminopyralid application of 30 g ae ha^{-1}. In combination, these results indicate that low rates of aminopyralid may be effective at shifting a Cascade meadow community towards less dominance by nonnative dicots and more dominance by native dicots. However, restoration success was limited by the presence of a dominant, nonnative monocot, Kentucky bluegrass, that was released regardless of aminopyralid rate because the herbicide was effective at controlling either nonnative dicots (low rates) or both nonnative and native dicots (high rates). A grass herbicide, such as fluazifop or sethoxydim, could be added to the treatment to control Kentucky bluegrass, although it is unlikely to control sheep fescue (Dunwiddie and Delvin 2006). Delayed development of nonnative dicots in 2010 clearly reduced efficacy of aminopyralid; whereas, some native dicots were susceptible to the herbicide regardless of treatment year. In addition, abundance of the native monocot, Hood's sedge, did not increase from treatment probably because of the substantial increases in cover of Kentucky bluegrass. Although timing of aminopyralid application was not studied, our research results suggest that July applications of aminopyralid may be more appropriate than June applications for controlling Canada thistle and other nonnative dicots in meadow ecosystems of the Cascades. However, a late-summer treatment timing (i.e., August or September) for aminopyralid may not be effective in Pacific Northwest plant communities because of reduced plant susceptibility to herbicides attributable to summer drought.

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