Herbicide Control Strategies for *Ventenata dubia* in the Intermountain Pacific Northwest

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Ventenata dubia is an exotic annual grass that has become increasingly invasive in various perennial grass systems throughout the Intermountain Pacific Northwest. Currently, little information is available to landowners about herbicide control options. In our first field study, we evaluated *V. dubia* control efficacy and perennial grass tolerance of herbicides applied pre-emergence (PRE) at two locations and as an early postemergence (EPOST) application at four different conservation reserve grasslands, with each grassland dominated by different perennial grass species. Treatments included flufenacet plus metribuzin (303 + 76 g ai ha^{-1} [0.27 + 0.07 lb ai ac^{-1}]), propoxycarbazone-sodium (49 g ai ha^{-1} [0.04 lb ai ac^{-1}]), rimsulfuron (53 g ai ha^{-1} [0.05 lb ai ac^{-1}]), sulfosulfuron (53 g ai ha^{-1} [0.05 lb ai ac^{-1}]), and imazapic (105 g ai ha^{-1} [0.09 lb ai ac^{-1}]). Rimsulfuron and flufenacet plus metribuzin applied PRE provided > 90% control 10 mo after treatment (MAT). Rimsulfuron and sulfosulfuron applied EPOST provided > 90% control 9 MAT. Herbicide injury to bluebunch and intermediate wheatgrass was negligible across treatments. Imazapic and sulfosulfuron applied EPOST resulted in significant injury to smooth brome and timothy. In our second study, we addressed the following question: Will fall herbicide plus fertilizer treatments improve *V. dubia* control compared with herbicide treatments alone? We imposed fall herbicide treatments in main plots and fertilizer treatments (fall N, fall P, fall K, fall PK, spring N, NPK) in split plots at three study locations. Herbicide treatments resulted in high levels of *V. dubia* control. Differences in *V. dubia* abundance among fertilizer treatments were negligible 9 MAT. Within herbicide control plots, spring N and NPK treatments resulted in significant increases in perennial grass cover and decreases in *V. dubia* cover (9 MAT). This result indicates that spring N applications timed to the onset of perennial grass growth could be utilized as a component of an integrated management strategy for *V. dubia* in invaded perennial grass systems.

Nomenclature: Flufenacet; imazapic; metribuzin; propoxycarbazone-sodium; rimsulfuron, sulfosulfuron; ventenata, *Ventenata dubia* (Leers) Coss. VENDU; bluebunch wheatgrass, *Pseudoroegneria spicata* (Pursh) Á. Love PSESP; intermediate wheatgrass, *Thinopyrum intermedium* Host THIIN; smooth brome, *Bromus inermis* Leyss. BROIN; timothy, *Phleum pratense* L. PHLPR.

Key words: Fertilization, integrated weed management, invasive plants.

Ventenata dubia (Leers) Coss is an exotic winter-annual grass in the Aveneae tribe within the Poaceae family that has invaded grassland ecosystems and hay pasture production systems in the Intermountain Pacific Northwest (Wallace et al. 2015). Although *V. dubia* has been present in this region since at least the 1950s (Barkworth et al. 1993), it has become a significant pest in the past decade within the Palouse Bioregion, which extends across west-central Idaho, southeastern Washington, and northeastern Oregon. Within the Palouse, land use patterns form an agricultural matrix comprising cereal cropping systems, Conservation Reserve Program (CRP) lands on erodable cropland, Palouse Prairie grassland remnants, and hay or pasture land on marginally productive cropland (Black et al. 1998).

Ventenata dubia invasion can produce nearly monotypic stands in CRP lands that were initially planted to monoculture or mixed stands of caespitose or rhizomatous perennial grasses. These monotypic stands of *V. dubia* leave soil prone to erosion because of its shallow root system (Scheinhost et al. 2009). This species is also a primary

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Management Implications

Ventenata dubia is an increasingly problematic invasive annual grass in the Intermountain Pacific Northwest. In the Palouse Bioregion, *V. dubia* has reduced forage production in hay and pasture, can negatively affect wildlife habitat and soil erosion management goals within Conservation Reserve Program (CRP) lands, and has invaded canyon grasslands and Palouse Prairie remnants. Currently, little information is available to land managers about how to control *V. dubia* across the range of perennial grass systems in which it invades. We used two field experiments to identify effective herbicide control options that also limit potential herbicide injury to perennial grass species and promote perennial grass competition. We evaluated flufenacet plus metribuzin (Axiom DF) at 303 + 76 g ai ha^{-1}, propoxycarbazone-sodium (Canter DG) at 49 g ai ha^{-1}, rimsulfuron (Matrix DG) at 53 g ai ha^{-1}, sulfosulfuron (Outrider DG) at 53 g ai ha^{-1}, and imazapic (Plateau SL) at 105 g ai ha^{-1} applied at PRE and EPOST application timings at two study sites and an EPOST application timing at four study sites. Rimsulfuron and flufenacet plus metribuzin provided the most consistent *V. dubia* control (> 90%) at the PRE timing. Rimsulfuron and sulfosulfuron provided the most consistent control (90%) at the EPOST timing. Sulfosulfuron can be used in grass hay, grazed rangelands and CRP lands, but our study demonstrated the potential for perennial grass injury to smooth brome and timothy. In comparison, rimsulfuron provided greater safety to perennial grasses but is restricted to nongrazed perennial grass systems. Our study also indicates that PRE applications of flufenacet plus metribuzin provide high levels of *V. dubia* control without injury to timothy, which provides an effective control option for timothy hay producers who have limited labeled control options. In our second field experiment, we evaluated various fertilizer treatments (NPK) with or without a fall herbicide application. Fertilizer treatments did not result in lower ventenata abundance (% cover) within the first growing season when used with herbicide applications. However, in the absence of an herbicide application, spring N only and NPK applications reduced *V. dubia* abundance because of increases in perennial grass competitiveness. These results suggest that N fertilization timed to the onset of perennial grass growth in the spring can be an important tool for managing *V. dubia*–invaded perennial grass systems.

invasion threat to intact Palouse Prairie grassland remnants (Nyamai et al. 2011). A recent study also indicates that *V. dubia* can host barley yellow dwarf virus (BYDV), which potentially facilitates BYDV infection of commercially important crops such as wheat and barley from *V. dubia* in adjacent CRP fields or prairie remnants (Ingwell and Bosque-Perez 2014). Finally, *V. dubia* negatively affects the productivity of mixed-grass or timothy hay systems because of decreased yields and loss of export markets (Fountain 2011).

Options for *V. dubia* control are needed given its current and potential effects in the Intermountain Pacific Northwest. A limited number of herbicides can provide effective control of winter annual grasses, but their use within perennial grass stands may be precluded by either labeling restrictions, site-specific factors that reduce herbicide efficacy, or variable tolerance of perennial grass species. Several strategies may be employed to optimize selective control of *V. dubia* within perennial grass–dominated stands. Selective control may be achieved by utilizing late fall herbicide applications that target *V. dubia* seedlings during a time when desirable perennial grasses are dormant, thereby decreasing herbicide injury to desirable grass species. In a field study of *V. dubia* emergence patterns within the Palouse Bioregion, 50% of total seedling emergence occurred between 33 and 94 growing degree days after soil moisture rose above the permanent wilting point in the fall, whereas a small fraction (1 to 13%) of total seedling emergence occurred in spring (Wallace et al. 2015).

Integrating herbicide treatments with fertilization strategies that maximize the productivity and competitiveness of perennial grass stands may also optimize *V. dubia* control. A recent study suggests that *V. dubia* is less efficient at assimilating nitrogen (N) under low and high N regimes compared with other exotic annual grasses and several perennial grass competitors (James 2008). Recently completed field experiments conducted in the Palouse Bioregion also found that soil phosphorous (P) and potassium (K) available to plants were lower in high-density *V. dubia* infestations compared with low-density infestations (Mackey 2014). Understanding the response of *V. dubia* to differing nutrient regimes under field conditions should help facilitate fertilization strategies that favor perennial grass stands invaded by *V. dubia*.

We conducted two field studies to aid development of *V. dubia* control strategies in the Palouse Bioregion. The objective of the first study was to evaluate *V. dubia* control with several herbicides and to evaluate the tolerance of resident perennial grasses to herbicide treatments. The objective of the second study was to evaluate the response of *V. dubia* and resident perennial grass species at field sites that differed in perennial grass composition to different fertility (NPK) inputs, with and without herbicide treatments, to determine how fertilization strategies may be integrated with *V. dubia* control strategies.

Materials and Methods

Herbicide Efficacy Field Trials. In 2011 and 2012, field trials were conducted at four locations to evaluate the effectiveness of herbicides for *V. dubia* control (Table 1). Two field trials were located near Moscow, ID, in adjacent CRP lands on silt loam soils with different primary (> 20% cover) perennial grass species: (1) intermediate wheatgrass (*Thinopyrum intermedium* Host) monoculture (Moscow-I) and (2) a mixed stand of smooth brome (*Bromus inermis* Leyss) and orchardgrass (*Dactylis glomerata* L.) (Moscow-II). The third field trial was located near

Table 1. Land use, soil texture, precipitation and description of dominant perennial grasses at study locations.[a]

Location	Land use	Soil texture	Precip[b]	Dominant perennial grasses (> 20% cover)
			cm	
Herbicide efficacy trials (2011–2012)				
Grangeville, ID	CRP	Loam	52 (56)	Timothy (PHLPR)
Anatone, WA	Grassland	Silt loam	43 (52)	Bluebunch wheatgrass (PSESP)
Moscow-I, ID	CRP	Silt loam	61 (68)	Smooth brome (BROIN), orchardgrass (DACGL)
Moscow-II, ID	CRP	Silt loam	61 (68)	Intermediate wheatgrass (THIIN)
Herbicide × fertility management trials (2012–2013)				
Moscow-III, ID	CRP	Silt loam	61 (58)	Smooth brome (BROIN), orchardgrass (DACGL)
Moscow-IV, ID	Mixed hay	Silt loam	61 (58)	Orchardgrass (DACGL)
Usk, WA	Timothy hay	Clay loam	52 (43)	Timothy (PHLPR)

[a] Abbreviations: Precip, precipitations; CRP, Conservation Reserve Program.

[b] Precipitation (cm) during 9-mo winter annual growing season window (October–June); 30-yr average is followed by precipitation for given study year in parentheses.

Grangeville, ID, on loam soils in CRP land in a 7-yr-old timothy (*Phleum pratense* L.) stand, which also contained several other perennial grass species at low abundance. Lastly, the fourth field trial was located near Anatone, WA, in conservation-reserved canyon grasslands on clay loam soils with a native stand of bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Love]. Mean precipitation from October to June, the approximate growing season of *V. dubia*, ranges from 43 to 61 cm yr^{-1} (17 to 24 in yr^{-1}) across study locations (Table 1). Each site had high *V. dubia* population densities, and the dominant perennial grasses at these trial locations encompass the majority of perennial grass species established in CRP lands, mixed grass hay, Palouse Prairie, and canyon grassland systems within this region.

At the two Moscow locations, we evaluated six herbicide treatments using a pre-emergent (PRE) an early postemergent (EPOST) application timing. The experimental design at the Moscow locations was a randomized complete block with a 2 by 6 factorial treatment structure arranged as a split plot with four replicates. Main plots (18 by 9 m; 60 by 30 ft) consisted of two application timings, PRE and EPOST. Split plots (3 by 9 m) consisted of the six herbicide treatments. Field trials at Grangeville and Anatone evaluated the same six herbicide treatments at only the EPOST application timing. Treatments were arranged as a randomized complete block with six EPOST herbicide treatments and four replicates. Plot size was 3 by 10 m.

Herbicide treatments included an untreated control, a commercial premix of flufenacet plus metribuzin (Axiom® DF, Bayer CropScience) at 303 + 76 g ai ha^{-1}, propoxycarbazone-sodium (Canter® DG, Wilbur-Ellis Company) at 49 g ai ha^{-1}, rimsulfuron (Matrix® DG, Dupont CropProtection) at 53 g ai ha^{-1}, sulfosulfuron (Outrider® DG, Monsanto Company) at 53 g ai ha^{-1}, and imazapic (Plateau® SL, BASF Corporation) at 105 g ai ha^{-1}. Preliminary field trials were performed or label recommendations were used to select an application rate for each herbicide treatment that provides activity on *V. dubia* or other exotic winter annual grasses while also minimizing perennial grass injury. A nonionic surfactant was added to each treatment at 0.25% (v/v), with the exception of imazapic, where methylated seed oil (MSO) was added at 1.0% (v/v). Herbicide treatments were broadcasted using a CO_2-pressurized backpack sprayer calibrated to deliver an application volume of 187 L ha^{-1} (20 gal ac^{-1}). PRE treatments were applied on October 10. EPOST treatments were applied between November 1 and 10 across field trials and occurred at the one- to two-leaf stage (1 to 2 cm) of *V. dubia.*

Foliar ground cover (%) was visually estimated in 1-m^2 (10.8 ft^2) gridded-quadrats (5% increments) at two fixed intervals (3 and 6 m) per plot along a lengthwise transect in mid-September to describe abundance of *V. dubia* (standing plant litter) and dominant perennial grasses by species at each study site. Cover estimates were taken again in July 2012 approximately 9 and 10 mo after treatments (MAT) for EPOST and PRE application timings, respectively. At this evaluation date, *V. dubia* control (%) was estimated relative to the untreated control. Control ratings considered differences in *V. dubia* population densities as well as plant fecundity. Perennial grass injury (%) was also estimated relative to the untreated control using plant height and the proportion of reproductive stems as indicators. Finally, cover was evaluated again in July 2013 to determine whether *V. dubia* control resulted in lower *V. dubia* and higher perennial grass abundance one growing season after herbicide treatments. At each evaluation date, cover of other plant species was estimated by functional group (annual forb, perennial forb, other annual grasses). Bare ground and plant litter were additionally estimated.

Herbicide by Fertilizer Management Field Trials. In 2012 and 2013, field trials were conducted at three locations to determine how fertilizer programs might influence *V. dubia* abundance with and without selective herbicide applications. Field trials were located in a 7-yr-old timothy hay stand in Usk, WA, a mixed grass hay stand primarily containing orchardgrass with several perennial grass species at lower densities in Moscow (Moscow-IV), and a mixed-grass CRP stand containing primarily smooth brome and orchardgrass in Moscow (Moscow-III) (Table 1).

The experimental design was a randomized complete block with a 2 by 7 factorial treatment structure arranged as a split plot design with four replicates. Main plots (21 by 6 m) consisted of a selective herbicide and an untreated control. Herbicide treatments were based on previous herbicide efficacy field trial results and label restrictions. Sulfosulfuron (53 g ai ha^{-1}) was applied EPOST (October 20) at the mixed hay and CRP sites, and flufenacet plus metribuzin (303 + 76 g ai ha^{-1}) was applied PRE (November 2) at the timothy hay location. Split plots (3 by 6 m) consisted of seven fertilizer treatments (fall N, fall P, fall K, fall PK, spring N, NPK, and an untreated control). A standard soil fertility test and a local grass pasture fertilization guide (Mahler 2005) were used to determine application rates for a full NPK fertilizer application; components of the full NPK application were evaluated in individual treatments in the field study. Fertilizer recommendations differed slightly across study sites, so the same rate was applied across all field trials. The full NPK treatment consisted of 89 kg P ha^{-1} (80 lb P $ac^{-}1$) and 134 kg K ha^{-1} (120 lb P ac^{-1}) applied in the fall as triple superphosphate and potash, respectively, and 45 kg N ha^{-1} (40 lb N ac^{-1}) applied as urea and split between fall and spring applications. Fall fertilizer applications were made between October 22 and 30, and spring fertilizer applications were made between April 11 and 17.

Foliar cover (%) of *V. dubia* and perennial grass was visually estimated in a 1-m^2 gridded quadrat (5% increments) permanently located within each split plot in mid-September at the CRP location. Plot establishment occurred after hay harvest at the other field trial locations. Consequently, these study sites were visually evaluated for uniform perennial grass and *V.dubia* abundance based on basal cover of perennial grasses and *V. dubia* litter. Cover was estimated in July 2013 to describe abundance of *V. dubia* and perennial grasses by species. Ground cover (%) of other species was estimated by functional group (annual forb, perennial forb, other annual grasses).

Statistical Analysis. For the herbicide efficacy trials, ANOVA was used to determine the effects of herbicide and application-timing treatments on *V. dubia* control, perennial grass injury, and foliar cover. Sites were first analyzed separately using general linear models in R 3.0 (aov package; R Core Team 2013) to evaluate the effect of herbicide treatment by application timing interactions at the Moscow locations and EPOST herbicide treatments at Grangeville and Anatone locations on *V. dubia* control and perennial grass injury. Repeated measures ANOVA was conducted to determine the effect of herbicide application on *V. dubia* and perennial grass cover across years at each site, using only the EPOST application timing. To provide statistical comparisons of herbicide treatment effects on *V. dubia* control across an environmental gradient, we then pooled data across sites and conducted ANOVAs by application timing using linear mixed effect models in R (lmer package). The Moscow trials were pooled for analysis of PRE treatments, and all trials were pooled for analysis of EPOST treatments. Site and block nested within site were used as a random effect. For the herbicide by fertilizer management field trials, ANOVAs were conducted by site to determine the effects of herbicide and fertilizer treatments on *V. dubia* and perennial grass cover 9 mo after treatment. All response variables were arcsine square root–transformed to meet the assumption of normality before analysis. Back-transformed means are presented. When significant main effects were detected ($P < 0.05$), mean separation tests were conduct using Fisher's protected LSD test ($\alpha \leq 0.05$).

Results and Discussion

Herbicide Efficacy Field Trials. Herbicide treatment was highly significant ($P < 0.001$) in analysis of *V. dubia* control after PRE treatments when pooled across sites (Figure 1). *Ventenata dubia* control with sulfosulfuron (53 g ai ha^{-1}), rimsulfuron (53 g ai ha^{-1}), and flufenacet plus metribuzin (303 + 76 g ai ha^{-1}) did not differ significantly, with control values ranging from 89 to 97%. These herbicide treatments resulted in greater *V. dubia* control compared with imazapic (105 g ai ha^{-1}) and propoxycarbazone-sodium (49 g ai ha^{-1}). In analysis of PRE treatments by site, comparisons among herbicides produced similar trends (Table 2). High levels of *V. dubia* control, coupled with low variability across sites, were observed with rimsulfuron (97 to 98%), sulfosulfuron (86 to 92%), and flufenacet plus metribuzin (90 to 93%). In comparison, *V. dubia* control varied considerably across sites with imazapic (63 to 83%) and propoxycarbazone-sodium (58 to 73%). Seedling emergence monitoring at

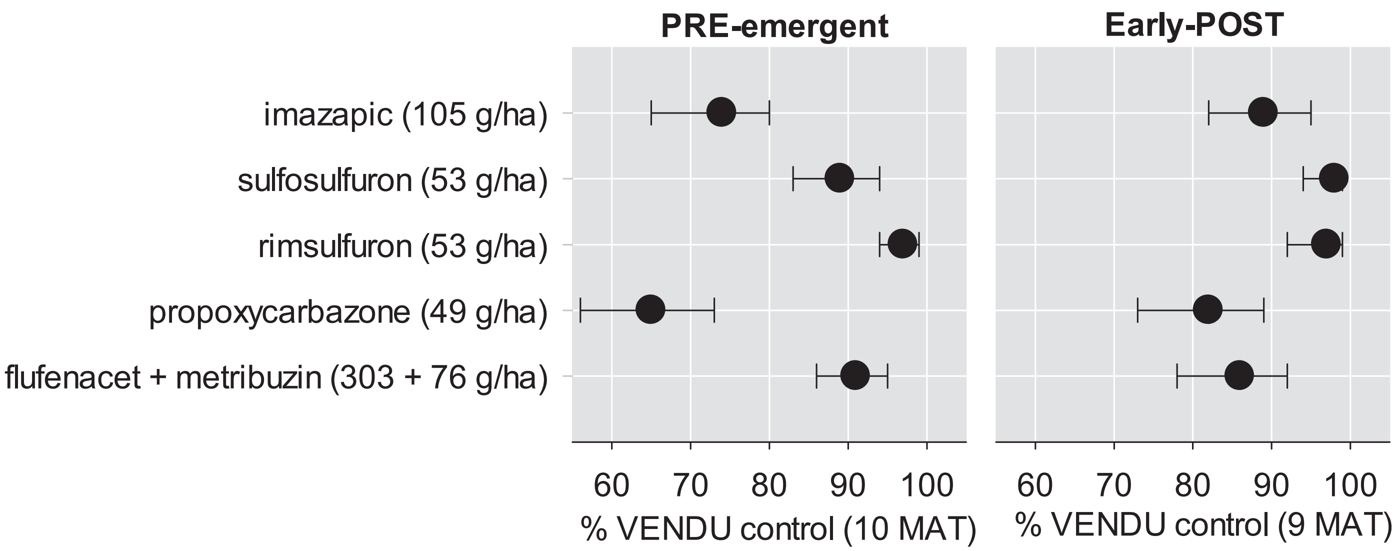

Figure 1. Effect of herbicide treatments applied pre-emergence (PRE) and early postemergence (EPOST) on *Ventenata dubia* (VENDU) control (%) approximately 10 and 9 mo after herbicide treatments (MAT), respectively. Error bars denote 95% confidence intervals. Data pooled across field trials.

the Moscow-I site indicated that PRE treatments occurred approximately 10 to 14 d before initial *V. dubia* seedling emergence at the Moscow locations.

Each EPOST herbicide treatment averaged > 80% control of *V. dubia*, when pooled across sites (Figure 1). *Ventenata dubia* control with sulfosulfuron (98%), rimsulfuron (97%), imazapic (89%), and flufenacet plus metribuzin (86%) did not differ signficantly. EPOST applications of propoxycarbazone-sodium resulted in significantly lower control levels (82%) compared with sulfosulfuron and rimsulfuron but did not differ from other EPOST treatments. Comparisons among EPOST treatments also produced similar trends when analyzed by site (Table 2). Control ratings ranged from 88 to 99% and 93 to 99% across study locations for rimsulfuron and sulfosulfuron, respectively, whereas imazapic resulted in more variable control levels, ranging from 72 to 95%. Propoxycarbazone-sodium and flufenacet plus metribuzin also resulted in variable levels of *V. dubia* control across study locations, ranging from 77 to 88% and 75 to 96%, respectively. In general, we observed higher levels of of *V. dubia* control across herbicides at the Anatone location, which had lower *V. dubia* infestations and received comparatively less late fall (October to December)

Table 2. *Ventenata dubia* control 10 and 9 mo after pre-emergent (PRE) and early postemergent (EPOST) herbicide treatments, respectively, at four locations with varying dominant or codominant perennial grass stands.

		Ventenata dubia control[a,b]					
		Moscow-I		Moscow-II		Grangeville	Anatone
Herbicide	Treatment	PRE	EPOST	PRE	EPOST	EPOST	EPOST
	g ai ha^{-1}	%					
Imazapic	105	83	91 (b)	63 e	72 de	95 a	92 ab
Sulfosulfuron	53	86	94 (b)	92 ab	93 ab	99 a	99 a
Rimsulfuron	53	98	98 (a)	97 a	88 a-d	99 a	99 a
Propoxycarbazone-sodium	49	73	79 (c)	58 e	83 b–d	88 a	77 b
Flufenacet + metribuzin	303 + 76	93	89 (b)	90 a–c	76 c–e	96 a	75 b

[a] Means within study sites followed by the same letter are not different at P = 0.05. Letters enclosed in parentheses denote means comparisons at the herbicide treatment level.

[b] *Ventenata dubia* control (%) based on ground cover and reproductive maturity relative to the nontreated control using a 0 to 100% scale.

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Table 3. Perennial grass injury 10 and 9 mo after pre-emergent (PRE) and early postemergent (EPOST) herbicide treatments, respectively, at four locations with varying dominant or codominant perennial grass stands.

		Perennial grass injury[a–c]					
		Moscow-I		Moscow-II		Grangeville	Anatone
		BROIN/DACGL		THIIN		PHLPR	PSESP
Herbicide	Treatment	PRE	EPOST	PRE	EPOST	EPOST	EPOST
	g ai ha^{-1}	%					
Imazapic	105	13	10 (a)	0 c	0 c	55 a	0 a
Sulfosulfuron	53	13	11 (a)	0 c	9 ab	16 b	5 a
Rimsulfuron	53	0	0 (b)	14 a	4 bc	20 b	3 a
Propoxycarbazone-sodium	49	8	1 (ab)	0 c	0 c	4 b	0 a
Flufenacet + metribuzin	303 + 76	0	0 (b)	0 c	0 c	0 b	0 a

[a] Abbreviations: BROIN/DACGL, smooth brome/orchardgrass; THIIN, intermediate wheatgrass; PHLPR, timothy; PSESP, bluebunch wheatgrass.

[b] Means within study sites followed by the same letter are not different at P = 0.05. Letters enclosed in parentheses denote means comparisons at the herbicide treatment level.

[c] Perennial grass injury (%) relative to the untreated control using a 0 to 100% scale.

precipitation (106 mm) than other locations (120 to 166 mm).

The timing of herbicide treatments (PRE, EPOST) was not significant ($P < 0.05$) in analysis of *V. dubia* control at the Moscow-I location (Table 2). However, a signifcant ($P < 0.05$) herbicide by application timing treatment was detected at the Moscow-II location. At this location, *V. dubia* control with propoxycarbazone-sodium was significantly greater when applied EPOST (83%) compared with PRE (58%). General trends suggest that EPOST treatments of imazapic, sulfosulfuron, and propoxycarbazone result in comparatively greater *V. dubia* control compared with PRE treatments. In contrast, flufenacet plus metribuzin and rimsulfuron applied PRE may result in comparatively greater *V. dubia* control than EPOST treatments.

Herbicide treatment was highly significant ($P < 0.001$) in analysis of perennial grass injury at each location, with the exception of Anatone, where low levels of injury to bluebunch wheatgrass were observed across treatments 9 MAT (Table 3). Both PRE and EPOST treatments of imazapic and sulfosulfuron resulted in observable levels (10 to 13%) of smooth brome and orchardgrass injury. Symptoms included stunted growth and decreased seedhead production relative to the untreated control for both species, although smooth brome injury was more pronounced. Smooth brome and orchardgrass injury were not observed after rimsulfuron and flufenacet plus metribuzin applications and was minimal (1 to 8%) after propoxycarbazone-sodium application. Both PRE and EPOST treatments of rimsulfuron and EPOST treatments of sulfosulfuron resulted in observable levels (4 to 14%) of injury to intermediate wheatgrass. Symptoms were limited to stunted growth compared with the untreated control. With the exception of flufenacet plus metribuzin, herbicides applied EPOST resulted in timothy injury 9 MAT. Imazapic applications resulted in significant injury (55%) to timothy. Symptoms included both stunting and decreased seedhead production. Sulfosulfuron and rimsulfuron resulted in 16 and 20% timothy injury, respectively.

A significant ($P < 0.05$) herbicide treatment by evaluation timing interaction was detected in analysis of *V. dubia* foliar cover across sites. In the spring after EPOST fall herbicide applications (9 MAT), each herbicide treatment resulted in significantly lower *V. dubia* cover (%) compared with the untreated control (Table 4). Differences among herbicide treatments at this evaluation timing closely followed observed differences in *V. dubia* control ratings. However, *V. dubia* cover in herbicide-treated plots did not differ from the untreated control 21 MAT (Table 4). Across sites, *V. dubia* cover significantly increased from 9 to 21 MAT or remained statistically similar within herbicide treatments. Notably, the change in *V. dubia* cover within untreated control plots was variable across sites, increasing at one location and decreasing at two locations. This result corresponds to general field observations, which suggest that interannual variation in *V. dubia* abundance is common, even within invaded sites supporting well-established *V. dubia* populations. At the Moscow-I location, perennial grass cover comprising smooth brome and orchardgrass was significantly greater ($P < 0.05$) at 21 MAT compared with 9 MAT across herbicide treatments, suggesting that the 8 to 19% average increase in cover was a product of productive growing conditions in the second year rather than a result of herbicide treatments. At the

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Table 4. Foliar cover (%) of *Ventenata dubia* 9 and 21 months after early postemergent herbicide treatments (MAT) at four locations with varying dominant or codominant perennial grass stands.

		Ventenata dubia foliar cover[a]							
		Moscow-I		Moscow-II		Grangeville		Anatone	
Herbicide	Treatment	9 MAT	21 MAT	9 MAT	21 MAT	9 MAT	21 MAT	9 MAT	21 MAT
	g ai ha^{-1}	%							
Imazapic	105	1 d	14 ab	29 b	19 bc	1 d	41 a-c	7 d	11 cd
Sulfosulfuron	53	2 d	14 ab	5 d	26 b	0 d	41 a-c	0 e	8 d
Rimsulfuron	53	0 d	17 ab	9 cd	33 b	0 d	56 a	1 e	13 cd
Propoxycarbazone-sodium	49	1 d	21 a	9 cd	29 b	4 d	32 bc	27 b	13 cd
Flufenacet + metribuzin	303 + 76	4 cd	19 a	20 bc	34 b	2 d	49 ab	18 bc	11 cd
Untreated control	—	10 bc	10 bc	60 a	27 b	28 c	42 a-c	57 a	7 cd

[a] Means within study sites followed by the same lowercase letter are not different at P = 0.05.

nearby Moscow-II location, a significant increase ($P < 0.05$) in intermediate wheatgrass cover was also observed in the second year (21 MAT), but interactions among herbicides and year were also detected. At this location, rimsulfuron and flufenacet plus metribuzin treatments resulted in higher perennial grass cover 9 MAT (43 and 37%, respectively) compared with the untreated check (28%). However, at 21 MAT, intermediate wheatgrass cover was significantly higher in imazapic-treated plots (47%) compared with other treatments (37 to 40%). At the Grangeville location, no herbicide treatment by evaluation timing effect was detected in analysis of timothy cover. However, general trends indicate that timothy injury following imazapic applications resulted in lower timothy cover (19%) in imazapic-treated plots 9 MAT when compared with timothy cover (24 to 45%) in other treatments. At the Anatone location, no differences were observed in bluebunch wheatgrass cover across herbicide treatments and evaluation timings.

The results of these field trials indicate that sulfosulfuron and rimsulfuron can provide satisfactory within-season control of *V. dubia* using either PRE or EPOST applications across a variety of perennial grass stands. EPOST applications may be preferrable to maximize herbicide residual activity during the late fall *V. dubia* emergence window, but producers may consider PRE applications if at least 90% *V. dubia* control can be achieved in areas with narrow late fall application windows. Our results also indicate that flufenacet plus metribuzin applied PRE provides high levels of *V. dubia* control.

Labeling restrictions and differences in perennial grass tolerance should be determing factors for the use of sulfosulfuron, rimsulfuron, and flufenacet plus metribuzin. As of 2015, sulfosulfuron can be applied in noncrop, CRP, rangeland, pasture, and grass hay fields using 14- and 30-d return intervals for grazing and hay harvest, respectively. Rimsulfuron was only labeled for use in noncrop, CRP, and rangeland where grazing did not occur. In certain regions, flufenacet plus metribuzin has been labeled for timothy hay and should provide high levels of *V. dubia* control and acceptable levels of crop safety with a PRE application timing. In recent years, *V. dubia* control options for timothy hay producers has been limited because of sensitivity of timothy to many annual grass herbicides.

In our study, sulfosulfuron did not injure wheatgrass species, but consistently injured smooth brome and timothy. These results are consistent with previous field observations as well as laboratory studies by Monaco and Creech (2004). Laboratory studies have shown that the persistence of sulfosulfuron decreases with increases in soil moisture levels (Arora 2009). Consequently, dry late fall and early spring conditions may result in greater perennial grass injury because of greater sulfosulfuron residual activity. Rimsulfuron is primarily used in summer annual field crops; thus, little is known about the susceptibility of perennial grasses to rimsulfuron.

Our observed levels of *V. dubia* control with imazapic are also consistent with several other studies that have demonstrated high, but sometimes variable, levels of downy brome (*Bromus tectorum* L.) and medusahead [*Taeniatherum caput-medusa* (L.) Nevski] control with imazapic, both invasive annual grasses with life history traits similar to *V. dubia* (Kyser et al. 2007; Monaco et al. 2005; Sbatella et al. 2011; Sheley et al. 2007). Reductions in imazapic efficacy for medusahead control has been attributed to the presence of medusahead litter at the soil surface (Kyser et al. 2007). Our results also support those of Mangold et al. (2013), who found consistently higher levels of downy brome control with EPOST (one- to two-leaf growth stage) applications of imazapic compared with PRE and POST (three- to four-leaf growth stage) applications in Montana rangelands.

Fall applications of several herbicides led to low levels of *V. dubia* abundance during the following growing season

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Table 5. Effect of herbicide and fertilizer treatments on foliar cover (%) of *Ventenata dubia* and perennial grasses at four locations 10 mo after treatment.

	Ventenata dubia and perennial grass foliar cover[a]								
	Moscow-III, ID			Moscow-IV, ID			Usk, WA		
Treatment	VENDU	BROIN/DACGL[b]		VENDU[c]	DACGL/ALOPR		VENDU	PHLPR/POAPR	
	%								
No herbicide									
No fertilizer	27	39	(27/12)	70 a	47	(37/10)	31	54	(49/5)
Fall N	27	38	(23/15)	62 ab	53	(45/8)	31	53	(50/3)
Spring N	16	55	(40/15)	42 cd	70	(67/3)	29	58	(49/9)
Fall P	20	44	(36/8)	58 ab	58	(51/7)	39	45	(42/3)
Fall K	25	38	(25/13)	49 bd	61	(55/6)	35	45	(42/3)
Fall PK	35	36	(20/16)	55 bc	64	(58/6)	25	37	(36/1)
NPK	26	38	(9/29)	35 d	75	(74/1)	16	74	(63/10)
Herbicide									
No fertilizer	6	49	(19/30)	7 e	66	(64/2)	3	51	(40/11)
Fall N	9	47	(44/3)	5 e	77	(72/5)	6	56	(51/5)
Spring N	2	54	(26/28)	7 e	69	(67/2)	12	52	(43/9)
Fall P	5	42	(31/11)	3 e	54	(51/3)	8	44	(40/4)
Fall K	4	37	(33/4)	6 e	64	(55/9)	6	51	(46/5)
Fall PK	5	48	(29/19)	9 e	62	(58/4)	3	52	(43/9)
NPK	6	40	(31/9)	3 e	75	(74/1)	10	72	(57/15)
Herbicide ($P < F$)	< 0.001	ns		< 0.001	< 0.01		< 0.001	ns	
Fertilizer ($P < F$)	ns	< 0.01		< 0.05	< 0.01		ns	< 0.01	
$H*F$ ($P < F$)	ns	ns		< 0.05	ns		ns	ns	

[a] Abbreviations: VENDU, *Ventenata dubia*; BROIN/DACGL, smooth brome/orchardgrass; DACGL/ALOPR, orchardgrass/meadow foxtail; PHLPR/POAPR, timothy/Kentucky bluegrass; ns, not significant; $H*F$, herbicide × fertilizer.

[b] Mean total perennial grass foliar cover is followed by mean cover by species in parentheses.

[c] Means within columns followed by the same letter are not different at P = 0.05. Mean separations only displayed for model with significant herbicide by fertilizer interactions.

(9 MAT). However, *V. dubia* increased across herbicide-treated plots the next growing season (21 MAT) at each of our study locations. Although not quantified, observations suggested that the residual activity of the selected herbicides did not provide complete control of spring-emerged cohorts, which can range from 1 to 13% of total emergence (Wallace et al. 2015). Visual assessments of *V. dubia* within herbicide-treated plots suggested that surviving plants were less fecund, a likely product of either late spring emergence or herbicide injury. These surviving plants and small but measureable contributions from the seedbank (Wallace et al. 2015) are likely sufficient to maintain *V. dubia* populations after a single herbicide application and suggests the need for sequential herbicide applications across more than one growing season. Moreover, we observed only small increases in perennial grass cover 9 MAT that could be contributed to release from *V. dubia* after herbicide control. These gains did not appear to result in greater competitive exclusion of *V. dubia* in the next growing season.

Herbicide by Fertility Management Field Trials. At the Moscow-III location, sulfosulfuron applied EPOST resulted in significantly lower *V. dubia* cover 9 MAT compared with the untreated herbicide control, ranging from 2 to 9% across fertilizer treatments (Table 5). However, no fertilizer or herbicide by fertilizer treatment effects were detected (P > 0.05). Fertilizer treatments did have a significant effect on perennial grass cover 9 MAT. Across herbicide treatments, spring N applications resulted in higher smooth brome and orchardgrass cover (54 to 55%) compared with other fertilizer treatments (36 to 48%), which did not differ from the untreated checks (39 to 49%; Table 5). At the Moscow-III location, smooth brome was generally more abundant than orchardgrass, which was patchy across the study site. Consequently, we have refrained from

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drawing inferences about species-specific responses to fertilizer treatments. Although not statistically different, spring N applications did result in lower *V. dubia* cover (16%) compared with other fertilizer treatments and the control (20 to 35%) in no-herbicide plots, which indicates that the observed increases in perennial grass cover after spring N applications resulted in lower *V. dubia* abundance.

At the Moscow-IV location, sulfosulfuron applied EPOST also resulted in significantly lower *V. dubia* cover 9 MAT compared with the untreated herbicide control, ranging from 3 to 7% across fertilizer treatments (Table 5). As a result, fertilizer treatments did not affect *V. dubia* cover 9 MAT within herbicide treatment plots. Within untreated herbicide controls, however, each fertilizer treatment except for fall N and fall P applications resulted in significantly lower *V. dubia* cover compared with the untreated fertilizer control. Notably, NPK applications decreased *V. dubia* cover 35%, and fall K and PK applications decreased *V. dubia* cover 15 to 21% compared with the fertilizer control. At this location, perennial grass cover was signficantly higher in herbicide-treated plots compared with the untreated herbicide control (Table 5). Across herbicide treatments, NPK applications resulted in greater perennial grass cover (75%) compared with other fertilizer treatments, with the exception of the spring N treatment. Perennial grass response to fertilizer treatments was primarily a function of increased orchardgrass tillering; meadow foxtail was a minor component (1 to 10%) across fertilizer treatments.

At the Usk location, flufenacet plus metribuzin applied PRE resulted in significantly lower *V. dubia* cover compared with the untreated control, ranging from 3 to 12% across fertilizer treatments (Table 5). No fertilizer or herbicide by fertilizer treatment effects were detected ($P > 0.05$). Fertilizer applications did significantly affect perennial grass cover. Across herbicide treatments, NPK applications resulted in higher perennial grass cover (72 to 74%) compared with other fertilizer treatments, which did not differ from the unfertilized control (Table 5). At this location, perennial grass response to fertilizer treatments was primarily a function of increased timothy tillering. Kentucky bluegrass (*Poa pratensis* L.) was present at low levels (1 to 15% cover). Notably, although not statistically different, *V. dubia* cover was lower (16%) in NPK plots compared with other treatments (25 to 39%) in the no-herbicide control treatments. The timothy cover response to NPK within no-herbicide plots (74%) compared with other treatments (37 to 58%) indicates that maximizing timothy productivity with fertility inputs has the potential to decrease *V. dubia* abundance within the crop growing season.

The results of our study suggest that timely applications of N at the onset of spring perennial grass growth can increase perennial grass crop competitiveness with *V. dubia*. Interactions among perennial grass and *V. dubia* abundance in response to P and K applied alone or in combination were too variable across study locations to make strong conclusions with regard to management recommendations. However, NPK treatments resulted in the highest level of perennial grass cover at two of three sites. Notably, we observed positive increases in perennial grass cover at field sites with high *V. dubia* abundance (27 to 70% cover). This result supports the observations of James (2008), who found *V. dubia* to be less efficient at N assimilation under high N regimes compared with other exotic annuals and perennial grasses. Manipulation of fertilization timing, placement, and nutrient source has been shown to increase crop competitiveness if the basic mechansims and timing of nutrient uptake that influence weed–crop interactions are well understood (DiTomaso 1995). We suggest that manipulation of fertilization strategies has the potential to improve *V. dubia* management by increasing perennial grass competitiveness, particularly in CRP, pasture, and haylands. However, further research is needed to elucidate the role of nitrogen cycling in *V. dubia* invasion dynamics in perennial grasslands.

Further studies are needed to determine multitactic control strategies that have the potential to reduce *V. dubia* seedbanks significantly within invaded perennial grass systems. Recent laboratory research has demonstrated that aminopyralid, a synthetic auxin herbicide, can reduce *V. dubia* seed production by 95% when applied at the seedling stage (Rinella et al. 2014). If similar results can be achieved under field conditions, aminopyralid applications targeting spring-emerged *V. dubia* seedlings may provide an effective *V. dubia* control option that also provides more desirable crop safety to perennial grasses than other available herbicides. Additional field research is needed to explore other management tactics, such as alternative spring-timed *V. dubia* control strategies, that can be integrated with the control strategies described here to further improve *V. dubia* control in invaded perennial grass systems.

In summary, the results of our studies indicate that the use of rimsulfuron, sulfosulfuron, and flufenacet plus metribuzin applied in the fall at a PRE or EPOST application timing provide within-season (1 yr) control of *V. dubia* across a range of perennial grass systems. Label restrictions and the potential for injury to specific perennial grass species should dictate herbicide selection. The addition of fertilizer did not improve within-season control of *V. dubia*, but our results suggest that spring N applications timed to the onset of perennial grass growth can increase the competitiveness of several perennial grass species, leading to decreased *V. dubia* abundance. Consequently, spring fertilization should be a useful tool in longer term *V. dubia* management plans.

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