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Author for correspondence:
Drew J. Lyon, Professor, Department of Crop and Soil Sciences, Washington State University, PO Box 646420, Pullman, WA 99164-6420.
Email: drew.lyon@wsu.edu

Russian thistle (*Salsola tragus* L.) control with soil-active herbicides in no-till fallow

Drew J. Lyon[1], Judit Barroso[2], Mark E. Thorne[3], Jennifer Gourlie[4] and Larry K. Lutcher[5]

[1]Professor, Department of Crop and Soil Sciences, Washington State University, Pullman, WA, USA; [2]Assistant Professor, Columbia Basin Agricultural Research Center, Oregon State University, Adams, OR, USA; [3]Associate in Research, Department of Crop and Soil Sciences, Washington State University, Pullman, WA, USA; [4]Research Assistant, Columbia Basin Agricultural Research Center, Oregon State University, Adams, OR, USA and [5]Professor, Morrow County Extension, Oregon State University, Heppner, OR, USA

Abstract

The benefits of no-till fallow, which include reduced soil erosion, improved soil health, and increased stored soil water, are in jeopardy because of the widespread development of glyphosate resistance in Russian thistle. The objective of this research was to evaluate the efficacy of soil-active, residual herbicides for Russian thistle control in no-till fallow. The combinations of sulfentrazone + carfentrazone and flumioxazin + pyroxasulfone, and metribuzin alone were each applied in late fall, late winter, and split-applied in late fall and late winter at three sites: Adams, OR, in 2017–2018; Lind, WA, in 2018–2019; and Ralston, WA, in 2019–2020. All treatments provided good to excellent control of the initial flush of Russian thistle when assessed in mid-May, except the late-fall application of metribuzin at all three sites, and the late-fall application of sulfentrazone + carfentrazone at Adams. Cumulative Russian thistle densities, evaluated monthly throughout the fallow season, were lowest for the sulfentrazone + carfentrazone treatments, except for the late-fall application at Adams. However, flumioxazin + pyroxasulfone and metribuzin provided greater control of tumble mustard and prickly lettuce than did sulfentrazone + carfentazone. Sulfentrazone + carfentrazone, flumioxazin + pyroxasulfone, and metribuzin can all be used for Russian thistle control in fallow. To reduce the risk for crop injury to subsequently planted winter wheat, a late-fall application of sulfentrazone + carfentrazone may be the preferred treatment in low-rainfall regions where winter wheat–fallow is commonly practiced. A late-winter application may be preferred in higher rainfall regions where a 3-year rotation (e.g., winter wheat–spring wheat–fallow) is common. Flumioxazin + pyroxasulfone should be considered if other broadleaf weeds, such as tumble mustard or prickly lettuce, are of concern. The use of these soil-applied herbicides will reduce the need for the frequent application of glyphosate for Russian thistle control in no-till fallow.

Introduction

Farmers rely on a preceding year of either tilled or no-till fallow to store water for wheat production in the low precipitation (<300 mm/yr) zone of east and south-central Washington and north-central Oregon (Hammel et al. 1981; Higginbotham et al. 2013; Schillinger and Young 2004). Precipitation in this zone, which is one of the largest contiguous dryland wheat–producing regions in the world, occurs mostly during winter (Schillinger and Papendick 2008; Schillinger et al. 2010). Summers are dry and warm or hot (Hagerty et al. 2019). Russian thistle thrives in this water-limited environment. It is one of the most troublesome weeds found in no-till fallow (Barroso et al. 2019; Lutcher 2015; Schillinger and Young 2000; Young 1986).

Russian thistle is a summer-annual broadleaf plant that, if left uncontrolled, develops an extensive root system (Pan et al. 2001; Schillinger 2007) and prolific aboveground biomass (Schillinger 2007). Individual plants can produce more than 40,000 seeds (Barroso et al. 2019). The lower stem of this tumbleweed species breaks off at ground level after the first hard (killing) frost in October or November. Seeds fall off the detached carcass as it rolls across the landscape during wind storms that are common to the area (Stallings et al. 1995).

Russian thistle plants can extract large volumes of water (Beckie and Francis 2009; Schillinger and Young 2000), and delayed or ineffective control is costly because the following winter wheat yield can be reduced by as much as 400 kg ha^{-1} (Schillinger and Young 2000). Those who practice no-till fallow typically use repeated applications of glyphosate to control Russian thistle (Lutcher 2015). This weed control strategy is less effective than it once was because of ongoing development of resistance to glyphosate (Barroso et al. 2018; Kumar et al. 2017). This problem, which is exacerbated by long-known resistance to acetolactate synthase–inhibiting herbicides (Peterson 1999; Prather et al. 2000; Saari et al. 1992; Stallings et al. 1994) and suspected resistance to triazine herbicides (Holt and Lebaron 1990; Warwick et al. 2010), may be a precursor to

Table 1. Sites, weed species evaluated, soil characteristics, and herbicide application dates.

Site (coordinates)	Year	Species counted	Soil series and texture	Organic matter	Soil pH	Late fall application date	Late winter application date
				%			
Horse Heaven, WA (46.11°N; 119.53°W)	2019	Prickly lettuce	Ritzville silt loam	1.0	6.5	11/26/2018	3/29/2019
Lind, WA (47.00°N; 118.56°W)	2019	Russian thistle; tumble mustard	Ritzville silt loam	2.1	5.9	11/28/2018	3/28/2019
Moro, OR (45.48°N; 120.73°W)	2019	Tumble mustard	Walla Walla silt loam	1.2	6.6	11/26/2018	3/26/2019
Adams, OR (45.72°N; 118.63°W)	2018	Prickly lettuce; Russian thistle; tumble mustard	Walla Walla silt loam	2.3	5.4	11/16/2017	3/12/2018
Adams, OR (45.72°N; 118.63°W)	2019	Prickly lettuce; tumble mustard	Walla Walla silt loam	2.3	5.4	11/15/2018	3/26/2019
Ralston, WA (46.99°N; 118.34°W)	2020	Russian thistle; tumble mustard	Ritzville silt loam	1.9	5.6	11/21/2019	2/21/2020

the gradual decline of no-till fallow. Reliance on tillage to control Russian thistle has resulted in soil erosion, degradation of the soil resource, and a reduction in air quality from windblown (<10 μm) particulate matter (Sharratt et al. 2010). Long-term sustainability of dryland fallow-based wheat production systems depends on the development of weed management plans that are less reliant on repeated applications of glyphosate. The objective of this research was to evaluate the efficacy of soil-active, residual herbicides for Russian thistle control in no-till fallow.

Materials and Methods

Field experiments were conducted at multiple sites during three fallow seasons from the fall of 2017 through summer of 2020 (Table 1). Three herbicides (sulfentrazone + carfentrazone [Spartan® Charge; FMC Corp., Philadelphia, PA]; flumioxazin + pyroxasulfone [Fierce®; Valent U.S.A. Corp., Walnut Creek, CA]; and metribuzin [Metribuzin 75, Loveland Products, Inc., Greeley, CO; or TriCor® DF, UPL NA, Inc., King of Prussia, PA]) were applied at 221 + 25, 106 + 134, and 552 g ai ha^{-1}, respectively, in the late fall, late winter, and as a 50% split application in the late fall and late winter. Herbicide treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} at 276 kPa. A check treatment, receiving no residual herbicide (only glyphosate or glyphosate + 2,4-D), was maintained for comparison purposes. The experimental design was a randomized complete block with four replications. Individual plots were 3 m wide by 9.1 or 10.7 m long.

Weed density was evaluated monthly from mid-May through mid-August. In mid-May, when weed densities were greatest, plants were counted on a per-species basis with either five 0.5-m^2 (OR sites) or two 1-m^2 (WA sites) randomly placed sampling frames $plot^{-1}$. Subsequent weed density evaluations were made by counting all plants within the entire plot area. Only Russian thistle density was evaluated after mid-May. Immediately after each weed density evaluation, all emerged plants were killed with either glyphosate applied at a rate of 1.26–1.89 kg ae ha^{-1}, glyphosate + 2,4-D ester at a rate of 2.52 + 0.385 kg ae ha^{-1}, or by hand, if weed density was low.

Winter wheat was then seeded on October 17, 2018, and October 15, 2019, at Adams and on September 17, 2019, at Moro. Winter wheat was evaluated in the fall and spring for crop injury symptoms. Grain was harvested using a plot combine. Grain samples were cleaned and weighed, and weights were converted to yield in kg ha^{-1}.

Russian thistle data for the May and cumulative (May + June + July + August) counts were analyzed using PROC GLIMMIX in SAS® statistical software (SAS Institute 2019). Count data on a square-meter basis were log transformed and analyzed in PROC GLIMMIX as a normal distribution using the Laplace method of maximum likelihood estimation. This transformation substantially reduced skewness, kurtosis, and heteroscedasticity of the studentized residuals. A significant ($P < 0.001$) interaction between location and treatment was found; therefore, data were analyzed separately by location, with block as the random effect and treatment as the fixed effect. Density counts for tumble mustard and prickly lettuce were also log transformed and analyzed using PROC GLIMMIX with a normal distribution and the Laplace method. Differences between treatments were compared with the PDIFF option of the least squares means (*lsmeans*) function at $\alpha = 0.05$. Data were back transformed for presentation in this article.

Grain yield data were tested for equal variance using the Levene test for homogeneity and for normality using the Shapiro-Wilk test. The data met the assumptions at $\alpha = 0.05$. Yield data were analyzed using PROC GLIMMIX in SAS as a normal distribution using the Laplace method of maximum likelihood estimation for each site. Block was treated as the random effect and treatment as the fixed effect. Means were compared to the check using the control option in the *lsmeans* function at $\alpha = 0.05$.

Results and Discussion

Russian thistle densities were great enough for evaluation at three of the six study sites: Adams, Lind, and Ralston. Precipitation varied across these sites (Figure 1), with Adams having the greatest precipitation during the course of the study (353 mm). Lind and Ralston had similar precipitation totals (164 and 185 mm, respectively), but Ralston received an unusually large amount of precipitation in May (61 mm). Russian thistle typically begins to emerge in the region in late April or early May, well after all herbicide treatments in this study were applied, and continues to emerge throughout the summer when sufficient rainfall is received.

Russian thistle Density in May

At Adams in 2018, Russian thistle density was reduced compared with the check with all application timings of sulfentrazone + carfentrazone and flumioxazin + pyroxasulfone (Table 2). Russian thistle density was not reduced relative to the check when

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Table 2. Russian thistle density in May of the fallow year at Adams, OR, in 2018; Lind, WA, in 2019; and Ralston, WA, in 2020.

Treatment	Rate	Timing	Russian thistle density[a]		
			2018	2019	2020
	g ai ha^{-1}			plants m^{-2}	
Check			15.3 a	14.7 a	2.7 a
Sulfentrazone + carfentrazone	221+24.5	Late fall	5.4 b	0.0 c	0.0 c
Sulfentrazone + carfentrazone	221+24.5	Late winter	0.0 d	0.0 c	0.0 c
Sulfentrazone + carfentrazone + sulfentrazone + carfentrazone	110+12.3	Late fall	0.5 d	0.0 c	0.0 c
	110+12.3	Late winter			
Flumioxazin + pyroxasulfone	106+134	Late fall	1.1 c	0.2 c	0.0 c
Flumioxazin + pyroxasulfone	106+134	Late winter	0.9 cd	0.4 c	0.2 c
Flumioxazin + pyroxasulfone + flumioxazin + pyroxasulfone	53+67	Late fall	0.0 d	0.0 c	0.0 c
	53+67	Late winter			
Metribuzin	551	Late fall	16.9 a	4.0 b	1.2 b
Metribuzin	551	Late winter	0.0 d	0.2 c	0.0 c
Metribuzin + metribuzin	276	Late fall	1.5 c	0.1 c	0.1 c
	276	Late winter			

[a]Within a column, means followed by the same letter are not significantly different (α = 0.05) according to the *lsmeans* function.

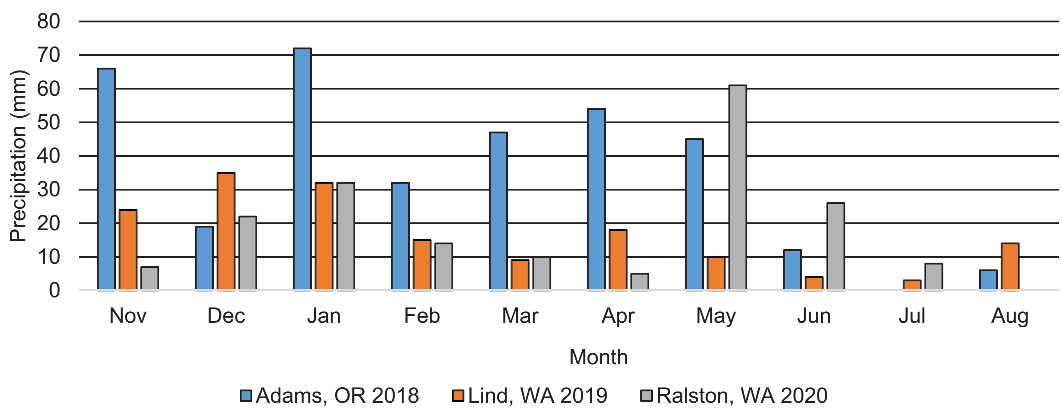

Figure 1. Total monthly precipitation from November through August at Adams, OR (2017–2018); Lind, WA (2018–2019); and Ralston, WA (2019–2020).

metribuzin was applied late fall. Metribuzin applied in late winter resulted in lower Russian thistle density than when it was applied in a split application. Russian thistle density was lower when sulfentrazone + carfentrazone was applied in late winter or in a split application than when applied in late fall. With flumioxazin + pyroxasulfone, Russian thistle density was lowest when it was applied in a split-application and greatest when applied in late fall. The late-winter application resulted in a Russian thistle density similar and intermediate to the other two flumioxazin + pyroxasulfone treatments (Table 2).

At Lind in 2019 and Ralston in 2020, all herbicide treatments resulted in reduced Russian thistle density compared with the check. However, Russian thistle density was greater in the late fall–applied metribuzin treatment than in all other herbicide treatments. At all three sites, Russian thistle density in May was greater in the late fall–applied metribuzin treatment than in all other herbicide treatments (Table 2).

Cumulative Russian thistle Density

A large majority of the Russian thistle plants at Adams emerged prior to the May census (Figure 2A). Russian thistle emergence in June, July, and August of 2018 occurred primarily in the check, the metribuzin treatments applied late fall or split-applied, and in the late-fall application of sulfentrazone + carfentrazone. No Russian thistle emergence was observed in June, July, or August when sulfentrazone + carfentrazone was applied in late winter. Kumar and Jha (2015) reported greater than 90% control of kochia [*Bassia scoparia* (L.) A.J. Scott] 8, 10, and 12 wk after the spring application of 210 g ai ha^{-1} of sulfentrazone in fallow near Huntley, MT. In May, no differences in Russian thistle density were observed among the five treatments with the lowest plant densities (Table 2). By August, cumulative Russian thistle densities were similar among the four treatments with the lowest plant densities: sulfentrazone + carfentrazone applied in late winter or split-applied, flumioxazin + pyroxasulfone split-applied, and metribuzin applied late winter (Figure 2A).

Similar to Adams in 2018, a large majority of the Russian thistle plants at Lind emerged prior to the May census (Figure 2B). No Russian thistle emergence was observed in August at Lind. In May, no differences in Russian thistle densities were observed at Lind among the eight treatments with the lowest densities (Table 2). By July, cumulative Russian thistle densities were similar among the four treatments with the lowest plant densities: all three sulfentrazone + carfentrazone treatments and the split-applied flumioxazin + pyroxasulfone treatment (Figure 2B).

Russian thistle densities at Ralston in 2020 were lower than at Adams in 2018 ($P = 0.011$) (Figure 2A and 2C). At Ralston, no differences in Russian thistle density in May were observed among the eight herbicide treatments with the lowest Russian thistle

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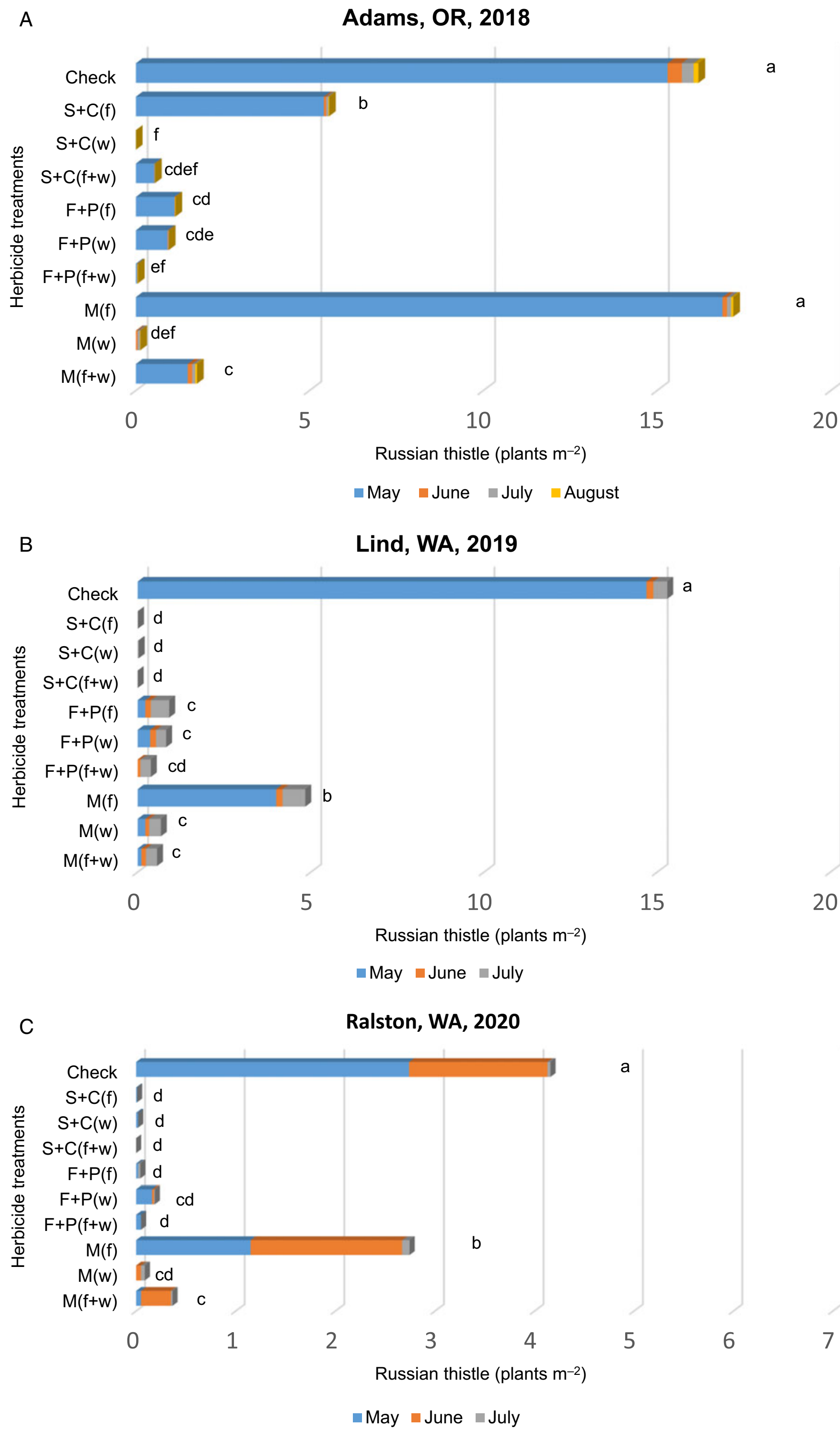

Figure 2. Cumulative Russian thistle density from May through August at (A) Adams, OR, in 2018; (B) Lind, WA, in 2019; and (C) Ralston, WA 2020. Bars followed by the same letter are not significantly different ($\alpha = 0.05$) according to the *lsmeans* function. Abbreviations: f, fall; F+P, flumioxazin + pyroxasulfone; f+w, split-applied fall and winter; M, metribuzin; S+C, sulfentrazone + carfentrazone; w, winter.

densities (Table 2). Russian thistle continued to emerge in June and July, particularly in the check and the treatment receiving metribuzin in late fall (Figure 2C). By July, cumulative Russian thistle densities were similar among the seven treatments with the lowest plant densities: all three application timings of sulfentrazone + carfentrazone and flumioxazin + pyroxasulfone, and the late-winter application of metribuzin.

Although the efficacy of sulfentrazone + carfentrazone for Russian thistle control was not affected by application timing at Lind or Ralston, efficacy was reduced at Adams when

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Table 3. Tumble mustard density in May of the fallow year at Adams, OR (averaged across 2018 and 2019); Moro, OR in 2019; and the average of Lind, WA, in 2019 and Ralston, WA, in 2020.

Treatment	Rate	Timing	Tumble mustard density[a]		
			Adams	Moro	WA[b]
	g ai ha^{-1}		plants m^{-2}		
Check			4.1 a	2.7 a	5.6 a
Sulfentrazone + carfentrazone	221+24.5	Late fall	1.4 b	2.6 a	1.0 b
Sulfentrazone + carfentrazone	221+24.5	Late winter	2.0 b	0.4 b	0.1 c
Sulfentrazone + carfentrazone + sulfentrazone + carfentrazone	110+12.3	Late fall	1.3 b	0.5 b	0.1 c
	110+12.3	Late winter			
Flumioxazin + pyroxasulfone	106+134	Late fall	0.0 c	0.0 b	0.0 c
Flumioxazin + pyroxasulfone	106+134	Late winter	0.0 c	0.0 b	0.0 c
Flumioxazin + pyroxasulfone + flumioxazin + pyroxasulfone	53+67	Late fall	0.0 c	0.0 b	0.0 c
	53+67	Late winter			
Metribuzin	551	Late fall	0.0 c	0.1 b	0.0 c
Metribuzin	551	Late winter	0.1 c	0.0 b	0.0 c
Metribuzin + metribuzin	276	Late fall	0.0 c	0.2 b	0.1 c
	276	Late winter			

[a]Within a column, means followed by the same letter are not significantly different ($\alpha = 0.05$) according to the *lsmeans* function.
[b]Data are the average of Lind, WA, in 2019, and Ralston, WA, in 2020.

sulfentrazone + carfentrazone was applied in late fall rather than late winter or split-applied. This may be explained partially by the greater precipitation received between the late-fall and late-winter applications at Adams (178 mm) compared to Lind (98 mm) and Ralston (68 mm). Sulfentrazone has a relatively high water solubility of 1,600 mg L^{-1} at a soil pH of 7.5 (Shaner 2014), which may have resulted in greater leaching of sulfentrazone from the seedling root zone at Adams than at the other two sites. Flumioxazin and pyroxasulfone have relatively low water solubility (1.79 and 3.49 mg L^{-1}, respectively) (Shaner 2014).

Like sulfentrazone + carfentrazone, the efficacy of flumioxazin + pyroxasulfone was not affected by application timing at Lind or Ralston, but application timing did affect efficacy at Adams (Table 2, Figure 2A). Russian thistle density was greater when flumioxazin + pyroxasulfone was applied in late fall than when it was applied in a split application.

The efficacy of metribuzin was affected by application timing at all three sites. Cumulative Russian thistle density was greatest when metribuzin was applied in late fall. At Adams, Russian thistle density was lowest when metribuzin was applied in late winter and intermediate when metribuzin was split-applied. At Lind and Ralston, the split application of metribuzin had cumulative Russian thistle densities similar to the late-winter application treatment. Metribuzin has a relatively high water solubility of 1,100 mg L^{-1} and a moderate half-life in soil of 30 to 60 d (Shaner 2014), which may partially explain its reduced efficacy on Russian thistle when applied in late fall, particularly at Adams, the site with the most precipitation.

Tumble Mustard and Prickly Lettuce

Although Russian thistle was the focus of this study, tumble mustard was evaluated in May at five sites (Adams in 2018 and 2019; Moro in 2019; Lind in 2019; and Ralston in 2020) and prickly lettuce was evaluated in May or June at three sites (Adams in 2018 and 2019; Horse Heaven, WA, in 2019). Both tumble mustard and prickly lettuce begin to emerge in fall and continue to emerge throughout the winter and early spring. There was a significant treatment by site interaction for tumble mustard ($P < 0.001$) and prickly lettuce ($P < 0.001$) density. However, we were able to pool tumble mustard data for Adams 2018 and 2019 ($P = 0.244$) and, despite a significant treatment by site interaction ($P = 0.001$) between Lind and Ralston, the treatment means separations were the same at both sites, so we pooled the data across both sites. The interaction was likely the result of plant density differences in the check (12.3 and 2.2 plants m^{-2}) and the late-fall application of sulfentrazone + carfentrazone (1.7 and 0.5 plants m^{-2}) at Lind and Ralston, respectively.

Flumioxazin + pyroxasulfone and metribuzin treatments reduced tumble mustard density compared with the check at all sites (Table 3). Tumble mustard densities in the sulfentrazone + carfentrazone treatments varied across sites. At Adams (2018 and 2019), tumble mustard density in all three sulfentrazone + carfentrazone treatments was less than in the check treatment but greater than any of the flumioxazin + pyroxasulfone or metribuzin treatments (Table 3). In Moro and at both Washington sites (Lind and Ralston), tumble mustard density in the late-winter and split-application treatments of sulfentrazone + carfentrazone was less than in the check and similar to the flumioxazin + pyroxasulfone and metribuzin treatments. Tumble mustard density in the late-fall application of sulfentrazone + carfentrazone was no different than the check at Moro; however, at the Washington sites, tumble mustard density in the late-fall application of sulfentrazone + carfentrazone was less than the check but greater than in any other herbicide treatment (Table 3).

Prickly lettuce density was lowest at all three sites in late-winter and split-applied treatments of flumioxazin + pyroxasulfone or metribuzin (Table 4). At Adams in 2018 and 2019, prickly lettuce density in all three sulfentrazone + carfentrazone treatments was similar to the check. At Horse Heaven, this was only the case with the late-fall application of sulfentrazone + carfentrazone. Prickly lettuce density was also not different from the check in the late-fall application of metribuzin treatment at Adams in 2018 and Horse Heaven (Table 4). At Adams in 2019, prickly lettuce density was greater in fall application treatments of flumioxazin + pyroxasulfone or metribuzin than in late-winter or split-applied treatments of either herbicide. This was not observed at the other two sites.

Late-fall treatments were included in this study because we were concerned about possible carryover effects in moisture-limited environments. We believed the late-fall treatments might increase the likelihood of significant postapplication rainfall and reduce the potential for injury to winter wheat planted in September or October of the following year. However, although late-winter

Table 4. Prickly lettuce density in May of the fallow year at Adams, OR, in 2018 and 2019, and Horse Heaven, WA, in 2019.

Treatment	Rate	Timing	Prickly lettuce density[a] Adams 2018	Adams 2019	Horse Heaven 2019
	g ai ha^{-1}		plants m^{-2}		
Check			4.9 a	23.5 a	3.3 a
Sulfentrazone + carfentrazone	221+24.5	Late fall	1.6 abc	22.0 a	2.8 a
Sulfentrazone + carfentrazone	221+24.5	Late winter	3.1 ab	15.2 ab	0.0 b
Sulfentrazone + carfentrazone + sulfentrazone + carfentrazone	110+12.3	Late fall	1.9 abc	22.0 a	0.0 b
	110+12.3	Late winter			
Flumioxazin + pyroxasulfone	106+134	Late fall	0.0 d	1.8 c	0.1 b
Flumioxazin + pyroxasulfone	106+134	Late winter	0.2 cd	0.4 d	0.0 b
Flumioxazin + pyroxasulfone + flumioxazin + pyroxasulfone	53+67	Late fall	0.2 cd	0.1 d	0.0 b
	53+67	Late winter			
Metribuzin	551	Late fall	4.2 a	8.8 b	2.4 a
Metribuzin	551	Late winter	0.8 cd	0.0 d	0.0 b
Metribuzin + metribuzin	276	Late fall	0.2 cd	0.0 d	0.0 b
	276	Late winter			

[a]Within a column, means followed by the same letter are not significantly different (α=0.05) according to the *lsmeans* function.

applications provided good to excellent control of Russian thistle with all three herbicides at all three sites (Figure 2A–2C), Russian thistle control was reduced with late-fall applications of metribuzin at all three sites and with sulfentrazone + carfentrazone at Adams.

No visible crop injury was observed in winter wheat planted after fallow at any of the sites (data not shown). Winter wheat grain yield data were collected at Adams in 2019 and at Adams and Moro in 2020. With one exception at Moro, no herbicide treatment resulted in a reduced grain yield compared to the check. At Moro in 2020, wheat grain yield following the late-winter application of sulfentrazone + carfentrazone was 3,000 kg ha^{-1} compared with 3,620 kg ha^{-1} following the check ($P = 0.021$). Unfortunately, we lack a second year of yield data from a site in the low-precipitation zone. Additional research is needed in the low-precipitation zone to confirm the risk for winter wheat yield reduction following a late-winter application of sulfentrazone + carfentrazone.

Sulfentrazone + carfentrazone provided excellent control of Russian thistle during the fallow season regardless of when it was applied at Lind and Ralston. The reduced efficacy of the late fall application of sulfentrazone + carfentrazone at Adams was likely the result of greater precipitation between November and March compared with Lind and Ralston (Figures 1 and 2). Late-fall applications of sulfentrazone + carfentrazone may be preferred in low-rainfall regions, where winter wheat–fallow is the predominant crop rotation, to reduce the risk for injury to the following winter wheat crop without losing efficacy on Russian thistle during fallow. Late-winter applications may be preferred in intermediate-rainfall regions where winter wheat–spring wheat–fallow is the predominate crop rotation. However, sulfentrazone + carfentrazone treatments generally provided poor control of tumble mustard and prickly lettuce, particularly at the Adams sites, which were the sites with the most precipitation. If broadleaf weeds other than Russian thistle are a concern, sulfentrazone + carfentrazone could be supplemented with late-winter applications of metribuzin.

Flumioxazin + pyroxasulfone provided excellent control of Russian thistle during the fallow season when it was split-applied and good control when it was all applied in late fall or late winter. Flumioxazin + pyroxasulfone also provided excellent control of tumble mustard and prickly lettuce (Table 4).

Metribuzin provided good to excellent control of Russian thistle during the fallow season when applied in late winter but poor control when applied in late fall. Russian thistle control was generally good when metribuzin was split-applied. Metribuzin provided excellent control of tumble mustard regardless of when it was applied, but prickly lettuce control was poor when metribuzin was applied in late fall. Metribuzin should only be applied in late winter for Russian thistle or prickly lettuce control in fallow.

The development and spread of glyphosate-resistant Russian thistle in the Pacific Northwest (Barroso et al. 2018; Kumar et al. 2017) is causing growers to find alternatives to glyphosate for Russian thistle control in fallow. Just as glyphosate-resistant kochia has growers in the US Great Plains using soil-residual herbicides as the foundation of kochia control (Kumar and Jha 2015), growers in eastern Oregon and Washington should consider soil-residual herbicides for Russian thistle control. Sulfentrazone + carfentrazone, flumioxazin + pyroxasulfone, and metribuzin can all be used for Russian thistle control in fallow. Their use will reduce the need for frequent glyphosate applications to control Russian thistle, which will reduce selection pressure for resistance to glyphosate. Where glyphosate-resistant Russian thistle is already present, it will be necessary to use these soil-applied herbicides to control Russian thistle in fallow.

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References

Barroso J, Gourlie JA, Lutcher LK, Liu M, Mallory-Smith CA (2018) Identification of glyphosate resistance in *Salsola tragus* in north-eastern Oregon. Pest Manag Sci 74:1089–1093

Barroso J, Lyon DJ, Prather T (2019) Russian thistle management in a wheat-fallow crop rotation. PNW 492, August. A Pacific Northwest Extension Publication. University of Idaho Cooperative Extension System, Oregon State University Extension Service, and the Washington State University Cooperative Extension System

Beckie HJ, Francis A (2009) The biology of Canadian weeds. 65. *Salsola tragus* L. (updated). Can J Plant Sci 89:775–789

Hagerty CH, Fickas KC, Wysocki D (2019) Agronomic zones of the dryland Pacific Northwest. PNW 354, March. A Pacific Northwest Extension Publication. University of Idaho Cooperative Extension System, Oregon

https://doi.org/10.1017/wet.2020.143 Published online by Cambridge University Press

State University Extension Service, and the Washington State University Cooperative Extension System

Hammel JE, Papendick RI, Campbell GS (1981) Fallow tillage effects on evaporation and seedzone water content in a dry summer climate. Soil Sci Soc Am J 45:1016–1022

Higginbotham RW, Jones SS, Carter AH (2013) Wheat cultivar performance and stability between no-till and conventional tillage systems in the Pacific Northwest of the United States. Sustainability 5:882–895

Holt JS, Lebaron HM (1990) Significance and distribution of herbicide resistance. Weed Technol 4:141–149

Kumar V, Jha P (2015) Effective preemergence and postemergence herbicide programs for kochia control. Weed Technol 29:24–34

Kumar V, Spring JF, Lyon DJ, Burke IC, Jha P (2017) Glyphosate-resistant Russian-thistle (*Salsola tragus*) identified in Montana and Washington. Weed Technol 31:238–251

Lutcher LK (2015) Delayed glyphosate application for no-till fallow in the driest region of the inland Pacific Northwest. Weed Technol 29:707–715

Pan WL, Young FL, Bolton RP (2001) Monitoring Russian-thistle (*Salsola iberica*) root growth using a scanner-based, portable mesorhizotron. Weed Technol 15:762–766

Peterson DE (1999) The impact of herbicide-resistant weeds on Kansas agriculture. Weed Technol 13:632–635

Prather TS, Ditomaso JM, Holt JS (2000) Herbicide resistance: definition and management strategies. Publication 8012. Oakland, CA: University of California, Division of Agriculture and Natural Resources

Saari LL, Cotterman JC, Smith WF, Primiani MM (1992) Sulfonylurea herbicide resistance in common chickweed, perennial ryegrass, and Russian thistle. Pest Biochem Phys 42:110–118

SAS Institute (2019) SAS OnlineDoc. Version 9.4. Cary, NC: SAS Institute

Schillinger WF (2007) Ecology and control of Russian thistle (*Salsola iberica*) after spring wheat harvest. Weed Sci 55:381–385

Schillinger WF, Papendick RI (2008) Then and now: 125 years of dryland wheat farming in the inland Pacific Northwest. Agron J 100:S166–S182

Schillinger WF, Papendick RI, McCool DK (2010) Soil and water challenges for Pacific Northwest agriculture. *In* Zobeck TM, Schillinger WF, eds. Soil and Water Conservation Advances in the United States. Special Publication 60:47–49. Madison, WI: Soil Science Society of America

Schillinger WF, Young FL (2000) Soil water use and growth of Russian thistle after wheat harvest. Agron J 92:167–172

Schillinger WF, Young FL (2004) Cropping systems research in the world's driest rainfed region. Agron J 96:1182–1187

Shaner DL, ed (2014) Herbicide Handbook. Tenth edn. Lawrence, KS: Weed Science Society of America. 513 p

Sharratt B, Wendling L, Feng G (2010) Windblown dust affected by tillage intensity during summer fallow. Aeolian Res 2:129–134

Stallings GP, Thill DC, Mallory-Smith CA (1994) Sulfonylurea-resistant Russian thistle (*Salsola iberica*) survey in Washington state. Weed Technol 8:258–264

Stallings GP, Thill DC, Mallory-Smith CA, Lass LW (1995) Plant movement and seed dispersal of Russian thistle (*Salsola iberica*). Weed Sci 43:63–69

Warwick SI, Sauder CA, Beckie HJ (2010) Acetolactate synthase (ALS) target-site mutations in ALS inhibitor-resistant Russian-thistle (*Salsola tragus*). Weed Sci 58:244–251

Young FL (1986) Russian thistle (*Salsola iberica*) growth and development in wheat (*Triticum aestivum*). Weed Sci 34:901–905

https://doi.org/10.1017/wet.2020.143 Published online by Cambridge University Press