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Russian thistle (*Salsola tragus*) postharvest control and plant dispersal

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Abstract

Russian thistle is one of the most important broadleaf weeds in the semiarid U.S. Pacific Northwest. It consumes soil water after wheat harvest, compromising the yield of the following crop. The objectives of this work were to determine the impact of post–wheat harvest herbicide application timing on Russian thistle control and of stubble height on Russian thistle postharvest control and plant dispersal. For the first objective, experiments were conducted at the Columbia Basin Agricultural Research Center, Adams, OR (CBARC), and the Lind Dryland Research Station, Lind, WA (LDRS), in 2020 and 2021. Herbicides evaluated included paraquat, glyphosate, and either bromoxynil + pyrasulfotole (CBARC) or bromoxynil + metribuzin (LDRS). The different post–wheat harvest application timings were 24 h and 1, 2, and 3 wk after harvest. For the second objective, two stubble heights (short and tall) were compared for their impact on control at CBARC and in a production field near Ione, OR. Paraquat provided the greatest control in all scenarios, with no differences in application timings or stubble height. Impacts of application timings were not clear for glyphosate or bromoxynil mixtures. For glyphosate treatments, control in short stubble was 11% greater than in tall stubble in both years. Control was also greater in short stubble for the bromoxynil + pyrasulfotole application in 2020. However, Russian thistle plant dispersal was greater in short stubble at both locations. At CBARC, plant dispersal in short stubble was 58%, compared to 18% in tall stubble. Near Ione, plant dispersal in flattened stubble was 88%, compared to 43% in nonflattened short stubble. Leaving tall stubble at harvest should be considered to reduce Russian thistle plant dispersal if the infestation is going to be left untreated after harvest; otherwise, short stubble might result in better Russian thistle control when using systemic herbicides, such as glyphosate.

Introduction

The rainfed cropping region of the U.S. inland Pacific Northwest (PNW) includes approximately 3.35 M ha of crops with average annual precipitation ranging from <300 to 600 mm (Schillinger 2020). The area is divided into cropping zones, depending on annual precipitation. For precipitation <300 mm, the most common crop rotation is winter wheat–fallow. The fallow period is used to accumulate soil moisture to maximize and stabilize yield of the following winter wheat crop seeded in September or October. Seventy percent of the annual precipitation falls from October to March (Schillinger 2020). For precipitation between 300 and 450 mm, a 3-yr rotation of winter wheat–spring crop–fallow can be another option to the winter wheat–fallow rotation. For higher-precipitation zones (>450 mm), annual cropping is also possible (Schillinger 2020). This research was concentrated in areas with <450 mm of annual precipitation, where Russian thistle is more problematic.

Water consumption by crop and weeds is an important component of the water balance in agroecosystems (Pivec and Brant 2009), especially in areas where water is the most limiting factor to ensure profitable yields, such as the low-precipitation areas of the inland PNW. To maximize crop available water, it is necessary to reduce water consumption by weeds not only during the crop cycle but during the fallow periods as well. Integrated weed management approaches can help to reduce water consumption by weeds by maintaining weed populations below harmful levels (Van Duivenbooden et al. 2000). These approaches integrate proactive long-term crop management decisions instead of reactive short-term interventions to avoid yield reductions in the crop (Moss 2019).

Russian thistle, a tumbleweed, is a dominant broadleaf weed in semiarid regions of the PNW, especially in no-till fallow fields (Barroso et al. 2019; Schillinger and Young 2000). This summer annual weed emerges from March to May, flowers in June through July, and produces viable

Table 1. Herbicide treatment, common name, trade name, formulation, application rate, and manufacturer evaluated for Russian thistle control in 2020 and 2021 and experimental sites in Adams, OR, and Lind, WA.

Treatment[a]	Site	Common name	Trade name	Formulation	Rate	Volume	Manufacturer
				g ai L^{-1}	g ai ha^{-1}	L ha^{-1}	
Bromoxynil + metribuzin	Lind	bromoxynil	Maestro® 4EC	480	560	187	Nufarm, Alsip, IL
		metribuzin	TriCor® 75 DF	75% AW/W	640	187	United Phosphorus, King of Prussia, PA
Bromoxynil + pyrasulfotole + NIS + Soln 32	Adams	bromoxynil + pyrasulfotole	Huskie™	210 bromoxynil + 37 pyrasulfotole	230 + 41	94	Bayer Crop Science, Triangle Park, NC
Glyphosate + AMS	Lind	glyphosate	RT 3®	660	3.1	94	Bayer Crop Science
Glyphosate + Flashpoint	Adams	glyphosate	Gly Star® Extra	648	3.2[b]	94	Albaugh, Ankeny, IA
Paraquat SL 2.0 + NIS	Adams, Lind	paraquat	Gramoxone® SL 2.0	240	841	187	Syngenta Crop Protection, Greensboro, NC

[a]NIS, nonionic surfactant at 0.25% v/v; Soln 32, liquid nitrogen 32% (32-0-0) as urea and ammonium nitrate solution at 2.5% v/v; AMS, ammonium sulfate 100%, 7.7 kg/380 L spray solution; Flashpoint, water conditioning, humectant, activator, 2.84 L/380 L.
[b]Rate is kg ai ha^{-1}.

seeds by mid-September (Schillinger 2007). In severe infestations, spring wheat yield can be reduced by between 20% and 50%, depending on precipitation (Young 1988). However, competition with this weed does not end at harvest. After wheat harvest in midsummer, this weed accelerates root elongation (Pan et al. 2001) as well as aboveground biomass growth and consumes 60% of the water taken during its entire life cycle, reducing soil water availability for the next crop (Schillinger and Young 2000).

Water consumption by Russian thistle after harvest, as well as seed production, can be prevented by controlling it postharvest in July or August, when it was not possible to control it in-crop (sometimes the late germination of Russian thistle prevents its control in-crop because of the advanced growth stage of the crop). After harvest, no-till growers try to control Russian thistle with herbicides, particularly with glyphosate, but the efficacy of this herbicide is decreasing owing to the increasing number of glyphosate-resistant biotypes in the region (Kumar et al. 2017; Barroso et al. 2018). Another widely adopted control option is the use of tillage. However, owing to its negative effects, such as increased soil erosion, reduction of soil organic matter, increased water evaporation, and high fuel use, the challenge for growers and researchers is to find different strategies and herbicides to reduce Russian thistle populations in no-till systems.

Several scientists found that the application of paraquat + diuron herbicides 7 d after harvest provided similar control to tillage and better control than applying glyphosate (Schillinger 2007; Young et al. 2008). However, herbicide efficacy can vary depending on several factors, such as weather, soil moisture status, or plant size. In general, when plants increase in size, herbicide efficacy decreases because of the reduced amount of active ingredient per biomass, cuticle thickening, and wax accumulation on leaves (Kirkwood 1999; Harbour et al. 2003). Thicker cuticles are less permeable to foliar-applied herbicides, reducing their effectiveness (Menendez et al. 2014). Although big plants are not easy to control with herbicides, if Russian thistle plants are left untreated after harvest, they will deplete soil water, produce seeds, and produce new infestations in their current and surrounding fields. At harvest, Russian thistle loses a significant part of its biomass and might be more susceptible to herbicides. It is important to determine if there is an optimum time to control Russian thistle postharvest that could maximize herbicide efficacy.

Furthermore, because Russian thistle seed survival in the soil seedbank is very short (less than a year) (Burnside et al. 1996), avoiding new seed entrances into the seedbank would help to reduce Russian thistle seedbank size. Therefore weed management practices that reduce Russian thistle plant movement to new sites would help to minimize the colonization of new areas or fields and quickly diminish the infestation in the current field if adequate management is applied in the following years. A single Russian thistle plant can produce more than 50,000 seeds (Stallings et al. 1995; Beckie and Francis 2009), and when the plant dies, the main stem breaks near the soil surface, leaving the plant free to roll and tumble with the wind, dispersing seeds in a range of 60 to 4,000 m from its original position (Stallings et al. 1995). Finding agricultural practices that prevent or reduce Russian thistle plant movement from its original spot (herein after referred to as plant dispersal) could help to decrease the infestation of this species in the PNW, because seed dispersion by tumbling plants is 37% higher than it is by stationary plants (Stallings et al. 1995).

The objectives of this study were to determine (1) the impact of postharvest herbicide application timing on Russian thistle control and (2) the impact of stubble height on Russian thistle postharvest control and plant dispersal.

Materials and Methods

Impact of Herbicide Application Timing on Russian Thistle Control

In 2020 and 2021, field experiments were conducted at the Columbia Basin Agricultural Research Center (CBARC) in Adams, OR (45.72°N, 118.63°W), and at the Lind Dryland Research Station (LDRS) in Lind, WA (47.00°N, 118.57°W). CRARC is located in the intermediated-precipitation zone (300 to 450 mm), whereas LDRS is located in the low-precipitation zone (<300 mm). At CBARC, Russian thistle seeds were spread on the soil surface in the experimental site on March 24, 2020, at a rate of 0.43 g m^{-2} and on March 10, 2021, at a rate of 0.11 g m^{-2}. At LDRS, experiments had natural Russian thistle infestations. The experimental design was a randomized split-plot block design at CBARC with four replicates, where the main plots were the application time after spring wheat (cultivar 'Ryan') harvest (untreated, 1 d after harvest [DAH], 1 wk

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Table 2. Environmental conditions (temperature, humidity, and wind speed) at the application times at the Columbia Basin Agricultural Research Center, Adams, OR, and the Lind Dryland Research Station, Lind, WA, in 2020 and 2021.[a]

Site	Year	Application date	Temperature	Humidity	Wind speed
			C	%	km h^{-1}
CBARC	2020	7 Aug	13.3	61	8
		14 Aug	11.1	40	5
		21 Aug	13.8	62	6
		28 Aug	8.9	65	3
	2021	28 Jul	21.3	59	5
		3 Aug	19.9	56	3
		10 Aug	10.8	62	3
		19 Aug	8.6	79	3
LDRS	2020	4 Aug	30.0	26	10
		11 Aug	23.3	28	10
		18 Aug	30.6	36	7
	2021	16 Jul	31.1	28	13
		23 Jul	26.1	22	13
		30 Jul	33.9	22	10

[a]Abbreviations: CBARC, Columbia Basin Agricultural Research Center; LDRS, Lind Dryland Research Station.

after harvest [WAH], 2 WAH, and 3 WAH) and the subplots were the herbicides tested (glyphosate, paraquat, and mixture of bromoxynil with metribuzin or pyrasulfotole)). The experimental design at LDRS was a randomized complete block design with four replicates. Specifications for the herbicide treatments applied at CBARC and LDRS can be found in Table 1.

At CBARC, herbicides were applied on August 7, 14, 21, and 28 in 2020 and on July 28 and August 3, 10, and 19 in 2021, corresponding to 24 h, 1 WAH, 2 WAH, and 3 WAH, respectively. Environmental conditions were collected at every application time (Table 2). Plot size was 4.3 × 27.3 m, and subplots were 4.3 × 9.1 m. Applications were made using a 4.3-m hooded sprayer with flat-fan nozzles (XR 11002, TeeJet® Technologies, Wheaton, IL, USA) calibrated to deliver 187 L ha^{-1} for paraquat and 94 L ha^{-1} for glyphosate and the premixture bromoxynil + pyrasulfotole. Visual Russian thistle control evaluations were conducted at 3 and 6 wk after treatment (WAT) using a scale of 0% (no control) to 100% (complete death).

At LDRS, in 2020, herbicides were applied on August 4, 11, and 18, corresponding to 1, 2, and 3 WAH (the 24-h timing was not used at this location). Environmental conditions were collected at every application time (Table 2). In 2021, herbicides were applied on July 16, 23, and 30, corresponding to 2, 9, and 16 DAH. Plot size was 3 × 10.5 m. Except for glyphosate, herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (XR 8004, TeeJet® Technologies) and calibrated to deliver 187 L ha^{-1}. Glyphosate was applied with flat-fan nozzles (XR 80015, TeeJet® Technologies) and calibrated to deliver 94 L ha^{-1}.

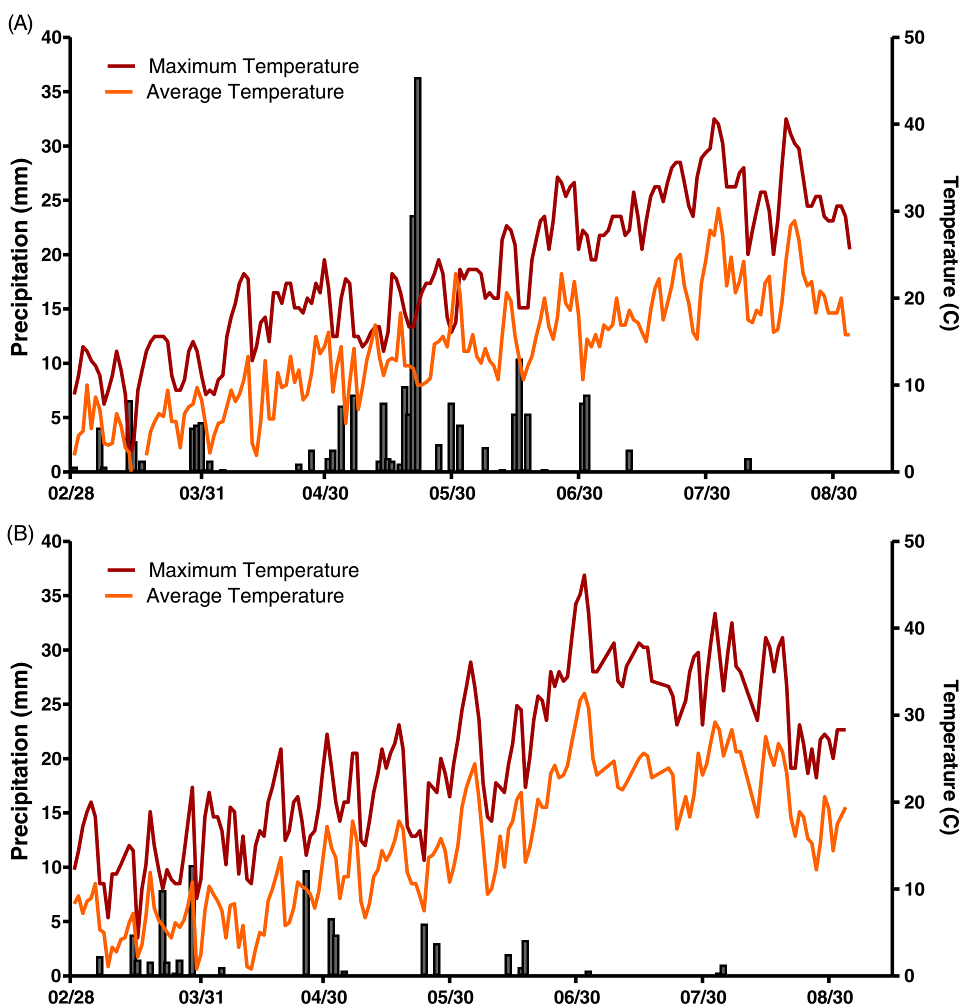

Figure 1. Average temperature, maximum daily temperature, and precipitation from March to August in 2020 (A) and in 2021 (B) at the Columbia Basin Agricultural Research Center, Adams, OR.

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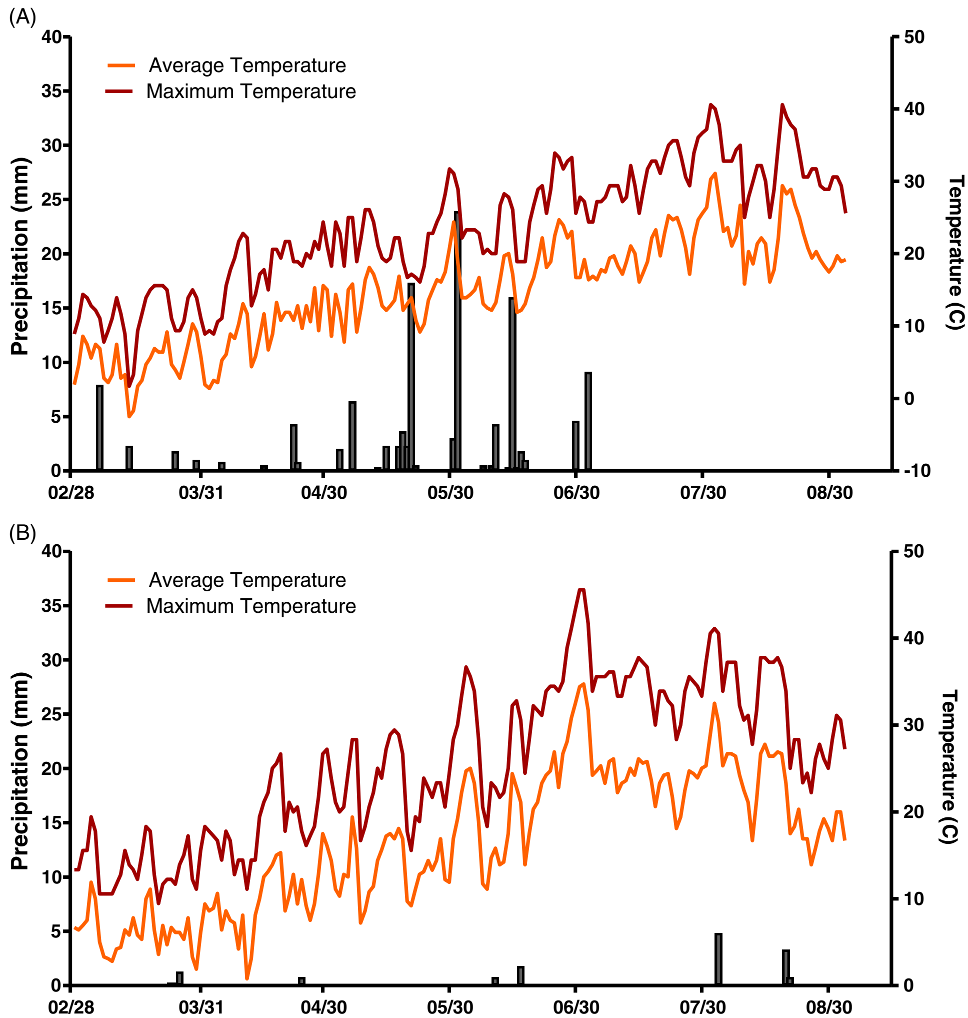

Figure 2. Average temperature, maximum daily temperature, and precipitation from March to August in 2020 (A) and in 2021 (B) at the Lind Dryland Research Station, Lind, WA.

Russian thistle control was visually evaluated at 3 and 4 WAT using a scale of 0% (no control) to 100% (complete death), except for the 16 DAH application timing in 2021, for which the 3 WAT was the only evaluation. Maximum and average daily temperatures and precipitation were obtained from local weather stations at CBARC (Figure 1) and LDRS (Figure 2).

Impact of Stubble Height on Herbicide Efficacy and Plant Dispersal

The experiments at CBARC, described in the previous section, were used to evaluate the effect of stubble height on herbicide efficacy and plant dispersal by dividing the subplots into two different cutting heights (38 cm and 12 cm in 2020 and 28 cm and 12 cm in 2021) with the combine at wheat harvest. The sub-subplot size was 4.3 × 4.6 m. Herbicide efficacy was evaluated visually at 3 and 6 WAT in 2020 and 2021 using a scale of 0% (no control) to 100% (complete death). Herbicide treatments are described in the previous section and in Table 1. Russian thistle plant dispersal, estimated as the number of plants moving out from the thistle's original spot, was evaluated only in the untreated plots. Two permanent sampling frames of 0.5 m^2 (1 × 0.5 m) were located per sub-subplot, with a total of 12 frames per sampled plot, corresponding to 6 sampling frames per stubble height and repetition. Russian thistle plants were counted at the end of October (initial count) and again the following spring (April 21 in 2021 and April 7 and May 26 in 2022) to estimate plant dispersal or movement of plants out of the plot area.

In addition to the experiments at CBARC, another experiment was established in a grower field near Ione, OR (45.44 N, 119.88 W), in 2020 to collect more information on Russian thistle plant dispersal. The experiment was a randomized block design with three replicates. The treatments were two stubble types: standing stubble and stubble flattened by the combine wheels. Plots were 100 × 1 m (three interrow spacing). In this experiment, all Russian thistle plants in the plots were counted and categorized into three plant sizes (big, medium, or small). Plants considered big were taller than 35 cm (with a long and short diameter of 133 cm and 121 cm, respectively), plants considered medium were between 28 and 35 cm tall (with a long and short diameter of 82 cm and 71 cm, respectively), and plants considered small were shorter than 28 cm (with a long and short diameter of 43 cm and 35 cm, respectively). In this experiment, Russian thistle plants were counted on October 20 (initial count) and again on December 18 in 2020 and on February 5, March 31, and May 26 in 2021 to estimate plant dispersal.

Plant dispersal percentage was estimated according to the following equation:

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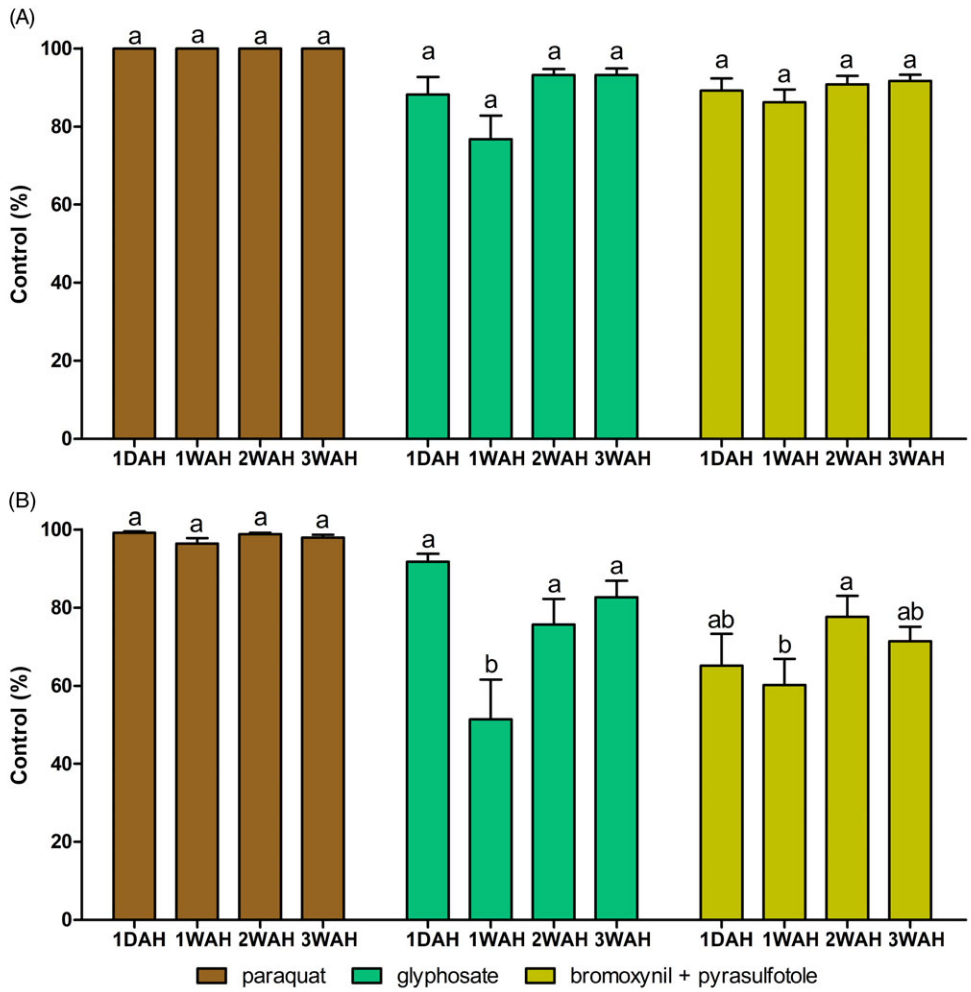

Figure 3. Percentage control of Russian thistle at the Columbia Basin Agricultural Research Center, Adams, OR, with different herbicide treatments applied 1 d after harvest (DAH), 1 wk after harvest (WAH), 2 WAH, and 3 WAH in 2020 (A) and in 2021 (B). Bars indicate the means, and whiskers indicate the standard error of the mean. Bars with different letters indicate significant differences among application timings for each herbicide according to Tukey's multiple comparison test ($P < 0.05$). Note that results include data pooled from the evaluations conducted at 3 and 6 wk after treatment.

$$\mathrm{PD}p = 100 - \left(\frac{\mathrm{Plants}_{t_x}}{\mathrm{Plants}_{t_0}}\right)$$

where PDp is plant dispersal percentage, Plants_{t_0} is the initial number of plants (initial count before plants were dispersed), and Plants_{t_x} is the number of plants on the following evaluation dates ($x = 1, 2, 3, \ldots n$). Total plant dispersal in this study was determined using data from the last evaluation date.

Statistical Analysis

Objective 1

At CBARC, data for Russian thistle control were analyzed using a mixed-model analysis of variance (ANOVA) to account for repetitive measures due to the different evaluation times on the same plots. Initially, the fixed effects were year, herbicide, spraying date, and evaluation time. However, significant interactions between years were observed, and years were analyzed separately. The nested random effects were plot and evaluation time. In 2020, the paraquat treatments were not included in the analysis because all the values were 100%. At LDRS, because the ANOVA assumptions were not met even after transformation, evaluation timings were averaged and analyzed as a unique evaluation time in a one-way ANOVA.

Objective 2

Data from the experiments to study the effect of stubble height on Russian thistle control were analyzed with a three-way ANOVA, where the three factors were year, herbicide, and stubble height. However, significant interactions between years were observed, and years were analyzed separately to facilitate interpretation. Averaged data from the four application timings were considered for the analysis. The paraquat treatments were not included in the analysis because all the values were 100%. Data from the experiments to study the effect of stubble height/type on Russian thistle plant dispersal were analyzed with a two-way ANOVA, where the factors were year and stubble height for CBARC and plant size and stubble height for the experiment in Ione.

When the ANOVA assumptions were not met, data were transformed prior to the analyses. Residuals were checked with Levene's test for homogeneity of variance and with Shapiro's test for normality. The Tukey test was used for post hoc analysis to determine the significant differences between treatments. Analyses

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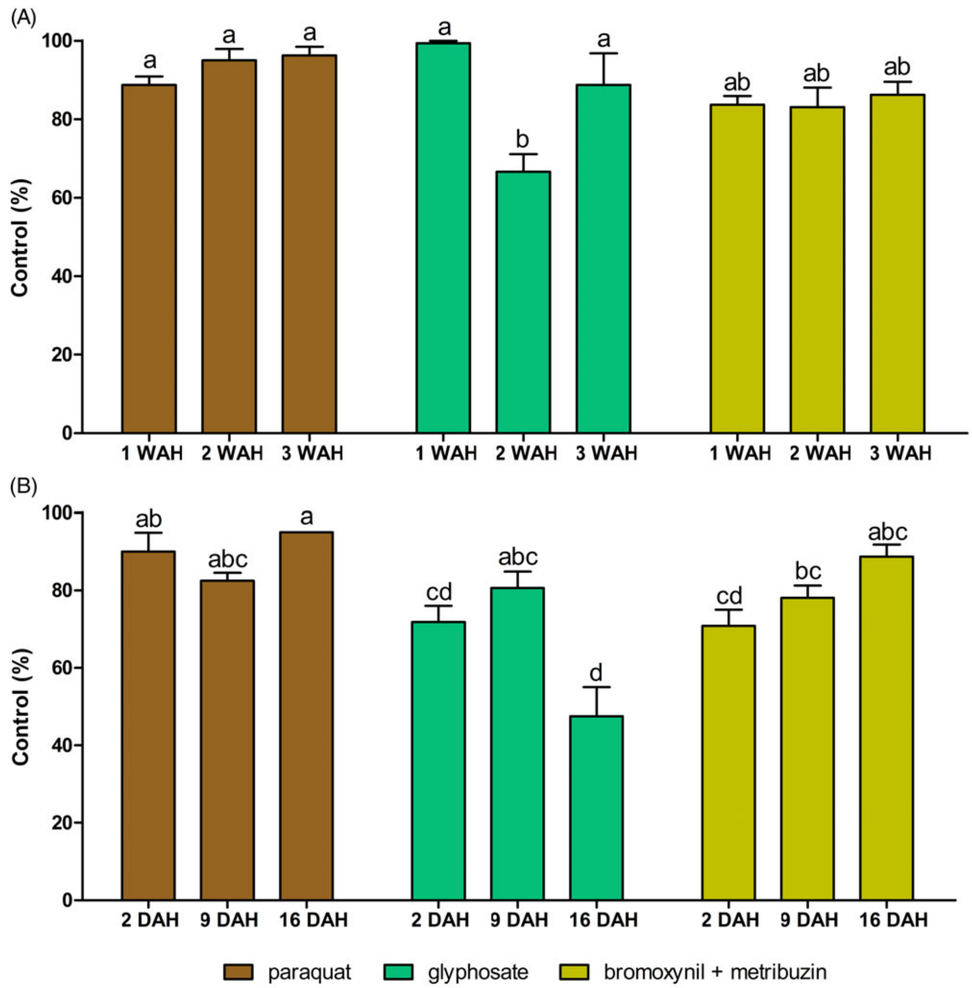

Figure 4. Percentage control of Russian thistle at Lind Dryland Research Station, Lind, WA, with different herbicide treatments applied at 1, 2, and 3 wk after harvest (WAH) in 2020 (A) and at 2, 9, and 16 d after harvest (DAH) in 2021 (B). Bars indicate the means, and whiskers indicate the standard error of the mean. Bars with different letters indicate significant differences among application timings for each herbicide according to Tukey's multiple comparison test ($P < 0.05$). Note that results include data averaged from the evaluations conducted at 3 and 4 wk after treatment (WAT), except for the application at 16 DAH in 2021, which was evaluated only at 3 WAT.

were conducted in Rstudio 2021.09.1 (R Core Team 2020). Figures were performed using the software GraphPad Prism 6.0 (GraphPad Software, San Diego, CA, USA).

Results and Discussion

Impact of Herbicide Application Timing Postharvest

At both sites, 2021 was drier and warmer than 2020. At CBARC, the accumulated precipitation from March to August in 2021 (65 mm) was 45% lower than it was in 2020 (187 mm), and at LDRS, that difference was 88% (14 mm vs. 122 mm). In 2021, temperatures during June and July were ≈5 C warmer than they were in 2020 at both locations (Figures 1 and 2).

At CBARC, paraquat provided a control of 100% and 98% in 2020 and 2021, respectively, with no differences in application timings (Figure 3). On average across application times, control with glyphosate was 89% and 75% in 2020 and 2021, respectively, and control with bromoxynil + pyrasulfotole was 91% and 69%, respectively. In 2020, no differences in Russian thistle control were found among herbicide application timings. However, in 2021, glyphosate control was reduced when applied 1 WAH (51%) compared to the other application timings (80% to 94%). Control with the premixture of bromoxynil + pyrasulfotole was less at 1 WAH (60%) than at 2 WAH (77%) but was not significantly different from applications made at 1 DAH or 3 WAH (Figure 3 B).

At LDRS, paraquat also resulted in the greatest Russian thistle control averaged over the three application timings (93% in 2020 and 89% in 2021). Control with glyphosate and the premixture of bromoxynil + metribuzin was similar in 2020 (86%) but in 2021 was more variable and depended on application time (the premixture had an average control of 79%, compared to 67% with glyphosate). Impacts of application timing depended on year and herbicide (except for paraquat). Glyphosate provided greater control at 1 and 3 WAH than at 2 WAH in 2020 (Figure 4 A) and at 9 DAH than at 16 DAH in 2021 (Figure 4 B). The premixture bromoxynil + metribuzin provided similar control at all application timings in both years (Figure 4 B).

Paraquat was the most consistent and effective herbicide to control Russian thistle postharvest in this study regardless of year or timing of application. This result agrees with Young et al. (2008), who found that this herbicide was more effective than glyphosate in controlling this weed species after harvest. However, Kumar

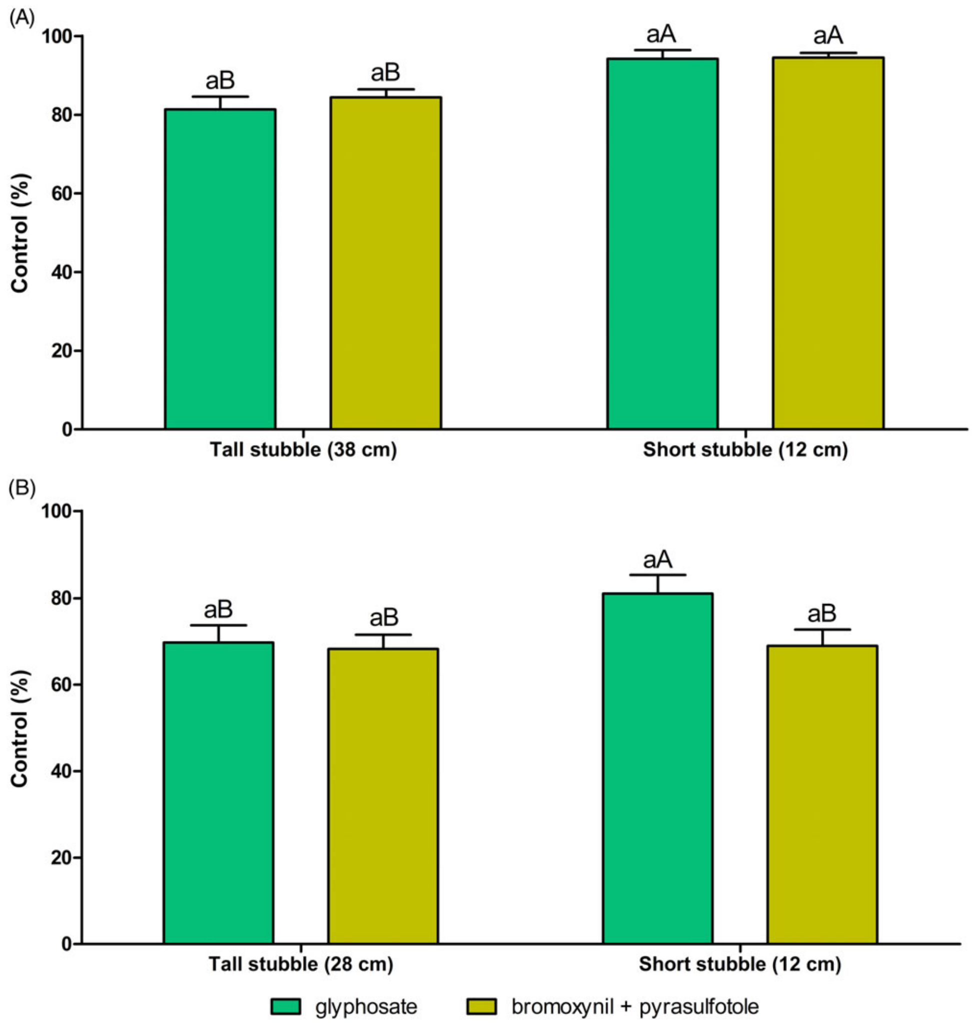

Figure 5. Percentage control of Russian thistle at the Columbia Basin Agricultural Research Center, Adams, OR, with different herbicides and stubble heights (tall and short) in 2020 (A) and in 2021 (B). Bars indicate the means, and whiskers indicate the standard error of the mean. Bars with the same lowercase letters indicate that means are not significantly different between stubble heights and bars with the same uppercase letters indicate no significant difference between the same herbicide across stubble heights according to Tukey's multiple comparison test ($P < 0.05$).

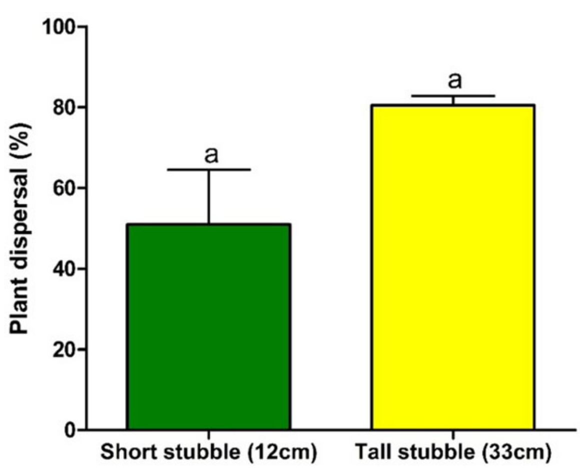

Figure 6. Percentage plant dispersal of Russian thistle at the final evaluation time (April 21 in 2021 and May 26 in 2022) at Columbia Basin Agricultural Research Center, Adams, OR, within two different stubble heights (short and tall). Bars indicate the means, and whiskers indicate the standard error of the mean. Bars with the same letters are not significantly different according to Tukey's multiple comparison test ($P < 0.05$).

et al. (2017) reported no differences between paraquat, glyphosate, and the premixture bromoxynil + pyrasulfotole applied to young plants (9 cm tall) grown in the greenhouse, obtaining 100% control with all treatments. Unlike the consistently effective control obtained with paraquat, control with glyphosate and bromoxynil mixtures was impacted by the postharvest application timing. In this study, in a dry year, glyphosate applications 1 or 2 WAH produced poorer control than earlier or later applications. It is possible that biotic (e.g., plant size, plant growth, plant stress levels) and abiotic factors (e.g., temperature, air humidity, soil moisture) were the cause of the differences. The greater control immediately after harvest could be the result of better herbicide coverage owing to a smaller plant size compared to later weeks (Wauchope et al. 1997), and the greater control with applications 3 WAH could be due to plants having resumed active growth following pruning at harvest (reduced stress). Results from this research might have benefited from having biomass data in addition to data only from the visual estimation. In the case of bromoxynil mixtures, they provided good control of Russian thistle, but the efficacy was impacted by application timing in the drier year, with later

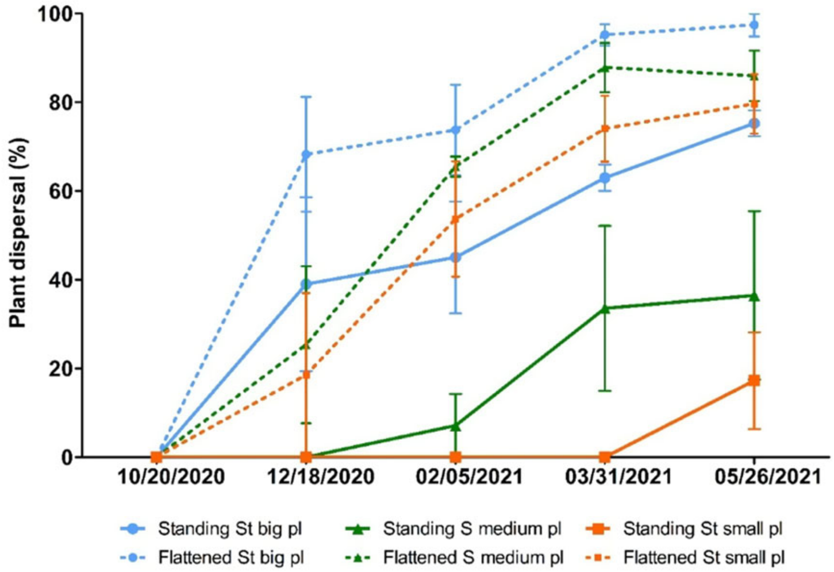

Figure 7. Percentage Russian thistle plant dispersal in Ione, OR, for different plant sizes (small, medium, and big) by stubble height (standing and flattened). Big plants were taller than 35 cm with diameters of 133 and 121 cm on average, respectively; medium plants were between 28 and 35 cm tall with diameters of 82 and 71 cm on average, respectively; and small plants were shorter than 28 cm with diameters of 43 and 35 cm on average, respectively. Markers (circles, squares, and triangles) indicate the means at different plant sizes by stubble height on each evaluation time, and vertical whiskers are the standard error of the mean.

applications tending to provide greater control at LDRS but without a general trend at CBARC.

Russian thistle control after harvest with glyphosate was inconsistent and likely influenced by weather conditions before, during, and/or after application. Control with glyphosate tended to be lower 1 WAH at CBARC and 14 to 16 DAH at LDRS. This variability in the results could be related to weather conditions (before, during, and/or after application) that had a greater effect on glyphosate activity than on paraquat or the bromoxynil mixtures. High temperatures during or after glyphosate application can reduce herbicide efficacy on stressed plants due to greater evapotranspiration leading to lower glyphosate translocation (Tanpipat et al. 1997) or due to greater levels of glyphosate sequestration in vacuoles (Ge et al. 2011). Also, the drier conditions in 2021 could have affected glyphosate efficacy, in agreement with Jordan (1977), who reported that applications of glyphosate at 40% relative humidity performed worse than applications at 100% relative humidity, independently of temperature.

Impact of Stubble Height on Herbicide Control and Plant Dispersal

Stubble height affected Russian thistle control with glyphosate and bromoxynil + pyrasulfotole but not with paraquat. Tall stubble reduced ($P < 0.05$) Russian thistle control by 11% with glyphosate and the premixture bromoxynil + pyrasulfotole in 2020, as well as with glyphosate in 2021 (Figure 5). The amount of herbicide intercepted by crop residue could depend on several factors, such as herbicide properties, stubble properties, and/or application properties. Paraquat was applied with a greater carrier volume than glyphosate or the premixture bromoxynil + pyrasulfotole, which may have increased the amount of herbicide that reached the target, regardless of stubble height. The premixture of bromoxynil + pyrasulfotole was not affected by stubble height in the second year, which could have been related to having thinner stubble in 2021 than in 2020 and lower height differences. In 2021, a record-breaking drought in the region led to very low crop yields and, consequently, less stubble.

Russian thistle plant dispersal was greatly affected by the stubble height in 2020/2021 and in 2021/2022 at CBARC. At the final plant dispersal evaluation date, regardless of year, on average, 58% of plants were dispersed in short stubble (12 cm), compared to 18% in tall stubble (38 cm) (Figure 6). Similarly, near Ione, significantly less plant dispersal occurred in standing stubble compared to flattened stubble at all evaluation times. The final evaluation indicated 87% plant dispersal in flattened stubble, compared to 43% in standing stubble, independently of plant size. However, plant dispersal was significantly impacted by plant size. Large plants had greater plant dispersal ($P < 0.001$) (97% in flattened stubble vs. 75% in standing stubble) than medium-sized plants (86% in flattened stubble vs. 36% in standing stubble) or small plants (79% in flattened stubble vs. 17% in standing stubble) (Figure 7).

The main dispersal mode of this species is tumbling. Russian thistle plants have a globose-elliptical shape that allows them to roll with the wind when they are disconnected from the ground after the plant dies (Crompton and Bassett 1985). For weed species with seeds dispersed by wind (anemochory), wind speed is one of the main factors determining propagule release (Borger et al. 2012). In the case of Russian thistle, not only is propagule release needed to disperse seeds; the whole plant has to be moved as well. However, based on results from Cutforth and McConkey (1997), who found reduced wind speed in tall wheat stubble (31 to 43 cm) compared to short wheat stubble (14 to 17 cm), wind speed might have impacted plant dispersal as well. If plant dispersal is prevented, Russian thistle plants will remain in the same place and seeds will be dispersed in the same area, forming dense seedling patches (Stallings et al. 1995) that will reduce the fecundity per plant by intraspecific competition, as well as by interspecific competition with crops. These patches will make the localized control measures easier. However, if Russian thistle plants are dispersed, seeds will be spread out, which will reduce the intraspecific competition of the new plants and increase the interspecific competition with crops.

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Practical Implications

To avoid water consumption and seed production after harvest, it is important to control Russian thistle plants present at harvest. Paraquat was the most consistent and effective herbicide to control Russian thistle postharvest in this study. Control with glyphosate and bromoxynil mixtures was impacted by postharvest application timing. In a dry year, glyphosate applications 1 or 2 WAH produced poorer control than earlier or later applications. For the bromoxynil mixtures, the control tended to be greater with later applications at LDRS, but there wasn't a clear trend at CBARC. We found that stubble height impacted herbicide performance when the herbicide used was not paraquat. Short stubble might increase the performance of postharvest Russian thistle chemical control for glyphosate and bromoxynil mixtures; however, short stubble will increase Russian thistle plant dispersal. If Russian thistle plants are going to be left uncontrolled postharvest, leaving tall stubble at harvest should be considered as part of an integrated weed management program to reduce plant dispersal. Alternatively, reducing plant size, for example, with mowing, could be another option to reduce Russian thistle plant and seed dispersal.

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