Weed Technology

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Weed-sensing technology modifies fallow control of rush skeletonweed (*Chondrilla juncea*)

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Research Article

Cite this article: Fischer JW, Thorne ME, Lyon DJ (2020) Weed-sensing technology modifies fallow control of rush skeletonweed (*Chondrilla juncea*). Weed Technol. **34**: 857–862. doi: 10.1017/wet.2020.76

Received: 13 April 2020
Revised: 8 June 2020
Accepted: 28 June 2020
First published online: 9 July 2020

Associate Editor:
Prashant Jha, Iowa State University

Nomenclature:
Aminopyralid; chlorsulfuron; clopyralid; glyphosate; metsulfuron; rush skeletonweed, *Chondrilla juncea* L.; winter wheat, *Triticum aestivum* L.

Keywords:
Light sensing sprayer; Conservation Reserve Program; chemical fallow

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Abstract

Rush skeletonweed is an aggressive perennial weed that establishes itself on land in the Conservation Reserve Program (CRP), and persists during cropping following contract expiration. It depletes critical soil moisture required for yield potential of winter wheat. In a winter wheat/fallow cropping system, weed control is maintained with glyphosate and tillage during conventional fallow, and with herbicides only in no-till fallow. Research was conducted for control of rush skeletonweed at two sites in eastern Washington, Lacrosse and Hay, to compare the effectiveness of a weed-sensing sprayer and broadcast applications of four herbicides (aminopyralid, chlorsulfuron + metsulfuron, clopyralid, and glyphosate). Experimental design was a split-plot with herbicide and application type as main and subplot factors, respectively. Herbicides were applied in the fall at either broadcast or spot-spraying rates depending on sprayer type. Rush skeletonweed density in May was reduced with use of aminopyralid (1.1 plants m^{-2}), glyphosate (1.4 plants m^{-2}), clopyralid (1.7 plants m^{-2}), and chlorsulfuron + metsulfuron (1.8 plants m^{-2}) compared with the nontreated check (2.6 plants m^{-2}). No treatment differences were observed after May 2019. There was no interaction between herbicide and application system. Area covered using the weed-sensing sprayer was, on average, 52% ($P < 0.001$) less than the broadcast application at the Lacrosse location but only 20% ($P = 0.01$) at the Hay location. Spray reduction is dependent on foliar cover in relation to weed density and size. At Lacrosse, the weed-sensing sprayer reduced costs for all herbicide treatments except aminopyralid, with savings up to US\$6.80 per hectare. At Hay, the weed-sensing sprayer resulted in economic loss for all products because of higher rush skeletonweed density. The weed-sensing sprayer is a viable fallow weed control tool when weed densities are low or patchy.

Introduction

Summer fallow is a common practice in the low rainfall region of eastern Washington (<300 mm annual average precipitation). Summer fallow is used to conserve soil water and to stabilize yield in the subsequent winter wheat crop (Donaldson et al. 2001). Additionally, weed control during summer fallow is critical prior to planting a future crop. Weeds are frequently found in patches distributed throughout production fields, with much of the land containing no weeds at all, or within populations that fall below the threshold at which a crop is threatened (Chancellor and Goronea 1994). However, weed control is still important because even sparse weed populations can decrease moisture and nutrients available to crops (Felton et al. 1991) and furthermore, proliferate into more severe infestations.

Rush skeletonweed is a weed that flourishes during the summer fallow phase and control is important to protect the upcoming wheat yield. Previous research on chemical control of rush skeletonweed demonstrates the effectiveness of several different herbicides (Heap 1993; Spring et al. 2018), but these herbicides are often uneconomical to farmers for broadcast applications on scattered populations, or there may be residual properties that are dangerous to future crops. Selective spot-spraying may be effective at mitigating high input costs required for perennial weed control in the fallow season and may limit problems with herbicide soil persistence.

Proximal sensing of weeds using differences in spectral reflectance of visible red (660 nm) and near-infrared (770 nm) light by electronic silicon-based sensors has resulted in the creation of “weed-sensing sprayers” that can distinguish between weeds and background soil (Lamb and Brown 2001; Woebbecke et al. 1995) and thus potentially minimize herbicide input costs. Initially, these technologies were used solely to develop weed maps for reference in a decision-making weed control system. Reflectance sensor technology has been utilized in weed science to assess biomass relationships in weeds and crops with high accuracy, allowing for selection of favorable crop cultivars and an assessment of herbicide dose-responses (Felton et al. 2002). Now, the ability to simultaneously detect and eliminate weeds has been recognized (Verhulst et al. 2009). The potential for herbicide use reduction is great with this technology.

Weed-sensing sprayers reduced herbicide use on fallow by 47% to 88% in North Dakota (Ahrens 1994), and up to 90% in Australia (Felton et al. 1991). Felton et al. (1991) found the use of a weed-sensing sprayer on perennial weeds was about 10 times less expensive than broadcast spraying, and seven times less expensive than broadcast spraying for annual weed control. Young et al. (2008) reported a 42% herbicide reduction on postharvest control of Russian thistle (*Salsola tragus* L.) in eastern Washington with a weed-sensing sprayer, while achieving control equal to broadcast applications. Another study conducted in eastern Washington and Oregon reported equal control of tumble pigweed (*Amaranthus albus* L.), tumble mustard (*Sisymbrium altissimum* L.), and prickly lettuce (*Lactuca serriola* L.) with applications of glyphosate through a weed-sensing sprayer compared to a broadcast sprayer in fallow (Riar et al. 2011). Biller (1998) was able to reduce herbicide input by 48% in controlling several broadleaf weed species in conventionally tilled corn (*Zea mays* L.) fields using a weed-sensing sprayer.

There is potential for a weed-sensing sprayer to be more effective against perennial weeds than broadcast spraying. Since herbicide product labels set legal limits on the amount of product or active ingredient permitted to be applied per hectare, an increased herbicide concentration could be applied to the weeds because less overall spray solution is being applied per hectare when spot spraying. Higher concentrations of herbicide being applied may provide better control of more persistent perennial weeds, and a more cost-effective chemical control program may minimize the need to cultivate, which in the case of rush skeletonweed, may decrease the spread of vegetative propagules by tillage. The use of increased concentrations of herbicides applied through a weed-sensing sprayer may pose additional risks. Herbicides with known soil persistence that can be injurious to future crops could be a limitation when used at higher concentrations. No research has been reported on the use of a weed-sensing sprayer for fallow control of rush skeletonweed.

The objectives of this experiment were to evaluate the efficacy and expense of various herbicide treatments applied with a weed-sensing sprayer compared to broadcast applications for control of rush skeletonweed in summer fallow.

Materials and Methods

Site Descriptions

Hay

One study site was near Hay, WA (46.38°N, 117.54°W; 508 m above sea level). The soil is a Walla Walla silt loam (Typic Haploxerolls), pH 7.2, with 2.5% organic matter content in the top 15 cm. The site was enrolled in the Conservation Reserve Program (CRP) from 2001 to 2013. Conversion to annual crop production occurred in autumn 2013 and consisted of an application of glyphosate at 945 g ae ha^{-1} followed by burning of aboveground biomass. Winter wheat was then direct-seeded (HORSCH LLC, Mapleton, ND) and the field was managed in a no-till winter wheat–summer fallow rotation since. A maintenance herbicide application was required to control annual weeds in the plot area at the initiation of the study. An application occurred on June 24, 2019, and consisted of a tank mixture of saflufenacil (Sharpen; BASF, Florham Park, NJ) at 50 g ai ha^{-1}, glyphosate (RT 3; Bayer CropScience, Research Triangle Park, NC) at 2,520 g ae ha^{-1}, a nonionic surfactant at 0.25% v/v, and crop oil concentrate at 0.75% v/v. The same tank mixture was applied on September 5, 2019, to prepare the plot area for winter wheat seeding. Winter wheat cultivar ‘Magic’ was planted 2.5 cm deep on September 19, 2019, at 101 kg ha^{-1} and fertilized with 100 kg ha^{-1} N and 22 kg ha^{-1} S.

Lacrosse

The second study site was initiated near Lacrosse, WA (46.49°N, 117.53°W; 458 m above sea level). The soil at the Lacrosse site is a Benge loam (Typic Haploxerolls), pH 7.2, with 1.6% organic matter content in the top 15 cm. The field was enrolled in the CRP from 2005 to 2014. Transition to annual crop production included burning aboveground biomass followed by a ripper shank tillage operation 15 cm deep. Spring wheat was planted in 2014, and the field has been in a winter wheat–summer fallow rotation since. The field is managed in a conventional tillage system and was cultivated with a disk on April 20, 2019. Anhydrous ammonia was applied as fertilizer on June 10, 2019, along with sulfur and phosphate to provide the field with 94 kg ha^{-1} N, 11 kg ha^{-1} S, and 11 kg ha^{-1} P. Fertilizer application also cultivates the soil and provides weed control. Volunteer wheat was problematic at the Lacrosse site, and clethodim (Cleanse 2EC; Winfield Solutions, St. Paul, MN) was applied to the plot area at 280 g ai ha^{-1} on April 4, 2019. On April 25, 2019, an application of glyphosate at 945 g ha^{-1} plus ammonium sulfate at 1.2% w/w was applied as an aid to tillage to correspond with normal farm operations at the Lacrosse site. Winter wheat cultivar ‘Northwest Duet’ was planted 5 cm deep on September 30, 2019, at 101 kg ha^{-1}.

Experimental Methods

Trials were established as a split-plot, randomized complete block design with four blocks and individual plot size of 3 m by 10.5 m. Herbicide and application type were the main and subplot factors, respectively. Broadcast rates of four herbicides were compared to those of spot-spraying delivered through a weed-sensing sprayer.

Broadcast herbicide treatments (Table 1) were applied using a CO_2-powered backpack sprayer and hand boom with six TeeJet XR11002 flat-fan nozzles (TeeJet Technologies, Spraying Systems Co., Wheaton, IL) at 50 cm spacing delivering 140 L ha^{-1}. Spot-spray treatments (Table 1) were applied through a weed-sensing sprayer (WEED-IT™; Reometron B.V., The Netherlands) equipped with 10 TP4002E nozzles (TeeJet Technologies) at 20-cm spacing delivering 275 L ha^{-1}. Banding nozzles were used with the weed-sensing sprayer because they achieve a quick high-output, low-drift spray pattern that is necessary to reach a narrow target and minimize nontarget contact. The sprayer was mounted on an all-terrain vehicle with a boom height 0.5 m above the ground. The majority of plants at the time of application were bolted with a mean height of 25 cm. Applications were made at both sites on October 8, 2018. Winter wheat stubble was present at the time of application and was 30 cm tall. Spray solution volume output through the weed-sensing sprayer was measured for each experimental plot.

Herbicide concentrations used in this study were selected based on the product label recommendations for broadcast applications in fallow. Some product labels provided acceptable spot-spray concentrations that were used for the weed-sensing sprayer. When a spot-spray concentration was not given on the label, the maximum annual concentration per hectare was used for the weed-sensing sprayer.

Preliminary plant counts were made before treatment in a 2-m-wide area through the middle of each plot and running the entire length of the plot. The majority of rush skeletonweed plants at the

Table 1. Treatment combinations of herbicide by application method applied to rush skeletonweed.

Herbicide[a]	Application[b]	Rate[c]	Trade name	Manufacturer
		g ae ha^{-1}		
Clopyralid	Weed-Sensing	546	Stinger	Corteva Agriscience, Wilmington, DE
Clopyralid	Broadcast	280	Stinger	Corteva Agriscience, Wilmington, DE
Aminopyralid	Weed-Sensing	122	Milestone	Corteva Agriscience, Wilmington, DE
Aminopyralid	Broadcast	21	Milestone	Corteva Agriscience, Wilmington, DE
Chlorsulfuron/metsulfuron	Weed-Sensing	22/13	Finesse	FMC Corporation, Philadelphia, PA
Chlorsulfuron/metsulfuron	Broadcast	13/8	Finesse	FMC Corporation, Philadelphia, PA
Glyphosate	Weed-Sensing	10,380	RT 3	Bayer CropScience, Research Triangle Park, NC
Glyphosate	Broadcast	5,296	RT 3	Bayer CropScience, Research Triangle Park, NC
Nontreated	Weed-Sensing	–		
Nontreated	Broadcast	–		

[a] All glyphosate treatments included ammonium sulfate at 1.2% (w/w). Aminopyralid and chlorsulfuron/metsulfuron treatments included a nonionic surfactant at 0.25% (v/v).
[b] Weed-sensing treatments were applied at 275 L ha^{-1}, broadcast treatments were applied at 140 L ha^{-1}.
[c] Chlorsulfuron/metsulfuron is reported as g ai ha^{-1}. Weed-sensing rates are reported as if total plot area is sprayed.

experimental sites were mature plants at the time of application. Plant counts occurred on November 28, 2018; and on April 18, May 20, and August 22, 2019.

Data were analyzed using the PROC GLIMMIX procedure in SAS (SAS Institute 2019). Biological count data generally follow a negative binomial distribution (Stroup 2015), and counts were analyzed using the PROC GLIMMIX procedure with a log link function. The Laplace method was used for maximum likelihood estimation. Herbicide, application method, and site were analyzed as fixed effects, while replicate was considered a random effect. The interaction between herbicide and application method was also evaluated, as were herbicide by site and application method by site interactions. The three-way interaction between herbicide, application method, and site was also tested. Mean differences between LSMEANS were determined by a *t*-test within the PROC GLIMMIX procedure with a significance level of 0.05.

Table 2. Herbicide treatments and mean counts of surviving rush skeletonweed plants in November and May following application.

Treatment	November 2018[a]		May 2019
	Hay[b]	Lacrosse	Combined
	plants m^{-2}		
Aminopyralid	0.22 b	0.3 bc	1.1 a
Chlorsulfuron/metsulfuron	0.53 c	0.2 ab	1.8 c
Clopyralid	0.22 b	0.24 abc	1.7 bc
Glyphosate	0.1 a	0.12 a	1.4 ab
Nontreated	0.91 d	0.34 c	2.6 d
Application Method			
Broadcast	0.25 B		1.4 A
Weed-Sensing	0.19 A		1.5 A

[a] Sites presented separately due to significant treatment-by-site interaction.
[b] Within a column, means followed by the same letter are not significantly different ($\alpha = 0.05$).

Table 3. Price of herbicide application for each sprayer and associated dollar savings at each site.[a]

Product	Product price	Broadcast price[b]	Weed-sensing price[b]		Price savings[b,c]	
			Lacrosse	Hay	Lacrosse	Hay
Finesse	0.59 g^{-1}	17.00	10.20	17.00	6.80	0.00
Milestone	105.00 L^{-1}	9.40	26.30	43.80	−16.90	−34.40
RT 3	6.00 L^{-1}	59.10	56.70	94.50	2.40	−35.40
Stinger	127.00 L^{-1}	100.00	93.60	156.00	6.40	−56.00

[a] Columns involving a price are expressed in US dollars (Jenks, 2019).
[b] Price per hectare.
[c] Negative values represent an economic loss.

Results and Discussion

Application Method

Application method affected herbicide efficacy in November ($P = 0.046$) with weed-sensing spray applications reducing plant density more than broadcast applications (Table 2). The rates used through the weed-sensing sprayer were higher than those used with broadcast treatments (Table 1). No application method by site interaction was observed in November ($P = 0.415$), so application method data were averaged across sites for analysis (Table 2). A concern with the weed-sensing sprayer was spray accuracy and the ability of the sensors to detect rush skeletonweed plants in wheat stubble (Ahrens 1994; Blackshaw et al. 1998). Blue spray dye was applied through the weed-sensing sprayer in a preliminary study (data not shown) and revealed full plant coverage. In this study, plants were observed for the presence of spray droplets on leaves following application with the weed-sensing sprayer, and there was no visual evidence that the sprayer was missing plants. In May, no application method by site interaction was observed ($P = 0.606$), so data were averaged across sites for analysis. Application method did not have an effect on the efficacy of herbicides at this time ($P = 0.547$).

The increased herbicide efficacy observed with the weed-sensing sprayer in November may be attributed to a greater herbicide concentration, but the increased carrier volume may have also improved herbicide performance. Increased carrier volume can increase herbicide efficacy (Brewster and Appleby 1990; Knoche 1994; Legleiter and Johnson 2016; Stougaard 1999).

The weed-sensing sprayer reduced average total spray volume, which is directly related to the area treated, by 52% ($P < 0.001$) at Lacrosse and 20% ($P = 0.01$) at Hay. Spray area reduction is dependent on weed density. With the exception of aminopyralid, all treatments applied with the weed-sensing sprayer at Lacrosse were more economical compared to the broadcast applications (Table 3). At Hay, the 20% reduction in spray area with the weed-sensing sprayer resulted in economic loss for all products except chlorsulfuron + metsulfuron, which broke even (Table 3). Increased herbicide concentration applied through the

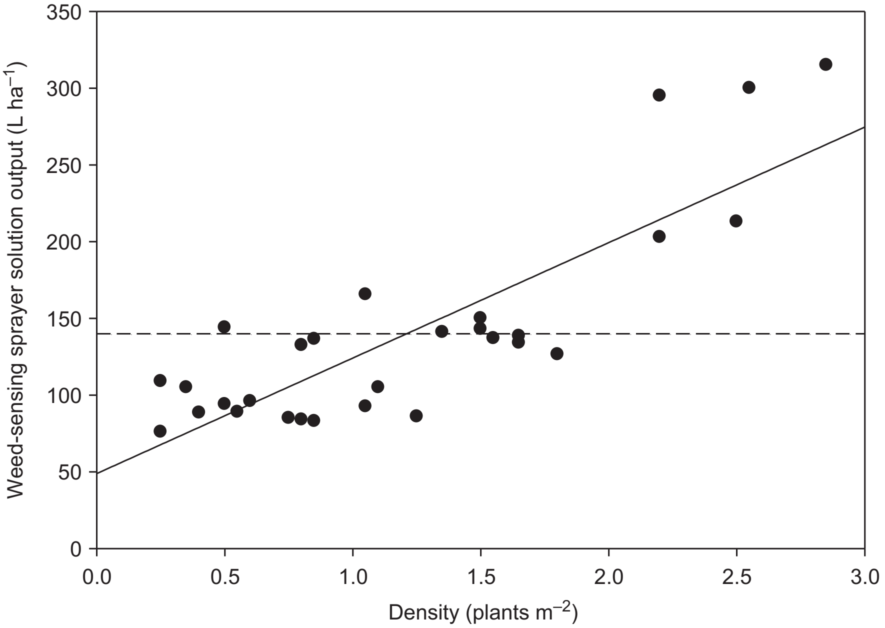

Figure 1. Linear relationship ($y = 75.27x + 48.9$; $R^2 = 0.70$) between rush skeletonweed density and spray output of weed-sensing sprayer. The horizontal dashed line represents the fixed spray output of the broadcast sprayer.

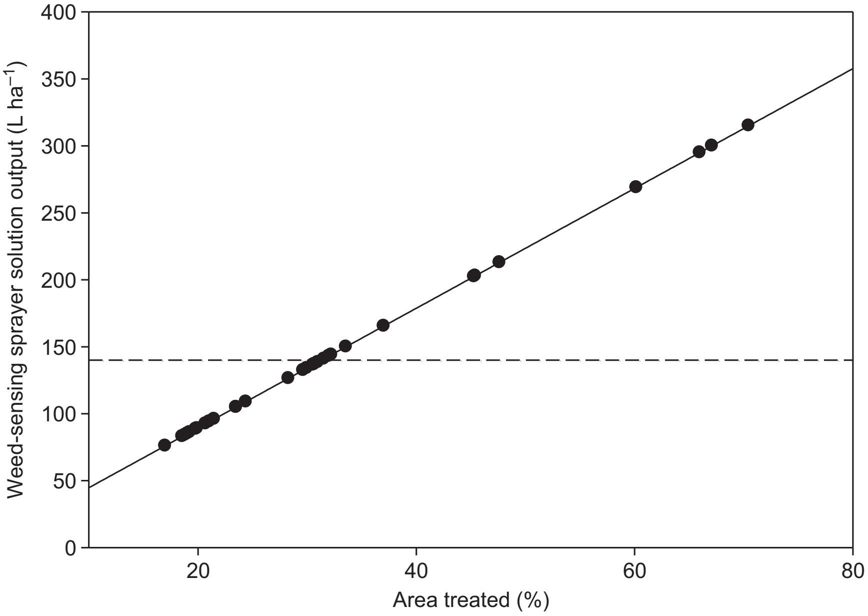

Figure 2. Linear relationship ($y = 4.47x + 42.3$; $R^2 = 1$) between percent of area treated with weed-sensing sprayer and spray output. The horizontal dashed line represents fixed spray output of broadcast sprayer.

weed-sensing sprayer makes economic savings dependent on weed density. Weed density at the time of application averaged 0.4 and 1.2 plants m^{-2} at Lacrosse and Hay, respectively. Despite a 20% reduction in spray area at Hay, the increased herbicide concentrations applied through the weed-sensing sprayer resulted in more product being applied per hectare than would have been applied with the broadcast sprayer. The results of this study are consistent with those of previous studies (Blackshaw et al. 1998; Wicks et al. 1998) that found weed-sensing sprayers reduced herbicide costs compared to broadcast applications when applied to low-density weed populations, such as was found at Lacrosse.

There was a linear relationship between plant density and sprayer output (Figure 1). The horizontal line at 140 L ha^{-1} represents the fixed sprayer output with the broadcast sprayer. At plant densities below the horizontal line, the weed-sensing sprayer applied less solution than the broadcast sprayer. In this study, the weed-sensing sprayer reduced solution output when plant density was <1.2 plants m^{-2} (Figure 1). Points that fall far from the output line may represent false triggering of the weed-sensing sprayer caused by crop residue or the presence of larger than average plants resulting in more solution being applied per plant.

The sprayer output data were converted to percent area treated (Figure 2). The sprayer output data suggest that the weed-sensing sprayer has the greatest opportunity to reduce herbicide use and cost compared to broadcast herbicide applications when weed cover is <30%. In Australia, some herbicide labels (Anonymous 2020) provide recommendations for weed-sensing sprayers when weed coverage is <30%. The ability to quickly measure percent weed coverage is rapidly evolving. The use of low-altitude and slow-flying unmanned aerial vehicles equipped with color-infrared cameras produces highly informative weed maps for a given field (Huang et al. 2018). Implementing these techniques will allow farmers to ascertain percent weed cover in order to decide when a weed-sensing sprayer may be preferred over a broadcast application.

A dramatic difference in price per hectare between broadcast and weed-sensing applications resulted from the different herbicide rates applied (Table 3). Aminopyralid was an effective herbicide in this study, but the rate used with the weed-sensing sprayer was nearly six times greater than that for the broadcast rate. Consequently, even a 52% reduction in spray volume at Lacrosse was not enough to offset the greater herbicide cost with the weed-sensing sprayer.

By spring, aminopyralid applied with the weed-sensing sprayer was no more effective than the broadcast aminopyralid treatment. Unfortunately, we do not know whether aminopyralid applied through the weed-sensing sprayer at the broadcast rate would have been as effective at reducing skeletonweed density as the higher rate used in this study. Glyphosate cost savings with the weed-sensing sprayer were small, but the rate was doubled for the weed-sensing sprayer. Like aminopyralid, glyphosate is an effective product for rush skeletonweed control and more savings may have been achieved if the broadcast rate had been applied through the weed-sensing sprayer. The motivation for using higher spot-spray rates was to test the possibility of achieving longer control through the fallow year while simultaneously reducing herbicide costs when weed populations are scattered, as is often the case with rush skeletonweed. While small reductions in herbicide use from the weed-sensing sprayer may not be economical, they still provide the benefit of reduced application to nontarget organisms and the environment (Blackshaw et al. 1998) while applying a potentially more effective higher rate to the target species.

Herbicide Treatments

Plant density measured in November had no herbicide by application method by site interaction ($P = 0.513$). While this is not significant at the 5% level, an exploration of the herbicide by application method interaction ($P = 0.058$) revealed a slightly reduced density of rush skeletonweed when chlorsulfuron + metsulfuron or aminopyralid were applied with the weed-sensing sprayer compared to their application with the broadcast sprayer (data not shown). While this effect may be explained by the much-increased concentration of aminopyralid applied with the weed-sensing sprayer compared to the broadcast sprayer, this would not explain the difference observed between application methods for chlorsulfuron + metsulfuron. There was a site by herbicide treatment interaction ($P < 0.001$), so data were analyzed separately by site (Table 2). At Hay, all herbicide treatments reduced rush skeletonweed densities compared to the nontreated check. Rush skeletonweed density was lowest in the glyphosate treatment. Aminopyralid and clopyralid treatments had the next lowest densities. For November counts at Lacrosse, only glyphosate and chlorsulfuron + metsulfuron treatments reduced rush skeletonweed densities lower than the nontreated check (Table 2).

In May, 7 mo after treatment (MAT), no herbicide treatment by application method by site interaction ($P= 0.340$), herbicide treatment by site interaction ($P = 0.339$), or herbicide by application method interaction ($P = 0.612$) were observed; therefore, data were averaged and analyzed across sites (Table 2). All herbicide treatments reduced rush skeletonweed densities compared to those of the nontreated check. Aminopyralid and glyphosate treatments reduced rush skeletonweed densities compared with the other treatments; however, no difference was found between glyphosate and clopyralid (Table 2). No treatment differences were observed for rush skeletonweed densities in April or August 2019. Spring conditions were not favorable in April for rush skeletonweed emergence, and all discernable control was lost by August.

Synthetic auxins are effective for control of rush skeletonweed. Wallace and Prather (2010) found that aminopyralid provided excellent control of rush skeletonweed when applied at 30 g ha^{-1}. Spring et al. (2018) found aminopyralid and clopyralid provided good control of rush skeletonweed in winter wheat at broadcast rates similar to those used in this study. Heap (1993) found several rates and tank mixtures of clopyralid to be very effective for the control of rush skeletonweed in Australia, and the same was found for populations in Idaho (Belles et al. 1980; Cheney et al. 1980). Both Belles et al. (1980) and Cheney et al. (1980) reported control with clopyralid breaking 1 yr after treatment, which is consistent with results from this study. Effective rush skeletonweed control requires multiple years of chemical management (Heap 1993). Metsulfuron is a widely used sulfonylurea for control of rush skeletonweed in Australia. Heap (1993) found similar results to this study with metsulfuron at 9 and 18 g ai ha^{-1} 1 yr after treatment. Metsulfuron rates used in this study were within this range. Rush skeletonweed density was significantly reduced compared with densities in the nontreated check, but control was poor by the spring following application. Emerging winter wheat was visually evaluated for herbicide injury at both sites in November 2019, 13 MAT, and there was no evidence of herbicide injury at that time.

Aminopyralid, clopyralid, and glyphosate were effective for control of rush skeletonweed in summer fallow. Aminopyralid and clopyralid are expensive herbicides for fallow weed control, especially at the recommended use rates for perennial weeds. By May, the same level of weed control was provided for each herbicide regardless of sprayer type or rate. Applying broadcast rates through the weed-sensing sprayer with multiple applications warrants further investigation. An application in fall and then spring might provide economic control of rush skeletonweed throughout the entire fallow year at a lower cost compared to broadcast applications. Future studies should focus on the use of similar rates through both the weed-sensing and broadcast sprayers to discern the role of rate relative to application method for reducing rush skeletonweed density. Aminopyralid and glyphosate were effective herbicides in reducing rush skeletonweed density through May of the following fallow year. The weed-sensing sprayer proved to be an economically effective tool for fallow control of rush skeletonweed at Lacrosse where the infestation was less dense. Rush skeletonweed density was reduced prior to winter wheat planting and input cost was less compared to broadcast applications.

Acknowledgments. This research was partially funded by an endowment from the Washington Grain Commission. The WEED-IT spray system used in this study was purchased with funds from the Mel and Donna Camp Endowment. The field studies were conducted on land graciously made available to the authors by Ryan Dorman and Casey Holling. No conflicts of interest have been declared.

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