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Evaluation of Harvest-Aid Herbicides as Desiccants in Lentil Production

Ti Zhang, Eric N. Johnson, and Christian J. Willenborg*

Desiccants are currently used to improve lentil dry-down prior to harvest. Applying desiccants at growth stages prior to maturity may result in reduced crop yield and quality, and leave unacceptable herbicide residues in seeds. There is little information on whether various herbicides applied alone or as a tank-mix with glyphosate have an effect on glyphosate residues in harvested seed. Field trials were conducted at Saskatoon and Scott, Saskatchewan, Canada, from 2012 to 2014 to determine whether additional desiccants applied alone or tank mixed with glyphosate improve crop desiccation and reduce the potential for unacceptable glyphosate residue in seed. Glufosinate and diquat tank mixed with glyphosate were the most consistent desiccants, providing optimal crop dry-down and a general reduction in glyphosate seed residues without adverse effects on seed yield and weight. Saflufenacil provided good crop desiccation without yield loss, but failed to reduce glyphosate seed residues consistently. Pyraflufen-ethyl and flumioxazin applied alone or tank mixed with glyphosate were found to be inferior options for growers as they exhibited slow and incomplete crop desiccation, and did not decrease glyphosate seed residues. Based on results from this study, growers should apply glufosinate or diquat with preharvest glyphosate to maximize crop and weed desiccation, and minimize glyphosate seed residues.

Nomenclature: Diquat; flumioxazin; glufosinate; glyphosate; pyraflufen-ethyl; saflufenacil; lentil, *Lens culinaris* Medik.

Key words: Desiccation, herbicide residue, MRL, seed yield, thousand-seed weight.

Los desecantes son actualmente usados para mejorar el secado de plantas de lenteja antes de la cosecha. Sin embargo, el aplicar desecantes en estadios de desarrollo anteriores a la madurez podría resultar en reducciones en el rendimiento y calidad del cultivo, y en residuos de herbicidas a niveles inaceptables en las semillas. Existe poca información acerca de si varios herbicidas aplicados solos o en mezclas en tanque con glyphosate tienen un efecto sobre los residuos de glyphosate en la semilla cosechada. Se realizaron experimentos de campo en Saskatoon y Scott, Saskatchewan, Canada, desde 2012 a 2014, para determinar si desecantes adicionales aplicados solos o en mezclas en tanque con glyphosate mejoran el secado del cultivo y reducen los residuos de glyphosate potencialmente inaceptables en la semilla. Glufosinate y diquat mezclados en tanque con glyphosate fueron los desecantes más consistentes, brindando un secado óptimo del cultivo y una reducción general en los residuos de glyphosate en la semilla sin tener efectos adversos sobre el rendimiento y peso de la semilla. Saflufenacil brindó un secado del cultivo bueno sin tener pérdidas de rendimiento, pero falló consistentemente en reducir los residuos de glyphosate en la semilla. Se encontró que pyraflufen-ethyl y flumioxazin aplicados solos o mezclados en tanque con glyphosate fueron opciones inferiores para los productores, ya que exhibieron un secado del cultivo lento e incompleto, y no disminuyeron los residuos de glyphosate en la semilla. Con base en los resultados de este estudio, los productores deberían aplicar glufosinate o diquat con glyphosate en pre-cosecha para maximizar el secado del cultivo y las malezas, y así minimizar los residuos de glyphosate en la semilla.

Canada is a major lentil producer, accounting for 39% of global lentil production. Over the past decade, lentil production in Canada has increased from 1.1 to 2.0 million tonnes (Food and Agriculture Organization of the United Nations Statistics Division [FAOSTAT] 2015). Most of the increased lentil production results from an increased number of hectares on which lentil is grown, owing largely to increased production efficiency (FAOSTAT 2015; Statistics Canada 2015). Despite improvements in production efficiency, harvesting a short, indeterminate crop remains a challenge for growers.

Uniform seed maturity at harvest time is critical to optimize field harvesting and seed quality. Lentil plants are considered mature when the bottom third of the pods have changed color from yellow to brown (Saskatchewan Pulse Growers 2011). This

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* Graduate Student, Research Assistant, and Assistant Professor, respectively, Department of Plant Sciences, University of Saskatchewan, 51 Campus Drive, Saskatoon, SK, Canada S7N 5A8. Corresponding author's E-mail: chris.willenborg@usask.ca

stage is considered the appropriate time to swath, desiccate, or apply preharvest herbicides to lentil crops; however, variations within a field can cause lentil plants to mature at different times. Moreover, lentil is an indeterminate plant with maturation progressing from lower to upper portions of the plant, and thus various stages of pod maturation can occur on the same plant (Saskatchewan Pulse Growers 2011). Collectively, these issues result in heterogeneous maturity at harvest, which can interfere with and delay harvest operations, resulting in poor harvesting efficiency as well as reduced seed yield and quality.

To help reduce this variation, growers apply herbicides to desiccate the crop and ensure rapid and even dry-down of weeds as well as crop seeds and foliage. The chemistry of desiccants and their application timing are critical because inappropriate rates or application timing can reduce crop yield and quality (Bennett and Shaw 2000; Boudreaux and Griffin 2011), and can also leave unacceptable levels of herbicide residue in seeds (Cessna et al. 1994, 2000, 2002). In western Canada, few herbicides have been registered as desiccants or harvest aids in lentil; those that have include diquat, glyphosate, saflufenacil, and glufosinate (Saskatchewan Ministry of Agriculture 2014). Glyphosate is the most popular product in lentil production because it provides excellent control of late-emerging annual weeds, and it can improve crop dry-down (McNaughton et al. 2015; Soltani et al. 2013). Because glyphosate is translocated via phloem, it can move throughout the plant and tends to accumulate in seeds if applied prior to physiological seed maturity (Cessna et al. 1994, 2000, 2002). However, the presence of glyphosate in lentil seed can be problematic, and concerns about glyphosate residues in lentil seed have caused trade restrictions in the past (Pratt 2011). For example, Canadian lentils were rejected in 2011 by the European Union because of glyphosate residues exceeding 0.1 ppm (Pratt 2011).

Diquat is a contact herbicide that has traditionally been used as a desiccant in lentil crops (Saskatchewan Pulse Growers 2016). It rapidly destroys plant tissues that it contacts, and has little to no translocation in the plant (Cobb and Reade 2010; Saskatchewan Ministry of Agriculture 2014). In Canada, glufosinate and saflufenacil are newly registered desiccants in lentil. Glufosinate is capable of translocation within the plant, but its movement is limited by rapid phytotoxic activity (Soltani et al. 2010). Saflufenacil exhibits rapid action similar to a contact herbicide; however, it is a weak acid that translocates both acropetally and basipetally in susceptible plants (Grossman et al. 2011). Apart from these registered herbicides, other herbicides may be potential desiccants in lentil crops. Pyraflufen-ethyl is labeled as a contact desiccant in cotton (*Gossypium hirsutum* L.) (Griffin et al. 2010) and potatoes (*Solanum tuberosum* L.) (Ivany 2005), whereas flumioxazin provides rapid desiccation of dry bean (*Phaseolus vulgaris* L.) (Soltani et al. 2013). Neither pyraflufen-ethyl nor flumioxazin are registered in lentil in western Canada.

There is currently limited information available on the effects of diquat, glufosinate, flumioxazin, saflufenacil, and pyraflufen-ethyl applied alone or in combination with glyphosate as desiccants for lentil dry-down. The addition of these contact herbicides to glyphosate could provide uniform crop desiccation and potentially improve weed control compared to when these herbicides are applied alone. Additionally, glyphosate seed residues may be reduced by the addition of these contact herbicides to glyphosate in a tank mix. Research is needed to identify herbicides or herbicide tank mixes that provide rapid and uniform lentil crop desiccation, have little to no effect on seed yield and quality, and leave minimal residues in the seed. Therefore, the objective of this study was to evaluate contact herbicides applied alone or in combination with glyphosate for their potential to provide lentil crop desiccation with minimal impact on seed yield and weight, and to reduce glyphosate residues in seed.

Materials and Methods

Experimental Site and Design. Six field experiments were conducted over a 3-yr period (2012, 2013, 2014) at Saskatoon (52.5°N, 106.5°W) and Scott (52.4°N, 108.8°W), Saskatchewan, Canada. Soil texture at Saskatoon ranged from clay to sandy loam, whereas the soil texture at Scott was a silt loam. The pH and organic matter content ranged from 7.5 to 7.9 and 2.4% to 4.5%, respectively, at Saskatoon. The Scott site had a pH of 5.3 to 6.8 and an organic-matter content of 2.4% to 2.6%. The experimental design was a randomized complete block design with four replicates. Each block

Table 1. Herbicide information for all products used in the experiments.

Herbicide common name	Herbicide trade name	Rate	Manufacturer	Address	Web site
		g ai ha^{-1} or g ae ha^{-1}			
Glyphosate	Roundup Weathermax	900	Monsanto Canada	1-900 Research Road, Winnipeg, MB	http://www.monsanto.ca
Pyraflufen-ethyl	NA[a]	10 + 20	NuFarm Canada	350-2618 Hopewell Place, Calgary, AB	http://www.nufarm.ca
Glufosinate	Good Harvest	300 + 600	AgraCity Crop & Nutrition Ltd.	318-111 Research Dr., Saskatoon, SK	http://www.agracity.ca
Flumioxazin	Valterra	105 + 210	Valent Canada	2150 Boul. St-Elzéar Ouest, Laval, QC	http://www.valentcanada.com
Saflufenacil	Heat	36 + 50	BASF Canada	100 Milverton Drive, Mississauga, ON	http://www.agro.basf.ca

[a] Not available as a stand-alone product in Canada.

consisted of 21 herbicide treatments plus an unsprayed control (Table 1). The herbicide treatments included pyraflufen-ethyl (10 and 20 g ai ha^{-1}), glufosinate (300 and 600 g ai ha^{-1}), flumioxazin (105 and 210 g ai ha^{-1}), saflufenacil (36 and 50 g ai ha^{-1}), and diquat (208 and 415 g ai ha^{-1}), with each herbicide applied alone or in combination with glyphosate (900 g ae ha^{-1}). Individual plot sizes were 2 m by 6 m at Saskatoon and 2 m by 5 m at Scott. All herbicides were applied with the recommended adjuvant, either Merge® (50% surfactant; 50% petroleum hydrocarbons solvent) or Agral 90® (90% nonylphenoxy polyethoxy ethanol). Merge® at 1% v/v was added to treatments containing pyraflufen-ethyl, whereas rates of 0.5 and 1 L ha^{-1} were added to the tank mix of saflufenacil and glyphosate and saflufenacil applied alone, respectively. Agral 90® at 0.25% v/v was added to treatments containing flumioxazin.

Experimental Procedure. In the fall prior to plot establishment, the entire experimental area received an application of either ethalfluralin (Saskatoon, 1,400 g ai ha^{-1}) or imazethapyr (Scott, 13 g ai ha^{-1}). A glyphosate burn off (900 g ha^{-1}) was made at both sites each spring before or immediately after seeding. Prior to sowing, lentil seed received a liquid seed treatment (0.73% fludioxonil; 1.10% metalaxyl) and inoculant (*Rhizobium leguminosarum* biovar *viceae*), which were applied at label rates. Lentil was seeded into fallowed plots with a small plot drill equipped with single shoot hoe openers on 22-cm row spacing. Seeding depth was 3 cm, with a seeding rate of 130 seeds m^{-2}. Plots were rolled at both sites immediately following planting to provide a smooth and level surface for harvest. The small-seeded red lentil cultivar CDC Maxim was planted at both sites, as it is the most widely grown lentil cultivar in western Canada.

Maintenance applications of herbicides were made at each site for postemergence weed control. At Saskatoon, a tank mixture of imazamox plus imazethapyr (30 g ai ha^{-1}) was applied between the five- and six-node stage of lentil development. At Scott, an in-crop application of quizalofop-p-ethyl (420 g ai ha^{-1}) was made when lentil was at the four-node stage. Any weeds not controlled by the herbicides were removed by hand to maintain weed-free plots. To prevent disease, prothioconazole (166 g ai ha^{-1}) was applied at Saskatoon and boscalid (294 g ai ha^{-1}) at Scott when lentil reached the early flowering stage.

Herbicide treatments were applied with an air-pressurized tractor-mounted sprayer equipped with shielding (110-015 AirMix nozzles, 275 kPa, 45-cm spacing) at Saskatoon, and with a CO_2-pressurized bicycle sprayer (110-003 AirMix nozzles, 276 kPa, 25 cm) at Scott. Both sprayers were calibrated to deliver 200 L ha^{-1} of spray solution. All desiccant treatments were targeted to be applied when the crop was at approximately 30% seed moisture content, with seed moisture content determined from randomly selected plants in border plots. Actual seed moisture contents at the time of application in 2012 and 2013 were 35% and 32%, and 40% and 35% at Saskatoon and Scott,

Table 2. Herbicide application date and environmental conditions at time of application at Saskatoon and Scott, SK from 2012 to 2014.

Site	Year	Herbicide application date	Temperature	Relative humidity
			C	%
Saskatoon	2012	August 28	26.0	42.7
	2013	August 19	30.1	30.5
	2014	August 29	23.0	38.0
Scott	2012	August 23	20.2	NA[a]
	2013	September 4	16.3	62.9
	2014	August 22	13.8	46.9

[a] Abbreviation: NA, no available data were recorded.

respectively. Application dates and environmental conditions are provided in Table 2.

Data Collection. Visual ratings of desiccation progress were made at 3, 7, 14, and 21 d after application (DAA) based on the Canadian Weed Science Society 0 to 100 rating scale. On this scale, 80% represents commercially acceptable weed control, whereas 70% to 80% represents commercially acceptable weed suppression. The visual ratings at 3, 7, 14, and 21 DAA were used to calculate an area under the desiccant progress curve (AUDPC):

$$AUDPC = \left(\frac{D_1 + D_2}{2}\right)(t_2 - t_1) + \left(\frac{D_2 + D_3}{2}\right)(t_3 - t_2) + \left(\frac{D_3 + D_4}{2}\right)(t_4 - t_3), \quad [1]$$

where D_1, D_2, D_3, and D_4 represent observed desiccation ratings at each evaluation day; t_1, t_2, t_3, and t_4 represent the number of days after each herbicide application (Jeger and Viljanen-Rollinson 2001; Simko and Piepho 2012). The four desiccation ratings were converted into a single relative value for reporting via the AUDPC equation, which models the progression of desiccation between ratings (McNaughton et al. 2015).

Lentils were harvested with a small plot combine at maturity. Harvested seed was dried for 1 wk at room temperature (21 C) to a constant moisture (13%); the seed was then cleaned, and the weight of the seed was recorded. The weight of 1,000 seeds (TSW) was then determined by weighing 250 seeds and multiplying by four. Glyphosate residue in seed was measured at both sites in 2012 and 2013. Seed samples (250 g) from the unsprayed control and the glyphosate treatments were collected at 7 DAA, cleaned, placed into plastic bags, and kept in a freezer at −20 C until all samples were collected. Samples were then sent to ALS Laboratories in Edmonton, AB, Canada. With the use of a standardized process provided by ALS Laboratories, high-performance liquid chromatography (HPLC) using column switching and postcolumn derivatization with fluorescence detection was employed to determine glyphosate and AMPA residue. Differential retention time was used to distinguish between glyphosate and AMPA, with a limit of detection of 0.02 ppm for both compounds.

Statistical Analysis. The assumptions of normality and homogeneity of variance of residuals were tested using the PROC UNIVARIATE procedure and Levene's test, respectively, in SAS 9.3 (SAS Institute Inc., Cary, NC). Data were analyzed with the use of the MIXED procedure in SAS 9.3, with heterogeneous variance structures modeled within site years as necessary. The REPEATED statement was used to model heterogeneous variances for yield data because these data did not meet the assumptions of ANOVA even after transformation. In the mixed model, herbicide treatment was considered a fixed effect, whereas replication and its interaction with herbicide treatment were considered random effects. To determine whether data could be combined across site years for analysis, the COVTEST option of PROC MIXED was used, with site year as a random term in the model (SAS Institute 2014). Where data could not be combined, data were analyzed within site years, with site year treated as a fixed effect. Means were separated using Tukey's HSD, with treatment differences declared significant at $P \leq 0.05$. Specific comparisons of interest were made between various herbicide treatments using single-degree-of-freedom contrasts.

Results and Discussion

Lentil Desiccation. The interaction between site year and herbicide treatment was significant for AUDPC and glyphosate residue; therefore, data were analyzed within site years (Table 3). At Saskatoon, most herbicide treatments tended to exhibit better desiccation than the untreated control

Table 3. P values derived from analysis of variance demonstrating area under desiccation progress curve (AUDPC), seed yield, thousand-seed weight (TSW), and glyphosate residue (GR), as influenced by herbicide desiccation treatments at Saskatoon and Scott, SK from 2012 to 2014.

Source	AUDPC	Yield	TSW	GR
	P value			
Site year (SY)	0.0621	0.0753	0.0699	0.1203
Herbicide (H)	<0.0001***	0.2547	0.4318	0.0044**
SY × H	<0.0001***	0.3831	0.3516	0.0037**

*,**,*** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

(Table 4). For example, glufosinate (300 or 600 g ha^{-1}) or diquat (415 g ha^{-1}) applied alone or in a tank mix with glyphosate resulted in desiccation progressing to the greatest extent, with some of these treatments showing two- to sixfold greater AUDPC than the nontreated control. Treatments containing saflufenacil (36 or 50 g ha^{-1}) or the lower rate of diquat (208 g ha^{-1}) exhibited enhanced crop desiccation, as much as fourfold greater than the untreated control (Table 4). Across all 3 yr at the Saskatoon site, crop desiccation was least enhanced by glyphosate, pyraflufen-ethyl, or flumioxazin applied alone (Table 4). Contrasts showed that adding other contact herbicides to glyphosate significantly improved desiccation over

Table 4. Tukey's HSD means comparison of lentil areas under desiccation progress curve (AUDPC) at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent differences between herbicide treatments in lentil desiccation.[a]

Herbicide	Rate	AUDPC[b] Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2012	Scott 2013	Scott 2014
	g ai/ae ha^{-1}						
Untreated	0	218 G	999 F	691 L	920 E	1,441 C	1,143 BC
Glyphosate	900	700 D–F	1,186 EF	836 J–L	1,148 A–E	1,596 A–C	1,329 A–C
Pyraflufen-ethyl	10	538 F	1,221 EF	788 KL	962 DE	1,484 BC	1,290 A-C
Pyraflufen-ethyl + glyphosate	10 + 900	871 C–E	1,358 C–E	942 G–K	1,276 A–E	1,527 A–C	1,273 A–C
Pyraflufen-ethyl	20	563 F	1,336 DE	856 I–L	999 C–E	1,496 A–C	1,232 A–C
Pyraflufen-ethyl + glyphosate	20 + 900	965 B–D	1,361 C–E	1,065 E–I	1,149 A–E	1,549 A–C	1,235 A–C
Glufosinate	300	1,531 A	1,512 A–D	1,258 B–E	1,444 A–C	1,668 AB	1,555 A
Glufosinate + glyphosate	300 + 900	1,532 A	1,606 A–D	1,324 A–D	1,362 A–E	1,610 A–C	1,538 AB
Glufosinate	600	1,614 A	1,598 A–D	1,518 A	1,389 A–D	1,694 A	1,560 A
Glufosinate + glyphosate	600 + 900	1,563 A	1,620 A–C	1,441 AB	1,439 A–C	1,670 AB	1,537 AB
Flumioxazin	105	580 F	1,205 EF	956 G–K	957 DE	1,476 BC	1,255 A–C
Flumioxazin + glyphosate	105 + 900	932 CD	1,350 DE	964 G–K	1,136 B–E	1,522 A–C	1,453 A–C
Flumioxazin	210	620 EF	1,348 DE	909 H–K	1,105 B–E	1,492 A–C	1,304 A–C
Flumioxazin + glyphosate	210 + 900	933 CD	1,436 A–E	958 G–K	1,185 A–E	1,540 A–C	1,130 C
Saflufenacil	36	956 B–D	1,366 BE	1,011 F–J	1,155 A–E	1,435 C	1,187 A–C
Saflufenacil + glyphosate	36 + 900	1,121 BC	1,384 BE	1,099 E–H	1,335 A–E	1,566 A–C	1,343 A–C
Saflufenacil	50	981 BC	1,502 A–D	1,103 E–H	1,084 C–E	1,536 A–C	1,276 A–C
Saflufenacil + glyphosate	50 + 900	1,032 BC	1,389 A–E	1,109 D–H	1,316 A–E	1,546 A–C	1,295 A–C
Diquat	208	1,229 B	1,515 A–D	1,205 C–F	1,370 A–D	1,409 C	1,176 A–C
Diquat + glyphosate	208 + 900	1,091 BC	1,499 A–D	1,136 D–G	1,400 A–D	1,557 A–C	1,300 A–C
Diquat	415	1,535 A	1,654 A	1,413 A–C	1,591 A	1,526 A–C	1,481 A–C
Diquat + glyphosate	415 + 900	1,527 A	1,633 AB	1,433 AB	1,533 AB	1,606 A–C	1,425 A–C
HSD		274	270	216	451	208	397
Estimates							
Glyphosate vs. TM + glyphosate		−457***	−278***	−311***	−165**	26	−24
TM vs. TM + glyphosate		−142***	−38	−45*	−107**	−47**	−21
TM (low rate) vs. TM (high rate)		−95***	−86***	−112***	−4	−40*	−10

*,**,*** significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

[a] Abbreviations: HSD, honest significant difference; TM, tank-mix partners.

[b] Means within a column followed by the same-letter are not significantly different on the basis of $HSD_{0.05}$.

glyphosate alone in all years, as did using higher rates of these herbicides (Table 4). In 2 of 3 yr (2012 and 2014), adding glyphosate to the herbicide tank mixes improved desiccation relative to the contact herbicides alone. Based on the nature of glyphosate and the tank-mix partners, these results are not unexpected, as glyphosate is a slower-acting herbicide than all other herbicides included in this study.

Similar results were observed at the Scott site, where in 2012, treatments containing diquat or glufosinate had the greatest desiccation efficiency, exhibiting a 57% greater AUDPC compared to the untreated control, whereas none of the other herbicides enhanced desiccation (Table 4). In 2013 and 2014, glufosinate applied alone provided better desiccation (15% greater AUDPC) than the untreated control (Table 4). In 2012 and 2013, adding glyphosate to the herbicide tank mixtures improved desiccation compared with the contact herbicides applied alone. In contrast, adding contact herbicides to glyphosate only improved desiccation in 2012 compared with glyphosate applied alone. The rate of the contact herbicide had only a minor effect on desiccation at Scott across all 3 yr of the study.

These results indicate that adding contact herbicides to glyphosate generally improved lentil crop desiccation compared to glyphosate or the tank-mix partner applied alone (Table 4). As expected, the contact herbicides glufosinate and diquat produced rapid phytotoxic effects on plant tissues that came into direct contact with the active ingredient (Table 4), resulting in rapid and efficient desiccation of lentil plants. Similarly, Soltani et al. (2013) reported that the contact herbicides glufosinate, saflufenacil, diquat, carfentrazone-ethyl, and flumioxazin enhanced dry bean desiccation when tank mixed with glyphosate.

In contrast, glyphosate, pyraflufen-ethyl, and flumioxazin applied alone generally did not effectively enhance crop desiccation compared with the untreated control (Table 4). The lack of effect of glyphosate is not surprising, given that it requires translocation to actively growing metabolic sinks to inhibit plant growth and thus, exhibits slower crop dry down than contact herbicides (Baylis 2000; Duke and Powles 2008; Schemenauer 2011). Interestingly, pyraflufen-ethyl and flumioxazin are labeled as contact herbicides and have been used as desiccants on potatoes and dry beans, yet they were not as effective on lentil as the other contact herbicides. This could result from a lower sensitivity of lentil plants to pyraflufen-ethyl and flumioxazin in comparison to glufosinate or diquat, but this has yet to be proven. Nevertheless, the results show that these products did not provide effective desiccation of lentil.

Table 5. Tukey's HSD means comparison of seed yield and thousand-seed weight (TSW) at Saskatoon and Scott, SK from 2012 to 2014.

Treatment	Rate	Yield	TSW
	g ai/ae ha^{-1}	kg ha^{-1}	g
Untreated	0	3,520	41.4
Glyphosate	900	3,393	40.5
Pyraflufen-ethyl	10	3,575	40.4
Pyraflufen-ethyl + glyphosate	10 + 900	3,364	40.3
Pyraflufen-ethyl	20	3,250	40.3
Pyraflufen-ethyl + glyphosate	20 + 900	3,434	40.2
Glufosinate	300	3,582	39.8
Glufosinate + glyphosate	300 + 900	3,189	40.4
Glufosinate	600	3481	40.1
Glufosinate + glyphosate	600 + 900	3,321	39.6
Flumioxazin	105	3,362	40.6
Flumioxazin + glyphosate	105 + 900	3,090	39.8
Flumioxazin	210	3,336	40.8
Flumioxazin + glyphosate	210 + 900	3,301	40.0
Saflufenacil	36	3,544	39.8
Saflufenacil + glyphosate	36 + 900	3,171	40.0
Saflufenacil	50	3,320	40.4
Saflufenacil + glyphosate	50 + 900	3,384	40.7
Diquat	208	3,387	40.6
Diquat + glyphosate	208 + 900	3,309	40.2
Diquat	415	3,458	39.6
Diquat + glyphosate	415 + 900	3,347	40.5
HSD[a]		NS	NS

[a] Abbreviation: HSD, honest significant difference.

Seed Yield and TSW. Glyphosate applied alone or in combination with tank-mix partners had no effect on seed yield or TSW (Table 3). The lack of effects observed for yield and TSW were consistent across all site years, as statistically significant interactions were not detected between herbicide treatment and site year (Table 3). Seed yield and TSW were unaffected by the addition of contact herbicides to glyphosate compared to glyphosate applied alone (Table 5). Likewise, applying higher rates of contact herbicides also did not affect lentil yield or TSW.

These results suggest that pyraflufen-ethyl, glufosinate, flumioxazin, saflufenacil, and diquat, applied

Table 6. Tukey's HSD means comparison of glyphosate residue (GR) at Saskatoon and Scott, SK, in 2012 and 2013. Estimate statements represent differences between herbicide treatments in glyphosate residue.[a]

Treatment	Rate	Glyphosate residue[b]			
		Saskatoon 2012	Saskatoon 2013	Scott 2012	Scott 2013
	g ai/ae ha^{-1}	ppm			
Glyphosate	900	3.5 A	0.7	3.7 AB	0.2
Pyraflufen-ethyl + glyphosate	10 + 900	3.1 AB	0.1	3.7 AB	0.1
Pyraflufen-ethyl + glyphosate	20 + 900	2.5 A–D	1.1	2.6 A–C	0.1
Glufosinate + glyphosate	300 + 900	1.6 DE	0.1	2.3 A–C	0.1
Glufosinate + glyphosate	600 + 900	1.7 C–E	0.2	1.2 BC	0.1
Flumioxazin + glyphosate	105 + 900	3.4 A	1.7	4.8 A	0.1
Flumioxazin + glyphosate	210 + 900	3.8 A	0.3	4.4 A	0.1
Saflufenacil + glyphosate	36 + 900	2.0 B–D	0.8	3.6 AB	0.1
Saflufenacil +glyphosate	50 + 900	2.8 A–C	0.3	3.3 A–C	0.1
Diquat + glyphosate	208 + 900	1.2 EF	0.3	1.1 BC	0.1
Diquat + glyphosate	415 + 900	0.7 F	0.1	0.5 C	0.1
HSD		1.3	NS	2.9	NS
Estimates					
Glyphosate vs. TM + glyphosate		1.2**	NS	1	NS
TM + glyphosate (low rate) vs. TM + glyphosate (high rate)		0.0	NS	0.7	NS

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

[a] Abbreviations: HSD, honest significant difference; NS, not significant; TM, tank-mix partners.

[b] Means within a column followed by the same letter are not significantly on the basis of $HSD_{0.05}$.

alone or in combination with glyphosate, will not affect lentil yield or seed weight if applied near 30% seed moisture content, as was targeted in this study. Similar results have been reported in other pulse crops when desiccants were applied close to, or at crop maturity. For example, preharvest use of glyphosate, glufosinate, or paraquat had no adverse effect on seed yield and weight in dry bean (Wilson and Smith 2002) or soybean (*Glycine max* L.) (Ellis et al. 1998; Ratnayake and Shaw 1992). Bennett and Shaw (2000) reported no differences in seed yield and TSW when glyphosate + sodium chlorate or paraquat + sodium chlorate were applied to soybean at full maturity. Similarly, Soltani et al. (2013) and McNaughton et al. (2015) observed no reduction in dry bean yields when desiccants (glyphosate and saflufenacil) were applied at full maturity.

Other studies have reported reductions in soybean seed yield and quality if desiccant applications were timed improperly (Azlin and McWhorter 1981; Cerkauskas et al. 1982; Whigham and Stoller 1979). Both Whigham and Stoller (1979) and Cerkauskas et al. (1982) observed reductions in soybean yield when paraquat was applied before crop maturity. Azlin and McWhorter (1981) observed similar effects, reporting that seed yield and quality were reduced when glyphosate was applied 3 to 4 wk before harvest. Such inconsistencies in the results between studies are likely attributable to the timing of herbicide application, as the application of desiccants before physiological maturity may inhibit photosynthesis during seed development, causing damage to immature seeds (Boudreaux and Griffin 2011; Retnayake and Shaw 1992).

Glyphosate Residue. Glyphosate residue varied between site years and therefore, glyphosate residue data were analyzed within site years (Table 3). None of the herbicide treatments exceeded 4.0 ppm of glyphosate (MRL set by Canada) at Saskatoon in 2012 (Table 6). When glyphosate was tank-mixed with glufosinate or diquat, glyphosate resides were lower than when glyphosate was applied alone, and did not exceed 2.0 ppm (MRL set by Japan) (Table 6). The addition of glufosinate (300 or 600 g ha^{-1}), saflufenacil (36 g ha^{-1}), or diquat (208 or 415 g ha^{-1}) to glyphosate decreased glyphosate residues between 43% and 73% compared to glyphosate alone (Table 6). Likewise, at Scott in 2012, glufosinate (600 g ha^{-1}) or diquat (208 or 415 g ha^{-1}) tank mixed with glyphosate produced residue levels that did not exceed 4.0 ppm or 2.0 ppm, respectively. Not surprisingly, contrasts showed that glyphosate residues were lower (1.2 ppm, on average) when contact herbicides were added to glyphosate at Saskatoon in 2012. A similar 1.0-ppm reduction was observed at Scott in 2012 when contact herbicides were added to glyphosate, but the reduction was not statistically significant. In contrast, pyraflufen-ethyl (10 or 20 g ha^{-1}), saflufenacil (50 g ha^{-1}) and flumioxazin (105 or 210 g ha^{-1}) did not affect glyphosate residues compared to glyphosate applied alone (Table 6).

There were no differences in glyphosate residues between desiccant treatments at Saskatoon or Scott in 2013; none of the treatments resulted in unacceptable levels of glyphosate residue. In addition, glyphosate residue was unaffected by herbicide rate (Table 6). The lack of differences may have resulted from reduced translocation of glyphosate to lentil seeds because of lower seed moisture contents at time of application in 2013 (32% and 35% at Saskatoon and Scott, respectively, compared with 35% and 40% at the respective sites in 2012). Indeed, decreased glyphosate residues with lower seed moisture at application also has been reported for wheat (*Triticum aestivum* L.), field pea (*Pisum sativum* L.), barley (*Hordeum vulgare* L.), flax (*Linum usitatissimum* L.), and canola (*Brassica rapa* L.) (Cessna et al. 1994, 2000, 2002).

Glyphosate residue is an important consideration for exporters because unacceptable glyphosate residue levels can cause rejection of shipments by importers. Currently, the two lowest MRLs are 2.0 ppm and 4.0 ppm, set by Japan and Canada, respectively (Bryant Christie Inc. 2015). Results from this study suggest that using glyphosate as a desiccant can result in unacceptable glyphosate seed residues (Japan MRL), even if glyphosate is applied near the recommended 30% seed moisture content. However, tank-mixing glufosinate (600 g ha^{-1}) or diquat (208 or 415 g ha^{-1}) with glyphosate consistently provided reductions in glyphosate residues such that residues typically did not exceed 2.0 ppm (Table 6). Other treatments, such as pyraflufen-ethyl and flumioxazin, failed to reduce glyphosate residues in lentil seed (Table 6). Saflufenacil is a popular product for lentil desiccation, but the results from this study were inconclusive in determining whether saflufenacil reduces glyphosate residues. Only once (36 g ha^{-1} rate in Saskatoon 2012) did the addition of saflufenacil reduce glyphosate residues; therefore, further research is required over more environments to determine the consistency of saflufenacil application in reducing glyphosate residues. Saflufenacil is a weak acid that is both phloem and xylem mobile (Grossman et al. 2011), which may limit its ability to interfere with glyphosate translocation. Ashigh and Hall (2010) reported reduced activity on buckwheat (*Fagopyrum esculentum* L.), cabbage (*Brassica oleracea* L.), and canola when glyphosate was tank-mixed with saflufenacil and thus, interference with glyphosate translocation may be species dependent.

The results of this study indicate that the addition of contact herbicides to glyphosate will improve lentil desiccation without negatively impacting lentil yield or TSW. Seed yield and weight were likely unaffected because the crop reached physiological maturity when desiccants were applied, resulting in minimal effects on seed development (Bennett and Shaw 2000; Boudreaux and Griffin 2011; Cerkauskas et al. 1982; Ellis et al. 1998; Ratnayake and Shaw 1992; Whigham and Stroller 1979; Wilson and Smith 2002). Furthermore, tank mixes of a contact herbicide produced faster crop desiccation than glyphosate alone, and their rapid action reduces translocation resulting in lower glyphosate seed residues (Bethke et al. 2013; Wehtje et al. 2008). However, only tank mixes containing glufosinate and diquat effectively and consistently reduced glyphosate seed residues relative to the glyphosate-alone treatment. Although saflufenacil also accelerated crop desiccation, it did not have a consistent impact on glyphosate residues, and in some years (2012), led to unacceptable glyphosate residues. Pyraflufen-ethyl and flumioxazin did not effectively desiccate the crop, and these treatments, when combined with glyphosate, did not reduce glyphosate residues. It is possible that lentil plants are less sensitive to pyraflufen-ethyl, and flumioxazin than the traditional desiccants (glufosinate and diquat). Soltani et al. (2005, 2010) and Ivany (2005) both reported differential sensitivity among crops to flumioxazin, saflufenacil, and pyraflufen-ethyl. Soltani et al. (2005) attributed these differences to genetic variability between market classes and differences in seed size among dry bean cultivars, as larger-seeded cultivars were more tolerant to flumioxazin than were smaller-seeded cultivars.

In summary, tank mixes of glufosinate + glyphosate or diquat + glyphosate applied at 30% to 40% seed moisture content provided excellent crop desiccation while reducing glyphosate seed residues, with no effect on yield or seed weight. Therefore, these tank mixes would be good options for growers seeking to manage weeds at harvest and where the application of glyphosate alone will not provide rapid crop desiccation. Saflufenacil provided good crop desiccation without yield losses, but failed to reduce glyphosate seed residues consistently when compared to glyphosate applied alone. Other contact herbicides, such as flumioxazin and pyraflufen-ethyl, did not provide efficacious crop desiccation, nor did they consistently decrease glyphosate residues. Moreover, some of the glyphosate residues observed for these treatments exceeded the MRL of Japan, an importer of Canadian lentils and thus, these herbicides should not be considered for lentil desiccation.

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