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Developing an Integrated Weed Management System for Herbicide-Resistant Weeds Using Lentil (*Lens culinaris*) as a Model Crop

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The escalating evolution of weed species resistant to acetolactase synthase (ALS)-inhibitor herbicides makes alternative weed control strategies necessary for field crops that are dependent on this herbicide group. A fully integrated strategy that combined increased crop seeding rates (2X or 4X recommended), mechanical weed control with a minimum-tillage rotary hoe, and reduced-rate non–ALS inhibitor herbicides was compared with herbicides, rotary hoe, and seeding rates alone as a method of controlling ALS inhibitor–tolerant Indian mustard as a model weed. The full-rate herbicide treatment had the lowest weed biomass (98% reduction) and the highest yield of all treatments in 3 of 4 site-years, regardless of seeding rate. The fully integrated treatment at the 4X seeding rate had weed suppression rates equal to the full herbicide treatment at the recommended seeding rate. The fully integrated and reduced-rate herbicide treatments at the 4X seeding rate reduced weed biomass by 89% and 83%, respectively, compared with the control at the recommended seeding rate. The rotary hoe treatment alone resulted in poor weed control (≤38%), even at the highest seeding rate. Fully integrated and reduced-rate herbicide treatments at 2X and 4X seeding rates had yields equal to those of the full herbicide treatment at the recommended seeding rate. Partially or fully integrated weed control strategies that combine increased crop seeding rates and reduced-rate non–ALS inhibitor herbicides, with or without the use of a rotary hoe, can control weeds resistant to ALS-inhibitor herbicides, while maintaining crop yields similar to those achieved with full-rate herbicides. However, combining increased seeding rate, reduced-rate herbicides, and mechanical rotary hoe treatment into a fully integrated strategy maximized weed control, while reducing reliance on and selection pressure against any single weed control tactic.

Nomenclature: Indian mustard, *Brassica juncea* (L.) Czern.

Key words: Canola-quality mustard, cultivation, cultural control, integrated pest management, integrated weed management, mechanical weed control, metribuzin, min-till rotary hoe, reduced herbicide rates, seeding rate, saflufenacil.

Herbicide resistance in weed species is an increasing problem globally due to overreliance on herbicides for weed control. There are currently 463 unique cases of herbicide-resistant weeds worldwide, with more than 200 cases in the United States and Canada (Heap 2016). Growing farm sizes, low herbicide costs, widespread adoption of herbicide-tolerant crops, and reduced tillage systems, among other factors, have encouraged herbicide reliance in North America, particularly over the last few decades (Owen et al. 2015). With the rise of herbicide-resistant weed species, however, there is a need to move away from single-tactic weed control towards integrated weed management (IWM) systems to minimize weed control failures and reduce further selection pressure for herbicide-resistant weeds.

IWM systems combine cultural, genetic, mechanical, biological, and chemical weed control strategies to increase weed control efficacy and reduce reliance on herbicidal weed control (Swanton and Weise 1991). Combining cultural and mechanical weed control into an integrated strategy has proven useful in organic cropping systems, where herbicide use is not permitted. A competitive oat (*Avena sativa* L.) variety grown at a high crop seeding rate, combined with POST harrowing, decreased weed biomass by 71% and increased grain yield by 25%, compared with standard organic practices (Benaragama and Shirtliffe 2013).

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In systems where herbicides are used, an integrated strategy can increase herbicide efficacy (Ball et al. 1997; Harker et al. 2009). Herbicide applied at one-quarter the standard recommended rate reduced wild oat (*Avena fatua* L.) seed production by over 90% when combined with tall barley (*Hordeum vulgare* L.) cultivars, high crop seeding rate, and crop rotation (Harker et al. 2009). Even when full herbicide rates were used, supplementing herbicide application with tall cultivars and crop rotation increased barley yield (Harker et al. 2009). Furthermore, supplementing herbicidal weed control with other tactics has been shown to slow herbicide resistance enrichment in resistant weed populations. When acetyl-CoA carboxylase (ACCase) inhibitor–resistant wild oats were treated with ACCase-inhibitor herbicides, a treatment that combined two-third herbicide rates with high crop seeding rates and competitive crops (barley, canola [*Brassica napus* L.], spring wheat [*Triticum aestivum* L.]) resulted in fewer herbicide-resistant weed seedlings compared with standard recommended herbicide and crop seeding rates (Beckie and Kirkland 2003). However, fully integrated strategies that combine cultural, mechanical, and chemical tools to combat herbicide-resistant weed species still need verification to address the global problem of herbicide-resistant weeds.

Lentil (*Lens culinaris* Medik.) is a suitable model crop to study control of herbicide-resistant weeds using IWM, due to the limitations of herbicidal weed control for this crop. This lack of control is due to both limited herbicide options and the presence of herbicide-resistant weed species. There are a number of herbicides registered to control grassy weeds in lentil, but few options exist for control of broadleaf weeds (Brand et al. 2007). Metribuzin was historically the only herbicide registered for POST control of broadleaf weeds, but it has many application restrictions due to crop safety concerns, including leaf chlorosis, stand reduction, and decreased yields (Friesen and Wall 1986; Ghosheh and El-Shatnawi 2003). The Crop Development Centre of the University of Saskatchewan developed lentil varieties tolerant to the imidazolinone (acetolactase synthase [ALS]-inhibitor) herbicides through mutation breeding in order to deal with the shortcomings in broadleaf weed control in lentil (Chant 2004; Slinkard et al 2007). Weed control in these ALS inhibitor herbicide–tolerant lentil varieties was initially excellent and, as a consequence, they have had very high adoption rates.

While ALS-inhibitor herbicides are effective, they are also one of the most susceptible chemistries to the development of herbicide-resistant weeds. Resistance to ALS inhibitor chemistries in weed populations can occur due to both target-site and metabolic mechanisms (Christoffers et al. 2010; Veldhuis et al. 2000). ALS-inhibitor resistance has been documented as having developed in fewer than five applications of ALS-inhibitor products (Beckie et al. 2006; Saari et al. 1994; Warwick et al. 2005). It is estimated that annually approximately 30% of crop acres on the Canadian prairies receive an application of an ALS-inhibitor product (Beckie et al. 2007). This selection pressure has resulted in selection of wild mustard (*Sinapis arvensis* L.), kochia [*Kochia scoparia* (L.) Schrad.], cleavers (*Galium* spp.), and other species resistant to the only broadleaf herbicides available that do not cause crop damage in lentil (Beckie et al. 2013). Weed control failures in lentil are now common once again and highlight the urgency of developing alternative weed control systems.

Several alternative weed control methods have been researched but have not been combined into an IWM system for herbicide-resistant weeds in lentil. The cultural strategy of increasing seeding rate has been shown to reduce weed competition (Ball et al. 1997; Baird et al. 2009), increase crop yield (Ball et al. 1997; Baird et al. 2009), and complement herbicidal weed control in lentil (Ball et al. 1997). However, increased seeding rates have not been widely adopted outside of organic systems due to concerns about seed costs and disease. Mechanical weed control tactics are rarely used outside organic production due to widespread adoption of reduced tillage systems in the North American prairies. However, recent research in organic field pea (*Pisum sativum* L.) and lentil suggests that multiple passes with a minimum-tillage rotary hoe can remove shallow-seeded weeds with minimal soil disturbance and minimal crop damage (Johnson 2011; Shirtliffe and Johnson 2012).

In this study, imidazolinone (ALS inhibitor)-tolerant lentil is used as a model crop to study control of herbicide-resistant weeds using IWM. Imidazolinone-tolerant 'Xceed®' Indian mustard was chosen as a model weed due to its morphological and genetic similarity to the weed wild mustard, which is very problematic in lentil production. The use of Indian mustard ensured that all weeds had resistance to ALS-inhibitor herbicides and that weed populations were equal among plots. The objective of this study was to systematically evaluate the weed control and crop yield effects of using integrated cultural, mechanical, and chemical tactics to control an herbicide-resistant weed in lentil.

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Materials and Methods

Site Description. Field experiments were conducted over 5 site-years in central Saskatchewan, Canada, at the Kernen Crop Research Farm (KCRF; 52.16°N, 106.52°W) in 2011, 2012, and 2013, and at the Alternative Cropping Systems Study at Agriculture and Agri-Food Canada Scott Research Farm (ACS; 52.36°N, 108.84°W) in 2011 and 2012. The KCRF is located on a Sutherland series clay loam (Bradwell Dark Brown Chernozem; 10% sand, 40% silt, and 50% clay), and ACS is on a loam soil (Dark Brown Chernozem; 38% sand, 40% silt, and 21% clay).

Experimental Procedures. The experimental design was a randomized complete block design with a factorial treatment structure, with four replicates. The two factors tested were seeding rate (three levels) and weed control strategy (six levels). While increased seeding rate is a weed control tactic (Ball et al. 1997; Baird et al. 2009), seeding rate was considered as a separate factor so that multiple levels could be tested alone and in combination with other weed control strategies. The three seeding rates targeted 130 plants m^{-2}, 260 plants m^{-2}, and 520 plants m^{-2}, which equated to 1X, 2X, and 4X the provincial recommended seeding rate for lentil (Saskatchewan Pulse Growers 2012). Seeding rates were calculated based on the actual germination percentage of the seed lot and a mortality rate of 10% in order to achieve the desired plant stand (Saskatchewan Pulse Growers 2012). The six levels of weed control applied were a control treatment, which received no in-crop weed control; a (mechanical) rotary hoe treatment; a saflufenacil herbicide treatment; a half-rate metribuzin herbicide treatment; an integrated treatment, which combined rotary hoe, saflufenacil, and half-rate metribuzin; and a full herbicide treatment, which combined saflufenacil and full-rate metribuzin. The two treatments that combined increased lentil seeding rates (2X or 4X the recommended) with integrated weed control treatment are hereafter referred to as the fully integrated treatment (2X or 4X).

Plots were seeded to the extra-small red imidazolinone (ALS inhibitor herbicide)-tolerant lentil variety 'CDC Impala.' Certified lentil seed was obtained from a local pedigreed seed grower. Lentils were seeded using a cone seeder with disk openers on 20-cm row spacing at KCRF and 25-cm row spacing at ACS. At KCRF plot size was 4 m by 6 m, while at ACS plot size was 4 m by 10 m. Tag Team® granular fungal and rhizobial inoculant (Novozymes, Saskatoon, SK) was applied with the seed at the recommended rate of 4.6 kg ha^{-1} at both sites. Granular fertilizer was mid-row banded at KCRF and seed placed at ACS at rates based on soil test recommendations. At KCRF imidazolinone-tolerant Xceed® Indian mustard was seeded in rows perpendicular to lentil at a rate of 100 seeds m^{-2} as a proxy for wild mustard. At ACS, Indian mustard was broadcast perpendicular to the direction of crop seeding, and the area was rotary hoed to incorporate seeds prior to seeding lentil.

All herbicides were applied using a tractor-mounted sprayer, with a single boom equipped with either TeeJet® AIXR 110015 nozzles (TeeJet Technologies, Glendale Heights, IL) at KCRF or Airmix® 110-015 nozzles (Greenleaf Technologies, Covington, LA) at ACS, calibrated to a pressure of 275 kPa. Prior to crop emergence, glyphosate was applied to the entire plot area at a rate of 450 g ai ha^{-1}. Saflufenacil herbicide was applied at 18 g ai ha^{-1} prior to crop emergence in the designated treatments. Both glyphosate and saflufenacil were applied in 100 L ha^{-1} spray volume at KCRF and 110 L ha^{-1} spray volume at ACS. Metribuzin herbicide was applied POST at either 103 g ai ha^{-1} for the half-rate treatments or 206 g ai ha^{-1} for the full-rate treatments. The full-rate metribuzin treatment was split into two application timings as recommended for increased crop safety (Saskatchewan Ministry of Agriculture 2014). The half-rate application was applied on the same date as the first full-rate application, and the full-rate treatments received a second application approximately 7 d later. A spray volume of 173 L ha^{-1} was used for both half- and full-rate treatments at both sites. In addition to herbicide treatments, plots were treated with pesticides as per label recommendations to control non-targeted weeds, insects, and diseases (Table 1).

In-crop rotary hoeing was performed using two passes of a minimum-tillage rotary hoe (Yetter Manufacturing, Colchester, IL), with the tractor driven at a speed of 15 km h^{-1}. Rotary hoeing was performed at the optimum stage for weed control, when the Indian mustard plants were at the white thread to early cotyledon stage. In some site-years, two rotary hoe operations were performed when a second cohort of mustard seedlings was observed emerging following the first rotary hoeing (Table 1).

Crop and weed populations were sampled in all plots prior to metribuzin application using a 0.25-m^2 quadrat placed near both the front and back of each plot. Quadrats were placed to avoid plot edges. Lentil, Indian mustard, and weeds were counted by species

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Table 1. Management of integrated weed management experiments at Kernen Crop Research Farm (KCRF) and Alternative Cropping Systems Study at Agriculture and Agri-Food Canada Scott Research Farm (ACS) sites in central Saskatchewan, Canada, in 2011, 2012, and 2013.[a]

	KCRF			ACS	
Field operation	2011	2012	2013	2011	2012
Seeding date	May 18	May 15	May 13	May 13	May 12
Glyphosate	May 20	May 18	May 14	May 14	May 11
Saflufenacil	May 20	May 18	May 14	May 14	May 11
Rotary hoe	June 9	May 27, June 8	May 21	May 30, June 9	May 29, June 4
Crop and weed counts	May 30	May 30	May 27	May 30	May 31
Insecticide[a]	NA	June 2 (D)	May 29 (D)	NA	NA
Sethoxydim	NA	June 2, June 19	June 26	NA	NA
Metribuzin (1st application)	June 8	June 1	May 28	June 1	June 1
Metribuzin (2nd application)	June 15	June 8	June 4	June 8	June 8
Imazamox	NA	June 18	May 29, June 26	NA	June 15
Fungicide	NA	June 29 (B), July 21 (PR), August 7 (B)	June 26 (PY)	July 28 (PY + B)	July 20 (PY + B)
Biomass	August 19	August 17	August 8	August 5 and 8	August 23
Desiccation (diquat)	August 30	August 21	August 20	August 22	September 5
Harvest	September 6	August 28	August 27	September 6	NA (hail damage)

[a] Abbreviations: NA, not applied. Insecticide: D, deltamethrin ([(S)-cyano-(3-phenoxyphenyl)methyl] (1R,3R)-3-(2,2-dibromoethenyl)-2,2-dimethylcyclopropane-1-carboxylate). Fungicides: PY, pyraclostrobin (methyl N-[2-[[1-(4-chlorophenyl)pyrazol-3-yl]oxymethyl]-phenyl]-N-methoxycarbamate); B, boscalid (2-chloro-N-[2-(4-chlorophenyl)phenyl]pyridine-3-carboxamide); PR, prothioconazole (2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1H-1,2,4-triazole-3-thione).

and recorded. Crop and weed biomass sampling was conducted at crop physiological maturity. Biomass samples were collected from the front and back of each plot using 0.25-m^2 quadrats, and then the crop and Indian mustard were separated from each other and other weed species. Samples were oven-dried at 70 C for 48 h and then weighed.

A four-step process was followed to calculate disease severity ratings in 2012 and 2013. First, each plot was divided into two portions that had either severe disease or little to no disease, and the percentage of plot area representing each portion was estimated. Second, within each of these two portions, the percentage of plant tissue exhibiting disease symptoms was determined. Next, for each portion of the plot, the percentage of plant tissue exhibiting symptoms was multiplied by the percentage of the plot occupied by that portion. Finally, these two values were then summed to obtain the final disease severity rating (Madden et al. 2007).

To facilitate harvest, the plots were desiccated with diquat at 415 g ai ha^{-1} when the bottom third of the lentil pods had turned a tan color and rattled when shaken (BBCH 83) (Saskatchewan Pulse Growers 2012). Once seeds were dry, a strip in the middle section of each plot was harvested with a plot harvester (harvested area = 8.4 m^2 at KCRF and 17.5 m^2 at ACS). In 2012 hail occurred at ACS following desiccation but prior to harvesting, and due to excessive shattering and resultant seed loss, the plots were not harvested for seed, resulting in no yield data for this site-year. The harvested samples were air-dried and cleaned using a KornService™ machine (Continental Agra, Newston, KS) prior to weighing.

Statistical Analysis. Statistical analyses were conducted using PROC MIXED in SAS (SAS Institute 2011) for a two-way factorial randomized complete block design. Seeding rate and weed control treatment were treated as fixed effects. The effects of site-year, replicate nested in site-year, and interactions of site-year with seeding rate, weed control, and seeding rate by weed control were considered random factors. Seeding rate was analyzed as a categorical variable due to the inclusion of only three seeding rates in the study and the likelihood of asymptotic, nonlinear rather than continuously increasing or decreasing relationships between seeding rates and the tested variables (Baird et al. 2009; Spies et al. 2010).

Model weed biomass data were analyzed with all site-years combined. A significant site-year by weed control treatment interaction was observed in the combined data and was further investigated by analyzing site-years separately. It was determined that the cause of this interaction was a small increase in saflufenacil efficacy at the ACS versus the KCRF

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location. This was not surprising, as previous research has found saflufenacil to bind to heavier clay soils and be less available for uptake by plants (Gannon et al. 2014). The clay content at KCRF is approximately 50% versus 21% at ACS, thus saflufenacil would be expected to have greater efficacy at ACS. Therefore, the combined analysis of model weed biomass data was pursued to increase the interpretive value of the study. The combined data required a square-root transformation, and heterogeneity of variances was modeled using autocorrelation functions based on site-year. Back-transformed estimates and standard errors are presented.

Yield data were analyzed with the 2011 and 2013 site-years grouped and the 2012 site-year analyzed separately. The 2012 data were analyzed separately due to a highly significant site-year by weed control treatment interaction ($P < 0.001$). In this year the study experienced severe disease pressure, and this caused the yield response to the treatments to be significantly different from the 2011 or 2013 results. While a significant ($P < 0.05$) site-year by weed control treatment interaction was still present in the combined 2011 and 2013 data, analyzing the years separately revealed that the trends and the rankings of the treatments were the same, and only the magnitude of yield response differed between the years. Yield data for the combined 2011 and 2013 site-years were log ($\log_{10}$) transformed to meet the assumption of homogeneity of variances for ANOVA; back-transformed estimates and standard errors are presented for these data. For both weed biomass and crop yield, least squared means were separated using Fisher's protected LSD, with significance declared at $P < 0.05$.

Results and Discussion

Model Weed Biomass. Indian mustard biomass was influenced by the interaction of seeding rate and weed control treatment (Tables 2 and 3). The full herbicide treatment provided the greatest and most consistent decrease in Indian mustard biomass. This treatment did not respond to increasing seeding rate with decreased Indian mustard biomass, but rather had low Indian mustard biomass at all three seeding rates. For four of the five remaining treatments, increasing the seeding rate to either 2X or 4X resulted in lower Indian mustard biomass (Table 3). In the control treatment, Indian mustard biomass decreased by 39% between the 1X and 2X seeding rates, but there was no significant reduction between the 2X and 4X rates (Table 3). For saflufenacil, half-rate metribuzin, and integrated treatments, Indian mustard biomass decreased between the 1X and 4X seeding rates, but not between the 1X and 2X rates (Table 3). The reduction in Indian mustard biomass between the 1X and 4X rates was 51%, 48%, and 65% for saflufenacil, half-rate metribuzin, and integrated treatments, respectively. In contrast, Indian mustard biomass of the rotary hoe treatment was similar across all seeding rates.

Table 2. Analysis of variance for model weed biomass and lentil seed yield as affected by seeding rate and weed control strategy at Kernen Crop Research Farm (KCRF) and Alternative Cropping Systems Study at Agriculture and Agri-Food Canada Scott Research Farm (ACS) sites in central Saskatchewan, Canada, in 2011, 2012, and 2013.

	Indian mustard biomass	Lentil yield	
Source of variation	2011–2013	2011 and 2013[a]	2012[b]
	P-value		
Seed rate (SR)	0.0004	0.0122	0.5663
Weed control treatment (WC)	<0.0001	0.0013	0.5934
SR*WC	0.0202	0.0002	0.4826
Site-year (SY)[c]	0.1067	0.1686	—[d]
Block(site-year)	0.0558	0.0387	—
SY*SR	0.4424	0.2042	—
SY*WC	0.0044	0.0388	—
SY*SR*WC	—	—[e]	—

[a] Yield for KCRF in 2011 and 2013, and ACS in 2011 (3 site-years).
[b] Yield for 2012 KCRF site-year. The 2012 ACS site was not harvested due to excessive seed loss following hail.
[c] Significance of random effects (site-year, block(site-year), SY*SR, SY*WC, and SY*SR*WC) calculated using the COVTEST option in the MIXED procedure of SAS.
[d] Not applicable.
[e] No P-value assigned due to variance component estimate of 0.

Table 3. Interaction of seeding rate and weed control treatment on model weed biomass ± SE, averaged across 5 site-years in central Saskatchewan, Canada, in 2011–2013.

	Indian mustard biomass [a]		
	Targeted seeding rate (plants m^{-2})		
	130	260	520
		$g\ m^{-2}$	
Control	283.6 ± 55.19 a	172.5 ± 43.59 bcd	190.0 ± 45.62 bc
Saflufenacil	234.2 ± 50.38 ab	180.3 ± 44.51 bcd	114.3 ± 35.93 cde
Rotary hoe	225.5 ± 49.48 ab	195.5 ± 46.24 ab	176.2 ± 44.02 bcd
Half-rate metribuzin	92.1 ± 32.50 ef	110.5 ± 35.37 de	48.2 ± 24.20 gh
Integrated	90.1 ± 32.17 efg	50.3 ± 24.66 fgh	32.0 ± 20.16 hi
Full herbicide	9.8 ± 12.26 ij	6.8 ± 10.59 ij	3.2 ± 8.08 j

[a] Means and SEs are back-transformed from square root for presentation. Since back-transformation resulted in asymmetrical upper and lower SEs, the larger SE of the two is presented. Means followed by the same letter were not significantly different based on Fisher's protected LSD ($\alpha = 0.05$).

For the full herbicide treatment, the recommended (1X) seeding rate was sufficient to maximize weed control. The lack of response to seeding rate by the full herbicide treatment was not unexpected based on previous findings. Increased seeding rates have been found to be more effective at reducing weed biomass in situations in which herbicides are used at reduced rates or fail to provide acceptable efficacy (Ball et al. 1997; O'Donovan and Newman 2004). The efficacy of the full herbicide treatment in this study was high at all seeding rates, with reductions in weed biomass between 99% and 97% of the control treatment at the recommended seeding rate.

Control, saflufenacil, half-rate metribuzin, and integrated treatments had higher weed suppression when seeded at either 2X or 4X seeding rates. This demonstrates that, even though lentil is widely regarded as a poorly competitive crop, increasing lentil density can provide weed management benefits when herbicides are not able to provide good weed control. These results agree with previous findings in lentil (Ball et al. 1997), but only partially agree with findings in field pea, another weakly competitive pulse crop (Beckie and Kirkland 2003). In a study under organic conditions, weed biomass decreased as field pea crop density increased over a range of 13 to 149 plants m^{-2} (Syrovy et al. 2014). In another study, however, field pea weed biomass did not decrease significantly when crop seeding rate was increased, even in the presence of uncontrolled weeds (Beckie and Kirkland 2003).

Only full herbicide, half-rate metribuzin, and integrated treatments gave additional model weed biomass reductions beyond the control treatment seeded at 2X or 4X rates. Indian mustard biomass of the fully integrated treatment (4X) was statistically similar to the full herbicide treatment at 1X and 2X seeding rates (Table 3). The Indian mustard biomass reduction of the fully integrated treatment (4X) compared with the control at 2X and 4X seeding rates equated to 81% and 83%, respectively. The level of weed control observed in the fully integrated treatment (4X) shows that increased seeding rate can interact with multiple-tactic weed control to allow producers to achieve acceptable weed control.

Mechanical weed control with a rotary hoe alone was not sufficient to control weed biomass. Even when higher seeding rates were used, the rotary hoe treatment did not differ from the untreated control (Table 3). A previous study in Saskatchewan, Canada, showed that rotary hoeing reduced weed biomass by 40% to 75% compared with untreated check (Shirtliffe and Johnson 2012). In another study, combining rotary hoe treatment with interrow cultivation reduced weed density by as much as 91% (Taylor et al. 2012). However, in these two studies, rotary hoe operations were performed three times during the early part of the crop growing cycle. In the current study, above-average moisture conditions, particularly during June (Table 4), made accessing the plots for multiple rotary hoe applications difficult. This, combined with recurrent flushes of weeds that typically occur after rainfall, likely hindered the efficacy of mechanical weed control in this study (Mohler 2004).

Lentil Yield. The interaction of seeding rate and weed control treatment was significant at the 2011 and 2013 sites (Tables 2 and 5). Yield of both full herbicide and saflufenacil treatments remained stable across the three seeding rates (Table 5). In contrast, lentil seed yield in the half-rate metribuzin, integrated, rotary hoe, and control treatments responded favorably to

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Table 4. Growing season precipitation and temperature data for Kernen Crop Research Farm (KCRF) and Alternative Cropping Systems Study at Agriculture and Agri-Food Canada Scott Research Farm (ACS) during an integrated weed management study conducted across 5 site-years from 2011 to 2013 in central Saskatchewan, Canada.

		Rainfall				Temperature			
Location	Month	2011	2012	2013	Normal[a]	2011	2012	2013	Normal
		mm				C			
KCRF	May	26	150	11	47	11.3	10.4	13.2	11.5
	June	119	113	121	61	15.9	16.2	15.9	16.0
	July	96	90	40	60	18.5	19.2	17.8	18.2
	August	40	66	14	39	17.0	18.3	18.7	17.3
	Total	281	419	186	207	—	—	—	—
ACS	May	31	51	—	36	10.1	9.7	—	10.9
	June	190	165	—	63	14.4	15.1	—	15.2
	July	76	56	—	71	17.0	18.6	—	17.0
	August	52	51	—	43	16.3	17.0	—	16.3
	Total	349	323	—	213	—	—	—	—

[a] The 1970–2000 Canadian climate normals were obtained for KCRF from Saskatoon Diefenbaker Airport and for ACS from Scott CDA weather stations from Environment Canada (http://climate.weather.gc.ca/climate_normals).

increased seeding rates. Yield of the integrated treatment increased significantly as seeding rate increased from the recommended rate (1X) to 2X and from 2X to 4X (Table 5). Yield of half-rate metribuzin, rotary hoe, and control treatments increased from 1X to 2X but not from 2X to 4X. While the full herbicide treatment had yields significantly greater than any other treatment when the recommended seeding rate was used, its yields were similar to those of integrated and half-rate metribuzin treatments seeded at either 260 or 520 plants m^{-2} (Table 5).

In 2012 neither seeding rate nor weed control treatment had an effect on lentil yield (Table 2; site mean = 2,216 ± 42 kg ha^{-1}). The weather and agronomic conditions during that season are possible reasons for this lack of response. In 2012 the KCRF site experienced double the normal growing season precipitation (Table 4). Under these conditions both seeding rate and weed control treatments affected foliar disease, with higher seeding rates exhibiting a trend of having greater disease severity ($P = 0.06$). Full herbicide and half-rate metribuzin weed control treatments had significantly higher disease severity than mechanical or integrated treatments ($P < 0.01$). The mechanical and integrated treatments shared in common rotary hoe application, and it could be speculated that the action of the rotary hoe may have led to some thinning of the lentil population and thus decreased disease pressure. In previous studies the rotary hoe has been noted to cause some stand

Table 5. Effect of seeding rate and weed control strategy on lentil seed yield ± SE averaged across 3 site-years at Kernen Crop Research Farm (KCRF) and Alternative Cropping Systems Study at Agriculture and Agri-Food Canada Scott Research Farm (ACS) in central Saskatchewan, Canada, in 2011 and 2013.[a]

	Lentil yield [b]		
	Targeted seeding rate (plants m^{-2})		
	130	260	520
	kg ha^{-1}		
Control	1155.8 ± 148.34 j	1576.2 ± 202.28 gh	1516.7 ± 194.65 gh
Saflufenacil	1424.0 ± 182.75 ghij	1552.7 ± 199.28 gh	1372.1 ± 176.10 hij
Rotary hoe	1143.1 ± 146.71 j	1729.8 ± 222.00 defgh	1786.1 ± 229.23 cdefg
Half-rate metribuzin	1641.0 ± 210.60 fghi	2232.5 ± 286.52 abc	2060.2 ± 264.40 abcde
Integrated	1647.8 ± 211.48 efghi	2002.6 ± 257.02 bcdef	2395.5 ± 307.44 a
Full herbicide	2233.1 ± 286.59 abc	2423.8 ± 311.07 ab	2375.7 ± 304.90 ab

[a] Yield data from KCRF in 2012 were analyzed separately due to a highly significant site-year × treatment interaction, and 2012 ACS yield data were not collected due to excessive seed loss following hail.

[b] Means and SEs are back-transformed from square root for presentation. Since back-transformation resulted in asymmetrical upper and lower SEs, the larger SE of the two is presented. Means followed by the same letter were not significantly different based on Fisher's protected LSD ($\alpha = 0.05$).

reduction in lentils, though not enough to reduce yields (Shirtliffe and Johnson 2012).

Supplementing herbicides with additional cultural and mechanical practices allowed herbicide application to be reduced without sacrificing crop yield. In the 3 site-years when yield was not influenced by excess moisture and disease pressure, both the integrated and half-rate metribuzin treatments had yields similar to those of the full herbicide treatment when either a 2X or 4X seeding rate was used. As the seeding rates required to maximize crop yield were lower than those optimal for weed management in these treatments, economic factors and the weed management objectives of the grower should be evaluated to determine the best treatment option.

The ability of lentil treated with half-rate metribuzin to produce a yield equal to lentil receiving the full herbicide treatment when a doubled seeding rate was used has practical implications for lentil growers. Metribuzin is a common lentil herbicide that is often not favored by growers due to the risk of crop injury (Friesen and Wall 1986; Saskatchewan Ministry of Agriculture 2014). By doubling their seeding rate, producers could realize yields equal to those obtained when the full rate of the herbicide is applied without the risk of injuring the lentil crop.

While it was possible to maximize yield without a fully integrated approach, combining chemical, cultural, and mechanical weed control tactics provided maximum weed biomass suppression. The fully integrated treatment had the added benefit over any other treatment of reducing reliance on any single tactic, reducing selection pressure for herbicide-resistant weeds and risk of weed control failure.

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