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Functionally diverse flax-based rotations improve wild oat (*Avena fatua*) and cleavers (*Galium spurium*) management

Research Article

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Abstract

Wild oat (*Avena fatua* L.) and false cleavers (*Galium spurium* L.) are currently a challenge to manage in less competitive crops such as flax (*Linum usitatissimum* L.). Increasing the functional diversity in crop rotations can be an option to improve weed management. Nonetheless, this strategy had not been tested in flax in western Canada. A 5-yr (2015 to 2019) crop rotation study was carried at three locations in western Canada to determine the effect of diverse flax-based crop rotations with differences in crop species, crop life cycles, harvesting time, and reduced herbicides on managing *A. fatua* and *G. spurium*. The perennial rotation (flax–alfalfa [*Medicago sativa* L.]–alfalfa–alfalfa–flax) under reduced herbicide use was found to be the most consistent cropping system, providing *A. fatua* and *G. spurium* control similar to the conventional annual flax crop rotation (flax–barley [*Hordeum vulgare* L.]–flax–oat [*Avena sativa* L.]–flax) with standard herbicides. At Carman, this alfalfa rotation provided even better weed control (80% *A. fatua*, 75% *G. spurium*) than the conventional rotation. Furthermore, greater *A. fatua* control was identified compared with a conventional rotation in which two consecutive winter cereal crops were grown successfully in rotation (flax–barley–winter triticale [×*Triticosecale* Wittm. ex A. Camus (*Secale* × *Triticum*)]–winter wheat [*Triticum aestivum* L.]–flax). Incorporation of silage oat crops did not show consistent management benefits compared with the perennial alfalfa rotation but was generally similar to the conventional rotation with standard herbicides. The results showed that perennial alfalfa in the rotation minimized *G. spurium* and *A. fatua* in flax-cropping systems, followed by rotations with two consecutive winter cereal crops.

Introduction

Weed management in flax (*Linum usitatissimum* L.) is challenging due to its uncompetitive nature, resulting in yield losses ranging from 20% to 30% (Liu et al. 2009; Sánchez Vallduví and Sarandón 2011; Stevenson and Wright 1996). Weed competition not only reduces flax seed yield but can also reduce seed oil content and iodine levels (Bell and Nalewaja 1968; Friesen 1986). Weed control in flax is further hampered by limited herbicide options for in-crop weed management. At present, Group 1 (acetyl CoA carboxylase [ACCase] inhibitors), Group 4 (synthetic auxins), and Group 6 (photosystem II inhibitors) herbicides are the widely used herbicides for flax in Canada (Flax Council of Canada 2017). The efficacy of these herbicides, especially ACCase herbicides, is declining due to the evolution of herbicide resistance (Beckie et al. 2020; Heap 2021), further impairing weed management in flax.

Wild oat (*Avena fatua* L.) has been a troublesome weed in many cropping systems on the Canadian Prairies due to its competitive characteristics (Kirkland 1993; Willenborg et al. 2005) and its resistance to ACCase- and acetolactate synthase (ALS)-inhibiting herbicides (Beckie et al. 2019). Weed surveys have shown that *A. fatua* was found in 42% of flax fields surveyed, even after an in-crop herbicide had been applied (Leeson et al. 2005). Cleavers (*Galium* spp.) is the ninth most abundant weed species on the Canadian Prairies and has been increasing in relative abundance at a faster rate than almost any other weed over the past 30 yr (Leeson 2012; Leeson et al. 2005). Of the many *Galium* species, false cleavers (*Galium spurium* L.) is the primary species of concern on the prairies (De Roo et al. 2019). *Galium spurium* can impact the quantity and quality of yield in flax crops due to its climbing and tangling nature, which causes lodging and difficulties in harvesting operations (Malik and Vanden Born 1987). Management of *Galium* species is complicated by the ability of populations to act as both winter or summer annuals under prairie conditions (Defelice 2002; Malik and Vanden Born 1987). Moreover, Galium's germination time can highly vary within a season (De Roo 2016). *Galium* species have also developed resistance to ALS-inhibiting herbicides in some regions (Beckie et al. 2020), and these resistant populations appear to be increasing in frequency. Perhaps more concerning is that next to kochia [*Bassia scoparia* (L.) A.J. Scott], *A. fatua* and *G. spurium* have the highest risk rating for developing glyphosate resistance (Beckie 2010), thus demanding long-term sustainable weed management strategies.

Managing herbicide-resistant weeds calls for integrated weed management systems that restrict weed emergence, reduce weed growth and reproduction, minimize weed interference with crops, and reduce the build-up of weed seedbanks (Harker et al. 2017). To achieve these objectives, cropping systems need to be designed using multiple weed management strategies that are both short-term and long-term in nature. Short-term integrated weed management strategies such as competitive cultivars, high crop density, and narrow row spacing are the predominant strategies that have proven to be effective when integrated into cereal and broadleaf crops (Harker and O'Donovan 2013; Shirtliffe and Benaragama 2014), including flax (Kurtenbach et al. 2019). Such cultural strategies are effective in *A. fatua* management (Harker et al. 2009; O'Donovan et al. 1999) but less is known about *G. spurium*.

In addition to integrating short-term cultural weed control strategies, diversifying crop rotations can diversify available herbicide modes of action and reduce the number of herbicide applications required for weed control, both of which are important for long-term herbicide resistance management (Beckie and Harker 2017; Harker et al. 2017). Increasing crop rotational diversity imposes a greater number of stress and mortality factors at different stages of a weed's life cycle (Liebman and Staver 2001; Teasdale 2017) and has been identified as an effective long-term strategy to manage weeds. In a global meta-analysis, Weisberger et al. (2019) found that diversifying crop rotations away from simple crop rotations reduced weed density by 49%. Further, their analysis showed that diversifying rotations with more functionally diverse crops, rather than just increasing species diversity, was crucial for weed management. Moving from less diverse to more functionally diverse cropping systems allows growers to rely on more indirect tactics such as competitive crops, varied planting dates from fall to delayed seeding in the spring, and harvesting dates. Having a silage crop allows an early harvest that prevents weed seed production and/or returns to the seedbank (Liebman and Nichols 2020). Therefore, differences in crop growth, phenology, and management practices are critical in developing effective crop rotations for weed management. Rotating functionally diverse crops is even more critical when weeds show a wide diversity in morphological and physiological traits. Examples include *A. fatua* (Miller et al. 1982) and *G. spurium* (De Roo et al. 2019; Malik and Vanden Born 1987).

Crop rotations have been an essential weed management tool for farmers on the Canadian Prairies. Yet these crop rotations are mainly diversified using annual spring crops. Adoption of functionally diverse crop rotations, including perennials and annual crops, remains low (Leeson and Beckie 2014). Cropping systems with diverse annual crop rotations, including spring and winter cereals harvested for grain and forage combined with integrated cultural practices, could be viable options for extensively grain-based farmers. Initial work done by O'Donovan et al. (2013) and Harker et al. (2016) identified that combining diverse crop rotations with high seeding rates and reduced herbicides rates was effective in managing *A. fatua* in barley (*Hordeum vulgare* L.) and canola (*Brassica napus* L.), respectively. Likewise, incorporation of perennial crops such as alfalfa (*Medicago sativa* L.) was reported to be an effective strategy to manage weeds in some cropping systems, especially with regard to *A. fatua* (Entz et al. 1995; Ominski et al. 1999). How such integrated systems (where diverse crop rotations are integrated with high seeding rates) can fit into flax-based rotations has not yet been explored. Flax is often grown in rotation with cereals to prevent diseases, and at least 3 yrs are recommended between the cultivation of two successive flax crops (Flax Council of Canada 2017). This allows for longer rotations with more functionally diverse crops to manage challenging weeds. Currently, adequate weed control cannot be achieved in flax if herbicides are excluded; thus, integrated cropping systems with reduced herbicides may be a good alternative. This study aimed to determine the effect of functionally diverse flax-based crop rotations with reduced herbicides and high seeding rates on the longer-term management of weeds. *Avena fatua* and *G. spurium* were used as test species to represent problematic monocot and dicot weeds on the Canadian Prairies. We hypothesize that functionally diverse crop rotations with reduced herbicides and with high seeding rates can replace conventional low-diversity flax rotations with herbicides for sustainable weed management.

Materials and Methods

Site Conditions

Field experiments were carried out at three locations in western Canada. One site was located at the Kernen Research Farm at Saskatoon, SK, Canada (52.152861°N, 106.544861°W) on a Black Chernozemic loam (pH: 7.7; organic matter: 2.9%), another at the Indian Head Research Farm, SK, Canada (50.53305°N, 103.65125°W) on a Black Chernozemic clay (pH: 7.4; organic matter: 3.4%), and one site at Carman Research Farm at Carman, MB, Canada (49.48836°N, 98.03913°W) on a Gleyed Black Chernozem (pH: 5.5; organic matter: 6%). The experiment was conducted for 5 yr, from 2015 to 2019.

Experimental Treatments and Design

The experiment consisted of 17 treatments (crop rotations) having eight unique crop rotations with two herbicide regimes, giving 16 crop rotation combinations. Of the 16 combinations, eight rotations were under a standard herbicide system (SH), where in-crop herbicides for *A. fatua* and *G. spurium* control were applied in all phases except in the first-year flax phase. For comparison, the same rotations also were under a reduced herbicide system (RH), where no in-crop herbicides were applied during the second and fourth years. Crop rotations under both systems received in-crop herbicides in the final year of the flax phase. The 17th crop rotation treatment was considered the most functionally diverse crop rotation, as it comprised a 3-yr alfalfa crop under the RH system. The crop rotation flax–barley–flax–oat–flax under a standard herbicide system (Table 1) was considered the conventional crop rotation, and it was used as the rotation of comparison throughout the study. All crop rotations under both herbicide systems used a 2X seeding rate during the second and fourth years, while a 1X seeding rate was used during other phases. The only exception to this was the rotation with two consecutive winter cereal crops (flax–barley–winter triticale [×*Triticosecale* Wittm. ex A. Camus (*Secale* × *Triticum*)]–winter wheat [*Triticum aestivum* L.]–flax), in which both winter cereal phases were seeded at a 2X seeding rate. Thus, the seeding rate effect was uniform among all other crop

Table 1. Cropping systems (crop rotations and herbicide combinations) description at Kernen, SK, Carman, MB, and Indian Head, SK, Canada (2015–2019).[a]

Treatment	2015	2016	2017	2018	2019	Rotation abbreviation	Herbicide system
1	Flax 1X seed NH	Barley (G) 2X seed NH	Flax 1X seed H	Oat 2X seed NH	Flax 1X seed H	F-B-F-O-F	RH
2	Flax 1X seed NH	Barley (G) 2X seed H	Flax 1X seed H	Oat 2X seed H	Flax 1X seed H	F-B-F-O-F	SH
3	Flax 1X seed NH	Barley (G) 2X seed NH	LL canola 1X seed H	Oat 2X seed NH	Flax 1X seed H	F-B-C-O-F	RH
4	Flax 1X seed NH	Barley (G) 2X seed H	LL canola 1X seed H	Oat 2X seed H	Flax 1X seed H	F-B-C-O-F	SH
5	Flax 1X seed NH	Barley (G) 2X seed NH	LL canola 1X seed H	Oat (S) 2X seed NH	Flax 1X seed H	F-B-C-SO-F	RH
6	Flax 1X seed NH	Barley (G) 2X seed H	LL canola 1X seed H	Oat (S) 2X seed H	Flax 1X seed H	F-B-C-SO-F	SH
7	Flax 1X seed NH	Barley (G) 2X seed NH	LL canola 1X seed H	Winter wheat 2X seed NH	Flax 1X seed H	F-B-C-WW-F	RH
8	Flax 1X seed NH	Barley (G) 2X seed H	LL canola 1X seed H	Winter wheat 2X seed H	Flax 1X seed H	F-B-C-WW-F	SH
9	Flax 1X seed NH	Barley (G) 2X seed NH	Peas 1X seed H	Winter triticale 2X seed NH	Flax 1X seed H	F-B-P-WT-F	RH
10	Flax 1X seed NH	Barley (G) 2X seed H	Peas 1X seed H	Winter triticale 2X seed H	Flax 1X seed H	F-B-P-WT-F	SH
11	Flax 1X seed NH	Barley (G) 2X seed NH	Peas 1X seed H	Oat 2X seed NH	Flax 1X seed H	F-B-P-O-F	RH
12	Flax 1X seed NH	Barley (G) 2X seed H	Peas 1X seed H	Oat 2X seed H	Flax 1X seed H	F-B-P-O-F	SH
13	Flax 1X seed NH	Barley (G) 2X seed NH	Peas 1X seed H	Oat (S) 2X seed NH	Flax 1X seed H	F-B-P-SO-F	RH
14	Flax 1X seed NH	Barley (G) 2X seed H	Peas 1X seed H	Oat (S) 2X seed H	Flax 1X seed H	F-B-P-SO-F	SH
15	Flax 1X seed NH	Barley (G) 2X seed NH	Winter triticale 2X seed H	Winter wheat 2X seed NH	Flax 1X seed H	F-B-WT-WW-F	RH
16	Flax 1X seed NH	Barley (G) 2X seed H	Winter triticale 2X seed H	Winter wheat 2X seed H	Flax 1X seed H	F-B-WT-WW-F	SH
17	Flax 1X seed NH	Alfalfa 0 or 1 cut NH	Alfalfa 2 cuts NH	Alfalfa 2 cuts NH	Flax 1X seed H	F-A-A-A-F	RH

[a]Abbreviations: G, grain; H, herbicide applied; NH, no herbicide applied; S, silage ;SH, standard herbicide system; RH, reduced herbicide system; 1X, standard seeding rate; 2X, double the standard seeding rate; LL, LibertyLink®.

rotations and was not considered as a treatment. All treatments were established in a randomized complete block design with four replicates. All crop rotations began with a flax crop and ended with a flax crop to determine changes in weed density and biomass as a function of the intervening treatments.

Crop Establishment and Weed Management

In the first year (2015), *A. fatua* was cross-seeded and *G. spurium* was broadcast over the entire experimental area at densities of 150 and 300 seeds m^{-2}, respectively. At all three locations, crops were seeded using no-till seeders with hoe openers at 20-, 25-, and 30-cm row spacing at Carman, Kernen, and Indian Head, respectively. In all years, except in 2019, all standard herbicide treatments (SH system) received a glyphosate burndown before crop emergence. In 2015, no in-crop herbicides were applied to any plot during the first year to allow for weed establishment. In 2015, flax (‘CDC Glas’; SeCan, Kanata, ON, Canada, K2K 0E3) was direct-seeded into standing cereal stubble at a standard rate of 450 seeds m^{-2} in all plots. In 2016, treatments 1 to 16 were seeded to barley (‘CDC Copeland’; SeCan, Kanata, ON, Canada, K2K 0E3) at a 2X seeding rate (400 seeds m^{-2}), and treatment 17 was seeded to alfalfa (‘Algonquin’; Cailliau Seed Company Ltd, Enchant, AB, Canada, T0K 0V0) at 9 kg ha^{-1}. Barley under the RH system did not receive

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Table 2. In-crop herbicides used for the individual crops at Kernen, SK, Carman, MB, and Indian Head, SK, Canada.[a]

Crop	Trade name	Common name	Application rate	Formulation	Manufacturer
Barley	Refine® SG	Thifensulfuron + tribenuron	15 g ai ha^{-1}	S	FMC Canada Ltd., Mississauga, ON, L5N7Y2
	Attain® A	Fluroxypur	108 g ai ha^{-1}	EC	Corteva Agriscience, Calgary, AB,T2P 1M4
	Axial® BIA	Pinoxaden	60 g ai ha^{-1}	EC	Syngenta Canada Inc., Guelph, ON, N1G 4Z3
Flax	Select®	Clethodim	45 g ai ha^{-1}	EC	Arista LifeSciences, Cary, NC 27513
	Bucktril® M	Bromoxynil + MCPA	560 g ai ha^{-1}	EC	Bayer CropScience Inc., Calgary, AB, T2Z 3X2
	Amigo® (adjuvant)		0.5% v/v		Arysta LifeScience, Cary, NC, 27513
Canola	Select®	Clethodim	45 g ai ha^{-1}	EC	Arista LifeSciences, Cary, NC, 27513
	Liberty ®	Gluphosinate	500 g ai ha^{-1}	S	BASF Inc. Canada, Mississauga, ON, L5R 4H1
Pea					
	Odyssey®	Imazomox + imazathapyr	30 g ai ha^{-1}	WDG	BASF Inc. Canada, Mississauga, ON, L5R 4H1
	Merge®(adjuvant)		0.5% v/v	EC	BASF Inc. Canada, Mississauga, ON, L5R 4H1
Oat	Stellar® A	Florasulam + fluroxypyr	102.5 g ai ha $^{-1}$		Corteva Agriscience, Calgary, AB, T2P 1M4
	MCPA-Ester	MCPA	354 g ai ha^{-1}		Nufarm Agriculture Inc., Calgary, AB, T3K 0S3
Winter wheat/Spring wheat	Velocity® A	Thiencarbozone	5 g ai ha^{-1}	S	Bayer CropScience Inc., Calgary, AB, T2Z 3X2
	Velocity®B (Infinity)	Pyrasulfutole + bromoxynil	205 g ai ha^{-1}	S	Bayer CropScience Inc., Calgary, AB, T2Z 3X2
Winter triticale/Spring triticale	Infinilty®	Pyrasulfutole + bromoxynil	200 g ai ha^{-1}	EC	Bayer CropScience Inc., Calgary, AB, T2Z 3X2
	Achieve Liquid®	Tralkoxydim	200 g ai ha^{-1}	SC	Nufarm Agriculture Inc., Calgary, AB T3K 0S3
	Turbocharge® (adjuvant)		0.5% v/v	EC	Syngenta Canada Inc., Guelph, ON, N1G 4Z3

[a]Abbreviations: S, suspension; SG, soluble granule; SC, suspension concentrate; EC, emulsifiable concentrate; WDG, water-dispersible granules.

any *A. fatua* or *G. spurium* herbicides in the second year (2016), while barley under the SH system treatments received standard herbicides (Table 2). Herbicides were not applied to alfalfa in any year of the study. Alfalfa was cut twice during the growing season when the crop was at 10% bloom to simulate haying events. In the fall of 2016, treatments 15 and 16 were seeded to winter triticale ('Luoma'; Corns Seeds, Grassy Lake, AB, Canada, T0K0Z0) at a 2X seeding rate (400 seeds m^{-2}). Significant winter injury was evident in the spring of 2017 at both the Kernen and Indian Head locations; therefore, treatments were reseeded to spring triticale ('Bunker'; FP Genetics, Regina, SK, Canada, S4N 6E1) at a 2X seeding rate (400 seeds m^{-2}).

In 2017, treatments 1 and 2 were seeded to flax (CDC Glas) at 450 seeds m^{-2}; treatments 3 to 8 were seeded to LibertyLink® canola ('L130'; Bayer CropScience, Bayer CropScience Inc., Calgary, AB, Canada, T2Z 3X2) at 125 seeds m^{-2}, and treatments 9 to 14 were seeded to field pea ('CDC Meadow'; Sask Pulse Growers, Saskatoon, SK, Canada, S7N 3R3) at 90 seeds m^{-2}. Treatments containing winter cereals were seeded with 'Emerson' (Canterra Seeds, Winnipeg, MB, Canada, R3T 1Y7) winter wheat and 'Metzger' (Haney Farm Ltd, AB, Canada, T0K 1V0) winter triticale at 400 seeds m^{-2}. Again, low plant survivability was observed for overwintering cereals at Kernen in the spring of 2018, so spring wheat ('Utmost'; FP Genetics, Regina, SK, Canada, S4N 6E1) and spring triticale ('Bunker'; FP Genetics, Regina, SK, Canada, S4N 6E1) were seeded into winter cereal treatments to supplement winter cereal stands. Therefore, treatments 7, 8, 9, 10, 15, and 16 (Table 1) at Kernen and Indian Head were considered different from those treatments at Carman, as there was no winter cereal crop at Kernen and in some years at Indian Head. The crop rotations with winter wheat or winter triticale in the fourth year at Kernen and Indian Head were replaced with spring wheat and spring triticale, respectively, under both herbicide systems. Further, the crop rotation with two winter cereals (flax–barley–winter triticale–winter wheat–flax) was replaced with flax–barley–winter triticale–spring wheat–flax at Indian Head and flax–barley–spring triticale–spring wheat–flax at Kernen.

In 2018, 'Triactor' (Canterra Seeds, Winnipeg, MB, Canada, R3T 1Y7) was seeded in the grain oat (*Avena sativa* L.) treatments and 'Haymaker' (SeCan, Kanata, ON, Canada, K2K 0E3) was seeded into silage oat treatments, both at a density of 400 seeds m^{-2}. Herbicides were not applied under the RH system in 2018, while they were under the SH system. Treatments seeded to silage oat were cut when the plants reached the soft dough stage at Zadoks 85 (Zadoks et al. 1974). In 2019, flax (CDC Glas) was direct seeded into all plots at a rate of 450 seeds m^{-2}. Pre-seed burnoff was applied using 675 g ae ha^{-1} glyphosate + 18 g ai ha^{-1} carfentrazone at Kernen, 1.3 kg ae ha^{-1} glyphosate at Indian Head and 157 g ai ha^{-1} clopyralid + 880 g ai ha^{-1} MCPA-Ester at Carman.

Data Collection and Analysis

Weed Sampling

In all years, weed (*A. fatua* and *G. spurium*) emergence counts were taken at 2 to 3 wk after planting in two 1-m^2 quadrats placed randomly at the front and back of each plot. Weed counts were taken

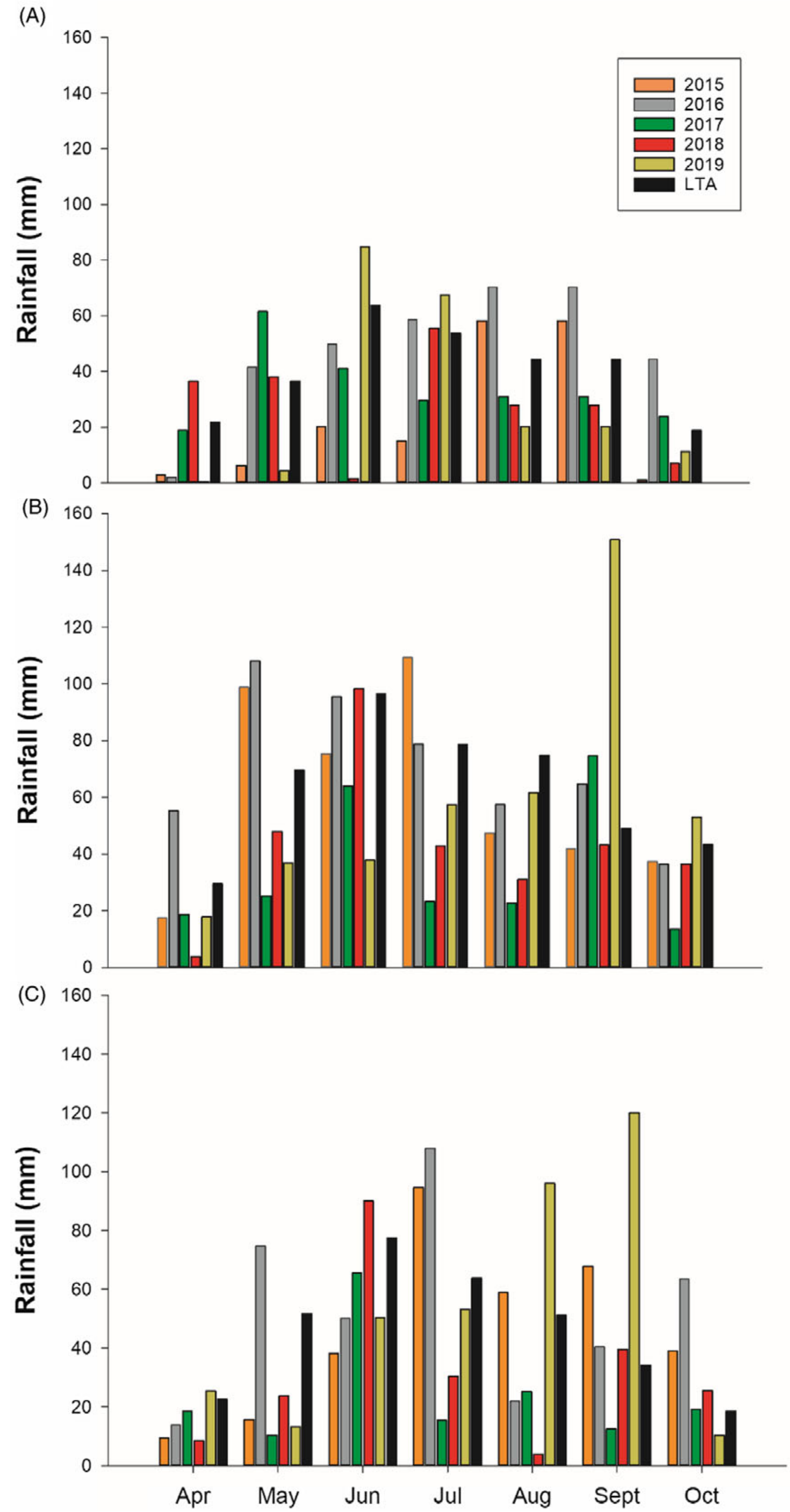

Figure 1. Monthly precipitation from April to October from 2015 to 2019 at (A) Kernen, SK, (B) Carman, MB, and (C) Indian Head, SK, Canada. LTA, long-term average.

at the species level to identify *A. fatua* and *G. spurium*. Aboveground weed biomass was taken when crops reached the late flowering stage at Zadoks 65. Shoot biomass of both weeds was sampled in 0.5-m^2 quadrats placed randomly at the front and back of each plot. All biomass samples were placed in paper bags and oven-dried at 80 C for 48 h and then weighed.

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Table 3. Probability values for crop rotations and mean differences for treatment contrasts for *Avena fatua* density and biomass at Kernen, SK, Carman, MB, and Indian Head, SK, Canada (2015–2019).[a]

	Kernen		Carman		Indian Head	
	Density	Biomass	Density	Biomass	Density	Biomass
	plants m^{-2}	kg ha^{-1}	plants m^{-2}	kg ha^{-1}	plants m^{-2}	kg ha^{-1}
Crop rotation	<0.0001	<0.0001	0.0016	0.0001	<0.0001	<0.0001
Contrasts[b]						
SH vs. RH	62 (8.6)***	161 (133)***	8 (0.57)	297 (18.7)*	21.65 (0.95)	145 (4.9)*
Alfalfa vs. others (SH)	6 (1.84)	40 (8.8)**	26 (4.2)	577 (77)**	97 (9)***	738 (63.9)***
Alfalfa vs. others (RH)	56 (17.2)***	121 (26)*	19 (3)	875 (116.8)***	118 (11)***	883 (76.5)***
Alfalfa vs. silage oat	13 (4.3)	26 (5.9)	23 (3.2)	841 (118)***	97 (9.6)***	617 (55)***
Alfalfa vs. winter crops	NA	NA	30 (5.6)***	417 (61)***	145 (15.8)	1,175 (113.2)***
Winter vs. silage crops	NA	NA	7 (3.1)	424 (34)**	48 (3.6)	558 (35.4)**
Silage oat vs. seed oat	16 (13.6)	31 (21.9)	8.0 (3.44)	116 (41)	10 (0.6)	263 (12)
Winter vs. summer crops	NA	NA	12 (0.9)**	494 (32)***	42 (2.9)*	392 (20)**

[a]Values in parentheses are standard errors for mean differences. Significant at: *P = 0.05; **P = 0.01; ***P = 0.001. NA, not applicable.
[b]Abbreviations: RH, no herbicides applied in the second and fourth year but herbicides applied in the fifth-year crop (flax); SH, full rate herbicides applied in the second-, fourth- and fifth-year crops.

Statistical Analysis

Data were analyzed using a repeated-measures ANOVA model using the PROC GLIMMIX procedure in SAS (SAS Institute 2011). Due to differences in crop rotations (differences in winter cereal treatment) among sites, data were analyzed separately for each site. *Galium spurium* and *A. fatua* density and biomass at all crop phases were considered for the analysis. Therefore, the weed density and weed biomass reported in this study are the average across all 5 yr of the study for each treatment. Cropping systems were considered as a fixed effect, while block was deemed to be random. Year (time) was considered a repeated factor, while plot was considered the repeated subject. After considering several covariance structures, a compound symmetry covariance structure was used with Akaike's information criterion value. The assumptions (homogeneous variance and normal distribution of residuals) of the ANOVA were tested using PROC UNIVARIATE with the Shapiro-Wilk test and residual plots. Data were either log transformed or modeled with a negative binomial distribution depending on the residual analysis. All cropping systems were compared with the conventional crop rotation (flax–barley–flax–oat–flax under the SH system) using a Dunnett's test. Treatment comparison was followed by a preplanned contrast carried out to compare different treatment groups. All data were presented on a back-transformed scale.

Results and Discussion

Growing Season Precipitation

Total growing season precipitation at Kernen was lower than the long-term average (30-yr) in all years, with 2015 being the driest of the 5 yr (43% drier) (Figure 1A). At Carman, total precipitation was near the long-term average in 2015 and 2016, whereas 2017 and 2018 were 46% and 31% lower than the 30-yr long-term average, respectively (Figure 1B). Greater rainfall amounts were received in 2019 than in 2017 and 2018, but it was 13% drier than the 30-yr long-term average. At Indian Head, the years 2015, 2017, and 2018 were 30% lower than the long-term average (Figure 1C).

Cropping Systems Effect on Weed Control at Each Location

Kernen

Crop rotations had differences in *A. fatua* density at Kernen. According to contrasts, the rotations under the SH system had 73% lower *A. fatua* density compared with the RH system (Table 3), indicating better weed control with the use of standard herbicides. All crop rotations in the RH system had significantly greater *A. fatua* density than the conventional rotation (flax–barley–flax–oat–flax under the SH system), which had a mean density of 17 plants m^{-2} (Figure 2A). The only exception was the alfalfa rotation, which had a statistically similar and low *A. fatua* density (28 plants m^{-2}), indicating better *A. fatua* control than the other crop rotations compared with the conventional rotation. Contrasts indicated that the alfalfa rotation had a low *A. fatua* density compared with the average of all rotations under the RH system (84 plants m^{-2}) and was comparable to the rotations under the SH system (22 plants m^{-2}). Furthermore, the alfalfa rotation was found to have significantly lower *A. fatua* density than the rotations containing either silage crops or winter crops (Table 3). Across both herbicide systems (RH and SH), having silage oat in the rotation did not impact *A. fatua* densities differently than when oat was harvested for grain (Table 3).

Crop rotations also had significant differences in *A. fatua* biomass at Kernen (Table 3). Contrasts revealed that *A. fatua* biomass was lower in crop rotations in the SH system than in the RH system (90% reduction), indicating better *A. fatua* management was achieved with herbicides. In addition, all rotations under the RH system had significantly greater *A. fatua* biomass than the conventional crop rotation (11 kg ha^{-1}) (Figure 2B). Further, contrasts revealed that the alfalfa rotation had lower *A. fatua* biomass (58 kg ha^{-1}) compared with the average of all other rotations under the RH system (179 kg ha^{-1}).

Crop rotations showed differences in *G. spurium* densities at Kernen, where the rotations under the SH system had a lower *G. spurium* density than under the RH system (Table 4). *Galium spurium* densities were greater in most rotations under the RH system compared with the conventional crop rotation under the SH system, including the grain oat, silage oat, spring triticale, spring wheat, and alfalfa rotations (Figure 3A). All other crop rotations had *G. spurium* densities similar to those of the conventional crop rotation under the SH system. *Galium spurium* biomass differed among crop rotations at Kernen (Table 4). Crop rotations with three flax crops and the rotations with spring triticale followed by spring wheat under the RH system had greater *G. spurium* biomass and density than the conventional crop rotation under the SH system. All other crop rotations had *G. spurium* biomass similar to that of the conventional rotation (Figure 3B). According to contrasts, the alfalfa rotation had lower *G. spurium*

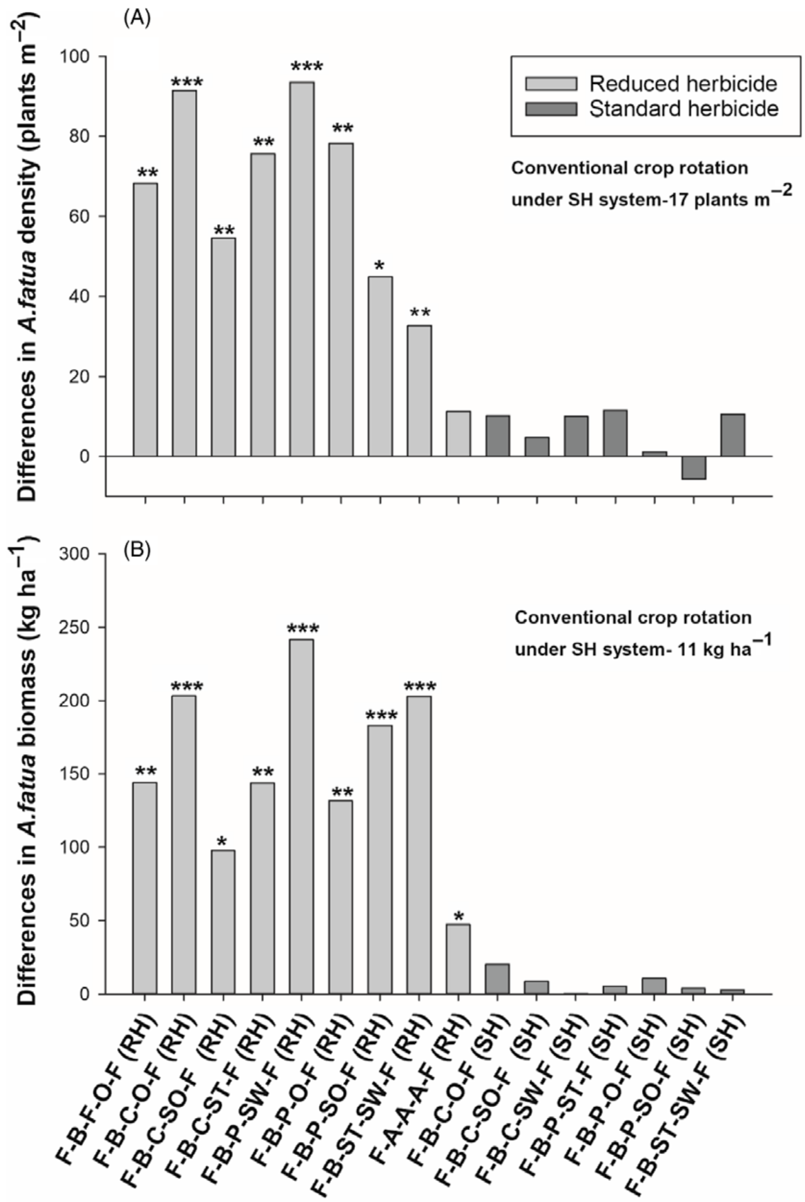

Figure 2. The effect of crop rotation on (A) *Avena fatua* density and (B) *Avena. fatua* biomass at Kernen, SK, Canada. Bars represent mean differences between the conventional crop rotation F-B-F-O-F (SH) and other crop rotations. Bars with asterisks indicate significantly different from the conventional crop rotation at *P = 0.05, **P = 0.01, and ***P = 0.001, obtained from Dunnett's test. ST, spring triticale; SW, spring wheat; F, flax; A, alfalfa; B, barley; O, oat; SO, silage oat; P, pea; C, canola; RH, reduced herbicide; SH, standard herbicide.

biomass (14 kg ha^{-1}) than the average of all rotations under the RH system (64 kg ha^{-1}).

Carman

Avena fatua density also differed among crop rotations at Carman (Table 3). Unlike at Kernen, *A. fatua* densities did not differ between the SH (65 plants m^{-2}) and the RH systems (75 plants m^{-2}) (Table 3). Crop rotations at the Carman site that had lower *A. fatua* densities than the conventional crop rotation included the rotation with two consecutive winter cereals as well as the rotations with grain oat and silage oat (Figure 4A). Lower *A. fatua* densities in the two winter cereal crop rotations under both herbicide systems were also found to be more effective at reducing *A. fatua* density (50% reduction) than having 3 yr of alfalfa. Further, the average of all winter crop rotations under both herbicide systems (61 plants m^{-2}) had lower *A. fatua* density than the average of all crop rotations that included only summer annuals (74 plants m^{-2}) (Table 3). Unfortunately, the Carman site was the only one that produced two winter crops in the rotation without losing them to early-season frost.

Avena fatua biomass at Carman was lower (23 %) in the rotations under the SH system compared with the RH system (Table 3). The crop rotations that had grain oat following pea and the rotation with two consecutive winter cereals had lower *A. fatua* biomass than the conventional crop rotation, regardless of the herbicide system (Figure 3B). Further, the alfalfa and single winter cereal crop rotation also exhibited lower *A. fatua* biomass compared with the conventional crop rotation (Figure 4B). The rotation containing alfalfa was found to have the greatest effect (80% biomass reduction) compared with all other systems in reducing

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Table 4. Probability values for crop rotations and mean differences for contrasts for *Galium spurium* density and biomass at Kernen, SK, Carman, MB, and Indian Head, SK, Canada (2015–2019).[a]

	Kernen		Carman		Indian Head	
	Density	Biomass	Density	Biomass	Density	Biomass
	plants m^{-2}	kg ha^{-1}	plants m^{-2}	kg ha^{-1}	plants m^{-2}	kg ha^{-1}
Crop rotation	<0.0001	0.0293	0.1359	<0.0001	0.0009	0.0538
Contrasts[b]						
SH vs. RH	4.8 (0.19)***	7 (0.41)*	35 (19.3)***	51 (5.7)***	353 (20.3)*	3.9 (0.3)
Alfalfa vs. others (SH)	3.3 (0.27)*	10 (1.2)**	3.8 (4.3)	1 (0.3)	686 (86)**	15 (2.79)
Alfalfa vs. others (RH)	2 (0.12)	17 (2.14)***	39 (45.1)	50 (11.9)*	1,040 (131)***	11.38 (2)
Alfalfa vs. silage oat	1 (0.30)	15 (2.04)***	24 (28.9)	9 (2.24)	1,104 (146)***	10 (1.9)
Alfalfa vs. winter crops	NA	13 (2)***	9 (12.2)	NA	559 (74.1)*	14 (3)
Winter vs. silage crops	NA	3 (0.18)	14 (13.8)	NA	545 (177)*	4 (0.65)
Silage oat vs. seed oat	0.62 (0.03)	3 (0.2)	4 (3.5)	15 (10)	97 (31.5)	4 (0.45)
Winter vs. summer crops	NA	0.5 (0.03)	17 (14.8)	NA	487 (28.8)**	1 (0.18)

[a]Values in parentheses are standard errors for mean differences. Significant at: *P = 0.05; **P = 0.01; ***P = 0.001. NA, not applicable.
[b]RH, no herbicides applied in the second and fourth year but herbicides applied in the fifth-year crop (flax); SH, full rate herbicides applied in the second-, fourth- and fifth-year crops.

A. fatua biomass. Further, the alfalfa rotation had lower *A. fatua* biomass than the average of all the rotations containing silage crops and winter cereal crops.

Overall, rotations in the SH system at the Carman site had lower *G. spurium* density than the rotations in the RH system (Table 4). Compared with the conventional crop rotation, only the alfalfa rotation exhibited a reduction (60 %) in *G. spurium* density (Figure 5A). Furthermore, contrasts indicated that the alfalfa rotation had a lower density of *G. spurium* compared with the average of all other crop rotations under both herbicide systems. This was also true when compared with the average of all the winter cereal–based rotations, which exhibited a similar *G. spurium* biomass (572 kg ha^{-1}) compared with the conventional crop rotation (Figure 5B). The rotation with a single winter cereal crop and the rotation with grain oat following pea under the SH system also exhibited a similarly low *G. spurium* biomass compared with the conventional crop rotation. Similar to the Kernen site, contrasts indicated that the alfalfa rotation had lower *G. spurium* biomass than the average of all crop rotations regardless of herbicide system. Winter crop–based rotations showed better *G. spurium* management than the crop rotations with summer annual crops (Table 4).

Indian Head

Results at the Indian Head site differed somewhat from those of the other two sites. *Avena fatua* densities did not differ between the two herbicide systems based on contrasts (Table 3), indicating herbicides were less effective at reducing *A. fatua* density at that site. Among all crop rotations, the rotation with spring wheat following canola (flax–barley–canola–spring wheat–flax) under the RH system, the alfalfa rotation (flax–-alfalfa–-alfalfa–-alfalfa–-flax) and the rotation with seed oat following canola (flax–barley–canola–oat–flax) under the SH system had a significant reduction (42%, 80%, and 49%, respectively) in *A. fatua* densities compared with the conventional rotation (Figure 6A). Contrasts revealed that the alfalfa rotation had lower *A. fatua* density (27 plants m^{-2}) compared with the average of all rotations under both herbicide systems (146 and 124 plants $m^{-2,}$ respectively). Furthermore, *A. fatua* density in the alfalfa rotation was lower than the average of all rotations containing both winter crops (173 plants m^{-2}) and silage crops (125 plants m^{-2}) under both systems.

Avena fatua biomass also differed among crop rotations at Indian Head (Table 3). At this site, the crop rotations with grain oat following canola, silage oat following canola, and spring wheat following canola all had significantly lower *A. fatua* biomass under both herbicide systems (Figure 6B). The alfalfa rotation had the greatest reduction in *A. fatua* biomass (79%) relative to the conventional crop rotation, as observed at the other two sites. Contrasts showed that the rotation containing alfalfa exhibited significantly lower *A. fatua* biomass (300 kg ha^{-1}) compared with the average of all other rotations under both SH (1,041 kg ha^{-1}) and RH (1,187 kg ha^{-1}) systems (Table 3). The alfalfa rotation also had a lower *A. fatua* biomass than the rotations with winter crops and silage crops under the RH system. Further, contrasts revealed that crop rotations with winter crops were better at reducing *A. fatua* biomass than rotations with silage crops (Table 3).

Crop rotations system did not exhibit differences in *G. spurium* density or biomass at Indian Head (Table 4). Further, none of the crop rotations showed significant differences in *G. spurium* density or biomass compared with the conventional crop rotation at Indian Head (Figure 7A and B). Contrasts indicated that rotations under the SH system had lower *G. spurium* density than rotations under the RH system, but no differences in biomass were identified (Table 4).

Overall, in this study we observed improved weed control (*G. spurium* and *A. fatua*) by including 3 yr of alfalfa in a crop rotation centered around flax production. Meiss et al. (2010) also noted better control of these two weed species in a perennial alfalfa rotation. While other studies demonstrated better *A. fatua* control with perennial alfalfa (Benaragama et al. 2019; Entz et al. 1995; Harker et al. 2016), ours is the first study to examine its inclusion to minimize weed densities before a flax crop under both RH and SH systems. Gulden et al. (2011) reported that after 10 yr in a rotation of flax–oat–alfalfa–alfalfa, the weed seedbank was reduced even when omitting herbicides in flax and oat. This study also shows that alfalfa is an essential crop in reducing the weed population over the long-term.

The improved weed control due to alfalfa could be due to a number of factors, including reduced soil disturbance, increased competition, reduced weed seedbank addition, or even enhanced weed seed predation (Chung and Miller 1995; De Heij and Willenborg 2020; Meiss et al. 2010; Ominski et al. 1999). Reduced weed seed production due to intense competition and reduced weed seed shed due to early harvesting for hay production are traits common to alfalfa crops and could well be the mechanisms responsible for improved *A. fatua* control identified in this study. Yet surprisingly, similar results were not observed for the

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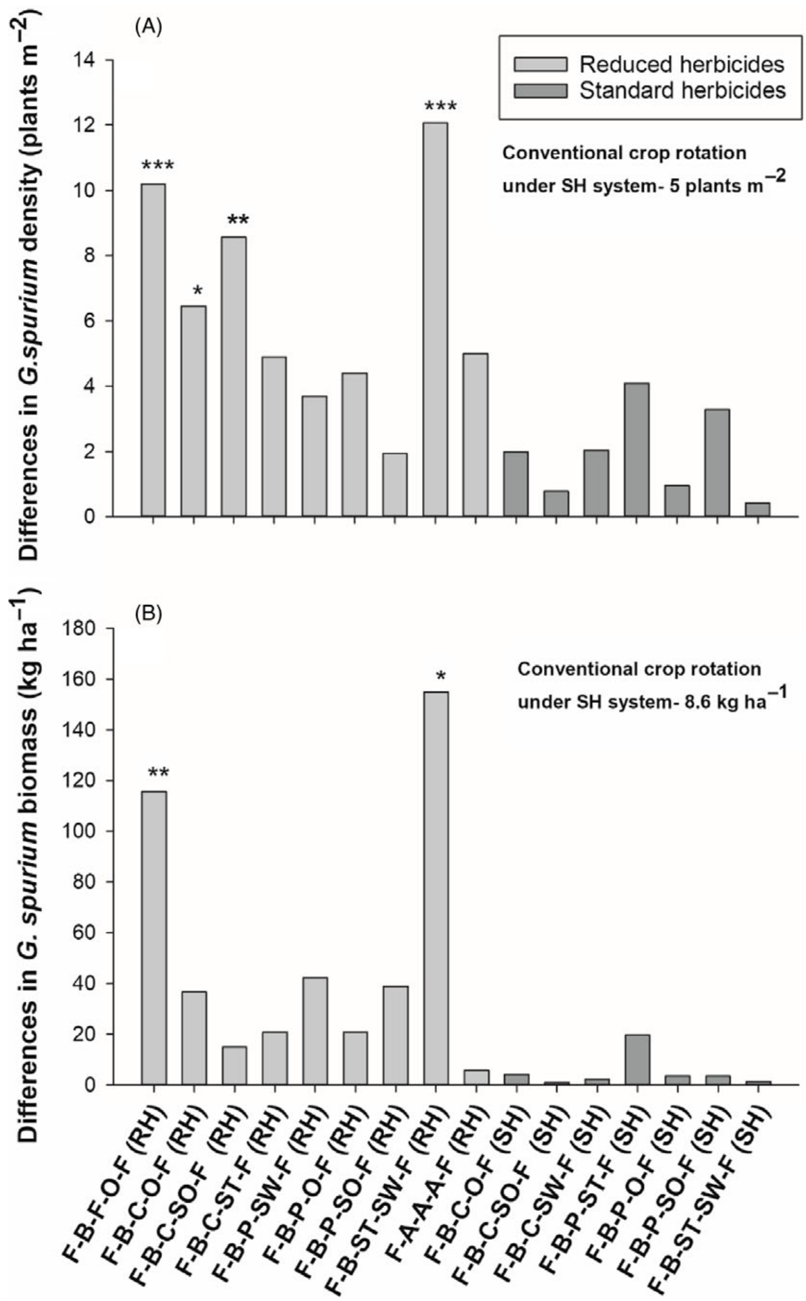

Figure 3. The effect of crop rotation on (A) *Galium spurium* density and (B) *G. spurium* biomass at Kernen, SK, Canada. Bars represent mean differences between the conventional crop rotation F-B-F-O-F (SH) and other crop rotations. Bars with asterisks indicate significantly different from the conventional crop rotation at *P = 0.05, **P = 0.01, and ***P = 0.001, obtained from Dunnett's test. ST, spring triticale; SW, spring wheat; F, flax; A, alfalfa; B, barley; O, oat; SO, silage oat; P, pea; C, canola; RH, reduced herbicides; SH, standard herbicides.

silage crop, indicating both the timing and number of forage harvesting events have a significant impact on future *A. fatua* populations. In fact, much of the impact of timing of forage harvest is a function of seed shed timing of weedy species. In contrast to *A. fatua*, seed retention of *G. spurium* is variable but generally greater than *A. fatua* (Burton et al. 2016; Tidemann et al. 2017). Therefore, reduced seed shed due to early harvesting may not be the primary mechanism of reduced *G. spurium* biomass and density in the rotation that contained alfalfa. Hence, having an annual silage crop (alternative to perennial crop) in the rotation may not be as beneficial for *G. spurium* compared with *A. fatua*. However, because *G. spurium* forms a tangling vine, cutting alfalfa for hay could have a supplementary impact on controlling this species. Moreover, the continuous ground cover provided by alfalfa may exert competition, thereby reducing seed production. It may also inhibit germination of *G. spurium*, thereby decreasing the *G. spurium* population over time. This is important, because *G. spurium* exhibits variation in emergence timing within and between years and often has multiple flushes (Defelice 2002; De Roo 2016; Royo-Esnal et al. 2010). These traits collectively make *G. spurium* challenging to control with the timing of in-crop herbicides, but the continuous cover provided by perennial crops is likely to improve long-term management of *G. spurium* in prairie crop rotations.

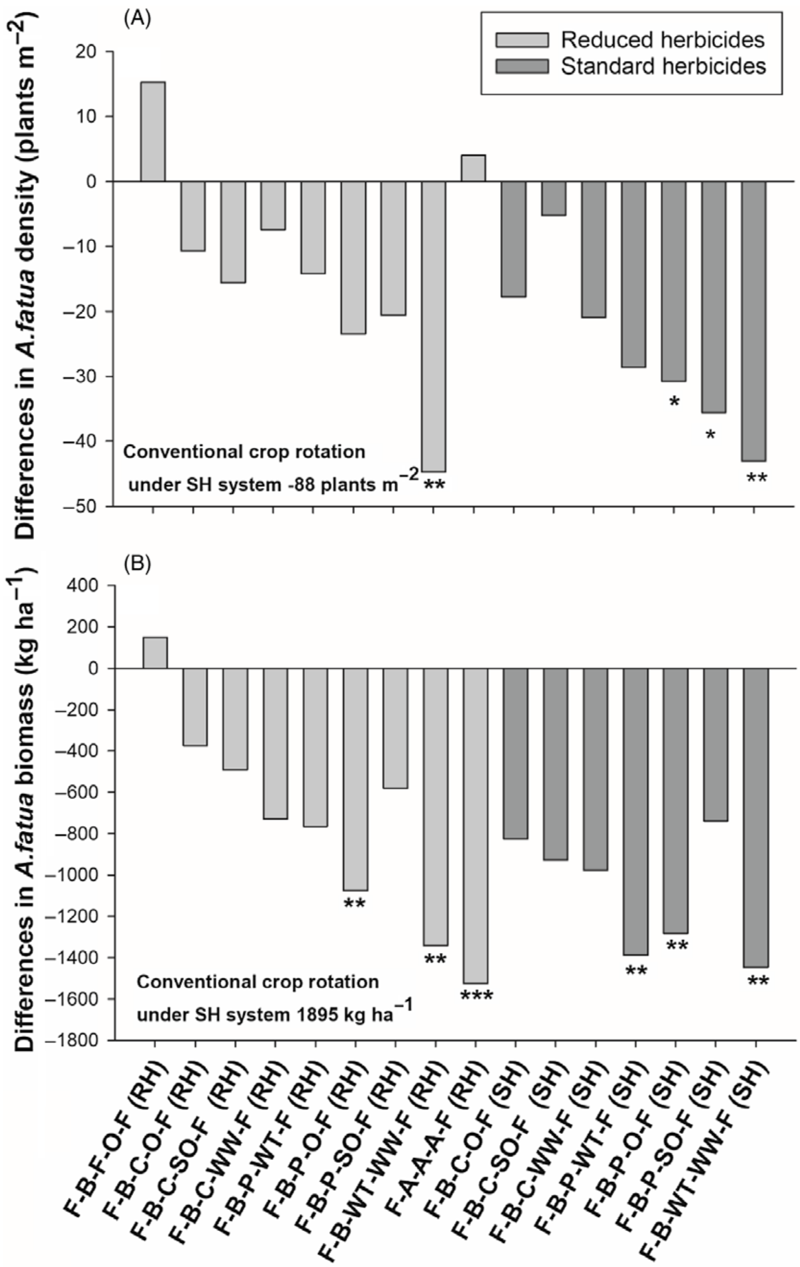

Figure 4. The effect of crop rotations on (A) *Avena fatua* density and (B) *A. fatua* biomass at Carman, MB, Canada. Bars represent mean differences between the conventional crop rotation F-B-F-O-F (SH) and other crop rotations. Bars with asterisks indicate significantly different from the conventional crop rotation at *P = 0.05, **P = 0.01, and ***P = 0.001, obtained from Dunnett's test. F, flax; A, alfalfa; B, barley; O, oat; WT, winter triticale; WW, winter wheat; SO, silage oat; P, pea; C, canola; RH, reduced herbicides; SH, standard herbicides.

Winter cereal crops in rotation with summer crops break the life cycle of summer annual weeds by incorporating diverse crop planting and harvesting dates. Alternating between winter and summer crops has been found to reduce weed densities in other studies (Blackshaw 1994; Thomas and Frick 1993). Our study identified that having a single winter crop in the rotation did not contribute to the improved management of *A. fatua* or *G. spurium*. However, having two consecutive winter crops did show some promise for the control of both *G. spurium* and *A. fatua* at Carman, which was the only site where good overwintering occurred. These results are congruent with those of Anderson (2005, 2008), who showed that weed control was more profound when two consecutive warm-season crops were followed by two successive winter crops. Our results, combined with those of Anderson (2005, 2008), support the idea that the stacking of crop phases (Derksen et al. 2002) will be more beneficial than rotating crops every season (Garrison et al. 2014). Winter cereals can be beneficial in weed management due to their early establishment during spring and the ability to compete better than spring cereals (Beres et al. 2010; Entz and Fowler 1991). However, we used a 2X seeding rate for all winter cereal crops in this study, which might have made them more competitive. We did this because poor establishment due to winterkill is common in winter cereals (Beres et al. 2010; Lafond and Fowler 1989), and it was likely the reason for the failure of these crops at Kernen and Indian Head. Among the three sites, only Carman and Indian Head had crop rotations with a single-season

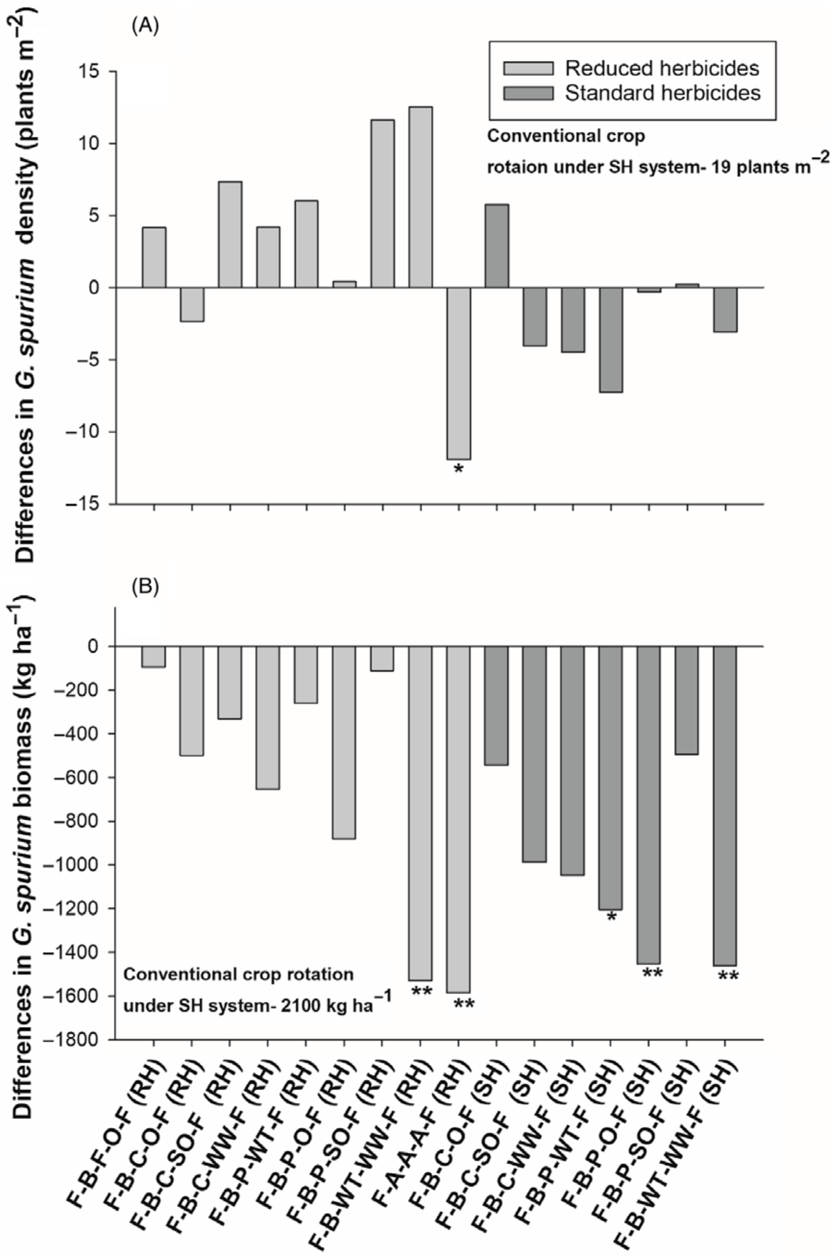

Figure 5. The effect of crop rotation on (A) *Galium spurium* density and (B) *G. spurium* biomass at Carman, MB, Canada. Bars represent mean differences between the conventional crop rotation F-B-F-O-F (SH) and other crop rotations. Bars with asterisks indicate significantly different from the conventional crop rotation at *P = 0.05 and **P = 0.01, obtained from Dunnett's test. F, flax; A, alfalfa; B, barley; O, oat; WT, winter triticale; WW, winter wheat; SO, silage oat; P, pea; C, canola; RH, reduced herbicides; SH, standard herbicides.

winter crop established. Yet at both of these sites, crop rotations with a single-season winter crop did not provide better *A. fatua* management than the conventional crop rotation.

Crop rotations containing different summer annual crops, including grain oat, spring wheat, and silage oat tended to show inconsistent *A. fatua* control compared with the conventional crop rotation. Perhaps more interesting is that we observed no effect on *A. fatua* management due to the use of silage crops in the rotation when compared with summer annual grain crops, winter crops, or alfalfa crops. This contrasts with the findings of Harker et al. (2003), who showed substantial reductions in *A. fatua* density could be achieved by growing silage barley compared with barley grown for grain. The lack of impact that silage crops had on controlling *A. fatua* in the current study could be due to numerous factors. First, to minimize *A. fatua* seed return to the seedbank, silage harvesting would have to be carried out before *A. fatua* seed shed. Differences in accumulated growing degree days and higher growing season temperatures can cause *A. fatua* to mature early and shed seeds before they can be removed with the silaging operation (Shirtliffe et al. 2000). Moreover, multiple cuts of alfalfa are taken each year, often for several years, whereas silage oat is only harvested only once annually, and that operation would need to be timed before *A. fatua* seed shatter in order to impact *A. fatua* populations. Second, the silage phase of the rotation occurred in the fourth year of the rotation, and thus its weed control benefit may not have been detected immediately in the following year, which was the fifth

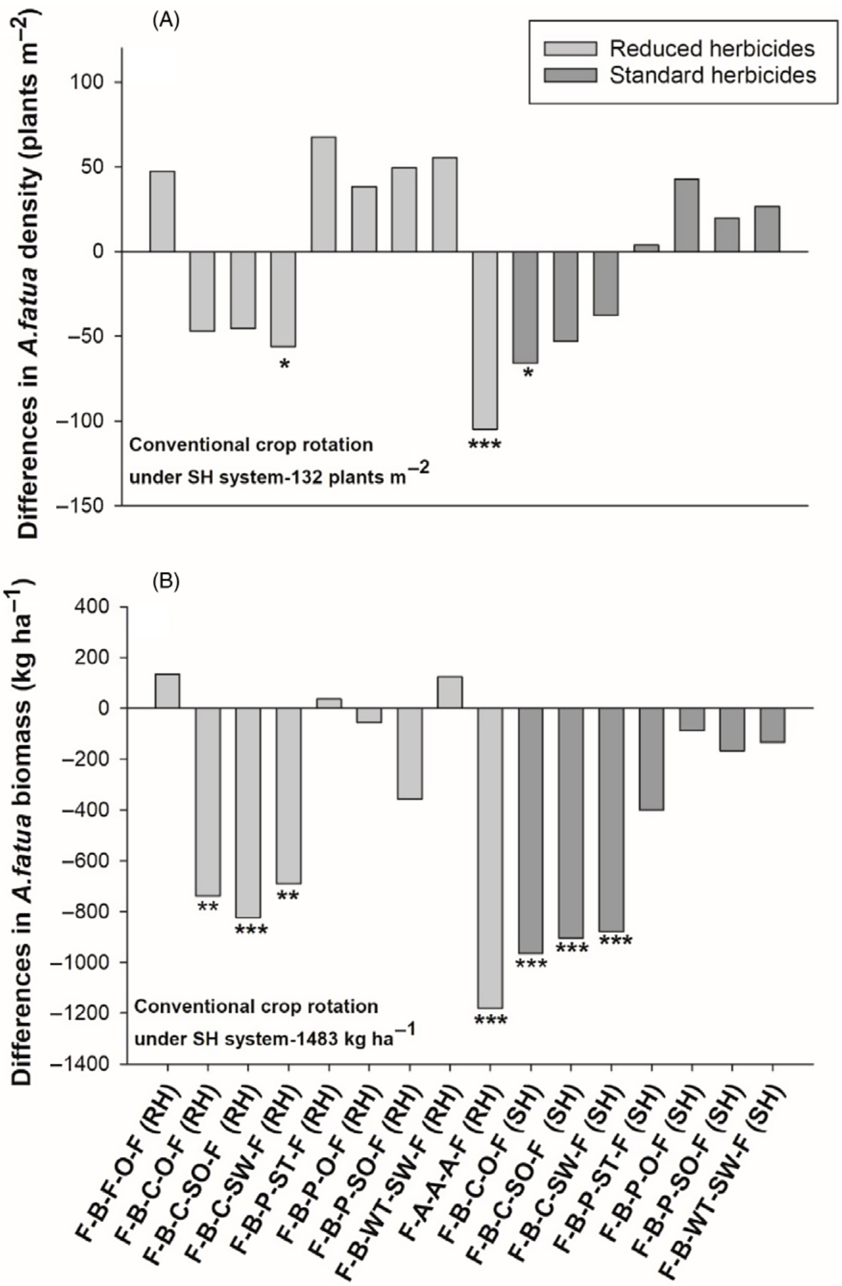

Figure 6. The effect of crop rotation on (A) *Avena fatua* density and (B) *A. fatua* biomass at Indian Head, SK, Canada. Bars represent mean differences between the conventional crop rotation F-B-F-O-F (SH) and other crop rotations. Bars with asterisks indicate significantly different from the conventional crop rotation at *P = 0.05 and **P = 0.01, obtained from Dunnett's test. ST, spring triticale; SW, spring wheat; F, flax; A, alfalfa; B, barley; O, oat; WT, winter triticale; WW, winter wheat; SO, silage oat; P, pea; C, canola; RH, reduced herbicides; SH, standard herbicides.

and final year of the study. *Avena fatua* is known to have dormancy characteristics (Beckie et al. 2012; Sharma et al. 1976) that may cause difficulties in the immediate detection of weed seed reduction by cultural strategies. It is nevertheless possible that the benefit of *A. fatua* seedbank depletion offered by silage crops (Harker et al. 2016) could possibly be recognized in longer rotation studies. Other studies that have reported positive results of silage crops on *A. fatua* included early-cut silage treatments for three consecutive years (Harker et al. 2003) or in two alternate years (Harker et al. 2016), which differed from the treatment regime in the current study. Our study included only a single silage crop, because rotations in which silage is cut early for 3 yr in a row or is grown in two alternate years of rotation are not common on the prairies and are unlikely to be adopted by grain growers.

None of the other crop diversification strategies (rotating canola, peas, and oat) were identified as comparatively effective in managing *A. fatua* or *G. spurium*. As summer annual crops, these crops did not add substantial functional diversity to the rotations, thus highlighting the importance of increasing functional diversity in crop rotations for reduced herbicide reliance in weed management.

Avena fatua and *G. spurium* are some of the most important weed species in the prairie cropping systems and are becoming increasingly problematic due to increased herbicide resistance.

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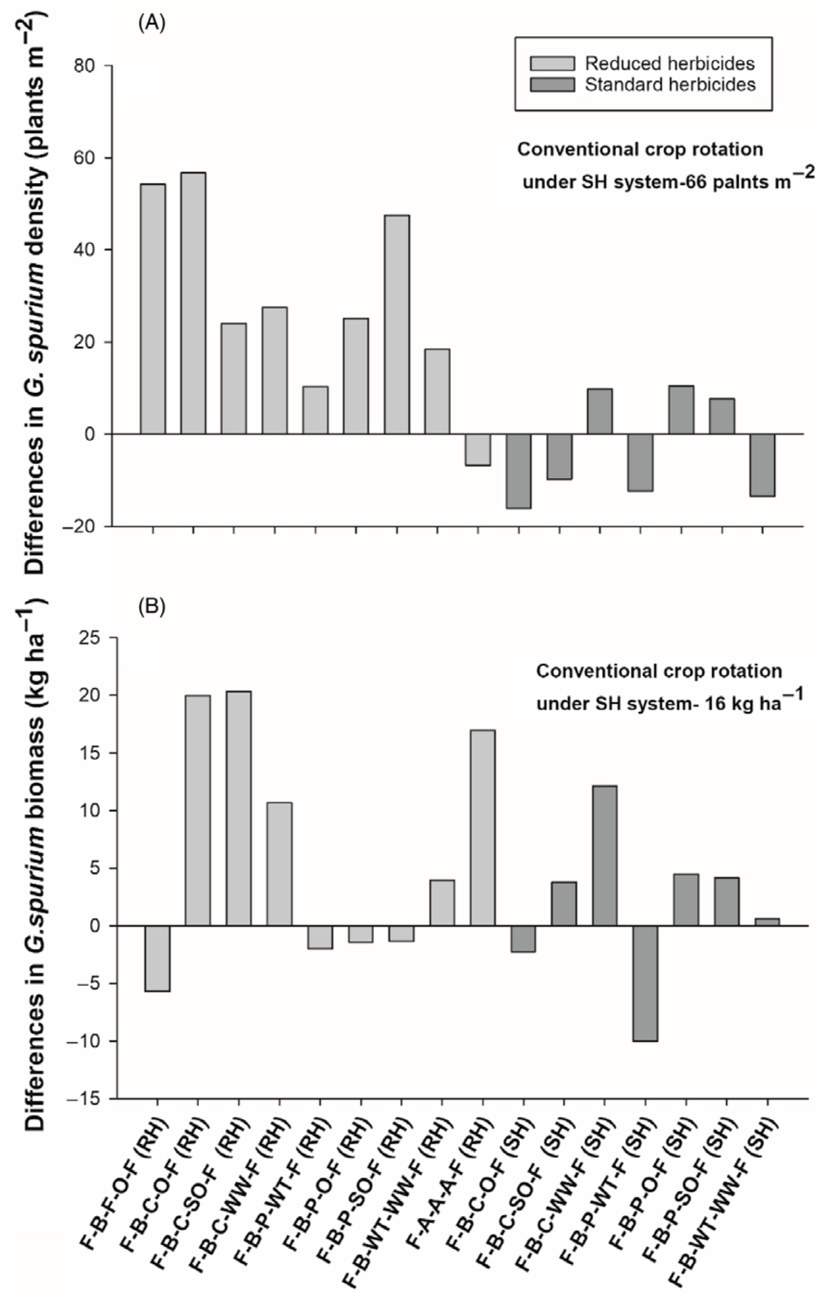

Figure 7. The effect of crop rotation on (A) *Galium spurium* density and (B) *G. spurium* biomass at Indian Head, SK, Canada. Bars represent mean differences between the conventional crop rotation F-B-F-O-F (SH) and other crop rotations. ST, spring triticale; SW, spring wheat; F, flax; A, alfalfa; B, barley; O, oat; WT, winter triticale; WW, winter wheat; SO, silage oat; P, pea; C, canola; RH, reduced herbicides; SH, standard herbicides.

In this study, we identified that crop rotation with 3 yr of an alfalfa crop (flax–barley–alfalfa–alfalfa–alfalfa–flax) was the most consistent in managing both *A. fatua* and *G. spurium* with reduced herbicides over the long term. However, alfalfa may not be attractive for grain growers due to a reduction in cash flow during the 3 yr the alfalfa is grown (Smith et al. 2018), unless there is a demand for hay in the region. Nevertheless, our results show it can have a marked impact on weed populations before growing flax, a crop for which few herbicide options exist. The alternative crop rotations we tested, such as the inclusion of winter cereals, were found to be promising, particularly when two winter crops were included in the rotation. However, the addition of a silage crop in the rotation did not produce better weed management compared with the standard flax–barley–flax–oat–flax rotation with standard herbicides. The inability to detect better weed management benefits in rotation containing silage oat does not preclude using silage crops in rotations, however, as the effect of silage crops in reducing weed seedbanks may not have been realized within the study period.

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References

Anderson RL (2005) A multi-tactic approach to manage weed population dynamics in crop rotations. Agron J 97:1579–1583

Anderson RL (2008) Diversity and no-till: keys for pest management in the US Great Plains. Weed Sci 56:141–145

Beckie HJ (2010) Predicting prairie weeds at risk for glyphosate resistance. Canadian Weed Science Society Annual Meeting Archives. http://www.weedscience.ca/annual-meeting/archives. Accessed: July 29, 2020

Beckie HJ, Ashworth MB, Flower KC (2019) Herbicide resistance management: recent developments and trends. Plants 8:161

Beckie HJ, Francis A, Hall LM (2012) The biology of Canadian weeds. 27. *Avena fatua* L. (updated). Can J Plant Sci 92:1329–1357

Beckie HJ, Harker KN (2017) Our top 10 herbicide-resistant weed management practices. Pest Manag Sci 73:1045–1052

Beckie HJ, Shirriff SW, Leeson, JY, Hall LM, Harker KN, Dokken-Bouchard F, Brenzil CA (2020). Herbicide-resistant weeds in the Canadian Prairies: 2012 to 2017. Weed Technol 34:461–474

Bell AR, Nalewaja JD (1968) Competitive effects of wild oat in flax. Weed Sci 16:501–504

Benaragama D, Leeson JL, Shirtliffe SJ (2019) Understanding the long-term weed community dynamics in organic and conventional crop rotations using the principal response curve method. Weed Sci 67:195–204

Beres BL, Harker KN, Clayton GW, Bremer E, Blackshaw RE, Graf RJ (2010) Weed-competitive ability of spring and winter cereals in the Northern Great Plains. Weed Technol 24:108–116

Blackshaw RE (1994) Rotation affects downy brome (*Bromus tectorum*) in winter wheat (*Triticum aestivum*). Weed Technol 8:728–732

Burton NR, Beckie HJ, Willenborg CJ, Shirtliffe SJ, Schoenau JJ, Johnson EN (2016) Evaluating seed shatter of economically important weed species. Weed Sci 64:673–682

Chung IM, Miller DA (1995) Natural herbicide potential of alfalfa residue on selected weed species. Agron J 87:920–925

De Heij SE, Willenborg CJ (2020) Connected carabids: network interactions and their impact on biocontrol by carabid beetles. BioScience 70:490–500

Defelice MS (2002) Catchweed bedstraw or cleavers, *Galium aparine* L.—a very "sticky" subject. Weed Technol 16:467–472

Derksen DA, Anderson RL, Blackshaw RE, Maxwell B (2002) Weed dynamics and management strategies for cropping systems in the Northern Great Plains. Agron J 94:174–185

De Roo AC (2016) Determining the Emergence Timing, Morphological Characteristics, and Species Composition of *Galium* Populations in Western Canada. MSc dissertation. Saskatoon, SK: University of Saskatchewan. 108 p

De Roo AC, Eckstein P, Benaragama D, Beattie AD, Willenborg CJ (2019) Evaluation of *Galium* species and populations using morphological characters and molecular markers. Weed Res 59:28–38

Entz MH, Bullied WJ, Katepa-Mupondwa F (1995) Rotational benefits of forages in Canadian prairie cropping systems. J Prod Agric 8:521–529

Entz MH, Fowler DB (1991) Agronomic performance of winter versus spring wheat. Agron J 83:527–532

Flax Council of Canada (2017) Growing Flax. https://flaxcouncil.ca/wp-content/uploads/2015/02/FCOC-growers-guide-v11.pdf. Accessed: May 15, 2020

Friesen GH (1986) Effect of weed interference on yield and quality of flaxseed oil. Can J Plant Sci 66:1037–1040

Garrison AJ, Miller AD, Ryan MR, Roxburgh SH, Shea K (2014) Stacked crop rotations exploit weed-weed competition for sustainable weed management. Weed Sci 62:166–176

Gulden RH, Lewis DW, Froese JC, Van Acker RC, Martens GB, Entz MH, Derksen DA, Bell LW (2011) The effect of rotation and in-crop weed management on the germinable weed seedbank after 10 years. Weed Sci 59:553–561

Harker KN, Kirkland KJ, Baron VS, Clayton GW (2003) Early harvest barley (*Hordeum vulgare*) silage reduces wild oat (*Avena fatua*) densities under zero tillage. Weed Technol 17:102–110

Harker KN, Mallory-Smith C, Maxwell BD, Mortensen DA, Smith RG (2017) Another view. Weed Sci 65:203–205

Harker KN, O'Donovan JT (2013) Recent weed control, weed management, and integrated weed management. Weed Technol 27:1–11

Harker KN, O'Donovan JT, Irvine RB, Turkington TK, Clayton GW (2009) Integrating cropping systems with cultural techniques augments wild oat (*Avena fatua*) management in barley. Weed Sci 57:326–337

Harker KN, O'Donovan JT, Turkington TK, Blackshaw RE, Lupwayi NZ, Smith EG (2016) Diverse rotations and optimal cultural practices control wild oat (*Avena fatua*). Weed Sci 64:170–180

Heap I (2021) The International Herbicide-Resistant Weed Database. www.weedscience.org. Accessed: March 23, 2021

Kirkland KJ (1993) Spring wheat (*Triticum aestivum*) growth and yield as influenced by duration of wild oat (*Avena fatua*) competition. Weed Technol 7:890–893

Kurtenbach ME, Johnson EN, Gulden RH, Duguid S, Dyck MF, Willenborg CJ (2019) Integrating cultural practices with herbicides augments weed management in flax. Agron J 111:1904–1912

Lafond GP, Fowler DB (1989) Soil temperature and water content, seeding depth, and simulated rainfall effects on winter wheat emergence. Agron J 81:609–614

Leeson JY (2012) Weed Survey of Saskatchewan Canola Fields. Saskatoon, SK: Agriculture and Agri-Food Canada, Saskatoon Research Center. 83 p

Leeson JY, Beckie H (2014) Experiences with integrated weed management and pesticide use in the Canadian Prairies. Pages 201–219 *in* Peshin R, Pimentel D, eds. Integrated Pest Management. Dordrecht, Netherlands: Springer

Leeson JY, Thomas AG, Hall LM, Brenzil CA, Andrews T, Brown KR, Van Acker RC (2005) Prairie Weed Surveys of Cereal, Oilseed and Pulse Crops from the 1970s to the 2000s. Weed Survey Ser. 05-1. Saskatoon, SK: Agriculture and Agri-Food Canada, Saskatoon Research Center. 395 p

Liebman M, Nichols VA (2020) Cropping system redesign for improved weed management: a modeling approach illustrated with giant ragweed (*Ambrosia trifida*). Agronomy 10:262

Liebman M, Staver CP (2001) Crop diversification for weed management. Pages 322–374 *in* Liebman M, Mohler CL, Staver CP, eds. Ecological Management of Agricultural Weeds. Cambridge: Cambridge University Press

Liu JG, Mahoney KJ, Sikkema PH, Swanton CJ (2009). The importance of light quality in crop-weed competition. Weed Res 49:217–224

Malik N, Vanden Born WH (1987) Growth and development of false cleavers (*Galium spurium* L.). Weed Sci 35:490–495

Meiss H, Le Lagadec L, Munier-Jolain N, Waldhardt R, Petit S (2010) Weed seed predation increases with vegetation cover in perennial forage crops. Agric Ecosyst Environ 138:10–16

Miller SD, Nalewaja JD, Mulder CEG (1982) Morphological and physiological variation in wild oat 1. Agron J 74:771–775

O'Donovan JT, Harker KN, Turkington TK, Clayton GW (2013) Combining cultural practices with herbicides reduced wild at (*Avena fatua*) seed in the soil seed bank and improved barley yield. Weed Sci 61:328–333

O'Donovan JT, Newman JC, Harker KN, Blackshaw RE, McAndrew DW (1999) Effect of barley plant density on wild oat (*Avena fatua*) interference, shoot biomass and seed yield under zero tillage. Can J Plant Sci 79:655–662

Ominski PD, Entz MH, Kenkel N (1999) Weed suppression by *Medicago sativa* in subsequent cereal crops: a comparative survey. Weed Sci 47:282–290

Royo-Esnal AJ, Torra JA, Conesa F, Forcella Recasens J (2010) Modeling the emergence of three arable bedstraw (*Galium*) species. Weed Sci 58:10–15

Sánchez Vallduví GE, Sarandón SJ (2011) Effects of changes in flax (*Linum usitatissimum* L.) density and inter-seeding with red clover (*Trifolium pratense* L.) on the competitive ability of flax against *Brassica* weeds. J Sustain Agric 35:914–926

SAS Institute (2011) SAS 9.3 User's Guide; The GLIMMIX Procedure. Cary, NC: SAS Institute. 373 p

Sharma MP, McBeath DK, Vanden Born WH (1976) Studies on the biology of wild oats. I. Dormancy, germination and emergence. Can J Plant Sci 56:611–618

Shirtliffe SJ, Benaragama D (2014) Sometimes you need a big hammer: evaluating and appraising selected nonherbicidal weed control methods in an integrated weed management system. Pages 170–195 *in* Martin RC, MacRae R, eds. Managing Energy, Nutrients, and Pests in Organic Field Crops. Boca Raton. FL: CRC Press

Shirtliffe SJ, Entz MH, Van Acker RC (2000) *Avena fatua* development and seed shatter as related to thermal time. Weed Sci 48:555–560

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Smith EG, Harker KN, O'Donovan JT, Turkington KT, Blackshaw RE, Lupwayi NZ, Johnson EN, Pageau D, Shirtliffe SJ, Gulden RH, Hall LM (2018) The profitability of diverse crop rotations and other cultural methods that reduce wild oat (*Avena fatua*). Can J Plant Sci 98: 1094–1101

Stevenson FC, Wright AT (1996) Seeding rate and row spacing affect flax yield and weed interface. Can J Plant Sci 76:537–544

Teasdale JR (2017) The use of rotations and cover crops to manage weeds. Pages 227–260 *in* Zimdahl RL, ed. Integrated Weed Management for Sustainable Agriculture. Cambridge, UK: Burleigh Dodds

Thomas AG, Frick BL (1993) Influence of tillage systems on weed abundance in southwestern Ontario. Weed Technol 7:699–705

Tidemann BD, Hall LM, Harker K N, Beckie HJ, Johnson EN, Stevenson FC (2017) Suitability of wild oat (*Avena fatua*), false cleavers (*Galium spurium*), and volunteer canola (*Brassica napus*) for harvest weed seed control in western Canada. Weed Sci 65:769–777

Weisberger D, Nichols V, Liebman M (2019) Does diversifying crop rotations suppress weeds? A meta-analysis. PLoS ONE 14(7):e0219847

Willenborg CJ, May WE, Gulden RH, Lafond GP, Shirtliffe SJ (2005) Influence of wild oat (*Avena fatua*) relative time of emergence and density on cultivated oat yield, wild oat seed production, and wild oat contamination. Weed Sci 53:342–352

Zadoks JC, Chang TT, Konzak CF (1974) A decimal code for the growth stages of cereals. Weed Res 14:415–421