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Cropping system rotation in combination with harvest weed seed control for wild oat (*Avena fatua*) management

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Research Article

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Abstract

Wild oat is a significant weed of cropping systems in the Canadian Prairies. Wild oat resistance to herbicides has increased interest in the use of nonchemical management strategies. Harvest weed seed control techniques such as impact mills or chaff collection have been of interest in Prairie crops, with wild oat identified as a key target. To evaluate the effects of crop rotation maturity, harvest management, and harvest weed seed control on wild oat, a study was conducted from 2016 to 2018 at four locations in the Canadian Prairies. Two-year crop rotations with either early, normal, or late-maturing crops were implemented before barley was seeded across all rotations in the final year. In addition, a second factor of harvest management (swathing or straight cut) was included in the study. Chaff collection was used in this study to quantify wild oat seeds that were targetable by harvest weed seed control techniques. The hypothesis was that earlier maturing crops would result in increased wild oat capture at harvest and, therefore, lower wild oat populations. Wild oat density and wild oat biomass were lowest in the early maturing rotations. In addition, wild oat exhibited lower biomass in swathed crops than straight-cut crops. Wild oat seedbank levels reflected a similar trend with the lowest densities occurring in early maturing rotation, then the normal maturity rotation, and the late maturing rotation, which had the highest seedbank densities. Wild oat densities increased in all crop rotations; however, only harvest weed seed control and crop rotation were implemented as control measures. Wild oat numbers in the chaff were not reflective of the earliness of harvest. Crop yields suggest that competitive winter wheat stands contributed to the success of the early maturing rotations compared to other treatments. Early maturing rotations resulted in reduced wild oat populations, likely through a combination of crop competitiveness and rotational diversity, and harvest weed seed control management effects from earlier maturing crops.

Introduction

Wild oat is a current and historically problematic weed for farmers in western Canada. In the proceedings of the first weed science-related conference in Canada, wild oat is noted as a problem for farmers in certain sections of western Canada (Vigor 1929); the southern Prairies were less infested because conditions were too dry for wild oat (Vigor 1929). By the 1950s, significant research was conducted on wild oat (considered a "companion crop" in spring cereals or flax), to evaluate cultural management strategies for this weed (Brown 1953). Selective graminicides, released between 1975 and 1985, went a long way to reducing concerns about wild oat on the Canadian Prairies. While wild oat remains one of the top 10 weeds on the Canadian Prairies, the density and frequency of this weed have decreased since the 1970s (Leeson 2016; Leeson et al. 2005, 2016, 2019).

The first case of herbicide-resistant wild oat in Canada was identified in 1989 with wild oat being resistant to the preseeding herbicide triallate, in Alberta (Heap 2024). Wild oat resistance to foliar, or postseeding herbicides was reported in Manitoba and Saskatchewan in 1990, where resistance was found to multiple herbicide active ingredients, including clodinafop, diclofop, fenoxaprop, sethoxydim, clethodim, and tralkoxydim (Heap 2024). Since that time, biotypes of wild oat that are resistant to Group 1 herbicides (e.g., acetyl-CoA carboxylase inhibitor) and Group 2 herbicides (e.g., acetolactate synthase inhibitor) (both groups as categorized by the Herbicide Resistance Action Committee), have become widespread throughout the Canadian

Prairies (Beckie et al. 2020). In the most recent surveys in Saskatchewan and Manitoba, 77% and 100%, respectively, of the tested wild oat populations were resistant to at least one herbicide mode of action (Geddes et al. 2024; C. Geddes, personal communication). Producers dealing with multiple herbicide resistance to the Group 1 and Group 2 herbicides have limited herbicide options for wild oat control. In canola, in-crop applications of glyphosate or glufosinate are still effective in cultivars specifically bred for tolerance to these products. However, in other crops, postseeding herbicide options are limited to the extent that none may be available, forcing a shift to preseeding, soil-applied herbicides. These products are difficult for producers to use because a lack of precipitation can reduce their efficacy, high levels of organic matter require higher rates or result in reduced efficacy (Tidemann et al. 2014), and efficacy for some is dependent on physical incorporation, which is often not feasible in no-till or minimum-till cropping systems. Some herbicides are registered only for suppression of wild oat, not its control. These factors have increased the need for integrated weed management strategies. Many integrated weed management strategies for wild oat have been investigated in western Canada (Harker et al. 2003, 2009, 2016; O'Donovan et al. 2013). However, many of these strategies require rotational changes in cropping systems or the use of crops for silage instead of grain, which may be problematic due to limited on-farm need or market access (Harker et al. 2016).

Harvest weed seed control (HWSC) has recently become a focus in weed management, with multiple commercially available systems having been developed to prevent seedbank inputs at harvest (Walsh et al. 2018). These methods include bale direct systems, narrow windrow burning, chaff lining or chaff tramlining, chaff carts, and impact mills (Walsh et al. 2018). HWSC has become an accepted and established practice for producers in Australia (Walsh et al. 2018). In western Canada, the adoption of impact mills has begun to increase, with an estimated 30 mills in Canada at this time, with the majority being used in Saskatchewan (Tidemann et al. 2024). For the early adopters, wild oat was the most referenced target weed that influenced the adoption of this HWSC tactic (Tidemann et al. 2024). Unfortunately, low and variable wild oat seed retention estimates at crop maturity (Burton et al. 2016, 2017; Desai et al. 2023; Tidemann et al. 2017) suggest that the impact of HWSC on this weed will be limited. Wild oat development, and resultant seed shatter, is linked to thermal time (Shirtliffe et al. 2000). Thus, while seed retention is variable, there is some consistency in relative development time in comparison to crop development. Research has also suggested that more wild oat seeds would likely be collected if the harvested crop was swathed rather than straight cut (Tidemann et al. 2017).

One of the most common cropping rotations in western Canada is a 2-yr canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.) rotation. In Saskatchewan, a 3-yr rotation that includes a pulse crop such as pea (*Pisum sativum* L.) or lentil [*Vicia lens* (L.) Coss. & Germ] is more common, while in rotations in Manitoba, wheat, canola, and soybean [*Glycine max* (L.) Merr.] are most common. However, there are opportunities in all regions to grow crops with diverse maturation times. Crops such as peas, lentils, and winter cereals are generally early maturing in their typical growing regions, while fababean (*Vicia faba* L.), flax (*Linum usitatissimum* L.), and soybean tend to mature later. Since a range of crop maturities is available, this study aimed to determine the efficacy in managing wild oat populations with combinations of HWSC with 1) earlier maturing crops and 2) harvest management (swathing vs. straight cutting). The hypothesis was that earlier maturing crops, particularly combined with swathing, would result in the highest proportion of wild oat seed production being targeted by HWSC to deliver the lowest in-crop wild oat populations. Since different crops were used in the rotations, it was hypothesized that more competitive crops in the rotation may also be beneficial for wild oat management.

Table 1. Treatment list used to study the effect of cropping system maturity, harvest management, and harvest weed seed control on wild oat densities from 2016 to 2018 in the Canadian Prairies.[a]

		Year		
Maturity	Harvest management	2016	2017	2018
Early	Swath	Peas	Winter wheat	Barley
Early	Straight cut	Peas	Winter wheat	Barley
Normal	Swath	Wheat	Canola	Barley
Normal	Straight cut	Wheat	Canola	Barley
Late	Swath	Fababean	Flax	Barley
Late	Straight cut	Fababean	Flax	Barley

[a]Each row provides a description of all factors associated with a specific treatment.

Materials and Methods

A 3-yr study was conducted from 2016 to 2018 with field trials at four locations: Lacombe and Beaverlodge, AB; Scott, SK; and Carman, MB. At each site, trials were established using a factorial, randomized, complete block design with three rotational maturities and two harvest management regimes for a total of six treatments (Table 1). The experiment was conducted as a 3-yr rotational cropping system, and the presented results, where applicable, show the cumulative effects of the cropping system treatments after those 3 yr. For the early maturing rotation, the crop phases were pea followed by winter wheat, the intermediate or "normal" maturing rotation was wheat followed by canola, and the late maturing rotation was fababean followed by flax (Table 1). Barley was planted in the final year of all rotations to allow wild oat population effects to be compared across rotations. Lack of winter wheat survival resulted in the data from the second and third years of the early maturing rotation being removed from the study at the Scott location.

Soil samples were taken across the trial area prior to study initiation to characterize the soil and to receive recommendations for fertility regimes based on soil test results of residual nutrients. Fertilizer was applied based on soil test recommendations, either mid-row or side-banded, according to available seeding equipment. Prior to crop seeding in the first year, a pre-seeding burndown application of glyphosate (900 g ae ha^{-1}) plus bromoxynil (290 g ai ha^{-1}) (water volume based on label recommendations, pressure and nozzles were site and equipment dependent) was imposed. Wild oat populations at the trial sites were supplemented by broadcasting 200 seeds m^{-2} across the trial area. Fungicides and insecticides were applied as required to manage diseases and pests. Herbicides were applied as required to control broadleaf weeds only. Site soil characteristics and environmental conditions were recorded (Table 2), and the varieties of each crop used were allowed to vary by site so that regionally appropriate crop varieties could be used. Wild oat plant densities in each plot were measured in two 0.5-m^2 quadrats each year just prior to in-crop herbicide applications. The quadrat location was marked and used for biomass sampling at wild oat panicle emergence in the corresponding year. The location of the quadrat shifted each year so as not to influence data collection in

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Table 2. Site characteristics, including soil information, plot information, crop varieties and growing season precipitation for each location involved in the study from 2016 to 2018.[a]

Site year	Soil texture	Soil organic matter	pH	Plot size and seeding information	Crop varieties	Growing season precipitation
		%				Long-term average %[b]
Beaverlodge 2016	Clay loam	8.5	6.2	3.7 m × 15 m	Harvest wheat	154
Beaverlodge 2017	21.6% sand, 49.1% silt,			30 cm row spacing, hoe	Meadow peas	127
Beaverlodge 2018	29.3% clay			openers	Snowdrop faba	124
					Gateway WW	
					Sapphire flax	
					L241CR canola	
					Canmore barley	
Carman 2016	Sandy clay loam	7.9	5.2	4 m × 8 m	Cardale wheat Agassiz peas	116
Carman 2017	58% sand, 15% silt,			19 cm row spacing, disc	Tabour faba	59
Carman 2018	27% clay			openers	Gateway WW	74
					L233P canola	
					Bethune flax	
					Canmore barley	
Lacombe 2016	Clay	8.8	7.3	3.7 m × 15 m	Harvest wheat	105
Lacombe 2017	19% sand, 37% silt,			30 cm row spacing, hoe	Meadow peas	73
Lacombe 2018	44% clay			openers	Snowdrop faba	83
					Gateway WW	
					Sapphire flax	
					L241CR canola	
					Canmore barley	
Scott 2016	Loam	2.7	6.2	3 m × 10 m	Shaw wheat Meadow peas	89
Scott 2017	23% sand			25 cm row spacing, knife	Snowdrop faba	90
Scott 2018	40% silt, 17% clay			openers	Emerson WW	70
					L140P canola Norlan flax	
					Champion barley	

[a]Abbreviations: Faba, fababean; WW, winter wheat.
[b]Long-term average, measured in millimeters, from the Canadian Climate Normals 1981–2010, from https://climate.weather.gc.ca/climate_normals/index_e.html

subsequent years. Thus, the wild oat density in the final year was sampled from the same quadrat where the density counts were taken in the final year. Biomass samples were dried at 70 C until weights stabilized, and then weighed.

Swathing of plots was conducted based on the industry-recommended plant stage for swathing for each individual crop (e.g., 25% of plants have one to three pods brown/black for fababean, 60% seed color change for canola, etc.). The height of swathing was variable depending on crop height and lodging, but it was typically a maximum of 15 cm from the ground level. The variability in swathing height is unlikely to affect the collection of wild oat seeds due to their typical presence above the crop canopy. Plots were harvested using plot combine equipment available at each location. However, each plot harvester was modified to allow for the collection of chaff; specific modifications were site and plot harvester specific (Figure 1). Chaff collection was used as the HWSC mechanism in this trial to allow collection and quantification of wild oat seeds captured and targetable in each treatment. Other HWSC techniques would provide approximately the same level of control (Walsh et al. 2017). It is likely that with different plot harvesters and collection methods there was variability in the efficiency and effectiveness of chaff collection, grain cleaning, and material separation. However, the mechanisms were optimized as much as possible at each location. Harvest was conducted by treatment where maturities differed. Similar to swathing, harvest height varied by crop, presence of lodging, etc., but was typically at a maximum of approximately 15 cm. Desiccation was allowed in the straight-cut treatments if required, particularly for fababeans; however, application was limited to saflufenacil [Heat LQ, 49.9 g ai ha^{-1}, with 494 mL ha^{-1} Merge (both products: BASF Canada, Mississauga, ON), water volume as per label recommendation, nozzles and pressures site and equipment dependent]. Glyphosate applications were not permitted to prevent reductions in wild oat seed viability. However, saflufenacil was erroneously considered as a contact herbicide, which is why its use was permitted. It is possible that because saflufenacil is systemic, there may have been some impacts on wild oat seed viability. Harvest and desiccation dates were recorded by site (Table 3). Grain yield and chaff weight were determined. Wild oat numbers in the chaff were quantified by using sieves, wind cleaners, and hand picking wild oat from the subsample. In the first year, both the full plot chaff sample was analyzed, as well as a subsample. Based on a preliminary analysis of that data across all locations, subsamples of chaff were found to be adequate and were used to quantify wild oat densities in chaff in subsequent years. Wild oat was collected and counted from chaff samples in 2016 and 2017.

Seedbank samples of wild oat were collected in 2018 after the final harvest using a 10-cm-diam soil corer to a depth of 5 cm. Cores were collected as soon as possible after combining in 2018 to limit loss of seeds to fall germination or predation. An extended “W” sampling pattern was used across each plot, and 12 cores per plot were combined. Samples were dried at a maximum temperature of 30 C for 5 to 7 d. Samples were passed twice through an 8-mm sieve to remove straw and rocks. The soil sample was then washed through a 1-mm sieve to collect wild oat seeds, which were then dried and counted.

Statistical Analysis

Data were analyzed using the Glimmix procedure in SAS (v. 9.3) and SAS Studio (SAS Institute Inc., Cary, NC). Error distribution

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Figure 1. Examples of chaff collection systems used on different plot combines in the study conducted from 2016 to 2018 to investigate crop rotation maturity, harvest management and harvest weed seed control effects on wild oat populations. Each combine has unique chaff and straw spreading setups and so each chaff collection system was unique to individual locations. These are three examples of systems used in this study.

selection, and ensuring data met the assumptions of ANOVA, was conducted through an examination of the residuals for normality and homogeneity of variance. Fixed effect variables were cropping rotation and harvest management system, and their interaction. Site-year (location * year) and replicate nested in site-year were random effects. A post hoc multiple comparison of means was conducted using Tukey's HSD test and significance was evaluated with a value of $\alpha = 0.05$. Additional analyses were conducted by site-year with the fixed effect variables remaining the same and replicate used as the random effect. By site-year analyses were included when site-year was tested as a fixed effect in preliminary analyses, site-year or its interaction with other fixed effects were significant in all cases. Individual site-year analyses allow us to examine the variability between sites, while the across-site-year analysis (site-year is random) allows an overall understanding of the trends that were occurring. Variables analyzed as above include wild oat density, biomass and seedbank in 2018, as well as wild oat density in chaff in 2016 and 2017, and crop yield in all years. A Poisson distribution with a Log link function was used for analysis of wild oat density in chaff, and wild oat seedling density, while a Gaussian distribution was used for wild oat biomass and crop yield. When non-Gaussian distributions were used in analysis, data and standard errors are presented on the original data scale through use of inverse link functions.

A repeated-measures analysis was conducted with the Glimmix procedure on wild oat density to examine population changes over time. A Poisson distribution was used. The year factor was specified as random (because data were collected repeatedly over years), the plot designated as the subject, the autoregressive (1) covariance structure used, and the residual option invoked. Replicates were considered random variables specifying the compound symmetry structure. Data and standard errors are presented on the original data scale through use of inverse link functions. Post hoc comparison of means were performed as described above.

Results and Discussion

Wild oat densities across sites in 2018 were affected by both treatment factors (crop rotation maturity and harvest management) and their interaction ($P < 0.0001$), resulting in the lowest densities in the early maturing rotation regardless of harvest management (Figure 2A). The highest densities were found in the straight cut treatment of the late-maturing rotation (Figure 2A). Regardless of the harvest management system, the early maturing rotation wild oat density was less than 50% of the density in the other rotations. The interaction of crop rotation maturity and harvest management system was significant at all locations except Lacombe ($P = 0.1577$), where only the individual factors were significant ($P < 0.0001$). At the three locations where the early maturing crop rotation was completed, densities were lowest or among the lowest in the early maturing rotation (Figure 2, B–D). The effect of swathing vs. straight cutting in that rotation at all three locations was variable. In Scott, where the early maturing rotation did not survive due to winterkill of the winter wheat, the lowest densities were found in the normal maturing rotation compared to the late, with no difference between the swathing and straight cutting treatments (Figure 2E). Across sites (Figure 2A), in both the normal and late-maturing cropping rotations, wild oat densities were lower in the treatments when swathing was used for harvest management. However, this effect is clearly quite variable when investigating the by-site results, which vary greatly between rotations (Figure 2, B–E).

Wild oat biomass trends were similar to those of wild oat densities; however, across sites, only rotational maturity and harvest management were significant as individual factors ($P < 0.001$, and $P = 0.004$, respectively), while their interaction was not ($P = 0.696$). When comparing rotations alone, wild oat biomass was lowest in the early maturing rotation, and it was equivalent between the normal and late-maturing rotations across sites (Figure 3A). Wild oat biomass was lower in treatments when

Table 3. Harvest and desiccation dates by treatment at each site-year.[a]

	Harvest date by treatment					
	Early	Normal	Late	Early	Normal	Late
Site year	Swath			Straight Cut		
Beaverlodge 2016	August 16	September 6	September 9	September 12	September 13	November 17[b]
Beaverlodge 2017	August 16	August 29	August 26	August 21	September 27	November 27
Beaverlodge 2018	August 15			September 5		
Carman 2016	August 15	August 24	September 14	September 2	September 2	November 9
Carman 2017	July 20	August 25	September 21	August 10	September 5	October 5
Carman 2018	July 24			August 17		
Lacombe 2016	August 25	August 30	September 19	September 6	September 14	November 4[c]
Lacombe 2017	August 16	August 25	September 2	August 23	September 8	September 18
Lacombe 2018	August 18			September 4		
Scott 2016	August 4	August 16	August 31	August 16	August 29	September 6
Scott 2017	N/A	August 18	August 28	N/A	September 5	September 11
Scott 2018	August 14			August 22		

[a]These dates describe differences in the treatments used to investigate cropping rotation maturity, harvest management, and harvest weed seed control effects on wild oat populations between 2016 and 2018.
[b]Dessication occurred on September 13.
[c]Dessication occurred on September 26.

preceding crops had been swathed compared to straight cut (Figure 3A). The lowest overall biomass was found in the early rotation, swathed treatment. At individual sites, the trends were not as distinct. In Beaverlodge, there was no significant effect on rotational crop maturity, harvest timing, or their interaction (P = 0.0932, 0.7767, and 0.5005, respectively). It is worth noting that the lowest biomass, however, occurred with the early maturing swathed treatment (Figure 3B). In Carman, only the cropping rotation maturity was significant (P < 0.0001), whereas harvest management (P = 0.0692) and the interaction of rotation maturity (P = 0.6471) were not. Biomass was approximately 50% lower in the early maturing rotations than normal and late-maturing rotations (Figure 3C). While harvest management was not significant, wild oat biomass tended to be lower in the swathed treatments (Figure 3C). In Lacombe there was a significant effect of rotational maturity (P = 0.0081) and harvest management (P = 0.0005), but not of their interaction (P = 0.9491). Wild oat biomass was greatest in the normal maturity rotation, while it did not differ in the early and late rotations (Figure 3D). Biomass was also lower in the swathed treatments. In Scott, no significant effect of any treatment factors on wild oat biomass was observed (Figure 3E).

Wild oat plant densities are expected to be proportional to the size of the seedbank; however, this may not be the case with seasonal influences potentially dramatically increasing or decreasing the proportion of dormant seed. If wild oat remains dormant in the seedbank, the emerged population may not reflect the seedbank size. Most wild oat seeds will emerge or expire after 4 to 5 yr, with a small percentage remaining dormant for up to 10 yr (Beckie et al. 2012). In this study, the seedbank densities were reflective of aboveground observations. Across sites, only crop rotation maturity affected seedbank densities (P < 0.0001), with the lowest density occurring in the early maturing rotations, followed by the normal maturing rotations, and finally, the late-maturing rotations (Figure 4A). Wild oat seedbank density in the early maturing rotation averaged >7,500 seeds m^{-2}, which was just more than half of the wild oat seeds measured in the late-maturing rotation (>14,000 m^{-2}). This is a similar seedbank reduction scale to that measured in rotational studies of the effect of implementing or omitting herbicide usage in rotation (Gulden et al. 2011), and shows the importance of crop maturity and rotation to success in managing wild oat. It is also interesting to note that in this study, the reduction occurred in the early maturing treatment that included HWSC, but no herbicides were applied. It is likely that if wild oat herbicides had been included in the study, the presence or absence of the herbicide would be the overwhelming influence on the wild oat seedbank (Gulden et al. 2011); however, a reduction in seedbank density by half indicates that the treatment combination used in this study, if added to a herbicide management program, could help reduce wild oat populations. At three out of four individual sites cropping rotation was also the only treatment factor that affected densities (P = 0.0272, 0.0007, and 0.0014 at Beaverlodge, Lacombe, and Scott, respectively) with the early maturing rotation having the lowest seedbank densities, or equivalent to the normal maturing rotations, with the highest densities found in the late-maturing rotations (Figure 4, B, D, and E). At Carman there was an interaction of rotational maturity and harvest management (P = 0.0147), which was evident in the different response in the late-maturing rotation in which the swathed treatment resulted in far lower seedbank densities than the straight cut treatment (Figure 4C). It is unclear why such a different response was observed at that site-year for that treatment combination in comparison to the other three locations. Aside from that outlier, there is a trend that generally supports the hypothesis that early maturing crops combined with HWSC provided greater suppression of the wild oat population.

The repeated-measures analysis conducted on wild oat densities begins to provide some insights into what aspects of the early maturing treatments are resulting in increased success of wild oat management (Figure 5). Populations in the first year were all quite similar, which would be expected from supplemented wild oat populations at the start of the trial. Treatment effects began to emerge in the second season, with the lowest wild oat densities observed in the normal maturing rotations (Figure 5). In the final year, separation occurred, with the early maturing rotations exhibiting lower densities than all but the swath treatment in the late-maturing rotation. It is important to note that densities did increase in all treatments tested, bearing in mind that herbicides were not included as a management component in this study. The trend in densities between years suggests potential links between the crops being used within and between the different rotations, and the successful management of wild oat populations. For

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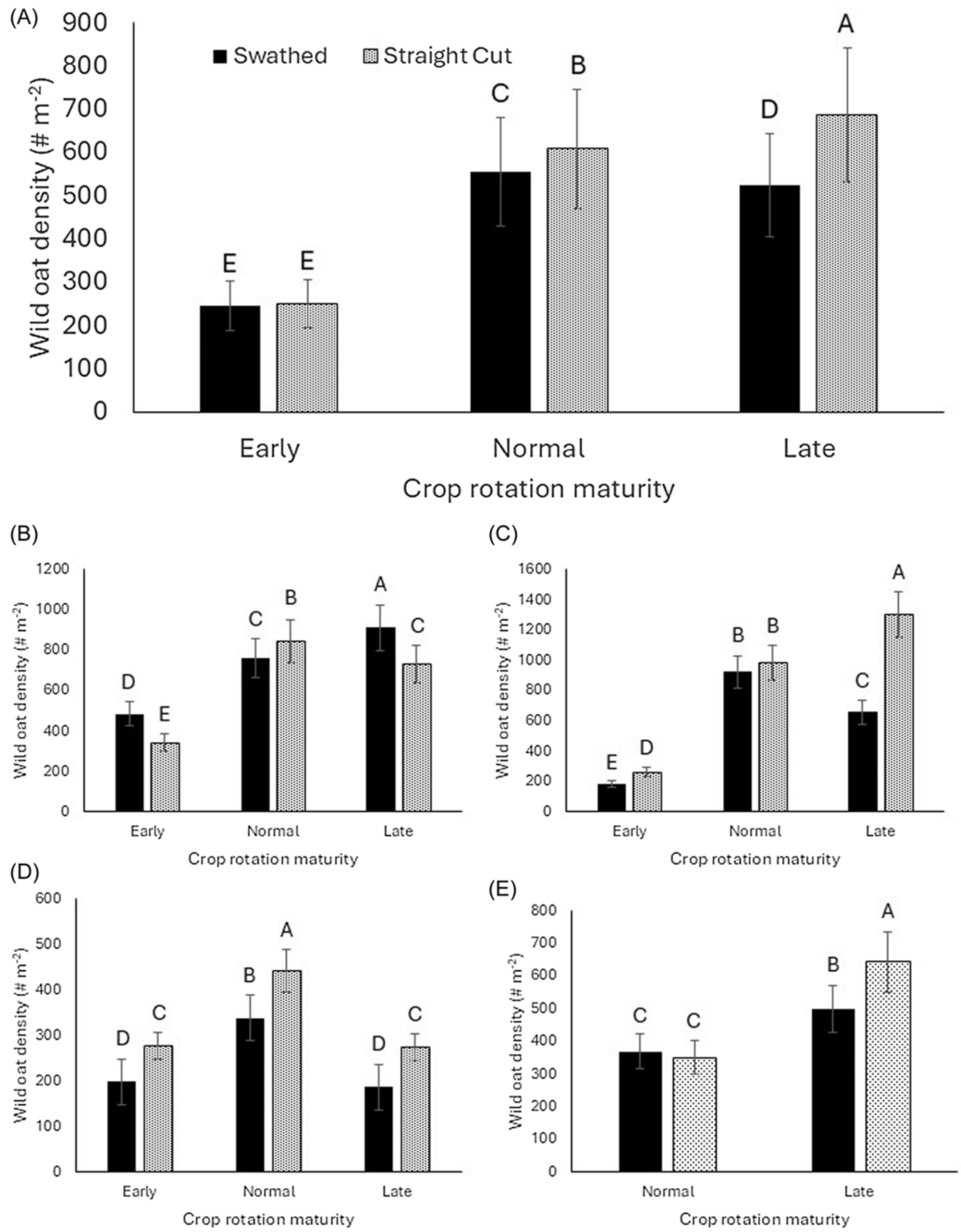

Figure 2. Wild oat plant density in the final year (2018) of the study examining the effects of crop rotation maturity, harvest management, and harvest weed seed control on wild oat populations. Black bars are the swathed harvest management system; patterned bars are the straight cut harvest management system in each rotation. Treatments with different letters indicate significant differences based on post hoc comparison of means using Tukey's HSD with a value of $\alpha = 0.05$. Error bars indicate standard errors of the means. A) Across sites, B) Beaverlodge, C) Carman, D) Lacombe, E) Scott.

example, within the early maturing rotation the winter wheat phase provided more successful management than the pea phase. Similarly, between rotations, the winter wheat provided quite successful wild oat management, whereas less success was observed with the flax and canola in the second year of the late and normal rotations, respectively. Some of the variation in success is likely related to the competitiveness of various crops (Dew 1972; Harker et al. 2016; Kurtenbach et al. 2019), as well as the relative time of emergence of the winter wheat compared to wild oat (Harker et al. 2016; O'Donovan et al. 1985).

The density of wild oat seeds collected in crop chaff at harvest in 2016 and 2017 was affected by crop rotation maturity, harvest management strategy, and their interaction ($P < 0.0001$ for all three variables in both years) across sites (Table 4). In 2016, across sites, the highest number of wild oats were collected in chaff from early, swathed treatment of pea, which aligns with the hypothesis that earlier maturing crops in combination with swathing may increase the proportion of seed retained for potential targeting with an HWSC treatment. However, the second highest number of wild oat seeds were collected in the late maturing, straight cut fababean treatment, which had been expected to have the fewest wild oat seeds. In 2017, the greatest number of wild oat seeds was found in chaff from the straight cut, normal maturing canola treatment, and lowest in the swathed, late-maturing flax treatment (Table 4). Within each site-year there was a significant amount of variation and very little consistency to the pattern of where greater numbers of wild oat seeds were collected in the chaff. In some site-years, the early maturing rotations produced the greatest number of wild oat

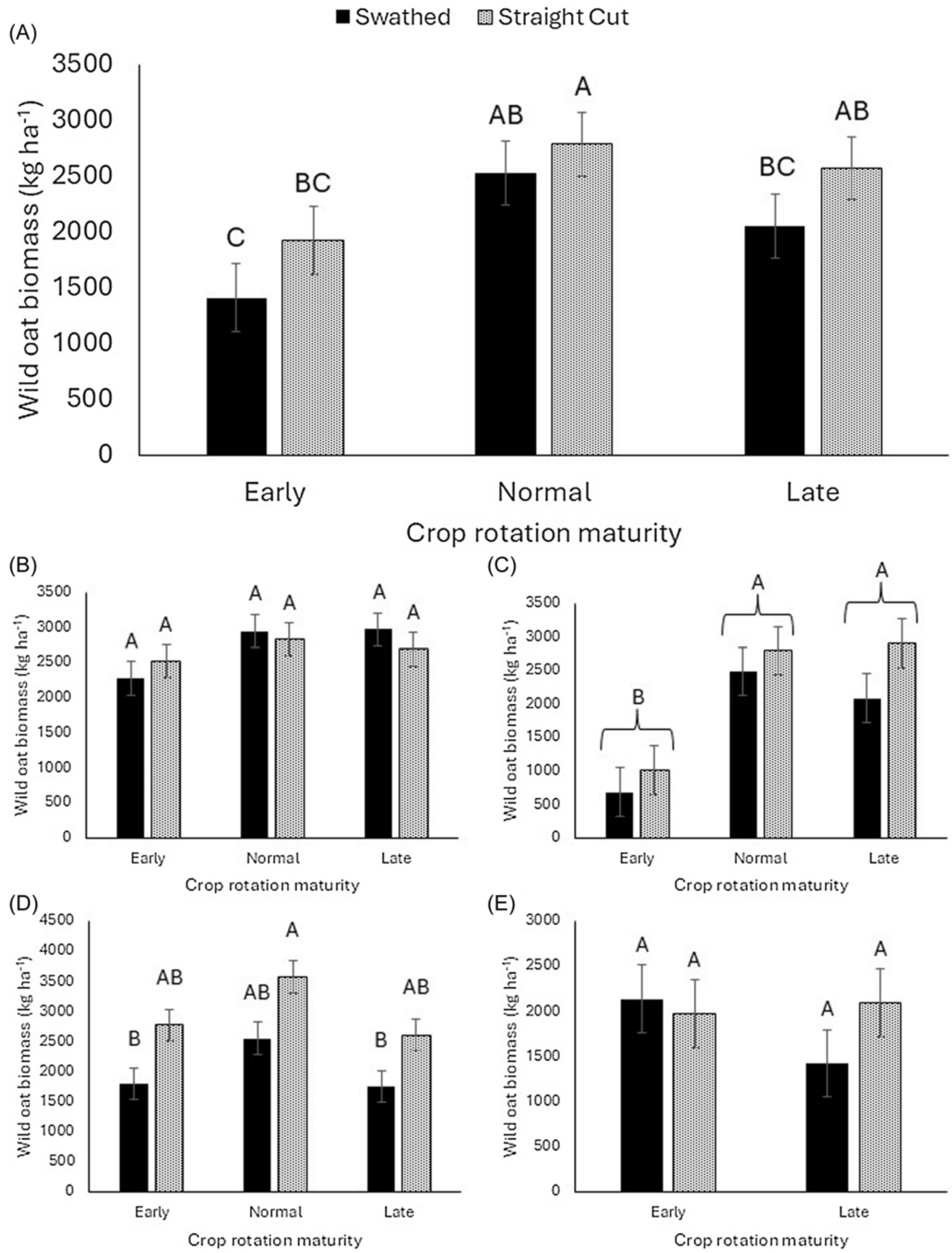

Figure 3. Wild oat biomass in the final study year (2018) as affected by crop rotation maturity and harvest management. Treatments with different letters indicate significant differences based on post hoc comparison of means using Tukey's HSD with a value of $\alpha = 0.05$. Brackets over a crop rotation indicate that only cropping rotation was significant, harvest management was not. Error bars indicate standard errors of the means. A) Across sites, B) Beaverlodge, C) Carman, D) Lacombe, E) Scott.

seeds, while other site-years they produced the lowest densities, and in the remaining site-years there was no difference in the number of wild oat seeds collected compared to other treatments. Similarly, in Beaverlodge in 2016, swathing resulted in more wild oat seeds being collected than straight cut treatments; however, in Scott in 2017, the opposite was true. Several factors may have played into the variability in the number of wild oat seeds found in the chaff, including variable weather, efficiency of the chaff collection devices, differences in combine settings between crops, and unidentified seed losses. Variable weather events such as early snowfall in 2016 in Lacombe, which could cause late-season tillering, or drought in Carman in 2017, which would have reduced competitiveness of the spring crops, could affect wild oat seed availability for collection at harvest (Table 2). Differences in wild oat densities in chaff by site (seed densities were low in Lacombe, but they were higher in Scott) could be related to the effectiveness of the chaff collection devices designed for each site's equipment. Recent observations have indicated that some weed seeds are lost to the straw or collected with the grain sample, while others are lost at the combine header (Winans et al. 2023), which would also lead to variability in the density of wild oat seedsbeing collected. Combine settings (sieve settings, rotor speed, wind speed, etc.) would affect losses to these various pathways. Overall, it becomes clear that while early maturing rotations are important, the variable data reported here do not allow us to conclude that the importance is related to increased wild oat capture by HWSC in early maturing rotations. Subsequent studies aiming to document the effects of shifting crop maturities to improve seed capture should determine

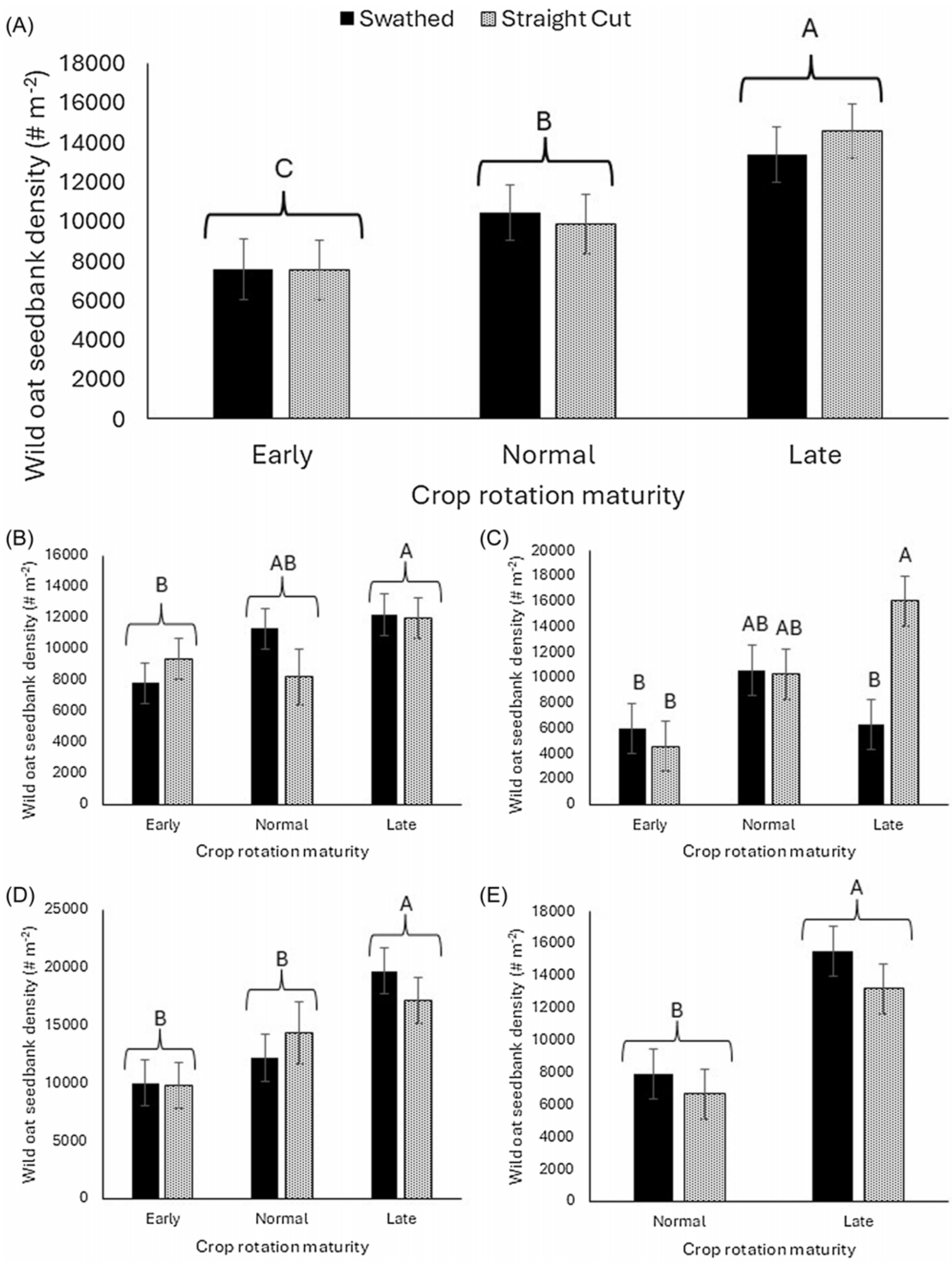

Figure 4. Wild oat seedbank densities as affected by crop rotation maturity and harvest management, measured in 2018. Treatments with different letters indicate significant differences based on post hoc comparison of means using Tukey's HSD with a value of α = 0.05. Brackets over a crop rotation indicate that only cropping rotation was significant, harvest management was not. Error bars indicate standard errors of the means. A) Across sites, B) Beaverlodge, C) Carman, D) Lacombe, E) Scott.

seed production, preharvest shedding, during harvest seed losses (header and straw loss), weed seed collected in the grain tank, and weed seed in the chaff fraction to identify the influence of HWSC on the fate of wild oat seed.

In the absence of strong evidence for improved efficacy of HWSC in early maturing rotations, crop yields provide some explanation for the operative factors that might be reducing wild oat populations. Yields in 2016 and 2017 were affected by crop rotation ($P < 0.0001$), which essentially indicated that differences existed in yields between crop types, as would be expected from the growth of those crop types (Figure 6). The winter wheat yields in 2017 are far higher than yields from the spring annual crops in the other rotations (Figure 6B). This coincides with significant separation in wild oat densities in the subsequent year (Figure 5), which suggests that the winter wheat was highly competitive with wild oat populations. Some of this competitive advantage likely stems from drought conditions that occurred at two out of the three locations where winter wheat was grown in the 2017 growing season (Table 2). The winter wheat emerged and grew before the drought intensified, while the spring annual crops suffered from limited available moisture, which reduced their competitive ability. In the final year of the study, when all rotations were in barley, there was no significant effect of any of the fixed effect variables on crop yield (Figure 6C), suggesting that the wild oat density differences observed (Figures 2 and 5) likely resulted from competitive impacts of the preceding winter wheat crop, and

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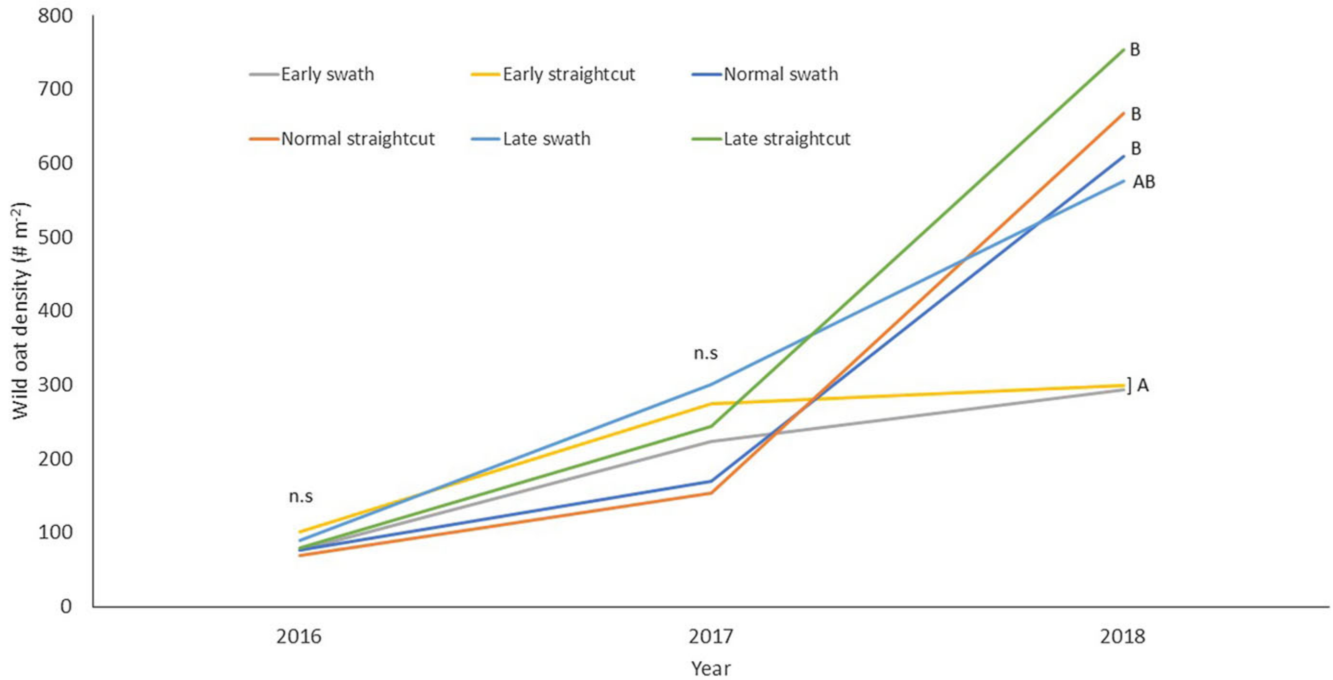

Figure 5. Wild oat population densities over time in each of the six treatments included in the crop rotation maturity, harvest management and harvest weed seed control effect on wild oat populations study. Post hoc comparison of means within each year used Tukey's HSD with a value of $\alpha = 0.05$. "n.s." indicates no significant differences. Treatments followed by different letters indicate significant differences.

not variability in the barley crop in that year. These trends are essentially maintained when assessing individual location yields (Table 5). Wheat was the highest-yielding crop at all locations in 2016, while in 2017, winter wheat significantly outyielded both crops grown in the other rotational treatments. The difference between the competitiveness of the winter wheat and the spring annual crops likely played a prominent role in the effect of the cropping rotation maturities on wild oat populations.

The early maturing crop rotation combined with HWSC resulted in the smallest wild oat populations, indicating the potential for highly effective integrated weed management of this species when these tactics are combined, and effective herbicides are used. Winter cereals can provide a competitive advantage compared to spring annuals in managing wild oat (Harker et al. 2016, Tidemann et al. 2023). This competitive advantage can be weakened if winter cereals do not successfully establish and overwinter (Beres et al. 2016; Harker et al. 2016, O'Donovan et al. 2005). Full winterkill, as occurred in Scott in 2017, is a rare event; however, winterkill resulting in poor stand establishment, and, therefore reduced crop competition, is common and can result in suboptimal management of the wild oat. While the winter wheat in this study was highly competitive relative to the spring-seeded crops in the second year of the rotations, the other crop phase in that rotation was pea, a relatively noncompetitive crop (Harker 2001), and yields were numerically the lowest for that crop in the first rotational year. Crops were intentionally chosen to try to balance highly competitive crops in the rotation so that no rotation was exceptionally competitive. It is impossible to portion out the benefit of the early maturing rotation between the competitiveness of the crops and the increased ability for HWSC, but it is likely a combination of both these factors that resulted in decreased wild oat populations in those treatments. While wild oat seed retention is typically low at harvest (Burton et al. 2016, 2017; Shirtliffe et al. 2000, Tidemann et al. 2017), studies on wild oat phenology indicate that the harvest of early maturing crops would occur when there were higher levels of wild oat seed retention compared to the timing of harvest of normal- or late-maturing crops. Increased capture of wild oat seed prevents seedbank inputs and would contribute to reduced populations (Tidemann et al. 2016). The wild oat numbers collected in the chaff in this study do not indicate that this is occurring; however, challenges and gaps in the methodology have been identified above. Harvest management showed a more limited impact compared to rotation on wild oat populations. Where there were effects, swathing generally had a more positive impact on managing wild oat than straight cutting. This may be a result of the plants being terminated and formed into a swath or windrow earlier in a plant's reproductive development phase when more seed was retained on the plant (Harker et al. 2003; Tidemann et al. 2017). Additionally, wild oat in the swath would be more protected from windy conditions that would likely increase seed shatter, because wild oat panicles tend to be above the crop canopy and exposed to those conditions. These factors would again increase wild oat seed availability for HWSC strategies.

Practical Implications

This study demonstrates that early maturing crops alone can significantly improve the management of wild oat, likely due to a combination of crop competitiveness and relative time of emergence. Within each crop rotation maturity, there are options for more competitive crops; choosing competitive crops can be beneficial for the management of wild oat (Dew 1972). Major challenges in the adoption of earlier maturing crops, which are typically fall-seeded crops such as winter wheat, include the risk of poor establishment and winterkill (Beres et al. 2016; Harker et al. 2016; O'Donovan et al. 2005), limited markets for some early

Table 4. Wild oat seed numbers in chaff samples collected during grain harvest at each location and averaged across sites.[a,b,c]

Year	Crop (rotation)[d]	Harvest management	Beaverlodge		Carman		Lacombe		Scott		Across sites	
			No. m–2									
2016	Pea (early)	Swathed	136 (24)	Ba	272 (14)	B	48 (4)	C	867 (81)	A	240 (116)	A
		Straight cut	114 (20)	Bb	293 (15)	B	41 (4)	C	765 (71)	B	221 (107)	BC
	Wheat (normal)	Swathed	187 (33)	Aa	581 (27)	A	40 (4)	C	157 (16)	C	175 (85)	D
		Straight cut	141 (25)	Ab	190 (11)	C	23 (3)	D	172 (17)	C	94 (46)	E
	Fababean (late)	Swathed	82 (15)	Ca	277 (14)	B	98 (7)	B	723 (67)	B	214 (104)	C
		Straight cut	68 (12)	Cb	312 (16)	B	141 (9)	A	750 (70)	B	230 (111)	AB
2017	Winter wheat (early)	Swathed	308 (66)	A	22 (4)	E	70 (10)	A	N/A		167 (71)	C
		Straight cut	237 (51)	B	9 (2)	F	57 (8)	AB	N/A		127 (54)	E
	Canola (normal)	Swathed	115 (25)	C	662 (90)	B	70 (10)	A	197 (34)	Bb	207 (88)	B
		Straight cut	52 (11)	D	751 (102)	A	46 (7)	B	433 (74)	Ba	253 (108)	A
	Flax (late)	Swathed	109 (24)	C	88 (13)	D	67 (10)	A	260 (45)	Ab	104 (44)	F
		Straight cut	15 (4)	E	116 (17)	C	14 (3)	C	566 (97)	Aa	141 (60)	D

[a]Treatments with different letters indicate significant differences based on post hoc comparison of means using Tukey's HSD with a value of $\alpha = 0.05$.
[b]For sites where two letters appear, the uppercase letter is a comparison between crops, and the lowercase letter is the comparison between harvest management.
[c]Standard errors of the mean appear in parentheses.
[d]The crop is listed with the crop rotation maturity it belongs to also listed in parentheses.

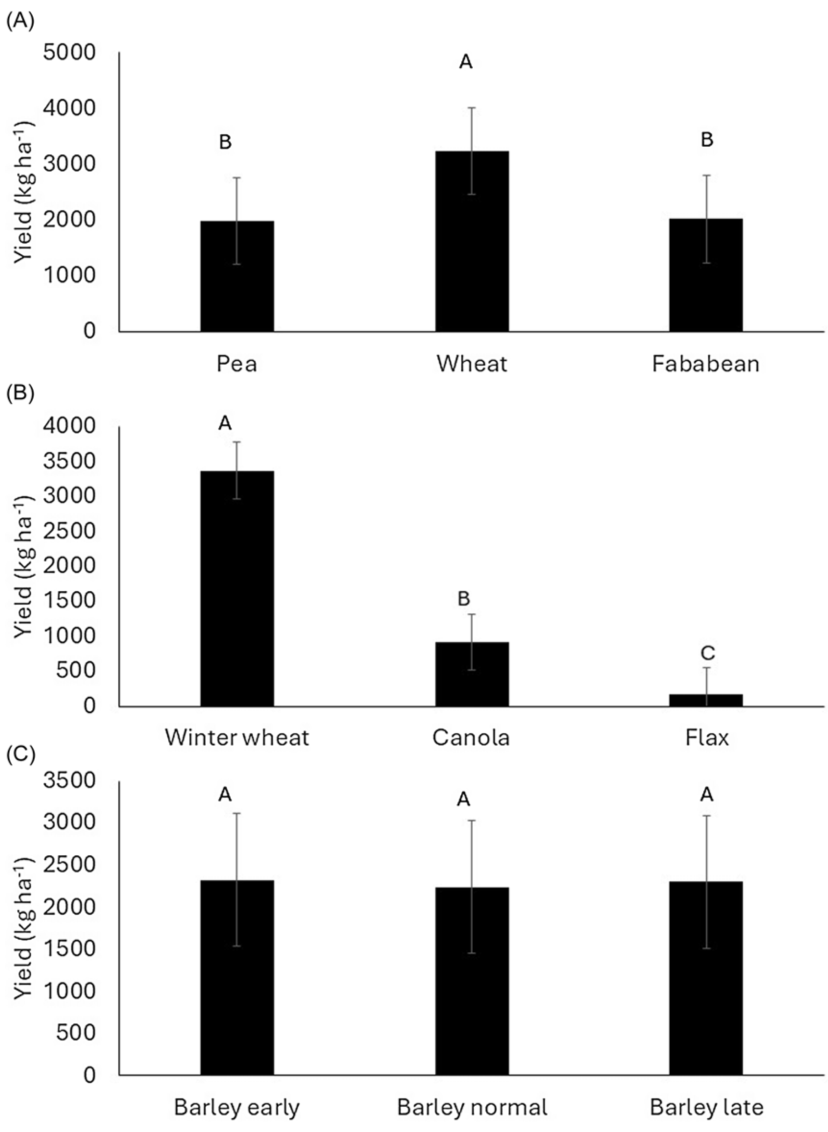

Figure 6. Crop yield in A) 2016, B) 2017, and C) 2018. Treatments with different letters indicate significant differences between treatments within that year based on post hoc comparison of means using Tukey's HSD with a value of $\alpha = 0.05$. Error bars indicate standard errors of the means. The leftmost bar in each graph represents the yield from the crop that was grown in the early maturing rotation, the center bar represents yields from the normal maturing rotation, and the righthand bar represents yields from the late maturing rotation.

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Table 5. Crop yields in each year at each location.[a,b,c]

Year	Crop (rotation)[d]	Harvest management	Beaverlodge		Carman		Lacombe		Scott	
			kg ha^{-1}							
2016	Pea (early)	Swathed	3,112 (276)	B	289 (62)	B	2,508 (246)	B	1,608 (164)	B
		Straight cut							2,451 (164)	A
	Wheat (normal)	Swathed	4,375 (276)	A	1,326 (67)	A	5,002 (246)	A	2,043 (164)	AB
		Straight cut							2,323 (164)	AB
	Fababean (late)	Swathed	2,787 (276)	B	493 (62)	B	4,402 (246)	A	462 (164)	C
		Straight cut							313 (164)	C
2017	Winter wheat (early)	Swathed	1,596 (176)	A	3,151 (274)	A	5,586 (208)	A	N/A	
		Straight cut					5,126 (208)	A		
	Canola (normal)	Swathed	795 (176)	B	3.7 (274)	B	1,425 (208)	BC	1,037 (106)	A
		Straight cut					2,222 (208)	B		
	Flax (late)	Swathed	192 (176)	C	4.4 (274)	B	293 (208)	D	24 (106)	B
		Straight cut					574 (208)	CD		
2018	Barley (early[e])	Swathed	2,183 (162)	A	771 (81)	B	5,188 (161)	A	N/A	
		Straight cut					4,260 (161)	B		
	Barley (normal)	Swathed	1,882 (170)	AB	1,160 (81)	A	5,100 (161)	A	1,836 (115)	
		Straight cut					3,061 (161)	C		
	Barley (late)	Swathed	1,607 (162)	B	1,373 (81)	A	5,124 (161)	A	1,270 (115)	
		Straight cut					4,787 (161)	AB		

[a]Treatments with different letters indicate significant differences based on post hoc comparison of means using Tukey's HSD with a value of $\alpha = 0.05$.
[b]Cells that are combined across the Swathed and Straight Cut treatments indicate that only cropping system maturity had a significant effect on yield.
[c]Standard errors of the mean appear in parentheses.
[d]The crop is listed with the crop rotation maturity it belongs to also listed in parentheses.
[e]The cropping system rotation here indicates only the preceding crops. Barley was seeded across the trials and matured and was harvested at the same time.

maturing crops like fall rye, and logistical challenges around overlap in seeding and harvest operations. However, wild oat management can be improved if these risks and challenges can be addressed. This study did not include the use of herbicides for wild oat control and increased wild oat densities, including in the earliest maturing treatments, highlighting the importance of using herbicides in the ongoing management of wild oat populations in Canadian Prairie cropping systems. The early maturing rotations combined with HWSC used here were inadequate; however, with the addition of other integrated weed management tactics such as increased seeding rates, use of crop silage, and herbicide applications, if required, it is likely that these populations could be managed effectively (Harker et al. 2016; Tidemann et al. 2023). Additionally, reduced wild oat populations from the use of early maturing crops and HWSC would result in reduced selection pressure for additional forms of herbicide resistance (Gressel and Levy 2006; Norsworthy et al. 2012). In addition to lower densities, use of HWSC when the highest number of wild oat seeds are available for management could result in reduced spatial spread of wild oat across farmer fields (Shirtliffe and Entz 2005). Similar to the way that herbicides provide the largest benefit for less-competitive crops (Gulden et al. 2011), it is likely that HWSC to control wild oat will show the most significant benefit in early maturing crops, although we could not document the effect in this study. Harvest management that cuts the wild oat as soon as possible (i.e., by swathing) may provide an incremental benefit within a crop type or to a rotational change. Canadian farmers have a unique ability to use relative time of emergence and relative time of maturity compared to other regions. When weeds are being targeted in winter cereals in some areas of the United States, for example, few options exist for improving the relative time of emergence of the crop compared to the weed's emergence other than selecting an alternative rotational crop, but few earlier maturing crops exist. Since spring annuals dominate western Canadian rotations, a unique opportunity exists to incorporate early maturing spring annuals or winter cereals with HWSC to improve wild oat management.

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Competing Interests. The authors declare they have no competing interests.

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