This is a “preproof” accepted article for Weed Science. This version may be subject to change in the production process, *and does not include access to supplementary material*.
DOI: 10.1017/wet.2025.14

Short title: Rotations for harvest weed seed control

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

Breanne D. Tidemann[1], K. Neil Harker[1], Robert H. Gulden[2], Greg Semach[3], Cindy Gampe[4], Larry Michielsen[1], Patty Reid[1], Elizabeth Sroka[1], Jennifer Zuidhof[1]

[1] Research Scientist (ORCID 0000-0002-1070-2044), Retired Research Scientist, and Research Technicians, Agriculture and Agri-Food Canada, Lacombe Research and Development Centre, Lacombe, AB, T4L 1W1

[2] Professor, University of Manitoba, Department of Plant Science, Winnipeg, MB, R3T 2N2

[3] Research Biologist, Agriculture and Agri-Food Canada, Beaverlodge Research Farm, Beaverlodge, AB, T0H 0C0

[4] Research Technician, Agriculture and Agri-Food Canada, Scott Research Farm, Scott, SK, S0K 4A0

Author for Correspondence: Breanne D. Tidemann; Email: Breanne.tidemann@agr.gc.ca

Wild oat is a significant weed of cropping systems in the Canadian Prairies. Wild oat resistance to herbicides has increased interest in non-chemical 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 impacts of crop rotation maturity, harvest management and harvest weed seed control on wild oat, a study was conducted from 2016-2018 at four locations in the Canadian Prairies. Two-year crop rotations with either early, normal, or late-maturity 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 in an attempt 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 biomass was lower in swathed crops than in straight-cut crops. Wild oat seedbank levels reflected a similar trend with the lowest densities in early maturing rotation, then the normal maturity rotation and the late maturing rotation 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 impact in earlier maturing crops.

Nomenclature: Wild oat, *Avena fatua* L.; barley, *Hordeum vulgare* L.

Keywords: chaff collection; crop rotation; diverse crop maturity; seed retention; harvest timing; integrated weed management; crop competitiveness

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 as 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 – 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 resistant to the pre-seeding (PRE) herbicide, triallate in Alberta (Heap 2024). Wild oat resistance to foliar, or post-seeding (POST) 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, Herbicide Resistance Action Committee (HRAC) Group 1 (Acetyl Co-A Carboxylase inhibitor) and Group 2 (Acetolactate synthase inhibitor) resistant biotypes of wild oat 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 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 POST herbicide options are limited to the extent that none may be available, forcing a shift to PRE, soil-applied herbicides. These products are difficult for producers to use because 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 only registered for suppression of wild oat, not control. These factors have increased the need for integrated weed management strategies. Many integrated weed management strategies have been investigated for wild oat in western Canada (Harker et al. 2003; Harker et al. 2009; Harker et al. 2016; O'Donovan et al. 2013). However, many of these strategies require rotational changes in cropping systems or utilizing 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 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 Australian producers (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 utilized in Saskatchewan (Tidemann et al. 2024). For the early adopters, wild oat was the most commonly 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; Burton et al. 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 two-year canola (*Brassica napus* L.) – wheat (*Triticum aestivum* L.) rotation. In Saskatchewan, a three-year 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 be later maturing crops. Since there is a range of crop

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

maturities available, this study aimed to determine the efficacy in managing wild oat populations with combinations of HWSC with i) earlier maturing crops and ii) 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.

Materials and Methods

A three-year study was conducted with field trials at four locations, Lacombe and Beaverlodge, Alberta (AB), Scott, Saskatchewan (SK), and Carman, Manitoba (MB) from 2016 to 2018. 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 three-year rotational cropping system, and the presented results, where applicable, show the cumulative effects of the cropping system treatments after those three years. 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. The trial site wild oat populations were supplemented by broadcasting 200 seeds m^{-2} across the trial area. Fungicides and insecticides were applied as required to deal with disease and pest pressures. Herbicide treatments were applied as required to control broadleaf weeds only. Site soil characteristics and environmental conditions were recorded

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

(Table 2), and the varieties of each crop used were allowed to vary by site so that regionally appropriate crop varieties could be utilized. 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 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 1 to 3 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 utilizing 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 utilized 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 15cm. 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 since saflufenacil is systemic, there may have been some impacts on wild oat seed viability. Harvest and desiccation dates were recorded

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

by site (Table 3). Grain yield and chaff weight were determined. Wild oat numbers in the chaff were quantified by utilizing 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 were 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 diameter 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 days. Samples were passed twice through an 8 mm sieve to remove straw and rocks. The soil sample was then washed through a 1mm sieve to collect wild oat seed, which were then dried and counted.

Statistical Analysis

Data were analyzed using Proc Glimmix in SAS 9.3 and SAS Studio (SAS Institute Inc., Cary, NC, USA). Error distribution selection, as well as 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 as well as 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 Honestly Significant Difference test and significance evaluated with α=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 as 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 look at the variability between sites, while the across site-year analysis (site-year is random) allows an overall understanding of the trends 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.

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

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 in Proc Glimmix on wild oat density to look at population changes over time. A Poisson distribution was utilized. The year factor was specified as random (as data was 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 done 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 where 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 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). Comparing rotations alone

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

wild oat biomass was lowest in the early maturing rotation and equivalent between the normal and late maturing rotations across sites (Figure 3A). Wild oat biomass was lower in treatments where 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, was in the early maturing swathed treatment (Figure 3B). In Carman, only the cropping rotation maturity was significant (p<0.0001), while harvest management (p=0.0692) and their interaction (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 highest in the normal maturity rotation, while the early and late rotations did not differ (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 remain dormant in the seedbank, the emerged population may not reflect the seedbank size. Most wild oat seeds will emerge or expire after four to five years, with a small percentage remaining dormant for up to 10 years (Beckie et al. 2012). In this study, the seedbank densities were reflective of above-ground observations. Across sites, only crop rotation maturity affected seedbank densities (p<0.0001) with the lowest density in the early maturing rotations, followed by the normal maturity rotations, and finally, the late maturing rotations (Figure 4A). Wild oat seedbank density in the early maturing rotation averaged over 7,500 seeds m^{-2}, just over half of the wild oat seeds measured in the late maturing rotation (over 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), showing 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 is from the early maturity treatment utilizing HWSC, but no herbicides were applied. It is likely that were wild oat herbicides

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

included in the study, the presence/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 utilized in this study, if added to a herbicide management program could help drive wild oat populations down. At three out of four individual sites cropping rotation was also the only treatment factor affecting 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 4B, D, E). At Carman there was an interaction of rotational maturity and harvest management (p=0.0147), clearly evident in the different response in the late maturing rotation where the swathed treatment showed far lower seedbank densities than in 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. In the second season treatment effects began to emerge, with the lowest wild oat densities observed in the normal maturity rotations (Figure 5). In the final year, separation occurred, with the early maturing rotations showing lower densities than all but the swath treatment in the late maturity rotation. It is important to note that densities did increase in all treatments tested, bearing in mind that herbicides were not an included 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 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 while 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

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

as the relative time of emergence of the winter wheat compared to wild oat (O'Donovan et al. 1985, Harker et al. 2016).

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 oat 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 a HWSC treatment. However, the second highest number of wild oat were collected in the late maturing, straight cut fababean treatment which had been expected to have the fewest wild oat seed. In 2017, the most wild oat seed were found in chaff from the straight cut, normal maturity canola treatment and lowest in the swathed, late maturity flax treatment (Table 4). Within each site year there was a significant amount of variation and very little consistency to the pattern of where increased wild oat seeds were collected in the chaff. In some cases the early maturing rotations allowed collection of the most wild oat seed, while in other cases they had the lowest densities, and in the remaining they were no different than the other rotations. Similarly, in Beaverlodge 2016 swathing resulted in more wild oat seed collected than straight cut treatments, however, in Scott 2017 the opposite was true. Several factors may have played into the variability of wild oat numbers 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 impact wild oat seed availability for collection at harvest (Table 2). Differences in wild oat densities in chaff by site (Lacombe had low densities, Scott had higher densities) could be related to the effectiveness of the chaff collection devices designed for each site's equipment. Recent work has 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 wild oat seed densities collected. Combine settings for different crops (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 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 trying to document the impact of shifting crop maturities to improve seed capture should determine seed production, pre-harvest shedding, during harvest seed losses (header and straw loss), and weed seed collected in the grain tank, as well as 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 reducing wild oat populations. Yields in 2016 and 2017 were affected by crop rotation ($p<0.0001$), which essentially indicated differences in yields between crop types, as would be expected from the growth of different crop types (Figure 6). The winter wheat yields in 2017 are far higher than yields of 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 the winter wheat was highly competitive with wild oat populations. Some of this competitive advantage likely stems from drought conditions experienced at two out of the three locations with winter wheat 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, reducing 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 (Figure 2 and Figure 5), likely resulted from competitive impacts of the preceding winter wheat crop, and not variability in the barley crop in that year. These trends are essentially maintained when looking at 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 utilized. 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

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

not successfully establish and over-winter (Beres et al. 2016; Harker et al. 2016, O'Donovan et al. 2005). Full winterkill, as was observed 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 sub-optimal 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 peas, a relatively non-competitive 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 the plants 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 as 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 work demonstrates that early maturing crops alone can significantly improve 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 like 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 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 herbicides' importance in the ongoing management of wild oat populations in Canadian Prairie cropping systems. It is clear that 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's likely 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 et al. 2005). Similar to how herbicides show the largest benefit in less competitive crops (Gulden et al. 2011), it is likely that HWSC for 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, there are few options to improve the relative time of emergence compared to the weed by selecting an alternative rotational crop, and there are few earlier maturing crops. Since spring annuals dominate western Canadian rotations, there is a unique opportunity to incorporate early maturing spring annuals or winter cereals with HWSC to improve wild oat management.

Acknowledgements

The authors gratefully acknowledge the technical support of Rebecca Dueck, and the assistance of numerous summer and co-op students.

Funding

Funding was provided by Alberta Canola through grant AFC2016F018R.

Competing Interests

The author(s) declare none.

References

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, 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

Beres BL, Tukrington TK, Kutcher HR, Irvine B, Johnson EN, O'Donovan JT, Harker KN, Holzapfel CB, Mohr R, Peng G, Spaner DM (2016) Winter wheat cropping system response to seed treatments, seed size, and sowing density. Agron J 108:1101-1111

Brown DA (1953) Wild Oats — Progress in cultural control. Weeds 2:295-299

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

Burton NR, Beckie HJ, Willenborg CJ, Shirtliffe SJ, Schoenau JJ, Johnson EN (2017) Seed shatter of six economically important weed species in producer fields in Saskatchewan. Can J Plant Sci 97:266-276

Desai HS, Mealled F, Seipel T, Shergill LS (2023) Harvest weed seed control: A potential non-chemical weed management tool for cereal and corn/soybean rotations in SE Montana. Proc Western Soc Weed Sci Vol. 76, 2023. ISSN: 0091-4487. Available at: https://wsweedscience.org/wp-content/uploads/WSWS-2023-Proceedings.pdf. Accessed June 13, 2024

Dew DA (1972) An index of competition for estimating crop loss due to weeds. Can J Plant Sci 52:921-927

Geddes CM, Pittman MM, Sharpe SM, Leeson JY (2024) Distribution, frequency and impact of herbicide-resistant weeds in Saskatchewan. Can J Plant Sci 104: 495-513. doi:10.1139/cjps-2024-0017

Gressel J, Levy AA (2006) Agriculture: The selector of improbable mutations. Proc Nat Acad Sci 103: 12215-12216

Gulden RH, Lewis DW, Forese 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 (2001) Survey of yield losses due to weeds in central Alberta. Can J Plant Sci 81:339-342

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, 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, Johnson EN, Pageau D, Shirtliffe SJ, Gulden RH (2016) Diverse rotations and optimal cultural practices control wild oat (*Avena fatua*). Weed Sci 64: 170-180

Heap I (2024) International Survey of Herbicide Resistant Weeds. Accessed April 25, 2024. Available online at: www.weedscience.org

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. Doi:10.2134/agronj2018.09.0593

Leeson JY (2016) Saskatchewan Weed Survey: Cereal, Oilseed and Pulse Crops 2014/15. Weed Survey Series Publication 16-1. Agriculture and Agri-Food Canada, Saskatoon, SK, Canada. 356 p

Leeson JY, Gaultier J, Grenkow L (2016) Manitoba weed survey of annual crops in 2016. Weed Surevey Series Publication 17-2. Agriculture and Agri-Food Canada, Saskatoon, SK, Canada. 203 p

Leeson JY, Hall LM, Neeser C, Tidemann B, Harker KN (2019) Alberta weed survey of annual crops in 2017. Weed Survey Series Publication 19-1. Agriculture and Agri-Food Canada, Saskatoon, SK, Canada. 275 p

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 Series Publication 05-1. Agriculture and Agri-Food Canada, Saskatoon, SK, Canada. 395 p

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60: 31-62

O'Donovan JT, Blackshaw RE, Neil Harker K, Clayton GW, McKenzie R (2005) Variable crop plant establishment contributes to differences in competitiveness with wild oat among cereal varieties. Can J Plant Sci 85: 771-776

O'Donovan JT, de St. Remy EA, O'Sullivan PA, Dew DA, Sharma AK (1985) Influence of the relative time of emergence of wild oat (*Avena fatua*) on yield loss of barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*). Weed Scie 33: 498-503. doi:10.1017/S0043174500082722

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

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

Shirtliffe SJ, Entz MH (2005) Chaff collection reduces seed dispersal of wild oat (*Avena fatua*) by a combine harvester. Weed Sci 53: 465-470

Tidemann BD, Geddes CM, Sharpe SM (2024) Early adopter insights on physical impact mill technology for harvest weed seed control in Canada. Can J Plant Sci 104: 485-494 https://doi.org/10.1139/cjps-2024-0015

Tidemann BD, Hall LM, Harker KN, Alexander BCS (2016) Identifying critical control points in the wild oat (*Avena fatua* L.) life cycle and the potential effects of harvest weed-seed control. Weed Sci 64: 463-473

Tidemann BD, Hall LM, Harker KN, 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

Tidemann BD, Hall LM, Johnson EN, Beckie HJ, Sapsford KL, Raatz LL (2014) Efficacy of fall-and spring-applied pyroxasulfone for herbicide-resistant weeds in field pea. Weed Technol 28: 351-360

Tidemann BD, Harker KN, Shirtliffe S, Willenborg C, Johnson E, Gulden R, Lupwayi NZ, Turkington TK, Stephens EC, Blackshaw RE (2023) Using integrated weed management systems to manage herbicide resistant weeds in the Canadian Prairies. Front Agron 5:1304741

Vigor, S.H. (1929) The weed situation in western Canada. Pages 4-10 *in* Proceedings of a Conference on the Destruction of Weeds by Means of Chemicals. Edmonton: National Research Council

Walsh MJ, Aves C, Powles SB (2017) Harvest weed seed control systems are similarly effective on rigid ryegrass. Weed Technol 31: 178-183

Walsh MJ, Broster JC, Schwartz-Lazaro LM, Norsworthy JK, Davis AS, Tidemann BD, Beckie HJ, Lyon DJ, Soni N, Neve P, Bagavathiannan MV (2018) Opportunities and challenges for harvest weed seed control in global cropping systems. Pest Manag Sci 74: 2235-2245

Winans T, Massey R, Schreier H, Bish M, Bradley KW (2023) Harvest weed seed control in soybean with an impact mill. Weed Technol 37: 113-122

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Tables

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 2016-2018 in the Canadian Prairies. Each row provides a description of all factors associated with a specific treatment.

			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

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Table 2. Site characteristics, including soil information, plot information, crop varieties and growing season precipitation for each location involved in the study on cropping system maturity, harvest management, and harvest weed seed control effect on wild oat populations from 2016-2018.

Site year	Soil texture	Soil organic matter	pH	Plot size and seeding information	Crop varieties	Growing season precipitation
		%				% of long-term average[b]
Beaverlodge 2016 Beaverlodge 2017 Beaverlodge 2018	Clay loam 21.6% sand, 49.1% silt, 29.3% clay	8.5	6.2	3.7 m x 15m 30 cm row spacing, hoe openers	Harvest wheat Meadow peas Snowdrop faba[a] Gateway WW[a] Sapphire flax L241CR canola Canmore barley	154 127 124
Carman 2016 Carman 2017 Carman 2018	Sandy clay loam 58% sand, 15% silt, 27% clay	7.9	5.2	4 m x 8 m 19 cm row spacing, disc openers	Cardale wheat Agassiz peas Tabour faba Gateway WW L233P canola Bethune flax Canmore barley	116 59 74
Lacombe 2016 Lacombe 2017 Lacombe 2018	Clay 19% sand, 37% silt, 44% clay	8.8	7.3	3.7m x 15m 30 cm row spacing, hoe openers	Harvest wheat Meadow peas Snowdrop faba Gateway WW Sapphire flax L241CR canola Canmore barley	105 73 83

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Scott 2016					Shaw wheat	89
Scott 2017	Loam 23% sand 40% silt, 17% clay	2.7	6.2	3m x 10m 25 cm row spacing, knife openers	Meadow peas Snowdrop faba Emerson WW L140P canola Norlan flax Champion barley	90
Scott 2018						70

[a]WW= winter wheat, Faba= fababean

[b]Long-term average, measured in mm, from the Canadian Climate Normals 1981-2010 from https://climate.weather.gc.ca/climate_normals/index_e.html

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Table 3. Harvest and desiccation dates by treatment at each site-year. These 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. Des. = desiccation.

Site year	Harvest date by treatment					
	Early	'Normal'	Late	Early	'Normal'	Late
		Swath			Straight Cut	
Beaverlodge 2016	Aug 16	Sept 6	Sept 9	Sept 12	Sept 13	Nov 17 (des. Sept 13)
Beaverlodge 2017	Aug 16	Aug 29	Aug 26	Aug 21	Sept 27	Nov 27
Beaverlodge 2018		Aug 15			Sept 5	
Carman 2016	Aug 15	Aug 24	Sept 14	Sept 2	Sept 2	Nov 9
Carman 2017	July 20	Aug 25	Sept 21	Aug 10	Sept 5	Oct 5
Carman 2018		July 24			Aug 17	
Lacombe 2016	Aug 25	Aug 30	Sept 19	Sept 6	Sept 14	Nov 4 (des. Sept 26)
Lacombe 2017	Aug 16	Aug 25	Sept 2	Aug 23	Sept 8	Sept 18
Lacombe 2018		Aug 18			Sept 4	
Scott 2016	Aug 4	Aug 16	Aug 31	Aug 16	Aug 29	Sept 6
Scott 2017	N/A	Aug 18	Aug 28	N/A	Sept 5	Sept 11
Scott 2018		Aug 14			Aug 22	

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Table 4. Wild oat seed numbers in chaff samples collected during grain harvest at each location and averaged across sites. Treatments with different letters indicate significant differences based on post-hoc comparison of means using Tukey's Honestly Significant Difference with an α=0.05. Sites where two letters are given the uppercase letter is a comparison between crops, while the lowercase letter is the comparison between harvest management. The standard error of the mean is given in parentheses. The crop is listed with the crop rotation maturity it belongs to also listed in parentheses.

Year	Crop (rotation)	Harvest management	Beaverlodge		Carman		Lacombe		Scott		Across sites	
			--# 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

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Table 5. Crop yields in each year at each location. Treatments with different letters indicate significant differences based on post-hoc comparison of means using Tukey's Honestly Significant Difference with an α=0.05. Cells that are combined across the Swathed and Straight Cut treatments indicate that only cropping system maturity had a significant effect on yield. The standard error of the mean is given in parentheses. The crop is listed with the crop rotation maturity it belongs to also listed in parentheses.

Year	Crop (rotation)	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		

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

	Barley (early[a])	Swathed	2,183 (162)	A	771 (81)	B	5,188 (161)	A	N/A
		Straight cut					4,260 (161)	B	
2018	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]The cropping system rotation here only indicates the preceding crops. The barley was seeded across the trials and matured and was harvested at the same time.

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

Figures

Figure 1. Examples of chaff collection systems used on different plot combines in the study conducted from 2016-2018 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.

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

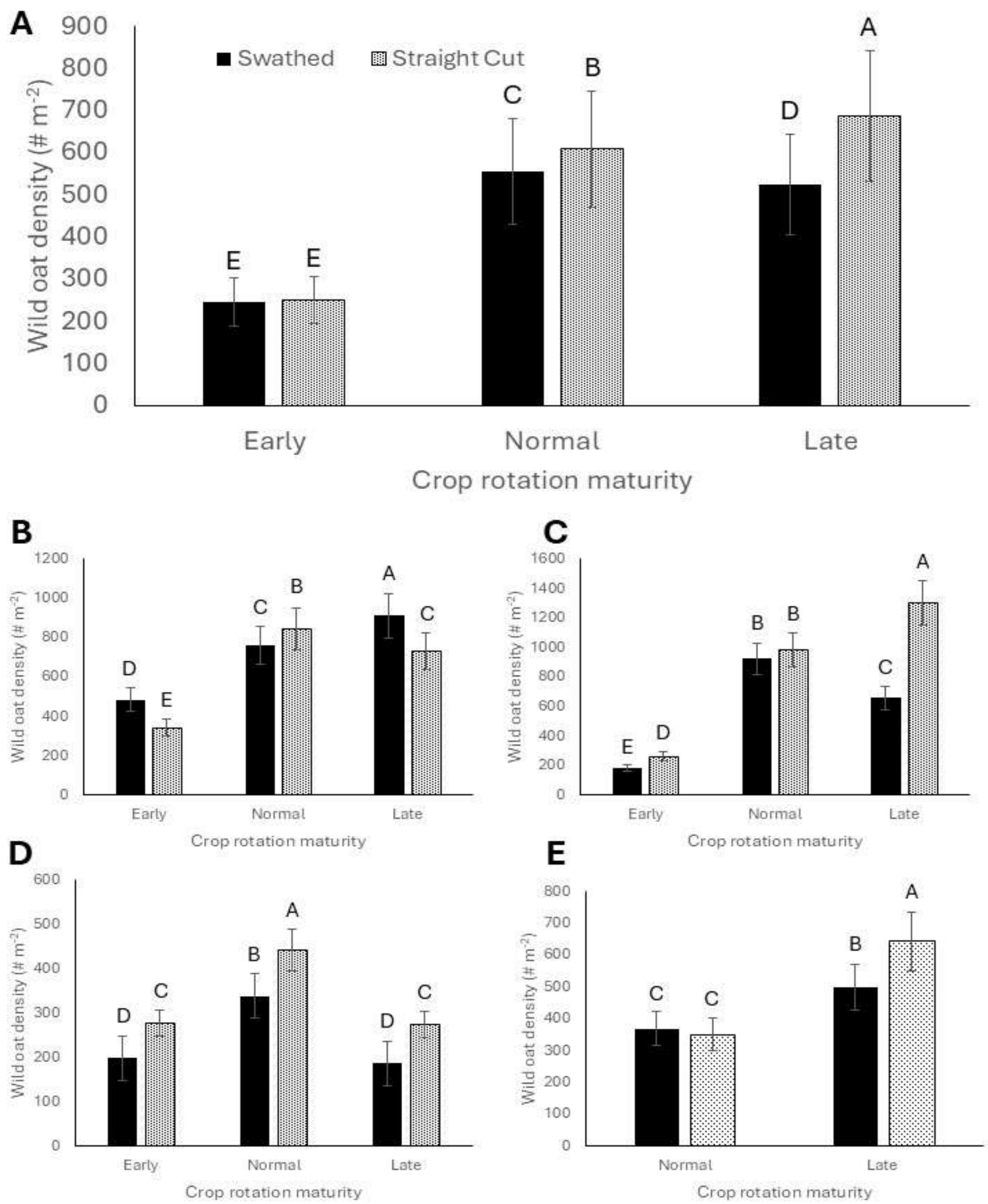

Figure 2. Wild oat plant density in the final year (2018) of the study examining the effects of crop rotation maturity, harvest management and harvest weed seed control on wild oat populations. Black bars are the swathed harvest management system while patterned bars are the straightcut harvest management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

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

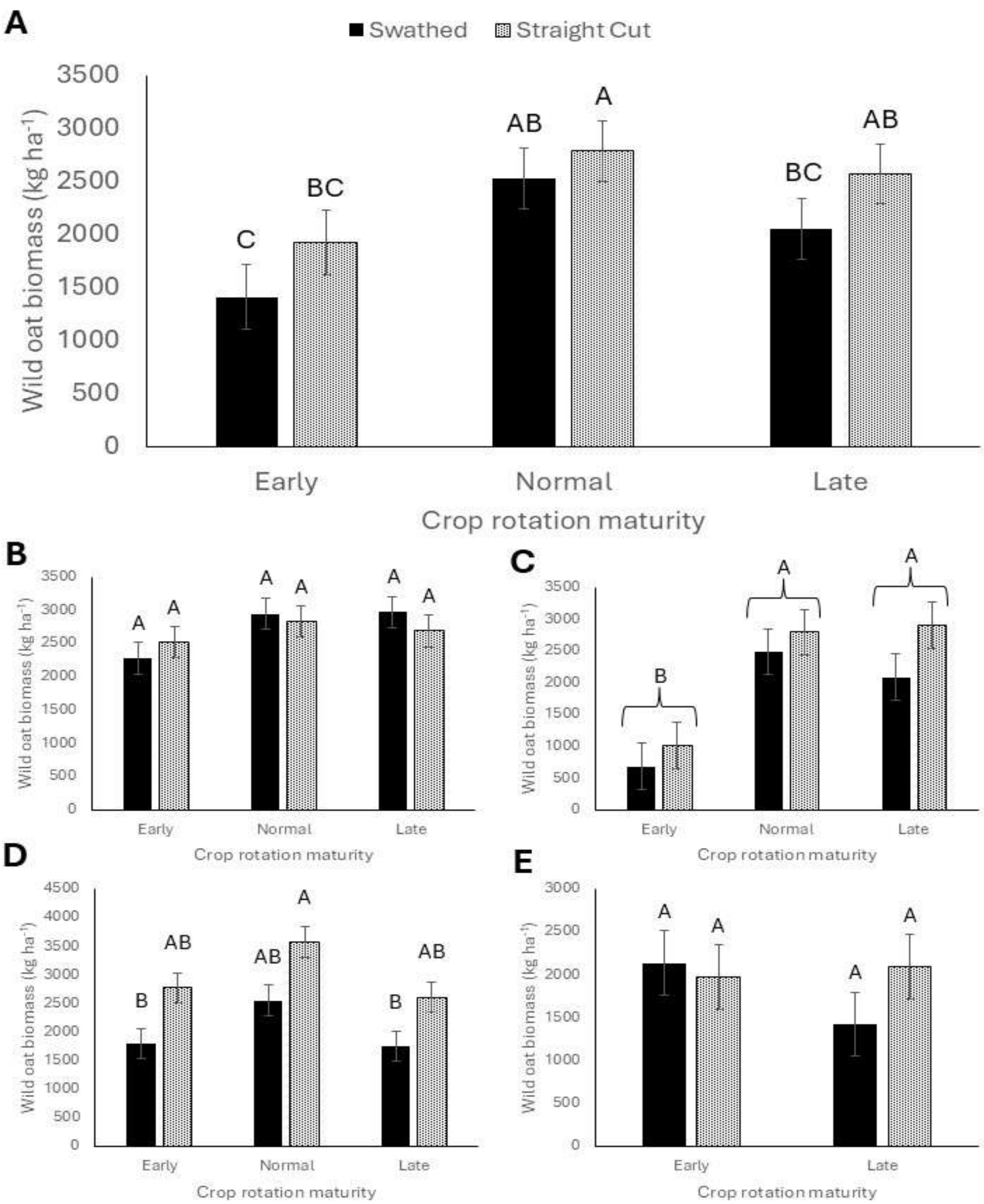

Figure 3. Wild oat biomass in the final study year (2018) as affected by crop rotation maturity and harvest management. Treatments with different letters indicate significant differences based on post-hoc comparison of means using Tukey's Honestly Significant Difference with an α=0.05. Brackets over 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.

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

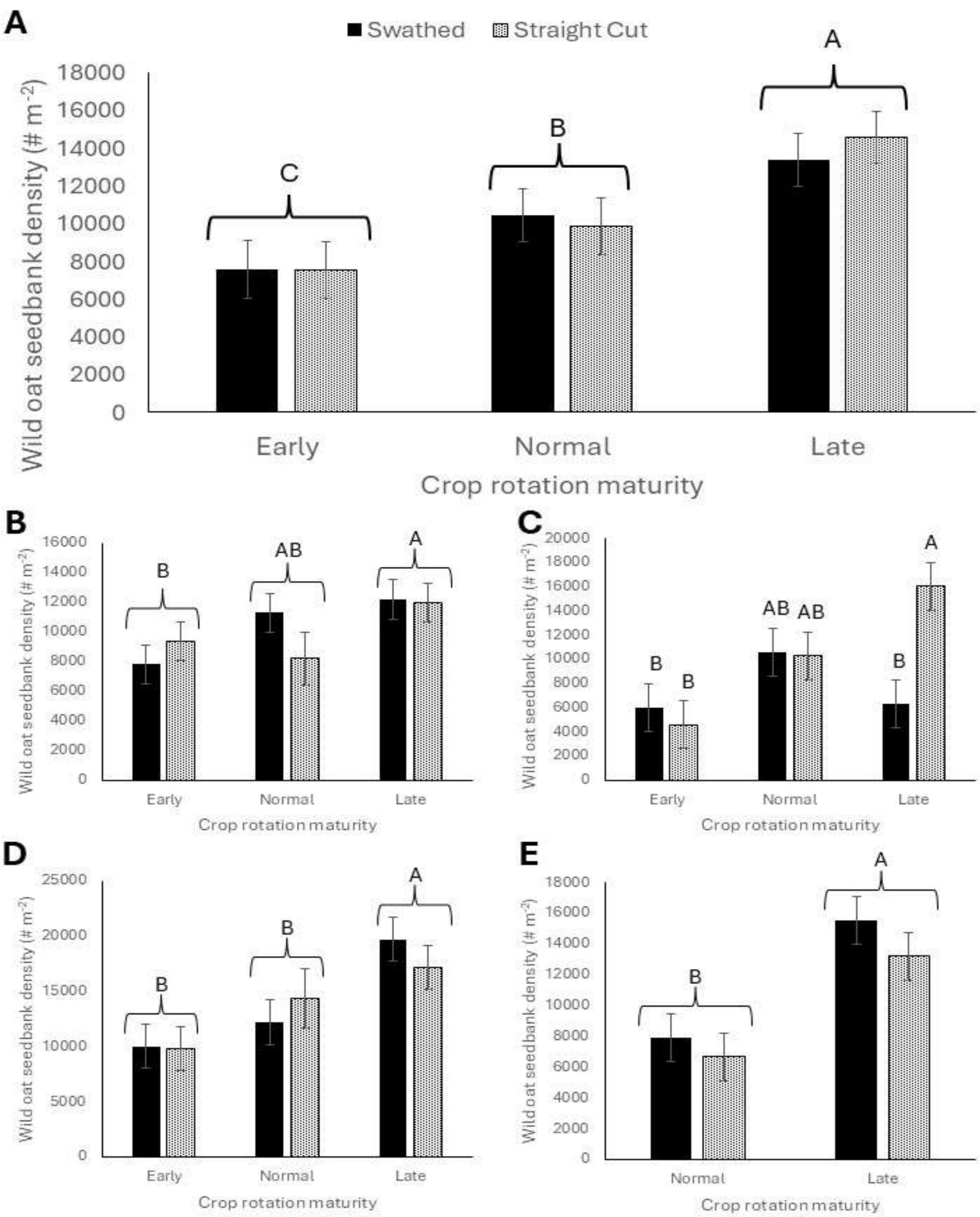

Figure 4. Wild oat seedbank densities as affected by crop rotation maturity and harvest management, measured in 2018. Treatments with different letters indicate significant differences based on post-hoc comparison of means using Tukey's Honestly Significant Difference with an α=0.05. Brackets over a 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.

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

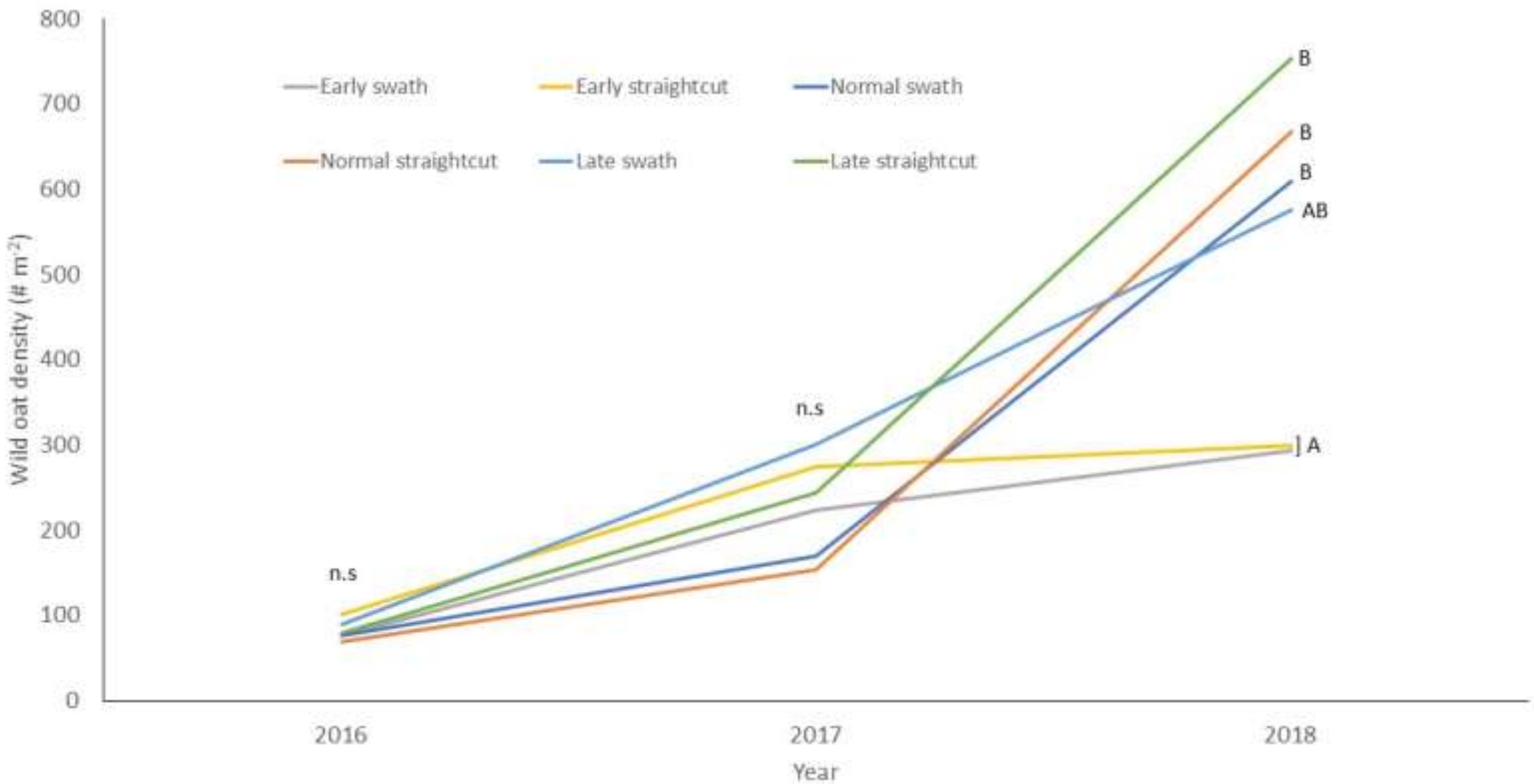

Figure 5. Wild oat population densities over time in each of the six treatments included in the crop rotation maturity, harvest management and harvest weed seed control effect on wild oat populations study. Post-hoc comparison of means within each year used Tukey's Honestly Significant Difference with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

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press

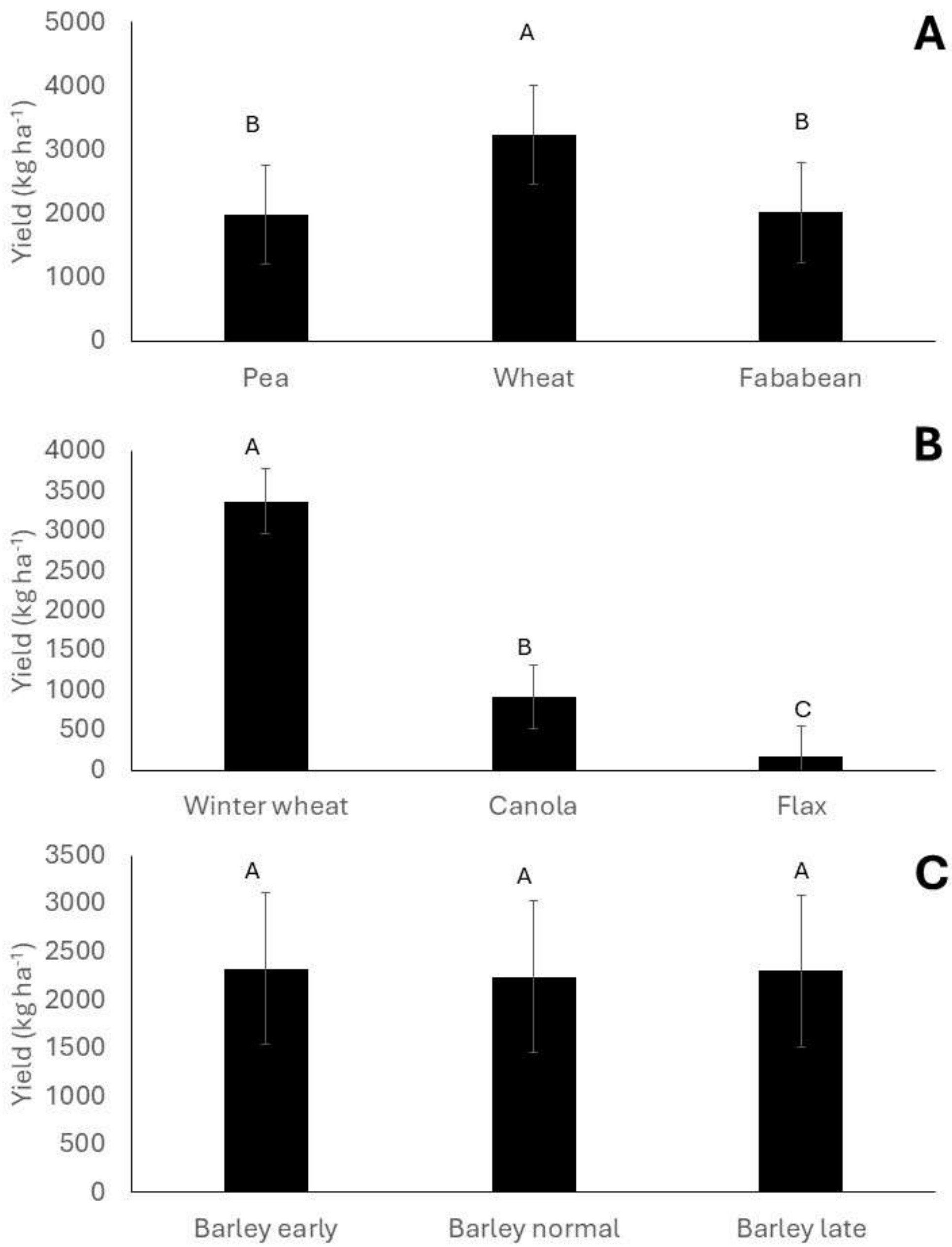

Figure 6. Crop yield in A) 2016, B)2017, and C)2018. Treatments with different letters indicate significant differences between treatments within that year based on post-hoc comparison of means using Tukey's Honestly Significant Difference with an α=0.05. Error bars indicate standard errors of the means. The leftmost bar in each graph is the yield from the crop that was grown in the early maturing rotation, the centre bar is yields from the normal maturing rotation and the righthand bar is yields from the late maturing rotation.

https://doi.org/10.1017/wet.2025.14 Published online by Cambridge University Press