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Diverse Rotations and Optimal Cultural Practices Control Wild Oat (*Avena fatua*)

K. Neil Harker, John T. O'Donovan, T. Kelly Turkington, Robert E. Blackshaw, Newton Z. Lupwayi, Elwin G. Smith, Eric N. Johnson, Denis Pageau, Steven J. Shirtliffe, Robert H. Gulden, John Rowsell, Linda M. Hall, and Christian J. Willenborg*

In western Canada, more money is spent on wild oat herbicides than on any other weed species, and wild oat resistance to herbicides is the most widespread resistance issue. A direct-seeded field experiment was conducted from 2010 to 2014 at eight Canadian sites to determine crop life cycle, crop species, crop seeding rate, crop usage, and herbicide rate combination effects on wild oat management and canola yield. Combining 2× seeding rates of early-cut barley silage with 2× seeding rates of winter cereals and excluding wild oat herbicides for 3 of 5 yr (2011 to 2013) often led to similar wild oat density, aboveground wild oat biomass, wild oat seed density in the soil, and canola yield as a repeated canola–wheat rotation under a full wild oat herbicide rate regime. Wild oat was similarly well managed after 3 yr of perennial alfalfa without wild oat herbicides. Forgoing wild oat herbicides in only 2 of 5 yr from exclusively summer annual crop rotations resulted in higher wild oat density, biomass, and seed banks. Management systems that effectively combine diverse and optimal cultural practices against weeds, and limit herbicide use, reduce selection pressure for weed resistance to herbicides and prolong the utility of threatened herbicide tools.

Nomenclature: Wild oat, *Avena fatua* L.; alfalfa, *Medicago sativa* L.; barley, *Hordeum vulgare* L.; canola, *Brassica napus* L.; wheat, *Triticum aestivum* L.

Key words: Alternative weed management, combined practices, crop life cycle, herbicide resistance, integrated weed management, perennial forage, selection pressure.

Each year, more money is spent on wild oat control ($500 million) than on any other weed in Canada (Leeson et al. 2006). Before selective wild oat herbicides were available, growers suppressed wild oat with delayed seeding, pre- and postseeding tillage, summer fallow, forage grass and legume rotations, and fall-seeded winter cereal crops (Brown 1953). Later, as rotations became less diverse and selective herbicides from one or two mode-of-action groups were repeatedly applied, wild oat became the major resistant weed on the Canadian Prairies (Beckie et al. 1999). Current estimates from random field surveys indicate that the majority of annually cropped acres in western Canada are infested with acetyl-CoA carboxylase (ACCase)-resistant (group 1-resistant) wild oat (H Beckie, personal communication). Because herbicides appear to be relatively nonrenewable resources (Duke 2012), alternative weed control methods are urgently required before the utility of critical herbicide tools is severely compromised or lost (Harker et al. 2012; Powles and Yu 2010). However, truly integrated weed management (IWM) research is still overshadowed by herbicide efficacy research in most weed research programs (Harker and O'Donovan 2013), and diverse weed management tactic adoption is limited. Wilson et al. (2009) state that "farmers understand but do not practice IWM."

Combining several weed management tactics can improve ecologically based weed management (Anderson 2005). Cultural practices such as crop rotation, planting competitive crop cultivars, silage production, and using higher than normal seeding rates have been shown to effectively suppress wild oat (Harker et al. 2003, 2009; O'Donovan et al. 1999, 2000). Combining some of those practices in summer-annual cropping systems can lead to synergistic gains in weed management (Blackshaw et al. 2008; Harker et al. 2009; O'Donovan et al. 2007). However, research combining those cultural practices with truly diverse rotations that include winter cereal crops or perennial forages to manage wild oat

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* First, second, and third authors: Research Scientists, Agriculture and Agri-Food Canada (AAFC), Lacombe Research Centre, 6000 C & E Trail, Lacombe, Alberta, Canada T4L 1W1; fourth, fifth, and sixth authors: Research Scientists, AAFC, Lethbridge, Alberta, Canada T1J 4B1; seventh, ninth and thirteenth authors: Research Assistant, Professor, and Assistant Professor, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A8; eighth author: Research Scientist, AAFC, Normandin, Quebec, Canada G8M 4K3; tenth author: Professor, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N; eleventh author: Agronomist (retired), University of Guelph, New Liskeard, Ontario, Canada P0J 1P0; twelfth author: Professor, University of Alberta, Edmonton, Alberta, Canada T6G 2P5. Corresponding author's E-Mail: neil.harker@agr.gc.ca

and reduce herbicide selection pressure has not been reported.

Increasing the diversity of crop or weed management strategies can be logistically and economically costly (Ervin and Frisvold 2015; Norsworthy et al. 2012; Owen 2015). Furthermore, low-diversity cropping systems require less technical expertise and management and are therefore more amenable to increasing farm-size trends. However, Davis et al. (2012) show that the "increased labor, information intensive management and ecosystem services arising from increased biological N fixations (via the clover and alfalfa crops) and contrasting crop phenologies and competitive abilities" in 3- and 4-yr rotations effectively substituted for some fertilizer and herbicide inputs in a 2-yr rotation, and that profits were similar. Similar research in different regions and cropping systems is imperative. Providing growers with options to reduce herbicide inputs, environmental impact, and selection pressure for weed resistance will make sustainable crop production more likely. The objective of our study was to determine if diverse crop rotations that include higher than normal seeding rates, early-cut silage, winter cereals, and perennial alfalfa can effectively reduce wild oat populations and herbicide input requirements compared to the most common summer annual crop rotation on the Canadian Prairies: repeated canola–wheat.

Materials and Methods

Field experiments were conducted at eight Canadian locations from 2010 to 2014 (Edmonton, AB [53.7°N, 113.6°W]; Lacombe, AB [52.5° N, 113.7°W]; Lethbridge, AB [49.7°N, 112.8°W]; Scott, SK [52.4°N, 108.8°W]; Saskatoon, SK [52.5°N, 106.5°W]; Winnipeg, MB [49.5°N, 98.0°W]; New Liskeard, ON [47.5°N, 79.6°W]; and Normandin, QC [48.5°N, 72.3°W]). In 2010, natural wild oat populations in plot areas were supplemented with 200 wild oat seeds m^{-2} to ensure adequate, uniform populations. Preseed glyphosate (450 to 900 g ae ha^{-1}) was applied prior to seeding spring- and fall-sown crops to control emerged weeds. All plots were direct-seeded and established on no-till fields (except those at Normandin) previously sown to wheat or barley. At Normandin, plots were fall-plowed and spring-harrowed (twice) prior to seeding. Soil samples were collected at each site before seeding and analyzed for soil nutrients. On the basis of the soil analyses, fertilizer additions (blends of monoammonium phosphate [MAP], urea, and potassium chloride) were made to achieve 100% of the soil test recommendations for each crop species. Most of the total fertilizer was side-banded 2 cm beside and 3 to 4 cm below the seed row with small amounts of MAP also placed with crop seeds. Seeding was usually performed with seeders equipped with knife or hoe openers and crops were seeded at optimal depths in 18- to 30-cm rows. At Normandin, seeding was done with a disc seeder; fertilizer was broadcast prior to harrowing. Fungicides and insecticides were applied as needed according to local disease and pest insect infestations. Plot dimensions were 3.7 by 15.2 m at most sites (5.8 by 6.0 m at Normandin).

At each site, 14 treatments (Figures 1–5) were arranged in a randomized complete block design with four replications. In-crop wild oat herbicides were applied at 0, 50, or 100% of recommended rates depending on the treatment regime. Crops were seeded at 1× or 2× rates as follows: canola, 150 seeds m^{-2} (1×); barley and wheat, 400 seeds m^{-2} (2×); field peas (*Pisum sativum* L.), 125 seeds m^{-2} (1×); fall rye (*Secale cereale* L.), winter triticale (× *Triticosecale* W.), and winter wheat, 600 seeds m^{-2} (2×); and alfalfa, 9 kg ha^{-1} (1×). Broadleaf weeds were treated with full rates of appropriate herbicides depending on local weed infestations. Early-cut barley silage was harvested 1 wk after head emergence (Zadoks' 65) (Zadoks et al. 1974). For the chemical fallow treatment (2011 and 2013), at least twice each growing season, glyphosate was applied alone (450 g ae ha^{-1}) or with an appropriate broadleaf herbicide to control emerged fallow weeds. Each treatment integrated different factors (crop species, crop life cycles, crop seeding dates and rates, harvesting dates, and herbicide rates) over three growing seasons (2011 to 2013) to influence wild oat demography. The cumulative effects of these treatments were determined after all of the treatments were differentiated during the 2013 growing season. The most popular crop rotation sequence on the Canadian Prairies, canola–wheat in a full herbicide rate regime, was considered as the standard treatment to compare 2013 and 2014 data to all other treatments.

Crop density was determined each spring from two 0.5-m^2 quadrats in each plot 2 wk after spring crop emergence. Wild oat density was determined from the same two 0.5-m^2 quadrats in each plot immediately before POST herbicides were applied. Crop and wild oat shoot biomass was also determined from the same two 0.5-m^2 quadrats immediately prior to early-cut barley silage harvest (1 wk after barley heading). For the five study years, the quadrats were placed in different areas each year so as not to overlap with quadrats from previous years. Biomass samples were dried at 60 C for two or more days before weight determination. Early-cut barley silage plots were swathed and the plant material was removed from the plot, dried at 60 C for two or more days, and weighed. Grain plots were swathed at the appropriate time and harvested with combines. Seed was cleaned and seed weights recorded for each plot (excluding chemical fallow and alfalfa). After the establishment year (2011), alfalfa was harvested two to three times each growing season depending on local growing conditions and practices, and total dry weight biomass was determined. Alfalfa was terminated in 2013 (late August) with a tank mixture of clopyralid (98 g ae ha^{-1}) and glyphosate (450 g ae ha^{-1}). In 2014 canola plots, seed oil and protein concentrations (8.5% moisture basis) were determined using a near infrared reflectance spectrophotometer (Foss Model 6500, FOSS NIRSystems Inc., Silver Spring, MD).

After canola harvest in the fall of 2014, plot soil was sampled for wild oat seed using a "W" pattern. Twelve soil samples were taken from each plot (eight at Scott) to a depth of 8 cm using a circular core sampler with an inside diameter of 10 cm. Subsamples were bulked into a single sample. Soil was dried at 30 C, sieved, and washed; wild oat seed was manually separated and counted and the data converted to seeds m^{-2} (O'Donovan et al. 2013).

Statistical Analyses. Data were analyzed with the PROC MIXED and GLIMMIX procedures of SAS (Littell et al. 2006; SAS Institute 2013). Replicates, site effects, and site interactions with fixed effects were considered random. Given our desire to make treatment inferences beyond study sites, it was appropriate to consider site effects and their interactions with fixed effects as random (Yang 2010). Experimental treatment effects were considered fixed.

Exploratory analysis indicated the possibility of heterogeneous variances among sites. The corrected Akaike's information criterion confirmed the benefit of modeling variance heterogeneity for all analyses (residual variance was modelled separately for each site). PROC MIXED was used to get an initial estimate of all covariance parameter estimates, including residual variance estimates for each site. These covariance estimates from PROC MIXED were then used in a final PROC GLIMMIX analysis using the "parms" statement (SAS Institute 2013). To model separate residual variance estimates for each site, the "group" option was set to "site" in the repeated (MIXED) and random (GLIMMIX) statements. Exploratory analysis also revealed that residual distributions for wild oat variables were not normal. Therefore, a geometric error distribution with a log-link function was used for all analyses of wild oat plant density, wild oat shoot biomass, and wild oat seed bank density. Means from the analyses of wild oat variables were back-transformed from log scale to original data scale using an inverse-link function.

Contrasts were constructed to compare crop and wild oat responses from the "standard" canola–wheat cropping sequence treatment to each of the other treatments. Site by treatment variance estimates were assessed to determine if they were different from zero. Specifically, variance was estimated using the restricted maximum likelihood approach. Also, the percentage of the site by treatment variance estimates relative to the sum of site plus the site by treatment variance estimates were used to help interpret the variability of treatment differences across sites. To further assist with interpretation of the consistency of responses to the treatments across sites, each variable was analyzed separately for each site using the same error distribution as that used for the combined analysis. Mean differences for each treatment relative to the "standard" canola–wheat cropping sequence treatment were determined by contrasts. The number of contrasts from the by-site analysis that agreed or disagreed with the same contrasts from the across-site analysis contrasts were summarized to provide information on the consistency of mean differences, termed "site compliance."

Results and Discussion

All treatment impositions only fully differentiated during the 2013 growing season. Therefore, even though some data were collected early in 2013 and in previous years, this paper focuses on data collected toward the end of the 2013 growing season (wild oat biomass) and in 2014. The discussion centers on the comparison between a standard canola–wheat rotation under a full herbicide rate regime (treatment 1) vs. all of the other treatments.

2013 Wild Oat Biomass. Several treatments led to wild oat biomass levels similar to treatment 1 (Figure 1). However, the only treatment without wild oat herbicides from 2011 to 2013 having wild oat biomass similar to treatment 1 was treatment 14 (alfalfa). Perennial alfalfa is known to provide effective management of annual weeds such as wild oat (Brown 1953; Entz et al. 1995; Ominski et al.

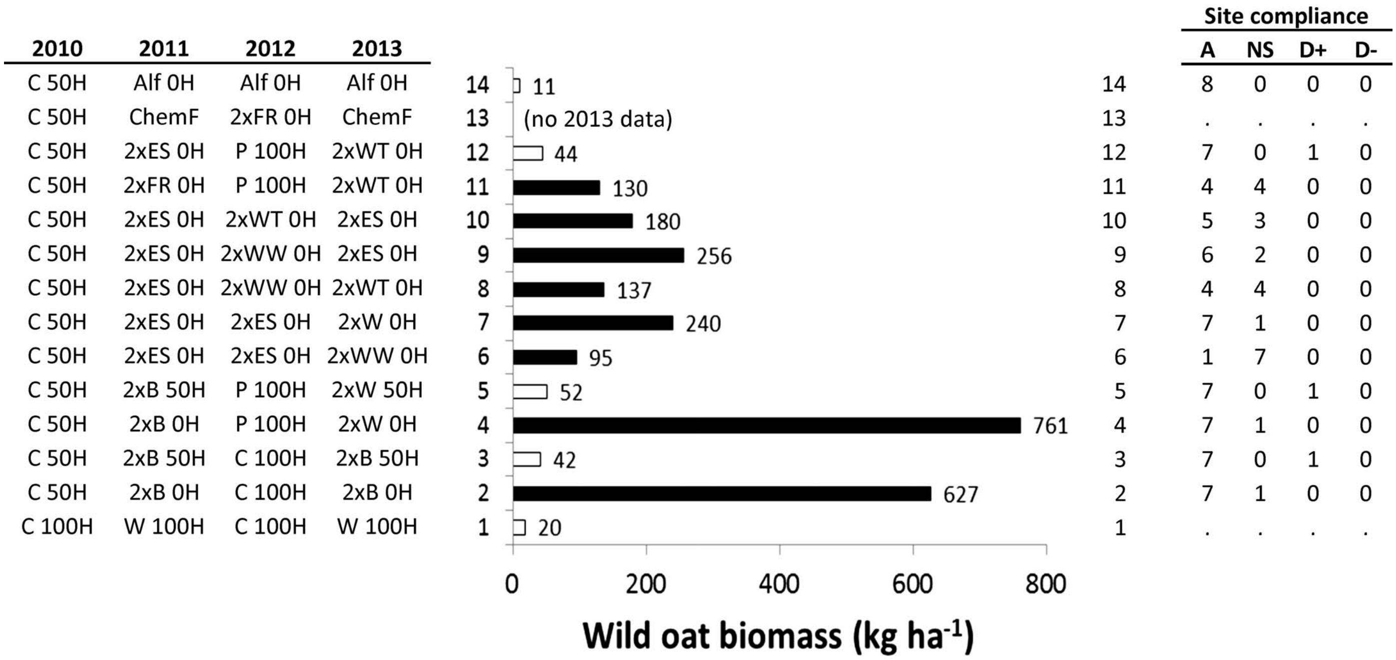

Figure 1. 2013 Wild oat biomass (across site means of eight sites) responses to crop life cycle, crop species, crop seeding rate, crop usage, and herbicide rate combination effects. 2 × indicates doubled crop seeding rate. C = canola, Alf = alfalfa, ChemF = chemical fallow, FR = fall rye, ES = early-cut barley silage, P = field pea, WT = winter triticale, WW = winter wheat, W = wheat, B = barley, H = herbicide. Canola in 2010 and 2012 was glufosinate-resistant. Numbers preceding H indicate the percentage of recommended wild oat herbicide applied in a given year. Black bars indicate values significantly greater than the 100% wild oat herbicide, canola–wheat–canola–wheat treatment (treatment 1). Site compliance indicates number of individual site contrasts to treatment 1 (canola–wheat–canola–wheat) in agreement with across-site contrasts to treatment 1: A = agreement, NS = not significant when across-site contrast is significant, D+ = significant difference (same pattern) when across-site contrast is not significant, D– = significant difference (opposite pattern) when across-site contrast is not significant.

1999). Furthermore, Beckie et al. (2014) demonstrate that ACCase-inhibitor resistance to wild oat evolves much more slowly in perennial vs. annual cropping systems. Given a relatively high site by treatment interaction variance percentage (45% relative to the sum of site plus the site by treatment variance estimates; Table 1), it seemed important to discuss how site contrasts differed from overall mean contrasts. Of the other treatments that excluded herbicides from 2011 to 2013, treatments

Table 1. Dependent variable treatment effect P values (ANOVA), means and site (S) by treatment (T) variances for 2013 and 2014.

Year and variable[a]	P value	Mean	Variance estimates S	Variance estimates S × T	S × T P value	%[b]
2013						
Wild oat biomass (kg ha^{-1})	< 0.001	200	1.62	1.31	**	45
2014						
Canola density (no. m^{-2})	0.285	87	1353	31	**	2
Canola biomass dry weight (kg ha^{-1})	0.057	8,504	3.11	0.03	—[c]	1
Wild oat density (no. m^{-2})	< 0.001	14	2.93	0.59	**	17
Wild oat biomass dry weight (kg ha^{-1})	< 0.009	75	0.256	0.681	**	73
Wild oat seed bank density (# m^{-2})	< 0.001	140	6.43	1.10	**	15
Canola yield (kg ha^{-1})	0.002	2,909	1.11	0.01	**	1
Oil concentration (%)	0.027	44.6	1.31	0.03	*	2
Protein concentration (%)	0.002	22.2	2.63	0.03	*	1

[a] Wild oat data were log transformed prior to statistical analyses.
[b] Site by treatment interaction variance as a percentage of the site plus the site by treatment variance estimates.
[c] Dash indicates P ⩾ 0.05.
* P < 0.05
** P < 0.01.

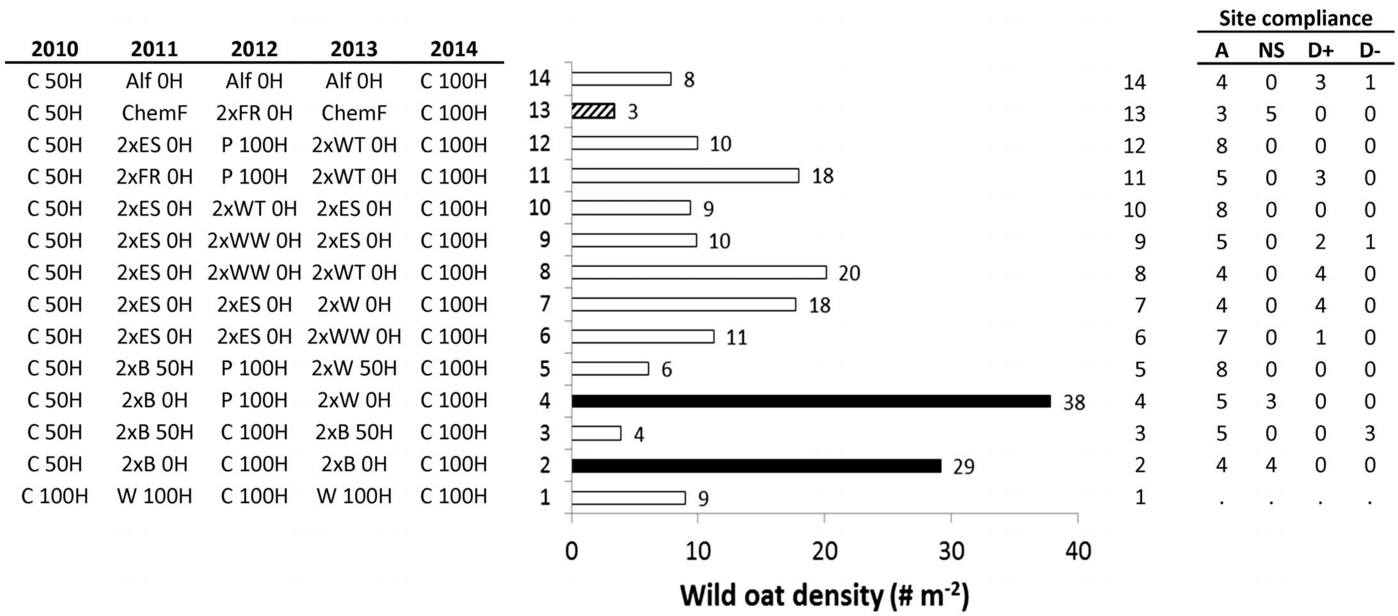

Figure 2. 2014 Wild oat density (across site means of eight sites) responses to crop life cycle, crop species, crop seeding rate, crop usage, and herbicide rate combination effects. 2× indicates doubled crop seeding rate. C = canola, Alf = alfalfa, ChemF = chemical fallow, FR = fall rye, ES = early-cut barley silage, P = field pea, WT = winter triticale, WW = winter wheat, W = wheat, B = barley, H = herbicide. Canola in 2010 and 2012 was glufosinate-resistant. Canola in 2014 was glyphosate-resistant. Numbers preceding H indicate the percentage of recommended wild oat herbicide applied in a given year. Black bars indicate values significantly greater than the 100% wild oat herbicide, canola–wheat–canola–wheat–canola treatment (treatment 1). Bars with angled lines indicate values significantly less than treatment 1. Site compliance indicates number of individual site contrasts to treatment 1 (canola–wheat–canola–wheat–canola) in agreement with across-site contrasts to treatment 1: A = agreement, NS = not significant when across-site contrast is significant, D+ = significant difference (same pattern) when across-site contrast is not significant, D− = significant difference (opposite pattern) when across-site contrast is not significant.

6, 8, and 10 had similar wild oat biomass as treatment 1 at seven, four, and three of eight sites, respectively (Figure 1, site compliance). Therefore, there was evidence that by the mid-2013 growing season, combinations of early-cut barley silage with winter cereals were also effectively controlling wild oat at several sites. Field peas in a full wild oat herbicide rate regime in combination with 2× seeding rates of early-cut barley silage and 2× seeding rates of winter triticale with no wild oat herbicides (treatment 12) also provided wild oat biomass reduction similar to treatment 1. A similar treatment that included fall rye in the place of early-cut silage (treatment 11) had wild oat biomass levels similar to treatment 1 at half of the sites. The two treatments that led to the highest wild oat biomass levels were those where no early-cut barley silage or winter cereals were included in the rotation and the barley and wheat crops included no wild oat herbicide in 2 of 5 yr (treatments 2 and 4).

2014 Wild Oat Density. Treatments 2 and 4 were the only treatments with higher wild oat density than treatment 1 (Figure 2). Those treatments involved zero wild oat herbicide in barley and did not include early-cut silage or winter cereals. We found that, without wild oat herbicides, it was difficult to effectively suppress summer annual wild oat in the absence of winter annual or perennial crops. Treatment 13 (fall rye and 2 yr of chemical fallow) had lower wild oat density than treatment 1. Similar to early-cut barley silage, chemical fallow prevented viable wild oat seed production.

All of the treatments in which wild oat herbicides were excluded for a 3-yr period (treatments 6 to 10, 14) had similar wild oat densities to the full wild oat herbicide regime (treatment 1) (Figure 2). The combination of early-cut barley silage (Harker et al. 2003) with 2× seeding rates of winter cereals or the growth of perennial alfalfa disadvantaged wild oat enough that herbicides were not required to effectively manage the wild oat populations. Winter cereals generally suppress wild oat better than spring cereals (Brown 1953; Beres et al. 2010; Thurston 1962b). Blackshaw (1994) demonstrated that growing a crop with a different life cycle than the target weed species can dramatically reduce the target weed. Several other treatments that included wild oat herbicides in 3 of 5 or 5 of 5 yr (treatments 3,

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2010	2011	2012	2013	2014	Treatment	Site compliance A	NS	D+	D-
C 50H	Alf 0H	Alf 0H	Alf 0H	C 100H	14	4	0	0	0
C 50H	ChemF	2xFR 0H	ChemF	C 100H	13	3	1	0	0
C 50H	2xES 0H	P 100H	2xWT 0H	C 100H	12	4	0	0	0
C 50H	2xFR 0H	P 100H	2xWT 0H	C 100H	11	3	1	0	0
C 50H	2xES 0H	2xWT 0H	2xES 0H	C 100H	10	4	0	0	0
C 50H	2xES 0H	2xWW 0H	2xES 0H	C 100H	9	4	0	0	0
C 50H	2xES 0H	2xWW 0H	2xWT 0H	C 100H	8	3	1	0	0
C 50H	2xES 0H	2xES 0H	2xW 0H	C 100H	7	2	2	0	0
C 50H	2xES 0H	2xES 0H	2xWW 0H	C 100H	6	3	0	1	0
C 50H	2xB 50H	P 100H	2xW 50H	C 100H	5	4	0	0	0
C 50H	2xB 0H	P 100H	2xW 0H	C 100H	4	3	1	0	0
C 50H	2xB 50H	C 100H	2xB 50H	C 100H	3	4	0	0	0
C 50H	2xB 0H	C 100H	2xB 0H	C 100H	2	3	1	0	0
C 100H	W 100H	C 100H	W 100H	C 100H	1	.	.	.	.

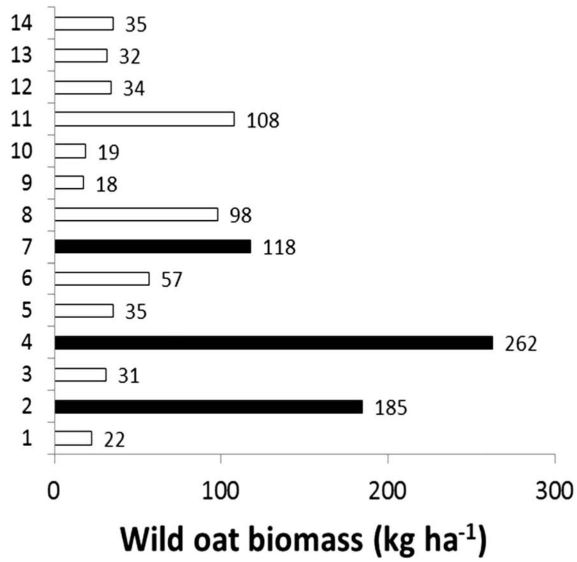

Figure 3. 2014 Wild oat biomass (across site means of four sites) responses to crop life cycle, crop species, crop seeding rate, crop usage, and herbicide rate combination effects. 2 × indicates doubled crop seeding rate. C = canola, Alf = alfalfa, ChemF = chemical fallow, FR = fall rye, ES = early-cut barley silage, P = field pea, WT = winter triticale, WW = winter wheat, W = wheat, B = barley, H = herbicide. Canola in 2010 and 2012 was glufosinate-resistant. Canola in 2014 was glyphosate-resistant. Numbers preceding Hindicate the percentage of recommended wild oat herbicide applied in a given year. Black bars indicate values significantly greater than the 100% wild oat herbicide, canola–wheat–canola–wheat–canola treatment (treatment 1). Site compliance indicates number of individual site contrasts to treatment 1 (canola–wheat–canola–wheat–canola) in agreement with across-site contrasts to treatment 1: A = agreement, NS = not significant when across-site contrast is significant, D+ = significant difference (same pattern) when across-site contrast is not significant, D– = significant difference (opposite pattern) when across-site contrast is not significant.

5, 11, 12) also led to similar levels of wild oat control; the latter treatments imposing more selection pressure for herbicide resistance than the former. These results demonstrate the effectiveness of combining multiple cultural techniques against weeds and confirm previous research (Blackshaw et al. 2005; Harker et al. 2009; O'Donovan et al. 2013).

Wild oat densities at four of eight sites were greater for treatments 7 and 8 than treatment 1 when the overall site means for the same comparison were not (D+ = significant difference [same pattern] when across-site contrast is not significant); therefore, those treatments did not reduce wild oat density as consistently as some of the other early-cut silage–winter cereal combination treatments. Site compliance data also revealed three comparisons with patterns different (D– = significant difference [opposite pattern] when across-site contrast is not significant) to the overall site mean contrasts (Figure 2). At Lacombe, Edmonton, and Saskatoon, even though wild oat herbicides were present each year (50% rates in barley), treatment 3 led to higher wild oat densities than treatment 1 (data not shown). Treatment 9 led to lower wild oat density than treatment 1 at New Liskeard. At Lethbridge, where alfalfa stands were relatively weak, wild oat density was greater in treatment 14 vs. treatment 1.

2014 Wild Oat Biomass. The New Liskeard site was terminated after the spring of 2014 due to canola devastation by Swede midge [*Contarinia nasturtii* (Keiffer) (Diptera: Cecidomyiidae)]. Furthermore, wild oat biomass levels in 2014 were so low at three sites (data were zero inflated) that the statistical analyses could only be completed at the remaining four sites. A single, full-rate application of glyphosate (450 g ae ha^{-1}) in glyphosate-resistant canola in 2014 provided a high level of weed control and kept weed biomass levels relatively low, similar to a study by O'Donovan et al. (2006).

Wild oat biomass responses to treatment effects were very similar to 2014 wild oat density responses. Several treatments that included early-cut barley silage in combination with winter cereals (treatments 6, 8 to 10), as well as perennial alfalfa (treatment 14), reduced wild oat biomass as well as the canola–wheat rotation did under a full wild oat herbicide regime (Figure 3). A very high site by treatment interaction variance (73%; Table 1), necessitates some discussion of how individual site contrasts differed from

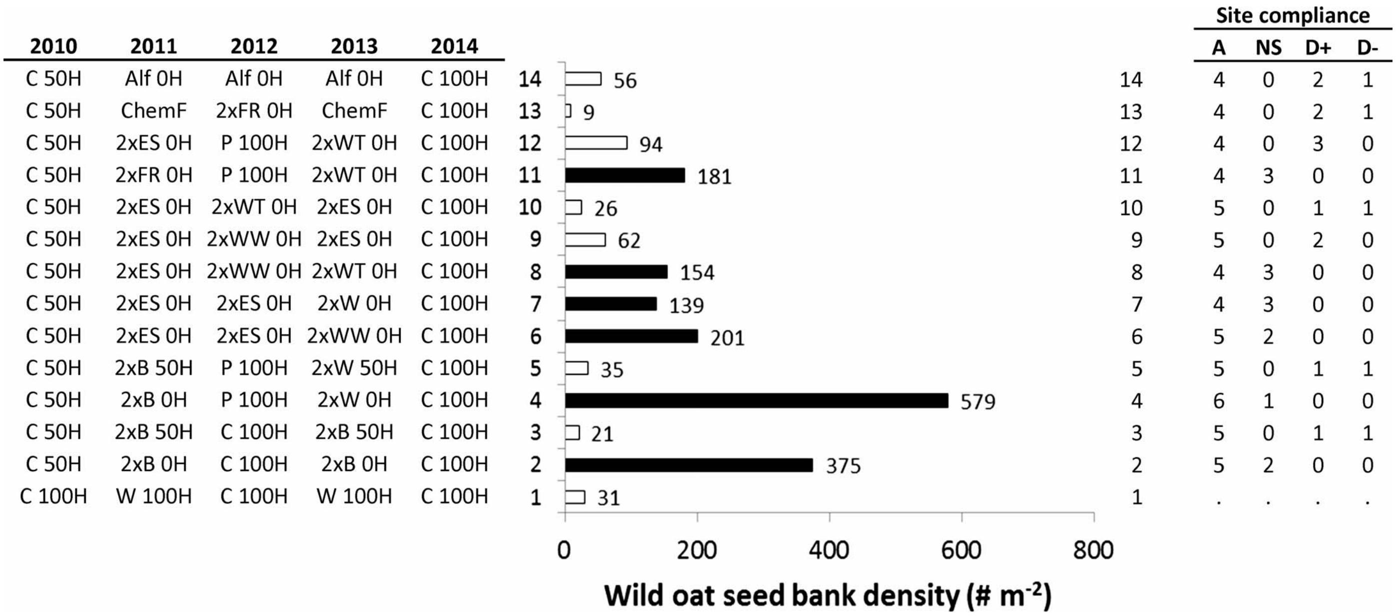

Figure 4. 2014 Wild oat seed bank density (across site means of seven sites) responses to crop life cycle, crop species, crop seeding rate, crop usage, and herbicide rate combination effects. "2 ×" indicates doubled crop seeding rate. C = canola, Alf = alfalfa, ChemF = chemical fallow, FR = fall rye, ES = early-cut barley silage, P = field pea, WT = winter triticale, WW = winter wheat, W = wheat, B = barley, H = herbicide. Canola in 2010 and 2012 was glufosinate-resistant. Canola in 2014 was glyphosate-resistant. Numbers preceding H indicate the percentage of recommended wild oat herbicide applied in a given year. Black bars indicate values significantly greater than the 100% wild oat herbicide, canola–wheat–canola–wheat–canola treatment (treatment 1). Site compliance indicates number of individual site contrasts to treatment 1 (canola-wheat-canola-wheat-canola) in agreement with across-site contrasts to treatment 1: A = agreement, NS = not significant when across-site contrast is significant, D+ = significant difference (same pattern) when across-site contrast is not significant, D− = significant difference (opposite pattern) when across-site contrast is not significant.

overall mean contrasts. As for 2014 wild oat density, treatment 7 was somewhat inconsistent. The overall mean response indicated higher levels of wild oat biomass in treatment 7 vs. treatment 1; site compliance indicated that biomass levels in treatment 7 were as low as in treatment 1 at two of the four sites (data not shown). Just as treatments 2 and 4 led to higher wild oat biomass in 2013 and wild oat density in 2014, the same treatments also failed to reduce 2014 wild oat biomass to levels similar to treatment 1.

2014 Wild Oat Seed Bank Density. In most respects, 2014 wild oat seed bank density responses to treatment effects were similar to 2014 wild oat plant density and biomass data. However, for wild oat seed density, fewer treatments reduced wild oat seed banks to levels similar to treatment 1 (Figure 4). Only two early-cut barley silage–winter cereal combination treatments (9 and 10) were as effective as treatment 1. Both of those treatments involved 2 yr of early-cut barley silage separated by 1 yr of a winter cereal. It appeared important to diversify selection pressure over time by separating early-cut silage treatments rather than employing them in consecutive years (treatments 6 and 7). Perennial alfalfa also effectively maintained wild oat seed banks at a relatively low level. At one site (Edmonton, data not shown), alfalfa reduced wild oat seed banks more than treatment 1 (site compliance, D-). O'Donovan et al. (2013) found that a combination of summer annual crop rotation with higher than normal barley seeding rates reduced wild oat seed bank levels compared to less optimal practices. Here, we demonstrate that including diverse crop life cycles (winter annual crops and perennial alfalfa) with summer annual canola, and strategically employing early-cut barley silage and 2 × seeding rates, will reduce wild oat growth and seed production enough to effectively manage wild oat seed banks.

One would expect that dormant wild oat seeds (Atwood 1914; Banting 1974; Beckie et al. 2012; Sharma et al. 1976; Thurston 1962a) would delay treatment effects since those seeds escape treatment imposition (plants are not available). Dormant seed bank effects may be envisioned by suggesting that weed seed banks have "memory" (Dekker 2013; Trewavas 1987); in this case, dormant seeds remaining in the seed bank during treatment selection only "remembered" environments prior to selection.

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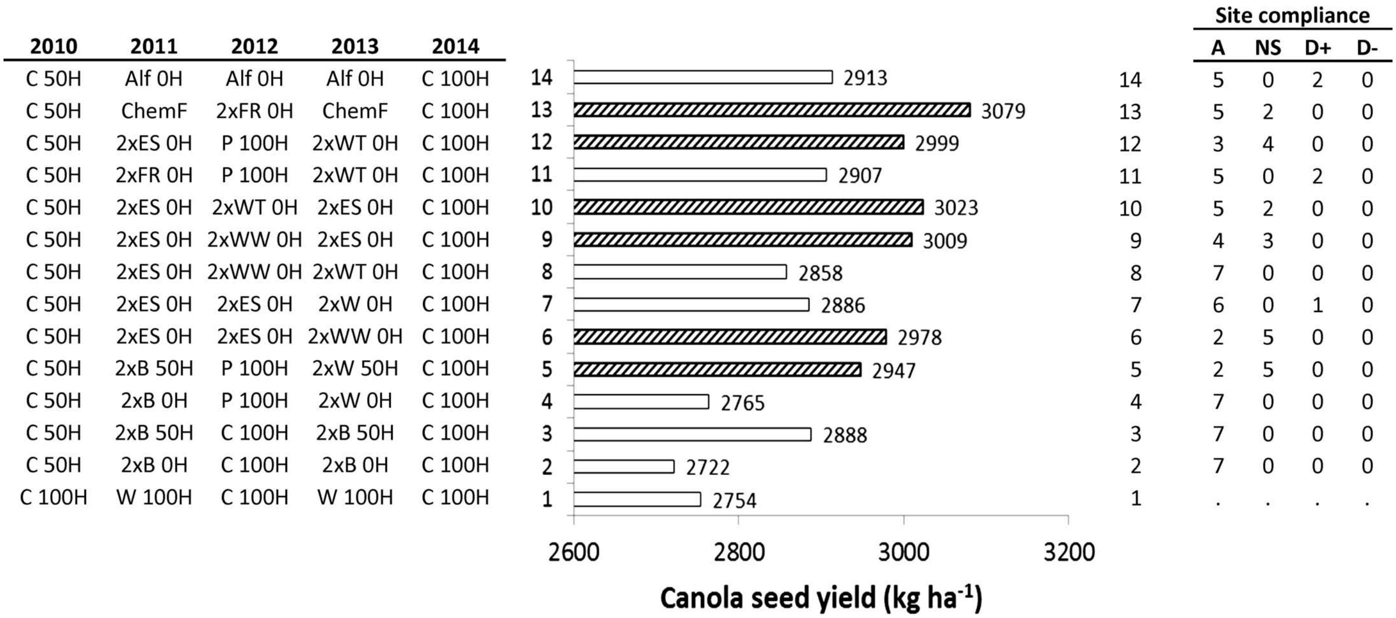

Figure 5. 2014 Canola seed yield (across site means of seven sites) responses to crop life cycle, crop species, crop seeding rate, crop usage and herbicide rate combination effects. 2× indicates doubled crop seeding rate. C = canola, Alf = alfalfa, ChemF = chemical fallow, FR = fall rye, ES = early-cut barley silage, P = field pea, WT = winter triticale, WW = winter wheat, W = wheat, B = barley, H = herbicide. Canola in 2010 and 2012 was glufosinate-resistant. Canola in 2014 was glyphosate-resistant. Numbers preceding H indicate the percentage of recommended wild oat herbicide applied in a given year. Bars with angled lines indicate values significantly greater than the 100% wild oat herbicide, canola–wheat–canola–wheat–canola treatment (treatment 1). Site compliance indicates number of individual site contrasts to treatment 1 (canola–wheat–canola–wheat–canola) in agreement with across-site contrasts to treatment 1: A = agreement, NS = not significant when across-site contrast is significant, D+ = significant difference (same pattern) when across-site contrast is not significant, D− = significant difference (opposite pattern) when across-site contrast is not significant.

Therefore, a more lengthy treatment imposition may have caused more treatments to reduce wild oat seed banks as well as treatment 1, and similar to wild oat density and biomass results. For the same reason, Harker et al. (2003) observed that early-cut silage and herbicide combination effects were sometimes most evident and beneficial in the third consecutive year of the silage treatments.

2014 Canola Seed Yield. Canola yield averaged 2,909 kg ha^{-1} across all sites and the site by treatment interaction variance percentage was very low (1%; Table 1). Generally, treatments including canola in 3 of 5 yr tended to yield lower than most other plots (Figure 5). High-frequency canola rotations have also failed to produce optimal canola yields in other studies (Harker et al. 2015; Johnston et al. 2005; O'Donovan et al. 2014). It is not surprising that treatment 13 had the highest numerical yield of all plots given greater soil moisture levels following chemical fallow and the likelihood of higher available nitrogen levels in the absence of cereal crop residues (i.e., less nitrogen immobilization). However, chemical fallow with glyphosate can impose a high amount of selection pressure for glyphosate-resistant weeds (Beckie et al. 2015).

Three of five treatments involving 2× seeding rates of winter cereals and 2× seeding rates of early-cut silage with no wild oat herbicide for three consecutive years (treatments 6, 9, 10) led to higher canola yields than repeated canola–wheat in a normal herbicide regime (Figure 5). The two remaining treatments having greater yields than treatment 1 (treatments 5 and 12) may have benefited from the relatively slow release of residual nitrogen from field pea residues (O'Donovan et al. 2014). Other treatments including field peas may have been negatively affected by a lack of wild oat herbicide in 2011 and 2013 (treatment 4) or had relatively high wild oat seed banks (treatment 11) (Figure 4). However, it is notable that treatment 11 did yield higher than treatment 1 at two of seven sites. Across-site means for treatments 5 and 6 were greater than treatment 1, while only two of seven sites had the same significant pattern. The latter demonstrates increased experimental power to detect differences with sites treated as random effects (Carmer and Walker 1988).

Canola following alfalfa (treatment 14) only yielded higher than treatment 1 at two of seven sites (across-site yield means were similar) (Figure 5). Canola was more difficult to establish following terminated alfalfa stands due to drier and less physically

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uniform soil conditions. Given the fact that one application of in-crop glyphosate in 2014 provided a high level of weed control (Figure 3), these data suggest that 2014 canola yields were probably not related to different levels of weed control in previous years as much as other factors such as canola rotation frequency and soil moisture and nitrogen levels. Nevertheless, canola yields in treatments that included no wild oat herbicide for three consecutive years (treatments 6 to 10, 14) were never less than the canola–wheat rotation under a full wild oat herbicide rate regime, and were often greater.

2014 Canola Oil and Protein Concentrations. Although treatment effects were significant for canola oil and protein concentrations (Table 1), there were no important differences among treatments relative to treatment 1. The oil concentration mean was 44.6% and ranged from 44.3 to 44.9%. The protein concentration mean was 22.2% and ranged from 21.9 to 22.7%. Treatments 13 and 14 both had higher protein concentrations (22.7%) than treatment 1 (22.0%) (data not shown). Decomposing alfalfa residues may have been responsible for higher canola protein levels in treatment 14; we have no explanation for treatment 13 effects. Site by treatment variance as a percentage of the sum of all variance estimates that included site was only 2% for oil and 1% for protein concentration (Table 1).

Management Implications. The most obvious method of reducing selection pressure for weed resistance to herbicides is to reduce herbicide use (Harker et al. 2012). Ironically, the most commonly recommended weed resistance management strategies involve more herbicide use such as an array of preplant or PRE residual herbicides; tank mixtures of different, effective herbicide modes of action; and the rotation of different herbicide mode-of-action groups over time (Norsworthy et al. 2012). Multistacked herbicide-resistant crops are also recommended for herbicide-resistance management (Green 2009). These herbicidal techniques may effectively delay weed resistance to herbicides in the short term, but will also select for multiple resistances in the long term (Duke 2012; Heap 2015).

Several of the cultural weed control systems described here precluded herbicide selection pressure for 3 yr without negative wild oat population and crop interference implications. Similar herbicide use reductions without negative weed population or economic consequences have also been demonstrated in a different cropping system regime (Davis et al. 2012). In both cases, it is notable that a combination of techniques over time, also described as "little hammers" (Liebman and Gallandt 1997), are important to ecologically manage weeds where "multiple and more subtle impacts on biological processes" are imposed (Maxwell 1999). Suppressing wild oat with alfalfa and winter cereal crops was practiced extensively before the advent of selective wild oat herbicides (Brown 1953); it is now prudent to resume implementation of those practices as well as other alternatives to herbicides. Implementation will be a challenge given that fact that growers "understand but do not practice IWM" (Wilson et al. 2009) or only adopt diverse weed management tactics in a limited fashion (Owen et al. 2015).

In future years, it will still be important to employ the most widely recommended herbicide resistance management strategies such as herbicide tank-mixtures with different, effective herbicide mode-of-action groups. However, it is important to research and implement alternative weed control strategies that preserve herbicide efficacy for long periods. Perennial crops such as alfalfa can be inserted in diverse cropping systems with little or no herbicide resistance selection pressure. Similarly, doubled seeding rates of winter cereals combined with doubled seeding rates of early-cut barley silage are also tools that can be used to preclude selection pressure for weed resistance to herbicides and to preserve the effective life of valuable herbicide tools, apparently relatively nonrenewable resources (Duke 2012). For those with current herbicide-resistant weed populations, these techniques may also provide weed management where herbicides are no longer efficacious.

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