The profitability of diverse crop rotations and other cultural methods that reduce wild oat (Avena fatua)1

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ARTICLE

The profitability of diverse crop rotations and other cultural methods that reduce wild oat (*Avena fatua*)[1]

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Abstract: With the increasing resistance of wild oat (*Avena fatua* L.) to herbicides, there is a need to evaluate the potential of alternative cropping systems based on integrated weed management principles. A 5-yr field study at eight sites across Canada was used to evaluate the profitability of alternative cropping systems that have the potential to control wild oat using cultural practices in conjunction with herbicides. Cultural practices included twice the recommended seeding rates, fall-seeded winter crops, barley (*Hordeum vulgare* L.) silage, fallow, and alfalfa (*Medicago sativa* L.). Seven of the 14 cropping systems in this study did not include wild oat herbicide for three consecutive years, controlling wild oat entirely by cultural practices. Cropping system profitability varied by location. For many locations, combinations of barley silage and fall-seeded winter crops without wild oat herbicide application were as profitable as a system of canola (*Brassica napus* L.) and wheat (*Triticum aestivum* L.) with wild oat herbicide applied every year. Unprofitable systems generally included those with fallow, alfalfa, and fall-seeded winter crops in regions with rates of high winter kill. Wild oat control can be achieved with diverse cropping systems that are as profitable as conventional annual cropping that relies on herbicide control of wild oat.

Key words: wild oat, herbicide resistance, cropping systems, net return.

Résumé : Face à la résistance grandissante de la folle avoine (*Avena fatua* L.) aux herbicides, il est impérieux d'évaluer l'utilité d'autres systèmes culturaux s'appuyant sur les principes de la lutte intégrée contre les mauvaises herbes. Les auteurs ont procédé à une étude sur le terrain de cinq ans, à huit endroits du Canada, pour déterminer la rentabilité d'autres systèmes culturaux susceptibles de faciliter la lutte contre la folle avoine en combinant des pratiques agronomiques à l'usage d'herbicides. Les pratiques culturales comprenaient l'ensemencement au double du taux recommandé, l'ensemencement de cultures d'hiver à l'automne, la culture d'orge (*Hordeum vulgare* L.) d'ensilage, la jachère et la culture de luzerne (*Medicago sativa* L.). Sept des quatorze systèmes examinés n'incluaient pas l'usage d'herbicides contre la folle avoine durant trois années consécutives, la lutte contre l'adventice étant assurée en entier par les pratiques culturales. La rentabilité du système varie selon l'emplacement. À de nombreux sites, combiner l'orge d'ensilage à l'ensemencement automnal de cultures d'hiver sans application d'herbicide contre la folle avoine s'avère aussi

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rentable qu'un système incluant la culture du canola (*Brassica napus* L.) et du blé (*Triticum aestivum* L.) avec application annuelle d'herbicide contre la folle avoine. Les systèmes non rentables étaient habituellement ceux incluant la jachère, la culture de la luzerne et l'ensemencement des cultures d'hiver en automne dans les régions où le gel est particulièrement meurtrier. On peut lutter contre la folle avoine en recourant à divers systèmes culturaux aussi profitables que les cultures annuelles, qui exigent une lutte chimique contre l'adventice. [Traduit par la Rédaction]

Mots-clés : folle avoine, résistance aux herbicides, systèmes culturaux, revenu net.

Introduction

Wild oat (*Avena fatua* L.) is a major weed in annual cropping systems on the northern Great Plains. Prior to herbicide options for wild oat control, cultural practices to manage wild oat were primarily fallow tillage, late seeding of spring crops, fall-seeded winter crops, and perennial forages (Brown 1953). In the past two or three decades, wild oat has been primarily controlled with annual applications of acetyl-CoA carboxylase (ACCase) or acetolactate synthase (ALS) inhibiting herbicides (mechanism of action group 1 or 2). Fallow has been nearly eliminated from cropping systems. With annual use of one or two herbicide groups for wild oat control, wild oat populations have become increasingly resistant to these herbicide groups (Heap 2017). Some alternative chemistry options for wild oat control are available, but their continual use also creates selection pressure for wild oat resistance. Wild oat resistance to one or more herbicide groups requires alternative management approaches for its control, such as integrated weed management (IWM). For barley (*Hordeum vulgare* L.), double seeding rates and competitive cultivars improved barley productivity by suppressing wild oat and increasing barley yield (O'Donovan et al. 2000). Wild oat seed production was lower when barley was seeded at double the recommended seed rates with taller and more competitive cultivars (Harker et al. 2009). Growing silage barley reduced wild oat densities (Harker et al. 2003).

Wild oat control using IWM would combine cultural practices, such as seeding rates, crop rotation, fall-seeded winter crops, tillage, and harvesting the wild oat infested crop as silage or cereal hay, with judicial herbicide application. These IWM systems would rely less on herbicides and more on long-term cultural management practices to control wild oat and other weeds. The objective of this study was to evaluate the profitability of some potential IWM cropping systems for wild oat control in the northern Great Plains. In the absence of profitability data, producers unfamiliar with cultural systems for wild oat control are unlikely to adopt these systems, fearing a reduction to their net income.

Material and Methods

Field study

A field study at eight locations in Canada was run from 2010 through 2014 (Harker et al. 2016). Six of the sites were in the prairies of western Canada (Edmonton, Lacombe, and Lethbridge, AB; Scott and Saskatoon, SK; Carman, MB) and two were in eastern Canada (New Liskeard, ON; Normandin, QC). The study used a randomized complete block design with 14 cropping system treatments and four replications (Table 1). Wild oat seeds were applied at 200 seeds m^{-2} prior to commencement of the study to supplement the seed bank population. Weeds were controlled prior to seeding with an application of glyphosate (450–900 g a.e. ha^{-1}). Fertilizer was applied based on soil test recommendations, with monoammonium phosphate applied with the seed and all other fertilizer side-banded 2 cm beside and 3 to 4 cm below the seed. In-crop wild oat herbicide was applied at 0%, 50%, or 100% of the recommended rate, depending on the cropping system treatments, and seeding rate was either the recommended rate or two times the recommended rate. Other weeds, primarily in-crop broadleaf weeds, were controlled with appropriate herbicides at recommended rates. Crops included in the study were canola (*Brassica napus* L.), spring and winter wheat (*Triticum aestivum* L.), barley (*H. vulgare*), winter triticale (× *Triticosecale* Wittm.), fall rye (*Secale cereal* L.), field pea (*Pisum sativum* L.), and alfalfa (*Medicago sativa* L.). Barley silage was swathed and harvested a few days after head emergence (early-cut) to ensure wild oat plants would not produce viable seed. Alfalfa was mowed at early flowering for baling. In the alfalfa establishment year, a cut was taken, but most of the forage was wild oat. Harvested forage plant material was removed from the field and a subsample was collected, weighed, and dried prior to determining dry weight. Grain crops were swathed when mature and harvested by a plot combine. In 2013, the alfalfa was terminated in late August, after the second cut, with an application of clopyralid (98 g a.e. ha^{-1}) and glyphosate (450 g a.e. ha^{-1}). While clopyralid was effective, it was a high-cost alternative. Plant and wild oat density measurements were taken in the field study and were reported by Harker et al. (2016). Field operations were similar across locations, but tillage and seed bed preparation were more intensive at Normandin.

System profitability

The analysis of profitability from the different cropping systems was determined as the annualized net present value (NPV) of returns over the 5 yr, and to include the Lethbridge location, the NPV for the last 4 yr was also determined. The NPV was the sum of the net return for each year, discounted by 5%. This provided a uniform income measure over time to compare the cropping systems. Comparison of cropping systems in each year was not appropriate due to different crops

Table 1. Cropping systems, crop, and weed control by year.

System	2010	2011	2012	2013	2014
1	C, 100H	W_S, 100H	C, 100H	W_S, 100H	C, 100H
2	C, 50H	B_G(x2), 0H	C, 100H	B_G(x2), 0H	C, 100H
3	C, 50H	B_G(x2), 50H	C, 100H	B_G(x2), 50H	C, 100H
4	C, 50H	B_G(x2), 0H	P, 100H	W_S(x2), 0H	C, 100H
5	C, 50H	B_G(x2), 50H	P, 100H	W_S(x2), 50H	C, 100H
6	C, 50H	B_S(x2), 0H	B_S(x2), 0H	W_W(x2), 0H	C, 100H
7	C, 50H	B_S(x2), 0H	B_S(x2), 0H	W_S(x2), 0H	C, 100H
8	C, 50H	B_S(x2), 0H	W_W(x2), 0H	T_W(x2), 0H	C, 100H
9	C, 50H	B_S(x2), 0H	W_W(x2), 0H	B_S(x2), 0H	C, 100H
10	C, 50H	B_S(x2), 0H	T_W(x2), 0H	B_S(x2), 0H	C, 100H
11	C, 50H	B_S(x2), 0H	P, 100H	T_W(x2), 0H	C, 100H
12	C, 50H	R_F(x2), 0H	P, 100H	T_W(x2), 0H	C, 100H
13	C, 50H	Chem fallow	R_F(x2), 0H	Chem fallow	C, 100H
14	C, 50H	Alfalfa, 0H	Alfalfa, 0H	Alfalfa, 0H	C, 100H

Note: C, canola; H, percent of recommended wild oat herbicide applied; W_S, spring wheat; B_G, barley grain; x2, seeding rate is twice the recommended rate; P, field pea; B_S, early-cut barley silage; W_W, winter wheat; T_W, winter triticale; R_F, fall rye.

across systems from 2011 to 2013. Net return over all years of the system captured the benefits and costs of a specific crop, seeding rate, or wild oat herbicide rate on the current as well as subsequent crops, including canola in 2014. For crop budgeting, 2016 production costs were used, and commodity prices used were a 6 yr average (2009–2014) (Table 2). The price for barley silage was proportional to barley grain [Alberta Agriculture and Forestry (AAF) 2017]. The earlier stage of harvest could alter the silage quality; however, the price of cereal hay was similar to silage on a dry weight basis. The cost of seed was about 15% higher than the commodity price, except alfalfa seed was \$4.15 kg^{-1} and hybrid canola seed was about \$26 kg^{-1}, depending on the hybrid and herbicide tolerance technology (AAF 2015*b*). Field operation costs for spraying, seeding, harvesting, ensiling barley, mowing/conditioning, raking, baling, and hauling bales were obtained from a farm machinery cost calculator (AAF 2015*d*). Baling cost was for a large round baler, with two swaths from the mower/conditioner raked into one for baling. Baling and bale hauling, and silage harvesting and ensiling costs, were yield-dependent.

Statistical analysis

The annualized net return data were analyzed by analysis of variance using PROC MIXED in SAS (SAS Institute Inc. 2017). The New Liskeard site was excluded from the analysis because Swede midge in 2010 and 2014 decimated the canola crop. Lethbridge did not have data for 2010, so it was included in a 4 yr analysis that included only years 2011 through 2014. The initial study year (2010) should not have cropping system effects and the last 4 yr could be viewed as on-going cropping systems with canola every fourth year. It was expected that over the diverse range of locations in this study, crop yield and wild oat densities could be location-dependent. The fixed effects in the statistical analysis were cropping system treatment, location, and their interaction. The random effect was replicate, nested within location. The Bonferroni adjustment was used for the treatment probability level comparisons to reduce type I errors. Experimental plots were on the same field site each year, but because the annualized net return was a sum of yearly net returns, there was no need to account for repeated measures. Contrasts of similar based treatments were constructed to compare treatment groupings. Comparisons of systems included fall-seeded winter cereals vs. spring cereal grains and oilseeds; silage vs. no silage; diversified (silage, fall-seeded winter cereals, fallow) vs. spring cereal grains and oilseeds; winter wheat and triticale vs. spring cereal grains and oilseeds; and diversified systems vs. conventional canola–wheat cropping.

Results

Canola net return

In 2010, there was a significant location ($p < 0.0001$) and treatment ($p = 0.003$) effect on net return (data not shown). Net return (\$ ha^{-1}) by location was Lacombe (1998) > St. Albert (1133) ≥ Scott (942) ≥ Normandin (794) ≥ Carman (576) ≥ Saskatoon (436). The canola net return for treatment 1 (W_SCW_S) was less than or equal to all other treatments because a different hybrid was used the first year of this treatment that yielded lower for all sites except Normandin. The lower yield from the different hybrid resulted in lower 2010 net return (\$230 ha^{-1}) or a 5 yr annualized net return of \$42 ha^{-1} ($p = 0.002$). The remaining 2010 treatments had similar net return (same treatments in the first year).

Table 2. Commodity prices and production costs.[a]

Item	Price or cost	Units
Commodity prices		
Wheat (HRS)	242	$ Mg^{-1}
Wheat (WW)	203	$ Mg^{-1}
Canola	510	$ Mg^{-1}
Barley grain	214	$ Mg^{-1}
Barley silage	64	$ Mg^{-1} dry matter
Field pea (yellow)	256	$ Mg^{-1}
Rye	238	$ Mg^{-1}
Triticale	238	$ Mg^{-1}
Alfalfa–cereal hay	64.20	$ Mg^{-1}
Alfalfa	122	$ Mg^{-1}
Selected input costs		
Nitrogen	1.08	$ kg^{-1}
Phosphorus (P_2O_5)	0.58	$ kg^{-1}
2,4-D B	28.37	$ L^{-1}
Clethodim	39.13	$ L^{-1}
Cloypyralid	143.00	$ L^{-1}
Glufosinate-ammonium	8.30	$ L^{-1}
Glyphosate (540)	6.40	$ L^{-1}
Imazamox	1.16	$ g^{-1}
MCPA (600 ester)	9.50	$ L^{-1}
Merge	6.42	$ L^{-1}
Pinoxaden	34.00	$ L^{-1}
Pyrasulfotole + bromoxynil	16.75	$ L^{-1}
Pyroxsulam	81.13	$ L^{-1}
Machinery costs		
Seed	30.57	$ ha^{-1}
Spray + water truck	9.79	$ ha^{-1}
Swath	42.16	$ ha^{-1}
Combine	95.58	$ ha^{-1}
Mower/conditioner	43.29	$ ha^{-1}
Rake	17.54	$ ha^{-1}
Silage (chop, haul, and pack)	11.50	$ Mg^{-1} wet
Baler	20.16	$ Mg^{-1}
Bale hauling	5.89	$ Mg^{-1}
Plow (Normandin)	66.51	$ ha^{-1}
Harrow (Normandin)	8.45	$ ha^{-1}
Spreader (Normandin)	13.34	$ ha^{-1}

[a]Data sources included Alberta Agriculture and Forestry (2015*a*, 2015*b*, 2015*c*, 2015*d*) and Government of Saskatchewan (2016).

In 2014, net return was influenced by treatment, location, and interaction ($p < 0.001$). Net return ($ ha^{-1}) by location was Lethbridge (1091) = Lacombe (1023) = St. Albert (1003) > Normandin (563) = Scott (541) ≥ Saskatoon (346) > Carman (−439). Previous systems, as dictated by the treatments, influenced canola production and net return (Table 3). The significant location × treatment interaction that occurred was primarily because Normandin and Carman (where canola received hail in 2014) differed from the other five locations. Canola on fallow and after alfalfa had the highest average net return, but was not different from some other previous land uses. Net return for 2014 was lowest when the previous crop was a cereal grain without the application of wild oat herbicide and was not different from the base system of canola–wheat with a full rate of wild oat herbicide. Contrasts based on system commonalities were used to identify differences resulting from the systems. In 2014, there was no difference in canola net returns when the 2013 systems were spring wheat or barley grain grown without wild oat herbicide [treatments 2 (B_GCB_G) and 4 (B_GPW_S)]. With a 50% rate of wild oat herbicide in 2013 applied to spring cereals, the net return in 2014 was $96 ha^{-1} higher ($p = 0.003$) than no wild oat herbicide in 2013. The cropping systems without wild oat herbicide for three consecutive years utilizing barley silage, fall-seeded winter crops, fallow, and alfalfa had a net return from canola in 2014 that was $77 ha^{-1} ($p < 0.0001$) higher than systems that used wild oat herbicide control at least once from 2011 to 2013. Without the fallow and alfalfa cropping systems, the net return difference was $47 ha^{-1} ($p = 0.002$). Finally, without wild oat herbicide for three consecutive years, the canola net return in 2014 was $48 ha^{-1} higher than annual spring cropping with herbicide control [treatments 1 (W_SCW_S), 3 (B_GCB_G), and 5 (B_GPW_S)]. Wild oat density in 2013 and 2014 for the systems with barley silage and fall-seeded winter crops from 2011 to 2013 were similar to canola–wheat cropping with wild oat herbicides (Harker et al. 2016). Canola production

Table 3. Average annualized net return ($ ha^{-1} yr^{-1}) over locations and for 5 and 4 yr, the 2014 canola net return, and the 4-yr annualized net return for Lethbridge, by cropping system.

System	5 yr	4 yr[a]	2014 canola	Lethbridge
1 W_SCW_S	385e	355cdef	486de	657abc
2 B_GCB_G	398de	334efg	467e	568cde
3 B_GCB_G	470abcd	426ab	562bcde	721a
4 B_GPW_S	408cde	300fg	501de	459fg
5 B_GPW_S	447bcde	387bcde	603abcd	610bcd
6 $B_SB_SW_W$	524a	468a	611abcd	666ab
7 $B_SB_SW_S$	504ab	442ab	553cde	607bcd
8 $B_SW_WT_W$	415cde	341defg	550cde	594bcde
9 $B_SW_WB_S$	478abc	417abc	640abc	642abc
10 $B_ST_WB_S$	493ab	406abcd	637abc	546def
11 R_FPT_W	416cde	330efg	593bcde	448g
12 B_SPT_W	471abc	397bcd	646abc	517defg
13 $F_CR_FF_C$	379e	281g	724a	502efg
14 AAA	415cde	328efg	680ab	461fg

Note: Means within a column not sharing a lowercase letter differ significantly at the $p < 0.05$ level. Crops for the middle 3 yr were reported in the system column as the first and fifth year was canola for all systems. C, canola; W_S, spring wheat; B_G, barley grain; P, field pea; B_S, early-cut barley silage; W_W, winter wheat; T_W, winter triticale; R_F, fall rye; F_C, chemical fallow; A, alfalfa. Seeding rate and wild oat herbicide rates are listed in Table 1.

[a]The 4-yr analysis was for the last 4 yr, allowing one more site to be included in the analysis.

Table 4. Average annualized 5-yr net return ($ ha^{-1} yr^{-1}) by location and cropping system.

System	Carman	Lacombe	Normandin	Saskatoon	Scott	St. Albert
1 W_SCW_S	−66ef	982a	379abc	107h	240e	668ab
2 B_GCB_G	−81f	936abcd	349bc	263cdef	245e	675ab
3 B_GCB_G	26cdef	1013a	339bc	334bc	384cd	730a
4 B_GPW_S	48de	879bcde	433ab	217efg	276de	597bc
5 B_GPW_S	−5ef	981a	389abc	239defg	417bc	664ab
6 $B_SB_SW_W$	180abc	971ab	455a	389ab	496ab	652ab
7 $B_SB_SW_S$	209ab	842de	429ab	447a	411bc	687ab
8 $B_SW_WT_W$	161abcd	948abc	351bc	189fgh	362cd	480d
9 $B_SW_WB_S$	222ab	861cde	334c	291bcde	505ab	655ab
10 $B_ST_WB_S$	257a	928abcd	375abc	200efgh	548a	650ab
11 R_FPT_W	174abc	878bcde	361abc	206efg	388c	489cd
12 B_SPT_W	130bcd	933abcd	374abc	331bcd	389c	669ab
13 $F_CR_FF_C$	191ab	669f	367abc	168gh	425bc	454d
14 AAA	206ab	816e	409abc	150gh	393c	516cd

Note: Means within a column not sharing a lowercase letter differ significantly at the $p < 0.05$ level. Crops for the middle 3 yr were reported in the system column as the first and fifth year was canola for all systems. C, canola; W_S, spring wheat; B_G, barley grain; P, field pea; B_S, early-cut barley silage; W_W, winter wheat; T_W, winter triticale; R_F, fall rye; F_C, chemical fallow; A, alfalfa. Seeding rate and wild oat herbicide rates were listed in Table 1.

benefited from crop sequencing and the legacy of wild oat control.

Annualized 5-yr net return

The annualized 5-yr net return from the treatments in this study indicated that there were differences from cropping system treatment, location, and their interaction ($p < 0.0001$). Because of the significant location × treatment interaction, the annualized net returns were presented by location and treatment (Table 4). The annualized net returns ($ ha^{-1} yr^{-1}) by site were ranked Lacombe (903) > St. Albert (613) > Scott (391) = Normandin (382) > Saskatoon (252) > Carman (118). Systems tended to be more profitable when they included either barley silage, barley grain in conjunction with wild oat control, or fall-seeded winter crops when there was not winter kill. The least profitable systems included the canola–wheat crop, chemical fallow, alfalfa, and when annual spring cereals did not use wild oat control.

The annualized net return for Carman was reduced by hail in 2014 and the low return from the canola crop that year. At Carman, low yield for the grain-only cropping systems [treatments 1–5 (W_SCW_S, B_GCB_G, B_GCB_G, B_GPW_S, and B_GPW_S)] in 2012, barley and spring wheat without wild oat control in 2013 [treatments 2 (B_GCB_G) and 4(B_GPW_S)], and some of the fall-seeded winter crops also contributed to lower net return. In 2013, the winter wheat in treatment 6 ($B_SB_SW_W$) was re-seeded to spring wheat because of winter kill, increasing costs. The more profitable cropping systems at Carman included barley silage, chemical fallow, and alfalfa.

Eight of the 14 systems at Lacombe had equal highest significantly annualized net returns (Table 4). Systems that were less profitable included chemical fallow, alfalfa, and when the spring wheat crop in 2013 did not have wild oat control [treatment 7 ($B_SB_SW_S$)]. Return was lower in 2014 when there was no wild oat control in 2013. Canola production after a spring cereal grain that did not receive wild oat control tended to have lower yield and return. The more profitable cropping systems included canola–wheat and canola–cereal and some of the diversified cropping systems [treatments 6 ($B_SB_SW_W$), 8 ($B_SW_WT_W$), 10 ($B_ST_WB_S$), and 12 (B_SPT_W)]. Three of these four systems did not use wild oat herbicides from 2011 to 2013. Winter wheat in 2012 had low yield, but in 2013, the fall-seeded winter crops were higher yielding and profitable.

At the Normandin location, there was little difference in the annualized net return by treatment. Treatments 2 (B_GCB_G), 3 (B_GCB_G), 8 ($B_SW_WT_W$), and 9 ($B_SW_WB_S$) had the lowest return, primarily due to low yield in 2012 for canola (treatments 2 and 3) and winter crops (treatments 8 and 9) (Table 4). There was a net loss from field pea production in 2012, but returns from the following crops were higher and covered most of the loss from the field pea. Alfalfa was a profitable option because of high yields in 2012 and 2013. Alfalfa in the cropping system was a viable option for this site.

At Saskatoon, treatments 6 ($B_SB_SW_W$) and 7 ($B_SB_SW_S$) with barley silage were more profitable than most of the other systems. These systems did not use wild oat herbicides from 2011 to 2013. The least profitable systems included canola–wheat cropping, chemical fallow, alfalfa production, and, depending on the year, fall-seeded winter crops. The annualized net return from the canola–wheat system was one-quarter to one-third that of the more profitable systems.

The annualized net return for the Scott location had some similarities across systems as the Saskatoon site. The canola–wheat and canola–cereals systems, alfalfa, and some of the fall seeded winter crops were the least profitable cropping systems. The net return for the canola–wheat system was about one-half that of the more profitable systems (Table 4). In 2012, all crops except barley silage, fall rye, and alfalfa had a negative net return because of low yields. Fall rye was planted on fallow in 2012. In 2013, winter triticale, alfalfa, and barley silage had higher returns than the other crops. Despite the good returns in 2012 after fallow and alfalfa returns in 2013, the annualized net return was lower for these systems because of lower returns in other years.

At St. Albert, nine of the 14 cropping systems had comparable high annualized net returns (Table 4). Net return was reduced by not controlling wild oat in wheat [treatment 4 (B_GPW_S)] or by including fallow or alfalfa in the cropping system. Winter wheat and winter triticale had low returns in 2012 and 2013. Treatment 8 ($B_SW_WT_W$) had these crops in 2012 and 2013 and the net return was negative those years for the treatments. Fall rye net return was less than most other crops, especially in 2011, reducing the annualized net return for treatment 11 (R_FPT_W). Fall-seeded winter crops were not profitable cropping options at this location.

Contrasts by location indicated that at Normandin, none of the contrasts were significant. St. Albert and Lacombe had similar results, as did Saskatoon, Scott, and Carman. At Lacombe and St. Albert, the systems with annual spring-seeded grain crops only [treatments 1–5 (W_SCW_S, B_GCB_G, B_GCB_G, B_GPW_S, and B_GPW_S)] had higher annualized net returns (\$50 ha^{-1} yr^{-1}, $p < 0.01$) than the cropping systems with barley silage and (or) fall-seeded winter crops. A system with alfalfa was less profitable (\$160 ha^{-1} yr^{-1}, $p < 0.001$) than a canola–wheat rotation. For these two locations, the canola–wheat system was at least as profitable as the cropping system alternatives in this study that used no wild oat herbicides for three consecutive years. At the other three locations, systems with only annual spring-seeded grain crops had lower net returns than systems with fall-seeded crops or barley silage when wild oat herbicide was not applied (\$62–\$195 ha^{-1} yr^{-1}, $p = 0.006$ to $p < 0.0001$). The canola–wheat system for these locations was one of the least profitable cropping systems. The alfalfa cropping system had a similar net return to the canola–wheat crop at Saskatoon, but was more profitable than canola–wheat at Scott (\$155 ha^{-1} yr^{-1}, $p = 0.009$) and Carman (\$265 ha^{-1} yr^{-1}, $p < 0.0001$).

Annualized 4-yr net return

Analyzing only the last 4 yr of the study allowed the Lethbridge location to be included because it had missing data for 2010. The 4-yr results might also be considered as ongoing systems with canola every fourth year for 11 of the systems [all except treatments 1–3 (W_SCW_S, B_GCB_G, and B_GCB_G)] and every second year for treatments 1–3. The cropping system, location, and interaction were significant in explaining the annualized net returns ($p < 0.0001$). The 4-yr annualized net return across all locations was lower (average of \$71 ha^{-1} yr^{-1}) than the 5-yr value because canola was highly profitable in 2010. The cropping system rankings of net return were very similar for the 5- and 4-yr values. Cropping systems of canola every second year with wild oat herbicides and of barley silage and winter wheat without wild oat herbicides were the more profitable systems at Lethbridge (Table 3). As was observed for Lacombe and St. Albert, the canola–cereal grain cropping systems at Lethbridge were among the more profitable systems. Systems with alfalfa, fallow, field pea, and winter triticale had lower annualized net returns. The fall-seeded crops at Lethbridge were as profitable as canola in 2012 and more profitable than barley silage or field pea. In 2013, winter wheat was the most profitable crop and winter triticale had similar net returns to other crops (data not shown). Barley silage and fall-seeded winter crops at Lethbridge were profitable cropping options at Lethbridge that did not require wild oat herbicides.

Discussion

Many of the cropping systems specified in this study were at least as profitable as the standard canola–wheat system used by many producers. Moreover, at most locations, barley silage and either winter or spring wheat without herbicides to control wild oat had net returns similar to another cycle of canola–wheat with herbicidal control of wild oat. Canola–wheat had a net return similar to other high-return systems at about one-half of the sites, but at other sites, canola–wheat was less profitable. The profitability of the cropping systems and the crops with the systems was dependent on location. Fall-seeded winter crops of rye, wheat, and triticale were more profitable crops at Lethbridge and Normandin and could be recommended as interval crops between canola. Fall-seeded winter crops at Lacombe, Scott, Saskatoon, and Carman generally had similar returns as other crops, but were inconsistent possibly due to lower winter survival. At St. Albert, fall-seeded winter crops were less profitable than spring cropping options. Field pea by itself was less profitable, other than at Lacombe, but might have contributed to the subsequent crop being more productive. Indeed, cropping systems with pea were among the more profitable systems at locations other than Saskatoon, Scott, and Lethbridge. Crops after an annual legume have been reported to have higher yield (O'Donovan et al. 2014). Chemical fallow in the cropping system reduced net returns, although the reduction was lower at Carman and Normandin. Carman and Normandin were also the only two locations where alfalfa production was as profitable as the other cropping systems. Establishing alfalfa for only 2 yr of production was not as profitable as other crops. However, canola returns in 2014 after alfalfa were generally high and the wild oat population was low (Harker et al. 2016). Yearly alfalfa returns can be high once the crop is established, but there was a cost and forgone income to establish the alfalfa stand and a cost to terminate the alfalfa. The alfalfa price would need to be about 60% higher for the alfalfa cropping system to have comparable net returns to the most profitable cropping systems. Alfalfa might be more profitable, for example, if established using barley silage as a companion crop. Income would not be foregone the establishment year and the alfalfa would have time after the silage harvest to grow and establish without competition from the companion crop.

It is well-documented that canola yields improve in more diverse cropping systems (Johnston et al. 2005; Sieling et al. 1997; O'Donovan et al. 2014; Harker et al. 2015). The net return differences reported for 2014 were due to yields being influenced by previous cropping and wild oat control. Compared with the base system of canola–wheat, canola yield in 2014 was 261 kg ha^{-1} ($p < 0.0001$) higher when the preceding crop was either silage barley or fall-seeded winter crops. These systems also had higher yield than spring wheat or barley grain systems without wild oat herbicide application (210 kg ha^{-1}, $p < 0.0001$). Canola yield was 215 kg ha^{-1} ($p = 0.0006$) higher after chemical fallow or alfalfa. Growing crops that require less herbicide prolongs the useful life of valuable herbicide tools and facilitates long-term cropping system sustainability. The higher canola yields in 2014 were associated with cropping systems that did not apply wild oat herbicide from 2011 to 2013, but managed wild oat by cultural practices. Davis et al. (2012) also found that weed populations, yields, and profits could be maintained in less herbicide-intensive cropping systems.

Silage was generally profitable in this study. For many producers, the production of silage might not be an option because they do not have a nearby market to sell the silage or they do not raise and feed cattle. Owning forage harvest equipment, or access to custom operators, could also be a deterrent. When silage price was discounted by 25% because of limited local markets for silage, all cropping systems with barley silage had lower annualized net returns (data not shown). At Carman and Normandin, the ranking of the cropping systems was similar compared with the full price for silage. At Lacombe, St. Albert, and Lethbridge, discounted barley silage systems were less profitable than grain-only systems, including canola–wheat. At Scott and Saskatoon, many of the systems with silage had the highest annualized net returns at the lower silage price and were greater than the canola–wheat cropping system. Including barley silage in a cropping system will depend on local marketing options for the silage as well as crop productivity.

For many regions in Canada, wild oat can be managed by rotating with crops such as silage and fall-seeded winter crops. Cultural practices can reduce the requirement for wild oat herbicide application and at the same time reduce selection pressure for further resistance evolution. The best system will depend on the regional productivity of crops. Where fall-seeded winter crops have little winter kill, they are a good option for wild oat management. Silage barley is a good production option where there are markets for the silage or when it can be used on the farm for cattle feeding. Chemical fallow and alfalfa production can help to control wild oat, but the income foregone during the fallow and alfalfa establishment years can make these options economically unattractive to some growers in certain regions. The long-term weed control benefits, which are somewhat intangible, may improve the overall economics of the system over the long term.

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References

Alberta Agriculture and Forestry. 2015*a*. Agriculture statistics yearbook 2014. Statistics and Data Development Branch, Alberta Agriculture and Forestry, Edmonton, AB. [Online]. Available from http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd15546 [9 Aug. 2017].

Alberta Agriculture and Forestry. 2015*b*. Average monthly prices for April 2014. Alberta Agriculture and Forestry. [Online]. Available from http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd14843 [9 Aug. 2017].

Alberta Agriculture and Forestry. 2015*c*. Custom rates survey summary 2014. Alberta Agriculture and Forestry. [Online]. Available from http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/inf14688 [9 Aug. 2017].

Alberta Agriculture and Forestry. 2015*d*. Farm machinery cost calculator. Alberta Agriculture and Forestry. [Online]. Available from http://www.agric.gov.ab.ca/app24/costcalculators/machinery/getmachimpls.jsp [15 Sept. 2017].

Alberta Agriculture and Forestry. 2017. What is my cereal silage worth? — frequently asked questions. Alberta Agriculture and Forestry. [Online]. Available from http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/faq8432 [1 Nov. 2017].

Brown, D.A. 1953. Wild oats: progress in cultural control. Weeds, **2**: 295–299. doi:10.2307/4040108.

Davis, A.S., Hill, J.D., Chase, C.A., Johanns, A.M., and Liebman, M. 2012. Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE, **7**: e47149. doi:10.1371/journal.pone.0047149.

Government of Saskatchewan. 2016. Crop planning guide 2016. [Online]. Available from http://publications.gov.sk.ca/documents/20/87217-Crop%20Planning%20Guide%202016%20web%20final.pdf [14 Sept. 2017].

Harker, K.N., Kirkland, K.J., Baron, V.S., and Clayton, G.W. 2003. Early harvest barley (*Hordeum vulgare*) silage reduces wild oat (*Avena fatua*) densities under zero tillage. Weed Technol. **17**: 102–110. doi:10.1614/0890-037X(2003)017[0102:EHBHVS]2.0.CO;2.

Harker, K.N., O'Donovan, J.T., Irvine, R.B., Turkington, T.K., and Clayton, G.W. 2009. Integrating cropping systems with cultural techniques augments wild oat (*Avena fatua*) management in barley (*Hordeum vulgare*). Weed Sci. **57**: 326–337. doi:10.1614/WS-08-165.1.

Harker, K.N., O'Donovan, J.T., Turkington, T.K., Blackshaw, R.E., Lupwayi, N.Z., Smith, E.G., Johnson, E.N., Gan, Y., Kutcher, H. R., Dosdall, L.M., and Peng, G. 2015. Canola rotation frequency impacts canola yield and associated pest species. Can. J. Plant Sci. **95**: 9–20. doi:10.4141/cjps-2014-289.

Harker, K.N., O'Donovan, J.T., Turkington, T.K., Blackshaw, R.E., Lupwayi, N.Z., Smith, E.G., Johnson, E.N., Pageau, D., Shirtliffe, S.J., Gulden, R.H., Rowsell, J., Hall, L.M., and Willenborg, C.J. 2016. Diverse rotations and optimal cultural practices control wild oat (*Avena fatua*). Weed Sci. **64**: 170–180. doi:10.1614/WS-D-15-00133.1.

Heap, I.M. 2017. International survey of herbicide resistant weeds. [Online]. Available from http://www.weedscience.org [24 Oct. 2017].

Johnston, A.M., Kutcher, H.R., and Bailey, K.L. 2005. Impact of crop sequence decisions in the Saskatchewan Parkland. Can. J. Plant Sci. **85**: 95–102. doi:10.4141/P04-090.

O'Donovan, J.T., Harker, K.N., Clayton, G.W., and Hall, L.M. 2000. Wild oat (*Avena fatua*) interference in barley (*Hordeum vulgare*) is influenced by barley variety and seeding rate. Weed Technol. **14**: 624–629. doi:10.1614/0890-037X(2000)014[0624:WOAFII]2.0.CO;2.

O'Donovan, J.T., Grant, C.A., Blackshaw, R.E., Harker, K.N., Johnson, E.N., Gan, Y., Lafond, G.P., May, W.E., Turkington, T.K., Lupwayi, N.Z., Stevenson, F.C., McLaren, D.L., Khakbazan, M., and Smith, E.G. 2014. Rotational effects of legumes and non-legumes on hybrid canola and malting barley. Agron. J. **106**: 1921–1932. doi:10.2134/agronj14.0236.

SAS Institute Inc. 2017. SAS analytical products 12.1 documentation. [Online]. SAS Institute, Inc., Cary, NC. Available from http://support.sas.com/documentation/121/index.html [8 Sept. 2017].

Sieling, K., Christen, O., Nemati, B., and Hanus, H. 1997. Effects of previous cropping on seed yield and yield components of oil-seed rape (*Brassica napus* L.). Eur. J. Agron. **6**: 215–223. doi:10.1016/S1161-0301(96)02049-7.