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Combining Cultural Practices with Herbicides Reduces Wild Oat (*Avena fatua*) Seed in the Soil Seed Bank and Improves Barley Yield

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A study was initiated in 2001at four locations in western Canada to investigate an integrated approach to managing wild oat, the region's worst weed. The study examined the effects of combining semidwarf or tall barley cultivars with normal or twice-normal barley seeding rates in either continuous barley or a barley–canola–barley–field pea–barley rotation. Herbicides were applied at 25, 50, and 100% of recommended rates. The first phase of the study was completed in 2005. This paper reports on the second phase, which was continued for four more years at two of the locations, Beaverlodge and Fort Vermilion, AB, Canada. The objective was to determine the long-term impact of the treatments on wild oat seed in the soil seed bank. In 2009 (final year), the diverse rotation combined with the higher barley seeding rate (optimal cultural practice) resulted in higher barley yields and reduced wild oat biomass compared to continuous barley and lower barley seeding rate (suboptimal cultural practice). In contrast to the first phase, barley yield was higher with the semidwarf cultivar, and cultivar had no effect on wild oat management. Wild oat seed in the soil seed bank decreased with increasing herbicide rate, but amounts were often lower with the optimal cultural practice. For example, at the recommended herbicide rate at Beaverlodge, an approximate 40-fold reduction in wild oat seed occurred with the optimal compared to the suboptimal cultural practice. The results indicate that combining optimal cultural practices with herbicides will reduce the amount of wild oat seed in the soil seed bank, and result in higher barley yields. Optimal cultural practices may also compensate for reduced herbicidal effects in terms of reducing wild oat seed accumulation in the soil seed bank and increasing barley yield. The results have implications for mitigating the evolution of herbicide resistance in wild oat.
Nomenclature: Wild oat, *Avena fatua* L.; barley, *Hordeum vulgare* L.; canola, *Brassica napus* L.; field pea, *Pisum sativum* L.
Key words: Crop seeding rate, cultural practices, direct seeding, diverse rotation, herbicide resistance, integrated weed management (IWM), optimal cultural practices, soil seed bank.

Wild oat is the most serious annual weed of field crops in western Canada, costing growers millions of dollars annually in lost yield. In addition, herbicide costs amount to CAD $500 million annually (Leeson et al. 2006). Traditionally, most registered herbicides have been very effective in controlling wild oat and reducing the amount of wild oat seed entering the soil seed bank. However, extensive herbicide use has resulted in the proliferation of herbicide-resistant wild oat biotypes, and surveys have indicated that over 20% of cropland in western Canada has wild oat biotypes that are now resistant to one or more herbicide groups (Beckie et al. 2008). It is important, therefore, that growers adopt integrated weed management (IWM) approaches with less dependence on herbicides to prevent the resistance problem from escalating further (Beckie 2006).

Several strategies have been recommended to facilitate the adoption of IWM by growers in western Canada (O'Donovan et al. 2007). These include the adoption of agronomic practices that give the crop a competitive advantage over weeds, and the implementation of diverse crop rotations rather than continuous monocultures. In some areas, particularly in Alberta, barley is sometimes grown continuously to accommodate demands for silage and feed grain uses for livestock production (Harker et al. 2009). In the past, this has resulted in increased levels of disease (Turkington et al. 2006), and has also contributed to the selection of herbicide resistance in wild oat (O'Donovan et al. 1994).

In western Canada, widely researched strategies in barley include increasing the barley seeding rate (Blackshaw et al 2005; O'Donovan et al. 1999, 2001, 2004) and growing competitive barley varieties (O'Donovan et al. 2000; Watson et al. 2006). Although implementing single cultural strategies (e.g., increasing crop seeding rate) can have some positive effects, it is generally felt that weed management in field crops can be most effective when several IWM strategies are combined with herbicide application (Anderson 2003, 2005; Harker et al. 2003). Growers control weeds with herbicides not only to increase crop yield and economic returns in the short term, but also to reduce the accumulation of weed seed in the soil seed bank over the long term. In 3-yr studies with continuous barley (O'Donovan et al. 2001), a barley–canola rotation (O'Donovan et al. 2004), and a barley–field pea rotation (Blackshaw et al. 2005), relatively high crop seeding rates significantly reduced the accumulation of wild oat seed in the soil seed bank, especially at reduced herbicide rates. Relatively few studies, however, have assessed the long-term impact of combining several cultural strategies on the accumulation of wild oat seed in the soil seed bank.

In 2001, a study was initiated at four locations in western Canada to investigate an IWM approach to wild oat management using several cultural strategies (Harker et al. 2009). The study examined the effects of combining semidwarf or tall barley cultivars with normal or twice-normal barley seeding rates in either continuous barley or a more diverse barley–canola–barley–field pea–barley rotation, at three herbicide rate regimes. The first phase of the study was completed in 2005. The results indicated that optimal cultural strategies (tall cultivars, twice-normal seeding rates, and a diverse crop rotation) reduced wild oat emergence, biomass, and seed production, and increased barley seed yield, especially at low herbicide rates (Harker et al. 2009). The present paper reports on the second phase of the study (four additional years from 2006 to 2009) at two of the original locations. The main objective was to determine the effects of

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Table 1. Herbicide common names, trade names, rates, manufacturer name and Web site URL.

Common name	Trade name	Recommended label rates	Formulation[a]	Manufacturer	Web site
		g ai ha^{-1}			
Bromoxynil/MCPA	Buctril M	280/280	EC	Bayer CropScience	www.bayercropscience.ca
Clethodim[b]	Select	15	EC	Arysta LifeScience	www.arystalifescience.com
Fenoxaprop	Puma Super	81	EC	Bayer CropScience	www.bayercropscience.ca
Florasulam/MCPA ester	Frontline	5/420	EC	Dow AgroSciences	www.dowagro.ca
Glufosinate	Liberty	500	S	Bayer CropScience	www.bayercropscience.ca
Glyphosate[c]	Roundup WeatherMax	450	S	Monsanto	www.monsanto.ca
Imazamethabenz	Assert	400	FL	Nufarm Agriculture Inc.	www.nufarm.ca
Imazamox/imazethapyr[d]	Odyssey	15/15	WDG	BASF Canada Inc.	www.agproducts.basf.com
Thifensulfuron/tribenuron[e]	Refine SG	15/15	S	E.I. Dupont Canada Co	www.dupont.ca/ag
Tralkoxydim[f]	Achieve Liquid	200	SC	Dow AgroSciences	www.dowagro.ca

[a] Abbreviations: EC, emulsifiable concentrate; FL, flowable; S, solution; SC, suspension concentrate; WDG, water-dispersible granules.
[b] Clethodim was applied with Amigo 30% phosphate ester surfactant (0.5% v/v).
[c] Glyphosate rates were determined as g ae ha^{-1}.
[d] Imazamox/imazethapyr was applied with Merge 50% surfactant blend plus 50% petroleum hydrocarbons solvent (0.5% v/v).
[e] Thifensulfuron/tribenuron was applied with Agral 90 nonionic surfactant (0.2% v/v).
[f] Tralkoxydim was applied with Turbocharge 39.5% surfactant blend plus 50% mineral oil solvent (0.5% v/v).

two rotational cycles (with original treatments maintained) on the accumulation of wild oat seed in the soil seed bank. The effect of the treatments on barley yield and wild oat biomass in 2009 was also determined.

Materials and Methods

In 2001 (the first year of the experiment), barley was direct-seeded on canola residue and 100 wild oat seeds m^{-2} were broadcast on the soil surface of each plot to supplement natural populations. The experiment was a randomized complete block with four replicates. Treatment factors were crop rotation (continuous barley or a barley–canola–barley–pea– barley rotation), barley cultivar (semidwarf or tall), barley seeding rate (200 or 400 seeds m^{-2}), and wild oat herbicide rate (25, 50, or 100% of recommended rate). Plot size was 3 by 15 m. Soil types at all locations and further experimental details from 2001 to 2005 are described by Harker et al. 2009.

From 2006 to 2009, field experiments were continued for a second crop rotation cycle at two of the original locations, Beaverlodge (55°13′N, 119°24′W) and Fort Vermilion (58°24′N, 116°0′W) in the Peace River region of northern Alberta. Experimental design and treatment variables were the same as the first cycle. Canola, barley, pea, and barley were direct seeded in May in 2006, 2007, 2008, and 2009, respectively with field-scale adapted direct seeders with 1-cm-wide knife openers in 23-cm row spacing. Fertilizer was side-banded as urea (46–0–0) during seeding at 2 cm beside and 3 to 4 cm below the seed (except for pea, which did not receive any nitrogen). The barley varieties were 'Vivar' (semidwarf) and 'AC Lacombe' (tall). Barley was seeded at a depth of 3 cm at 200 (normal seeding rate) or 400 seeds m^{-2}. Glufosinate-resistant canola ('Invigor 5020') and pea ('CDC Golden') were seeded at depths of 1 and 5 cm, and at seeding rates of 150 and 100 seeds m^{-2}, respectively.

Information on herbicides applied is presented in Table 1. Glyphosate was applied to all plot areas to remove weeds that emerged before seeding the crop each year. When barley reached the three- to four-leaf stage, herbicides for wild oat control (fenoxaprop, tralkoxydim, or imazamethabenz) were applied at 25, 50, or 100% of the recommended rates. Herbicides for wild oat control were varied to conform to recommended practices to reduce the risk of selecting for herbicide-resistant wild oat. Herbicides for dicot weed control were applied only at full recommended rates in tank mixtures with the herbicides for wild oat control. In barley, fenoxaprop/thifensulfuron/tribenuron were applied in 2006 and 2007, tralkoxydim/bromoxynil/MCPA ester in 2008, and imazamethabenz/florasulam in 2009. In canola (2006), glufosinate at 25, 50, or 100% was applied according to label specifications as a tank mixture with clethodim at 25, 50, or 100%. In pea (2008), imazamox/imazethapyr was applied at 25, 50, or 100%.

In 2009, wild oat biomass was taken at barley maturity from two 0.91-m^2 quadrats in each plot and dried to a constant weight at 30 C. The entire plots were harvested with a combine and barley seed yield was recorded. In the fall of 2009, the soil was sampled for wild oat seed using a W pattern (Thomas 1985). Eight soil samples were taken from each plot to a depth of 5 cm using a core sampler with a diameter of 3.85 cm. Since experiments were direct-seeded for 9 yr, it is unlikely that wild oat seed would have occurred below 5 cm depth. The soil was dried at 30 C and sieved; the wild oat seed was manually separated and counted and the data converted to seeds m^{-2}.

Data were analyzed using PROC MIXED of SAS (Littel et al. 1996; SAS 2004). Exploratory analysis revealed some non-normal data distributions and variance heterogeneity for wild oat responses. Therefore, wild oat data were log-transformed prior to the analysis of variance. Data were analyzed separately for each location since the location by treatment interaction was highly significant ($P < 0.001$) for all variables. The effect of replicate was considered random and the effects of the treatments were considered fixed. Preplanned contrasts were used to determine statistical differences between comparisons of interest. The mixed model also determined linear or quadratic responses to herbicide rate. Effects were considered significant at $P < 0.05$.

Results and Discussion

For ease of discussion, the canola–barley–pea–barley rotation will be referred to as the diverse rotation, as opposed

Table 2. P values from the ANOVA for the effects of crop rotation, barley variety, barley seeding rate, and herbicide rate on barley yield, wild oat biomass, and wild oat seed in the soil seed bank at Beaverlodge in 2009.

Effect[a]	Barley yield	Wild oat biomass	Wild seed in soil seed bank
R	< 0.001***	< 0.001***	< 0.001***
V	< 0.001***	0.353	0.906
S	< 0.001***	< 0.001***	< 0.001***
H	< 0.001***	< 0.001***	< 0.001***
R × V	0.295	0.300	0.798 (0.042)
R × S	0.458	0.182	0.348
R × H	< 0.001***	0.002**	0.004**
V × S	0.708	0.530	0.230
V × H	0.922	0.887	0.119
S × H	0.026*	0.135	0.546
R × V × S	0.322	0.776	0.970
R × V × H	0.405	0.985	0.829
R × S × H	0.096	0.004**	0.001***
V × S × H	0.307	0.629	0.880
R × V × S × H	0.707	0.667	0.134

[a] Abbreviations: R, rotation; V, barley variety; S, barley seed rate; H, herbicide rate.

*, **,*** Significant at 5, 1, and 0.1% levels, respectively.

Table 3. P values from the ANOVA for the effects of crop rotation, barley variety, barley seeding rate, and herbicide rate on barley yield, wild oat biomass, and wild oat seed in the soil seed bank at Fort Vermilion in 2009.

Effect[a]	Barley yield	Wild oat biomass	Wild seed in soil seed bank
R	< 0.001**	0.030*	0.005**
V	< 0.001**	0.848	0.142
S	0.034*	0.042*	0.009*
H	< 0.001**	< 0.001**	< 0.001**
R × V	0.026*	0.619	0.798
R × S	0.832	0.400	0.993
R × H	0.652	0.007**	< 0.001***
V × S	0.708	0.864	0.783
V × H	0.939	0.108	0.119
S × H	0.025*	0.329	0.794
R × V × S	0.322	0.172	0.829
R × V × H	0.259	0.618	0.203
R × S × H	0.655	0.638	0.491
V × S × H	0.957	0.662	0.620
R × V × S × H	0.439	0.877	0.712

[a] Abbreviations: R, rotation; V, barley variety; S, barley seed rate; H, herbicide rate.

*, ** Significant at 5, 1 and 0.1% levels, respectively.

to continuous barley. In addition, to facilitate comparisons between the two rotations (continuous barley and diverse), the results and discussion will be restricted to the final year of the study (2009) when barley was grown across the entire experiment.

The ANOVA indicated that herbicide rate, barley seeding rate, and crop rotation significantly ($P < 0.05$) affected wild oat variables at both Beaverlodge and Fort Vermilion whereas barley cultivar had no effect (Tables 2 and 3). This is in contrast to the findings of the first phase of this study where a tall barley cultivar was more competitive with wild oat than a semidwarf cultivar (Harker et al. 2009). However, in that phase of the study, both the tall (AC Bacon) and semidwarf (Peregrine) barley grown for 4 of the 5 yr (2001 to 2004) were hull-less cultivars, whereas in the present study both cultivars (AC Lacombe and Vivar) were hulled cultivars. The cultivars were changed in 2005 due to certified seed availability issues. Hull-less barley cultivars are generally less competitive with wild oat than hulled cultivars (O'Donovan et al. 2000). This difference in cultivars and cultivar type makes it difficult to draw comparisons between the two phases of the study in terms of cultivar effects on wild oat variables.

Some of the interactions between the factors were also significant, especially at Beaverlodge where rotation significantly ($P < 0.01$) interacted with seeding rate and herbicide rate for both wild oat variables (Table 2). Because barley cultivar had no effect on the variables at either location, data for wild oat variables are presented for the three significant treatment factors averaged across barley cultivars (Table 4).

With some minor exceptions, the cumulative effects of the treatments on the soil seed bank mirrored the effects on wild oat biomass at both Beaverlodge and Fort Vermilion in 2009 (Table 4). Since the main objective of the study was to determine the cumulative effect of the treatments on wild oat seed in the soil seed bank, this will be the main focus of the discussion. At the 25 and 50% herbicide rates at Beaverlodge, the combined effect of the diverse rotation and high seeding rate (optimal cultural practice) reduced wild oat seed in the seed bank to a greater extent than either factor alone (Table 4). Compared to the low seeding rate and continuous barley combination (treatments 1 and 5, suboptimal cultural practice), wild oat seed was reduced by 57% (treatment 4) and 93% (treatment 8) at the 25 and 50% rates, respectively (Table 4). It is also of significance that the 25% herbicide rate and optimal cultural practice (treatment 4) resulted in less wild oat seed in the soil seed bank than the 50% rate and suboptimal cultural practice (treatment 5) (Table 4). This suggests that cultural practices may compensate for suboptimal herbicidal effects in terms of reducing wild oat seed accumulation in the soil seed bank.

At Beaverlodge, as expected, the 100% herbicide rate was most effective in reducing both wild oat biomass and seed in the soil seed bank (Table 4). However, the greatest reductions occurred with the high seeding rate or diverse rotation, or a combination of both (optimal cultural practice). These factors reduced wild oat biomass and seed in the soil seed bank to very low levels (1 seed m^{-2} or less in the case of the seed bank). This was an approximate 40-fold reduction in wild oat seed compared to the suboptimal cultural practice (Table 4).

At Fort Vermilion, results were generally similar to Beaverlodge. However, the effects of the cultural practices were not as consistent (in terms of statistical significance) and there were fewer significant interactions (Table 4). At the 25 and 50% herbicide rates, wild oat seed in the soil seed bank was lowest with the optimal cultural practice (treatments 4 and 8). Compared to the suboptimal cultural practice (treatments 1 and 5), wild oat seed was reduced by 82% (treatment 4) and 59% (treatment 8) at the 25 and 50% herbicide rates, respectively (Table 4), when using optimal cultural practice. At the 100% herbicide rate there were no significant differences between any of the treatments. The reason for this is unclear, but in previous studies it was also difficult to detect the effects of crop seeding rate on weed seed in soil seed banks at full herbicide rates (O'Donovan et al. 2001). Anecdotal evidence (personal observations and consultations with extension specialists) suggests that herbicides tend to be more efficacious when applied to relatively small research plots compared to the large tracts of arable land that are common in western Canada. The reduced herbicide rates may better simulate the variability in efficacy that can occur at the farm level due to factors such as inclement weather,

Table 4. Effect of herbicide rate, barley seeding rate, and crop rotation on wild oat biomass in 2009, and wild oat seed in the soil seed bank (cumulative since 2001) at Beaverlodge and Fort Vermilion.

				Beaverlodge		Fort Vermilion	
Treatment	Herbicide rate	Barley seeding rate	Crop rotation	Wild oat biomass	Wild oat in soil seed bank	Wild oat biomass	Wild oat in soil seed bank
	% recommended	seeds m^{-2}		kg ha^{-1}	seeds m^{-2}	kg ha^{-1}	seeds m^{-2}
1	25	200	Continuous	2,000	3,640	1,370	7,990
2	25	200	Diverse	1,690	3,010	533	3,110
3	25	400	Continuous	1,150	2,300	727	4,130
4	25	400	Diverse	769	1,560	292	1,460
5	50	200	Continuous	1,530	2,730	26	194
6	50	200	Diverse	380	829	66	84
7	50	400	Continuous	545	1,280	5	84
8	50	400	Diverse	106	195	0	80
9	100	200	Continuous	54	37	0	34
10	100	200	Diverse	2	1	0	104
11	100	400	Continuous	0	0	0	64
12	100	400	Diverse	0	0	0	44

	P value			
	Beaverlodge		Fort Vermilion	
Treatment comparisons	Wild oat biomass	Wild oat in soil seed bank	Wild oat biomass	Wild oat in soil seed bank
1 vs. 2	0.720	0.614	0.014*	0.297
1 vs. 3	0.067	0.146	0.023*	0.206
1 vs. 4	0.017*	0.022*	0.003**	0.023*
2 vs. 4	0.040*	0.069	0.583	0.209
3 vs. 4	0.558	0.380	0.450	0.016*
4 vs. 5	0.078	0.016*	0.002	0.004**
5 vs. 6	< 0.001**	0.004**	0.401	0.068
5 vs. 7	0.008**	0.042*	0.216	0.060
5 vs. 8	< 0.001***	< 0.001***	0.077	0.013*
6 vs. 8	< 0.001***	< 0.001***	0.345	0.484
7 vs. 8	< 0.001***	< 0.001***	0.586	0.519
8 vs. 9	0.001**	< 0.001***	0.999	0.549
9 vs. 10	< 0.001***	< 0.001***	0.999	0.135
9 vs. 11	< 0.001***	< 0.001***	0.999	0.918
9 vs. 12	< 0.001***	< 0.001***	0.999	0.831

*,**,*** Significant at 5, 1, and 0.1 levels, respectively.

different stages of weed development, and general application errors.

The ANOVA indicated that all treatment factors (main effects) significantly ($P < 0.05$) affected barley yield at both locations in 2009 (Tables 2 and 3). Averaged across all other factors, the semidwarf barley (Vivar) produced 12 and 14% higher yield than the tall barley (AC Lacombe) at Beaverlodge and Fort Vermilion, respectively (data not shown). Vivar has previously been found to be higher yielding than AC Lacombe (Alberta Agriculture and Rural Development 2012) This is contrary to the findings for the first phase of this study where a tall barley cultivar (AC Lacombe) resulted in higher yield than a semidwarf cultivar (Peregrine) (Harker et al. 2009).

Since yield differences between the two cultivars were unlikely to be related to wild oat competition, further discussion will be restricted to the effects of herbicide rate, seeding rate, and crop rotation on barley yield averaged across the two barley cultivars. At all herbicide rates at both locations, the highest barley yields mostly occurred with the optimal cultural practice (Table 5). For example at the 100% rate the optimal cultural practice (treatment 12) resulted in barley yield increases of 14 and 25% (compared to the suboptimal practice, treatment 9) at Beaverlodge and Fort Vermilion, respectively (Table 5). In most cases, either the increased seeding rate or diverse rotation resulted in higher barley yields, but the highest yields often occurred when these factors were combined (Table 5).

Interestingly, with the optimal cultural practice at both locations, there were no differences in yield between the 50% (treatment 8) and 100% (treatment 12) herbicide rates (Table 5). In addition, the optimal cultural practice at the 50% rate (treatment 8) resulted in higher barley yield than the suboptimal practice at the 100% rate (treatment 9). These findings suggest that adopting optimal cultural practices may mitigate yield losses when herbicide efficacy is reduced. This synergistic effect of low herbicide rates and optimal cultural practice (tall cultivar, high seeding rate, and diverse rotation) was also evident with the first phase of this study (Harker et al. 2009), and when barley was seeded at relatively high seeding rates (Blackshaw et al. 2005; O'Donovan et al. 2001).

The higher barley yield with the optimal cultural practice was likely due, at least in part, to reduced wild oat competition since wild oat biomass was mostly lower with the high seeding rate and diverse rotation (Table 4). However, it is also possible that the higher yield with the diverse rotation resulted in less disease incidence compared to continuous barley. In barley fields in Alberta, the probability of foliar disease was lessened considerably when barley was planted in fields previously sown to a nonhost crop (Turkington et al. 2006).

Table 5. Effect of herbicide rate, barley seeding rate, and crop rotation on barley seed yield at Beaverlodge and Fort Vermilion in 2009.

				Beaverlodge	Fort Vermilion
Treatment	Herbicide rate	Barley seeding rate	Crop rotation	Barley yield	
	% recommended	seeds m^{-2}		kg ha^{-1}	
1	25	200	Continuous	2,310	1,820
2	25	200	Diverse	2,460	3,020
3	25	400	Continuous	3,310	2,490
4	25	400	Diverse	3,720	3,490
5	50	200	Continuous	2,600	2,930
6	50	200	Diverse	4,340	3,930
7	50	400	Continuous	3,850	2,800
8	50	400	Diverse	5,130	3,880
9	100	200	Continuous	4,340	2,950
10	100	200	Diverse	4,240	3,710
11	100	400	Continuous	4,420	2,910
12	100	400	Diverse	5,020	3,920

Treatment comparisons	Beaverlodge	Fort Vermilion
1 vs. 2	0.570	< 0.001**
1 vs. 3	< 0.001***	0.008**
1 vs. 4	< 0.001***	< 0.001**
2 vs. 4	< 0.001***	0.060
3 vs. 4	0.137	< 0.001***
4 vs. 5	< 0.001***	0.025*
5 vs. 6	< 0.001***	< 0. 001***
5 vs. 7	< 0.001***	0.594
5 vs. 8	< 0.001***	< 0.001***
6 vs. 8	0.005**	0.823
7 vs. 8	< 0.001***	< 0.001***
8 vs. 9	0.013*	< 0.001***
8 vs. 12	0.714	0.855
9 vs. 10	0.705	0.003**
9 vs. 11	0.767	0.878
9 vs. 12	0.013*	< 0.001***
10 vs. 12	0.005**	0.309
11 vs. 12	0.028*	< 0.001***

*,**,*** Significant at 5, 1 and 0.1% levels, respectively.

The results of the study have important implications for management of wild oat and optimization of barley yield over the long term. Of the three cultural practices investigated, implementing a diverse rotation and seeding barley at a relatively high rate proved most successful. Although either of these practices alone often resulted in higher yields and significantly less wild oat seed in the soil seed bank, the combined effects were sometimes synergistic especially at reduced herbicide rates. The diverse rotation also likely mitigated barley disease incidence, resulting in higher yields. Growing a tall compared to a semidwarf barley cultivar had no effect on wild oat management in this study, suggesting that cultivar selection was not as important as seeding rate and crop rotation. Selecting cultivars based on factors such as yield potential and disease resistance may, in some cases, be more important than selecting cultivars for weed management based on stature. However, cultivar selection as a component of an IWM system may still be important if hull-less barley or other less-competitive crops are grown.

The results of this study may also have implications for herbicide resistance management in wild oat and other weeds. The evolution of herbicide resistance is governed by several factors including gene mutation, initial frequency of resistant alleles, and gene flow (Jasieniuk et al. 1996). However, results of modeling studies have indicated that heavy weed infestations resulting in large amounts of weed seed entering the soil seed bank can increase the probability of selecting for resistance even when the rate of mutation is low (Jasieniuk et al. 1996). This presents a dilemma, since herbicides represent the most effective means of reducing weed seed production but also exert selection pressure for resistance development. Rotating herbicides according to mechanism of action is often touted as the best strategy to mitigate resistance development, but this has been questioned as to its long-term effectiveness (Harker et al. 2012). Even when herbicides with different mechanisms of action were rotated, multiple herbicide resistance in wild oat (Beckie et al. 2008) and other weeds (Juliano et al. 2010; Powles and Matthews 1991; Walsh et al. 2004) still evolved. Thus, reducing the amount of weed seed in the soil seed bank by combining herbicide application with optimal cultural practices may be of crucial importance in terms of delaying or preventing the selection of resistant weed biotypes. In fact, it has long been postulated that herbicide resistance is less likely to develop if weed seed populations in the soil seed bank are reduced through combinations of cultural practices and herbicide use rather than through herbicide use alone (Beckie and Kirkland 2003; Thill et al. 1994). With the evolution of weed resistance to herbicides continuing to expand globally (especially resistance to glyphosate) (Heap 2012), preventing weed seed accumulation in the soil seed bank using cultural approaches will be crucial to maintaining herbicide technology as a sustainable weed management strategy going forward. The results of this and other studies (e.g. Harker et al. 2009) clearly indicate that growers can adopt cultural practices that have the potential to make this goal a reality.

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