Weed Technology 2007 21:290–299

Beneficial Management Practices to Combat Herbicide-Resistant Grass Weeds in the Northern Great Plains

Hugh J. Beckie*

Wild oat and green foxtail are the two most abundant weeds and the most economically important herbicide-resistant grass weeds in the northern Great Plains of western Canada. Farmers in this region rarely proactively manage these weed species to prevent or delay the selection for herbicide resistance; they usually increase the adoption of integrated weed management practices only after intergroup herbicide resistance has evolved. The effectiveness of herbicide and nonherbicide practices to proactively or reactively manage herbicide-resistant wild oat and green foxtail are described, based on a decade of field trials, field-scale experiments, and field surveys in western Canada. Nonherbicide weed management practices or nonselective herbicides applied preplant or in crop, integrated with less frequent selective herbicide use in diversified cropping systems, have mitigated the evolution, spread, and economic impact of herbicide-resistant wild oat and green foxtail.

Nomenclature: Green foxtail, *Setaria viridis* (L.) Beauv. SETVI; wild oat, *Avena fatua* L. AVEFA.

Key words: Herbicide resistance, integrated weed management.

Green foxtail and wild oat rank first and second, respectively, in relative abundance among weed species in the northern Great Plains (prairies) of Canada (Leeson et al. 2005). By prairie province (Alberta, Saskatchewan, Manitoba), the relative abundance ranking changes only in Alberta, where wild oat is second and green foxtail is ninth (Leeson et al. 2002a, 2002b, 2003). Based on estimated crop yield loss, wild oat is the most economically important weed in the prairies; in contrast, the economic impact of green foxtail is ranked fourth among species, but is about one-tenth that of wild oat (O'Donovan et al. 2005).

Globally, wild oat and green foxtail are among the most economically important herbicide-resistant (HR) weeds (Heap 2006). Field surveys conducted since the early 1990s in the three prairie provinces have documented the nature, occurrence, and cost of HR wild oat and green foxtail (e.g., Beckie et al. 1999b, 1999c, 2002, 2003). The most recent random field surveys of HR weeds were conducted at 236 sites in Alberta in 2001 (Beckie et al. 2004a), 150 sites in Manitoba in 2002 (Beckie et al. 2004c), and 400 sites in Saskatchewan in 2003 (Beckie et al. 2006b).

In Alberta, acetyl-CoA carboxylase (ACCase, EC 6.4.1.2) inhibitor-HR wild oat was found in 20 of 190 fields (11%), whereas 13% of fields had acetolactate synthase (ALS, EC 4.1.3.18) inhibitor-HR wild oat. Half of the fields with either biotype originated in the subhumid Aspen Parkland ecoregion, which was attributed to historically high frequency of use of products from these groups. Intergroup (ACCase + ALS inhibitor)-HR wild oat was found in six fields. Herbicide-resistant green foxtail was not detected in the Alberta survey. Only 5% of farmers with HR biotypes had previously suspected or were aware of their occurrence.

In Manitoba, 33 of 84 fields (40%) had ACCase inhibitor-HR wild oat, whereas ALS inhibitor-HR wild oat was found in 13% of fields. Intergroup-HR wild oat was found in seven fields. ACCase inhibitor-HR green foxtail was found in 13 of 59 fields (22%), whereas ALS inhibitor-HR green foxtail was confirmed in one field, the first reported case in the prairies. Only 10% of Manitoba farmers with HR wild oat had previously suspected or were aware of their occurrence; none of the farmers with HR green foxtail suspected resistance.

In Saskatchewan, 30 of 291 fields (10%) had ACCase inhibitor-HR wild oat, whereas ALS inhibitor-HR wild oat was found in only 4% of fields. Intergroup-HR wild oat was found in three fields. Most HR populations originated in the Parkland region. Herbicide-resistant green foxtail was not detected in the Saskatchewan survey. Only 5% of farmers with HR biotypes had previously suspected or were aware of their occurrence. Thus, the results of the Saskatchewan survey are more similar to those in Alberta than in Manitoba. Low awareness among farmers in all three provinces may be partly due to the small infestation area of HR biotypes in most fields. Nevertheless, it is estimated that nearly 1 million ha of land in the prairies are infested with HR wild oat and green foxtail in a total field area of nearly 4 million ha (H. Beckie, unpublished data).

These three surveys focused on ACCase and ALS inhibitor resistance. Previous prairie surveys had documented the widespread occurrence of triallate/difenzoquat- or flamprop-resistant wild oat and dinitroaniline-HR green foxtail (Beckie et al. 1999b, 1999c, 2001a, 2001b, 2002). However, the use of these herbicides and thus their selection pressure has greatly diminished during the past decade. The manufacture of flamprop and difenzoquat was discontinued in the late 1990s and early 2000s, respectively. The combined use of triallate and dinitroaniline herbicides declined from one-third of cropped land annually in the early 1990s to only 5% in the 2000s; in contrast, ACCase plus ALS inhibitor use increased from about 50 to 80% of cropped land annually during this period (Beckie et al. 2004a, 2004c, 2006b).

Farmers in the prairies rarely proactively manage wild oat or green foxtail to prevent or delay the selection for herbicide resistance (Beckie and Gill 2006). Farmers usually increase the adoption of integrated weed management practices only after herbicide resistance has evolved, although herbicides continue to be the dominant method of weed control. Intergroup

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DOI: 10.1614/WT-06-083.1

* Plant Scientist, Agriculture and Agri-Food Canada, Saskatoon Research Centre, 107 Science Place, Saskatoon, Saskatchewan, Canada S7N 0X2. E-mail: beckieh@agr.gc.ca

herbicide resistance in these weed species has been the main impetus for changes in management practices and adoption of cropping systems that reduce selection for resistance.

The prime strategy for managing herbicide resistance in weeds is to reduce the selection pressure (efficacy, persistence, application frequency) for resistance evolution by any one selecting agent, while maintaining adequate weed control. Diversification of selection pressures on weed populations, such as varying the type and timing of herbicide application (e.g., selective or nonselective herbicides applied preplant, in crop, preharvest or postharvest), integrating cultural or mechanical weed management practices with reduced herbicide use, and diversifying the cropping system as a whole, is required to reduce the selection pressure of any one selecting agent (Boerboom 1999). Used singly, the effectiveness of nonherbicide practices is lower and less consistent than that of many herbicides and may be highly dependent on environmental conditions; when used in combination, however, weeds can be managed effectively (Blackshaw et al. 2004).

This symposium paper examines beneficial management practices to proactively or reactively manage HR wild oat and green foxtail, based on a decade of field trials, field-scale experiments, and field surveys. HR wild oat will be discussed most extensively because it has been assessed more comprehensively than green foxtail, reflecting their relative economic importance.

Practices to Combat Herbicide-resistant Wild Oat and Green Foxtail

Lowest (But) Effective Herbicide Rates. Because of slim profit margins, in-crop herbicides are applied at below-registered rates to nearly one-third of cropped land annually in the Canadian prairies (Leeson et al. 2004, 2006b; Thomas et al. 2003). When farmers apply herbicides at reduced rates, it is based primarily on their experience with a product's performance as affected by sensitivity or growth stage of the target weed species or environmental conditions. They expect good weed control, although they are aware of the increased risk of suboptimal control. However, herbicide rate reduction without a corresponding reduction in efficacy will have no effect on selection for resistance. Model simulations have suggested that it is not profitable to reduce herbicide rates to reduce selection pressure (efficacy or persistence) for resistance, unless accompanied by a compensating increase in nonherbicidal weed control (Diggle and Neve 2001). The resulting increase in the abundance of herbicide-susceptible (HS) weed populations would reduce crop yield and quality and increase weed seed return to the seed bank (Gorddard et al. 1996; Morrison and Friesen 1996).

Beckie and Kirkland (2003) examined the implication of reduced rates of ACCase inhibitors in a 4-yr diverse crop rotation in conjunction with variable crop seeding rates on the enrichment of HR (target-site based) wild oat. As simulations models predict, reduced herbicide efficacy decreased the proportion of HR individuals in the population after 4 yr. The high crop seeding rate compensated for a one-third reduction in herbicide rate by limiting total (HR plus HS) wild oat seed production and by reducing the number of HR seedlings recruited from the seed bank. The study concluded that the proportion and quantity of HR seed in the seed bank can be reduced without increasing the total seed bank population by manipulating agronomic practices to increase crop competitiveness against wild oat when ACCase inhibitor rates are reduced.

Herbicides applied at registered rates can select for major gene (e.g., target-site) resistance, whereas initially, suboptimal herbicide rates may select for both major and minor gene (i.e. quantitative) resistance. Evolution of quantitative resistance relies on outcrossing among plants, resulting in incremental accumulation in their progeny of minor genes with additive or multiplicative effects (Jasieniuk et al. 1996; Neve and Powles 2005). Therefore, the risk of such herbicide resistance is greatest in highly outcrossing species, not highly selfing weeds such as wild oat and green foxtail.

Recent trends in herbicide regulation and registration include more detailed information provided to users to adjust rates according to prevailing environment conditions and herbicide sensitivity, growth stage, or population densities of the target species (Anonymous 2006). Driven by environmental considerations, a primary regulatory objective in Canada is to promote the application of products at lowest effective rates (i.e., ≥80% control) (N. Malik, personal communication). Sprayer calibration and use of appropriate nozzle tips will enhance both the accuracy of applied herbicide dose and interception by weeds.

Herbicide Rotation by Site of Action. Performance and cost of herbicides usually rank higher than site of action when farmers select a herbicide. The lack of suitable herbicide options associated with crop rotation can be an impediment to herbicide group rotation (Bourgeois et al. 1997b; Légère et al. 2000). The level of adoption of herbicide group rotation for resistance management has increased markedly during the past decade. In the prairies in 1998, fewer than 50% of farmers practiced herbicide group rotation, even though awareness was high (Beckie et al. 1999a). By 2003, 70% (Saskatchewan) to over 90% (Manitoba) of farmers claimed to rotate herbicides by site of action; it is the most common herbicide resistance management practice cited by farmers in survey questionnaires conducted in the prairies (Table 1). In 2005, over half of the herbicide products sold in Canada had resistance management labeling, which includes group identification symbols on the label and guidelines for resistance management practices in the use directions (N. Malik, personal communication). The guidelines were a joint effort between the Pest Management Regulatory Agency (PMRA 1999) in Canada and the United States Environmental Protection Agency (2001). A prerequisite for herbicide group rotation is keeping field records of herbicides used each year. Crop and herbicide rotation software facilitate record-keeping and can flag high risk herbicide practices, such as repeated use of herbicides with the same site of action.

Evolution of target-site resistance in weed biotypes is attributed to frequent use of herbicides of the same site of action and their propensity to select for HR biotypes (Beckie et al. 2001a; LeBaron and McFarland 1990). The ease of selection by a herbicide is governed by several factors. The

Table 1. Top practices used by western Canadian farmers to proactively or reactively manage for herbicide resistance in weeds.

	Proactive[a]			Reactive[b]		
Practice	Alberta	Saskatchewan	Manitoba	Alberta	Saskatchewan	Manitoba
	%					
Herbicide group rotation[c]	82	70	91	82	70	91
Alternative herbicide				56	43	59
Patch management				23	29	26
Crop rotation	29	33	30	17	49	38
Herbicide-resistant crop[d]	4	2	7	16	31	22
Tillage	18	19	11	3	11	2
Fallow	17	24	8	<1	8	3
Glyphosate	14	10	15	6	15	16
Fall herbicide application	6	3	10	2	<1	<1
Silage	15	5	<1	13	1	8
Perennial/forage crops	8	1	11	<1	4	2
Delayed planting	8	8	7	3	4	1
Weed sanitation[e]	2	7	9	2	3	<1

[a] Based on questionnaires completed by 349 farmers in Alberta in 2001, 275 farmers in Saskatchewan in 2003, and 149 farmers in Manitoba in 2002 (H. Beckie, unpublished data).

[b] Based on questionnaires completed by 41 farmers in Alberta in 2001, 37 farmers in Saskatchewan in 2003, and 89 farmers in Manitoba in 2002 (H. Beckie, unpublished data).

[c] Use of this practice for proactive vs. reactive management was not distinguished; based on questionnaires completed by 580 farmers in Alberta in 2001, 827 farmers in Saskatchewan in 2003, and 356 farmers in Manitoba in 2002 (Beckie et al. 2004a, 2004c, 2006b).

[d] Canola, *Brassica napus* L.; recommended crop rotation frequency is 1 in 4 yr for disease management.

[e] Practices that reduce weed seed production or spread.

selection pressure imposed on the target weed species by a herbicide is the most important factor affecting the rate of evolution of resistance. Nonpersistent herbicides generally exert less selection pressure than those that control successive cohorts of germinating weeds throughout the growing season. The contribution of persistence to selection pressure, however, depends on timing of herbicide application and the germination characteristics of the target species in a geographic region. The soil residual activity of herbicides did not strongly influence selection pressure on wild oat in a competitive crop (canola, *Brassica napus* L.) in the prairies (Beckie and Holm 2002). The selection pressure exerted on wild oat by residual herbicides was the same as or lower than that of nonresidual herbicides. In the relatively short growing season in the prairies, few wild oat or green foxtail plants may emerge after postemergence application of a nonresidual herbicide and produce viable seeds in a competitive crop.

The risk of target-site resistance, defined by the mean number of applications before resistance is detected, varies by herbicide group (Figure 1). Knowledge of resistance risk could be an incentive for farmers to practice herbicide rotations to delay the rate of evolution of resistance. High-risk herbicides should be applied less often in rotations than lower-risk herbicides. At a minimum, use of high-risk herbicides in consecutive years in a field should be avoided. Admittedly, this recommendation may be impractical because ACCase and ALS inhibitors are the only postemergence selective herbicides for controlling wild oat or green foxtail. Preemergence selective herbicides (groups 3, 8) are used much less (applied to 5% of cropped area annually) than postemergence herbicide options because of reduced and less consistent efficacy, narrower weed spectrum, some rotational restrictions on subsequent crops, or prevalence of reduced-tillage regimes. Lower risk, nonselective herbicides, such as paraquat, amitrole, or glyphosate, should be used preplant to reduce the number of weeds selected with in-crop herbicides that pose a higher risk. Ideally, high-risk herbicides should not be used in fields with high weed densities because the number of HR

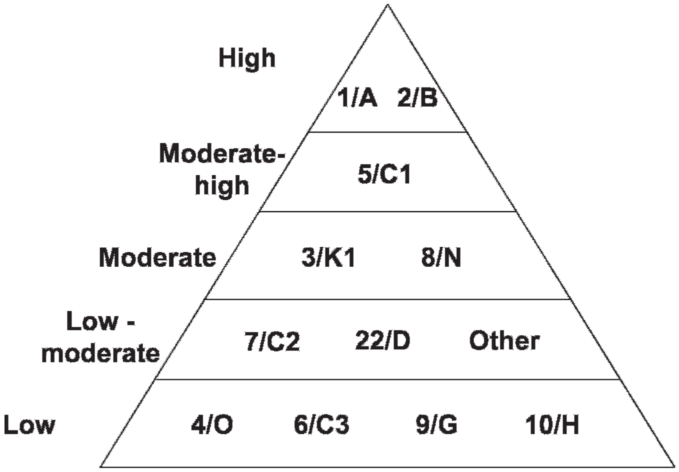

Figure 1. Classification of herbicide site of action by risk of selection for target-site resistance (high ≤ 10; moderate = 11 to 20; low > 20 applications; Beckie 2006). Site of action: 1/A, ACCase inhibitors; 2/B, ALS inhibitors; 3/K1, microtubule assembly inhibitors (e.g., dinitroanilines); 4/O, synthetic auxins; 5/C1 (e.g., triazines), 6/C3 (e.g., nitriles), 7/C2 (e.g., ureas)–photosystem II inhibitors (different binding sites or behavior); 8/N, lipid synthesis inhibitors (thiocarbamates); 9/G, enolypyruvyl-shikimate-3-phosphate synthase (EPSPS) inhibitor (glyphosate); 10/H, glutamine synthetase inhibitor (glufosinate); 22/D, photosystem I electron diverters (bipyridyliums); "other," insufficient information for all other sites of action to definitively categorize as low or as moderate risk. Numerical (Weed Science Society of America) and alphabetical (Herbicide Resistance Action Committee) herbicide groups are described in detail in Mallory-Smith and Retzinger (2003) or Heap (2006).

mutants is proportional to population size (Jasieniuk et al. 1996).

Cross-resistance patterns in weed species may be used as a guide for strategic herbicide use but cannot be accurately predicted based on field histories of herbicide use. Individuals in a population exposed to the same selection pressure can exhibit different patterns of cross-resistance, however, highlighting the probable short-term success of this approach. Wild oat patches with different cross-resistance patterns have been documented within a field (e.g., Andrews et al. 1998; Beckie et al. 2002; Bourgeois et al. 1997a).

Surveys in the 1990s indicated that incidence of aryloxyphenoxypropionate (APP) resistance in HR wild oat biotypes tended to be greater than that of cyclohexanedione (CHD) resistance (Beckie et al. 1999b, 1999c, 2002). In those surveys, weed populations were screened with only one representative APP herbicide (fenoxaprop-P) and one CHD herbicide (sethoxydim). However, with a greater number of APP and CHD herbicides used in resistance screening in surveys in the 2000s, most ACCase inhibitor-HR wild oat and green foxtail populations were found to be resistant to both APP and CHD herbicides (Beckie et al. 2004a, 2004c, 2006b). An apparently widespread point mutation in the ACCase gene, resulting in an amino acid change from isoleucine to leucine at position 1781, confers resistance to most APP and CHD herbicides in several grass weed species (Délye et al. 2003; Kaundun and Windass 2006). In various grass weed species, clethodim has often controlled ACCase inhibitor-HR biotypes in dicot crops (Bradley and Hagood 2001). In the Alberta and Saskatchewan weed surveys, clethodim controlled all ACCase inhibitor-HR wild oat biotypes (Beckie et al. 2004a, 2006b). Apparently, the point mutation(s) that confers resistance to this herbicide occurs relatively infrequently. Similar to the pattern of ACCase inhibitor cross-resistance, there is broad cross-resistance in wild oat to ALS inhibitors from different classes (Beckie et al. 2004a, 2004c, 2006b).

Herbicide resistance is often attributed to a lack of herbicide group rotation, i.e., frequent or repeated use of herbicides of the same site of action. However, there is direct evidence for the utility of herbicide group rotations in delaying the evolution of target-site resistance. In the prairies, herbicide group rotation has been credited in preventing or delaying ACCase inhibitor resistance in wild oat (Légère et al. 2000). Herbicide rotations or mixtures generally have the greatest effect in delaying resistance when the target weed species are highly self-pollinated, the mechanism conferring resistance is target-site based, and seed spread is restricted (Beckie et al. 2001b; Wrubel and Gressel 1994). Both wild oat and green foxtail meet the first criterion and the second one frequently. Thus, the effectiveness of this tactic is contingent on limiting HR weed seed production and movement.

Herbicide Rotation by Propensity for Metabolism. Intergroup herbicide resistance can be conferred by a non-target site mechanism, which commonly is enhanced metabolism (De Prado and Franco 2004). Metabolic resistance has been reported much more frequently in grass than broadleaf weeds (Werck-Reichhart et al. 2000). Metabolism-based resistance to herbicides of different sites of action will clearly limit the effectiveness of herbicide group rotation as a tool to delay the evolution of herbicide resistance. Testing populations to determine herbicide resistance patterns is even more important where intergroup resistance is suspected and will help identify remaining herbicide options for farmers (Beckie et al. 2000).

Herbicides that are not readily metabolized in weeds are less likely to select for metabolism-based resistance. For example, the relatively low incidence of dinitroaniline (e.g., trifluralin) resistance may be due to the paucity of detoxification mechanisms in target plants (Holt et al. 1993). Two major enyzme systems have been implicated in herbicide resistance due to increased detoxification—cytochrome P450 monooxygenases and glutathione *S*-transferases. These detoxification systems are expressed both constitutively and induced (upregulated) in response to herbicide safeners.

Herbicides used in rotations that are detoxified via pathways different from these two enzyme systems, or that are slowly or not metabolized (e.g., glyphosate, glufosinate, paraquat), will reduce the risk of selecting for metabolism-based, intergroup-HR weed biotypes (Beckie 2006). Most cases of cross-resistance across herbicide sites of action have occurred through the use of wheat (*Triticum aestivum* L.)-selective herbicides (Hidayat and Preston 2001). Thus, herbicides not selective in wheat, such as sethoxydim or clethodim, and nonselective herbicides used in HR crops, such as glyphosate or glufosinate, will be important tools for managing metabolic resistance in HR wild oat or green foxtail biotypes in the future.

Herbicide-Resistant Crops. The judicious use of HR crops can slow the selection of HR weeds by increasing herbicide rotation options, such as the substitution of high-risk herbicides with lower-risk products. Nonselective herbicides used in HR crops in Canada have been an important tool to manage HR weeds, such as those resistant to high-risk herbicides including ACCase and ALS inhibitors (Beckie et al. 2006a) (Table 1). As a result, the potential economic impact of these HR weeds has been diminished. However, frequent use of HR crops in cropping systems, resulting in recurrent application of herbicides of the same site of action, may select for other HR weed biotypes or augment the selection that has occurred previously. Potential impact of HR crops on selection for weed resistance is largely dependent on the size and intensity of the cropped area in an agricultural region, herbicide site of action, and abundance of weed species.

Occurrence of glufosinate-resistant weeds has not been reported in Canada or elsewhere. Glufosinate-resistant canola was grown on about 1.7 million ha in 2005 (Beckie et al. 2006a). About one-third of glufosinate-resistant canola producers tank-mix clethodim or another ACCase inhibitor with glufosinate to enhance grass weed control; glufosinate is rarely applied twice in crop (J. Leeson and G. Thomas, unpublished data). Depending on glufosinate efficacy, the tank-mix herbicide may contribute to ACCase inhibitor selection pressure in wild oat and green foxtail and thus reduce the utility of glufosinate in combating ACCase inhibitor resistance.

In the prairies, ALS inhibitor herbicides are often applied to one-third or more of cropped land each year (Leeson et al. 2006a). Use of residual ALS inhibitor products in consecutive years is a common practice. In Manitoba in 2002, 41% of residual ALS inhibitor herbicides were applied back to back. The largest class of HR weeds in Canada and worldwide are those resistant to ALS inhibitors. The use of ALS inhibitor herbicides in imidazolinone-HR crops will continue the selection for ALS inhibitor-HR wild oat and green foxtail. With the commercial release of imidazolinone-HR canola in 1995, wheat in 2004, and lentil (*Lens culinaris* L.) in 2006, ALS inhibitors could be used in every major crop in the prairies, including both conventional and imidazolinone-HR crops.

Since the introduction of glyphosate-resistant crops in the mid-1990s, several weed species resistant to the herbicide have been reported (Heap 2006). Although a minority of glyphosate-resistant biotypes are a result of glyphosate selection pressure in HR field crop production systems, the total infestation area of these biotypes is increasing rapidly. Glyphosate-resistant canola was grown on about 2.6 million ha in 2005 (Beckie et al. 2006a). Although the majority of glyphosate-resistant canola producers apply glyphosate twice in crop, less than 15% of the total area treated annually with herbicides receives an in-crop glyphosate application (Leeson et al. 2004, 2006b; Thomas et al. 2003). Selection intensity is generally greatest at this herbicide application timing (Beckie 2006). In comparison, frequency of total glyphosate usage ranges from 34% (Alberta and Manitoba) to 62% (Saskatchewan) of land cropped to cereals, oilseeds, or pulses (J. Leeson and G. Thomas, unpublished data). Relatively high glyphosate usage in Saskatchewan is linked to the adoption of no-till; 39, 27, and 13% of cropland in Saskatchewan, Alberta, and Manitoba, respectively, is planted using no-till practices (Statistics Canada 2002). Therefore, the contribution of glyphosate-resistant canola to overall glyphosate selection pressure in prairie cropping systems is relatively low. In contrast, the risk of evolved glyphosate resistance in weeds as a consequence of HR soybean [*Glycine max* (L.) Merr.] cultivation is markedly greater in eastern Canada. Sequential in-season applications combined with near glyphosate-resistant soybean monoculture in some regions creates a high selection pressure for the evolution of glyphosate-resistant weeds.

Herbicide Mixtures: Limited Usefulness. Acceptance by farmers of herbicide mixtures for resistance avoidance in broadleaf weeds has been aided by cost-incentive programs from industry, formulated mixtures, and the rapid evolution of resistance in specific cases. The herbicide combinations may be applied at lower individual herbicide rates (Little and Tardif 2005), especially when interacting synergistically (Gressel 1990).

If herbicides of different sites of action do not meet the criteria of similar efficacy and persistence, plus different propensity for selecting for resistance in target species, the effectiveness of mixtures for delaying target-site resistance will be reduced. Mixtures can inadvertently accelerate the evolution of multiple resistance if they fail to meet basic criteria for resistance management and are applied repeatedly (Rubin 1991). To effectively delay metabolic resistance, the herbicides used in mixtures must be degraded via different biochemical pathways (Wrubel and Gressel 1994). However, information on the mode of degradation of herbicides in plants is not known by farmers. Furthermore, mixtures to prevent or delay metabolic resistance in grass weeds, where this mechanism is most prevalent, may be cost-prohibitive unless the mixed graminicides interact synergistically and can be applied at lower rates. Because of increased cost and lack of availability of suitable mixing herbicides that meet the criteria outlined above, mixtures will likely have limited usefulness in wild oat or green foxtail resistance management.

Site-Specific Herbicide Application. Site-specific herbicide application, using a global positioning system and utilizing weed abundance as a basis for delineating application areas in a field, likely would allow some reduction in the overall selection pressure. Costs of acquiring reliable weed abundance distribution maps and herbicide application have limited its adoption by dryland farmers growing relatively low cash-value crops. Soils on the prairies were developed on material laid down by glaciers and their meltwaters, with the result that the majority of fields have significant topographic variation (Moss 1965). Wild oat seedling recruitment, biomass production, and fecundity are affected by landscape position, being greatest in lower-slope areas and least in upper-slope areas; green foxtail is much less affected by landscape position than wild oat (Forster and Shirtliffe 2004). I have often observed the same results over 20 yr of farming in the semiarid grassland region, where water is the greatest limiting factor in crop production. An economic threshold can be calculated using readily available information on herbicide prices and estimated crop yield loss as a function of mean wild oat density (Anonymous 2006) in each landscape position in a field. In my experience, herbicide application is usually not warranted on upper slopes; in most years, wild oat herbicides are applied to two-thirds or less area of a field.

The effect of precision herbicide application on the rate of evolution of resistance would depend on the frequency of herbicide application to specific areas of a field over time and the proportion of the field treated each year. If application frequency of grass weed herbicides to specific areas of a field (e.g., lower-slope areas) is similar to conventional herbicide application, HR wild oat or green foxtail seed movement from these field areas to those treated less frequently may negate any potential benefits of the technology. Furthermore, if these treated areas contain the majority of the weed population present in the field, then this tactic may still result in a selection pressure similar to that of a blanket application.

Site-specific management can be useful in monitoring and managing HR weed patches at early stages of development in a field over time. Unfortunately, most farmers in the prairies fail to detect small HR patches (H. Beckie, unpublished data). HR weed patch management after in-crop herbicide application is performed by fewer than one-third of farmers (Table 1), likely because of a lack of awareness of the benefit of this practice or inconvenience due to large farm size. A study conducted at a 64-ha no-till site in the prairies assessed how preventing seed shed from HR wild oat affected patch expansion over a 6-yr period (Beckie et al. 2005). Seed shed was prevented in two patches and allowed to occur in two patches (nontreated controls). Annual patch expansion was determined by seed bank sampling and mapping. Crop management practices, including herbicide application, were performed by the farmer. Area of treated patches increased by 35% over the 6-yr period, whereas nontreated patches increased by 330%. Patch expansion was attributed mainly to natural seed dispersal (nontreated) or seed movement by equipment at time of planting (nontreated and treated). Extensive (94 to 99%) seed shed from plants in nontreated patches before harvest or control of HR plants by alternative herbicides minimized seed movement by the combine harvester. Although both treated and nontreated patches were relatively stable over time, this study demonstrated that preventing seed production and shed in HR wild oat patches can markedly slow the rate of patch expansion. Consequently, herbicide effectiveness in a field is extended in space and time.

Limit Herbicide Resistance Gene Flow. Minimizing weed seed production is central to both HR and non-HR weed management programs. Cultural or mechanical practices affect weed population densities and seed production, and thus can delay the evolution of herbicide resistance by reducing the number of HR alleles in a population. Where high levels of HR alleles are believed to be present in unselected populations, it is important to maintain low population densities via nonchemical methods or by using herbicides with a relatively low likelihood to select for these HR alleles. This tactic is also useful in fields where the high-risk ACCase and ALS inhibitors have been used frequently for over 20 yr. Many of these fields are likely well advanced along the herbicide resistance evolution curve.

Gene flow through pollen or seed movement from HR weed populations can provide a source of HR alleles in previously HS populations. Because rates of gene flow are generally higher than rates of mutation, the time required to reach a high level of herbicide resistance in such situations is greatly reduced (Jasieniuk et al. 1996). Seed movement is responsible for the majority of gene flow in wild oat and green foxtail populations. HR wild oat and green foxtail seed spread within and among fields have been documented (Andrews et al. 1998; Li et al. 2000). Fields within farms are more likely to have HR weeds than randomly-picked fields, indicating movement of HR seed between fields via equipment (Beckie et al. 2002) or similar selection pressure among fields within a farm. Sharing of equipment among farmers has also been implicated in herbicide resistance (Debreuil et al. 1996). Weed seed spread by machinery, noncomposted manure, silage, or contaminated commercial seed stocks or feed (Stephenson et al. 1990) is generally greater than natural seed dispersal. For example, wild oat seeds can spread more than 150 m by a combine harvester (Shirtliffe and Entz 2005). As the incidence of herbicide resistance in wild oat and green foxtail increases in the prairies, seed movement in addition to selection will increasingly influence such occurrences.

Management practices that limit the spread of HR seed can slow the occurrence of herbicide resistance. In the prairies, farmers who reported practicing weed sanitation (e.g., cleaning harvesting and tillage equipment when moving between fields, covering the grain truck box, mowing or spraying ditches or uncontrolled weed patches, applying composted vs. fresh manure) were less likely to have HR wild oat than those who were less careful (Légère et al. 2000). Cleaning equipment when moving among fields and mowing weed patches, ditches, and headlands ranked fourth and fifth, respectively, in importance among herbicide resistance management practices cited by farmers in the prairies (Bourgeois et al. 1997b). If the HR population covers a wide area across the field, management should focus on reducing seed return and spread by using low-risk herbicides in conjunction with cultural practices, such as cutting the crop (hay, silage, or green manure) before or soon after flowering of the HR weed species, growing perennial crops, or collecting weed seeds at harvest. The adoption of these cultural practices by prairie farmers is generally low (Table 1). Wild oat, in contrast to green foxtail, may shed most seeds by cereal crop harvest in the prairies. Therefore, harvesting after extensive seed shed can reduce HR wild oat seed spread by equipment (Beckie et al. 2005).

Weed-Smart Cropping Systems and Practices. The judicious use of timely tillage has been cited often as an important practice to delay (Table 1: tillage, fallow) or manage HR weeds (Bourgeois et al. 1997b; Stephenson et al. 1990). Tillage may substitute for herbicide use or influence seed bank dynamics. Timely tillage can also stimulate weed germination before crop planting. Anecdotal field observations have frequently linked herbicide resistance in weeds to conservation-tillage systems, particularly no-till, which are increasingly being adopted by farmers because of increasing fuel costs and time efficiencies. Farmers may be further encouraged by economic incentives to adopt reduced-tillage systems that sequester carbon in soil and thus mitigate greenhouse gas emissions. In a field study by Beckie et al. (2004b), ALS inhibitor-HR wild oat was associated with such systems. Reduced tillage substitutes herbicide use for tillage to varying degrees. Reduced-tillage cropping can increase the abundance of specific weed species and consequently, result in greater herbicide use. The abundance of wild oat, a C_3 plant, is favored by reduced tillage, whereas green foxtail, a C_4 plant, is associated more with conventional tillage (Watson et al. 2001). An analysis of multiple studies, however, found little evidence that reduced tillage increases herbicide use (Nazarko et al. 2005; Zhang et al. 2000). In the absence of tillage, weed seedlings may be derived largely from seeds shed in the previous crop and concentrated near the soil surface. Consequently, there will be little buffering against resistance evolution from old seeds, which may have greater percentage susceptibility (Moss 2002).

Inclusion of competitive crops and competitive cultivars of a crop in rotations are viewed by farmers as being important in HR weed management (Bourgeois et al. 1997b). Quantitative trait loci for traits in wheat associated with weed competitiveness have been identified. These markers can be used by crop breeders to select for weed-competitive genotypes (Coleman et al. 2001). In the shorter term, crop competitiveness can be enhanced by increasing seeding rates. This practice is most cost-effective for cereals. In the prairies, increased crop seeding rate is the most consistent cultural practice for managing weeds and maintaining crop yields (Beckie and Kirkland 2003; Blackshaw et al. 2004). Blackshaw et al. (2005) found that a 50% increase in wheat seeding rate resulted in an equivalent reduction in weed biomass.

Crop rotations are dictated primarily by profit potential and not the management of HR weeds. Crop rotation, however, is frequently cited as one of the most influential factors in delaying or managing HR weeds (Bourgeois et al. 1997b; Stephenson et al. 1990) (Table 1). Diversity in sequences of crop types and phenologies in a rotation (i.e., dicot vs. monocot; winter- vs. spring- planted; cool vs. warm season; annual vs. perennial) may directly or indirectly reduce weed populations. Crop rotations can facilitate herbicide rotation or reduction. A field study in the prairies linked ACCase and ALS inhibitor resistance in wild oat to a lack of crop rotation diversity (Beckie et al. 2004b). Inclusion of fall-planted and perennial forage crops in annual spring crop-based rotations effectively slowed the evolution of herbicide resistance in this weed species. A field survey documented the ability of 3- to 6-yr alfalfa (*Medicago sativa* L.) stands to reduce wild oat populations in cropping systems through crop competition and cutting regime of the crop for hay (Ominski et al. 1999). The survey found that wild oat population densities were reduced by 96% in cereal fields that followed alfalfa vs. a cereal crop.

The potential value of crop rotation to delay or manage HR weeds will not be realized unless accompanied by diversification or reduction in herbicide use. Repeated use of herbicides with the same site of action will negate the weed suppression benefits associated with crop rotation. Whereas Beckie et al. (2004b) found a significant positive association between a lack of crop rotation diversity and wild oat resistance, no association between ACCase inhibitor resistance in wild oat and crop rotation was found in an earlier study by Légère et al. (2000). Frequent application of ACCase inhibitors to cereal, oilseed, and annual legume crops counteracted potential crop rotation benefits. Occurrence of resistance in wild oat was the lowest in rotations where frequency of fallow was the highest because of the reduced frequency of herbicide use.

The extent to which farmers alter their current farming systems to manage herbicide resistance in these grass weeds depends on the nature and magnitude of infestation of an HR biotype. In many cases, a farmer's response to weed resistance is to switch to an alternative herbicide (Table 1). For serious herbicide resistance problems, e.g., heavy infestations of intergroup-HR wild oat or green foxtail, a longer term, cropping systems approach may be required as illustrated below by a case study.

Case Study: Managing Intergroup Herbicide-resistant Wild Oat

The case study is based on one farmer's experience in managing intergroup-HR wild oat on his farm, located in northwestern Manitoba (Beckie and Gill 2006). The cropping history and herbicide use associated with the occurrence of intergroup-HR wild oat in one of the no-till fields on the farm is typical of fields in the prairies with evolved wild oat resistance (Table 2). ACCase inhibitors (diclofop, sethoxydim) had been applied seven times over an 11-yr period between 1986 and 1996. ACCase inhibitor resistance was first suspected in 1997 when fenoxaprop failed to control wild oat in spring wheat. Imazamethabenz, an ALS inhibitor, was subsequently applied in the same growing season but did not control the weed. The herbicide had only been used once before. Resistance test results indicated that the population was resistant to fenoxaprop, imazamethabenz, triallate (group 8), difenzoquat (group 26), and flamprop (group 25). Triallate and difenzoquat had been used periodically in the field (four applications between 1986 and 1995). Flamprop, however, had not been applied between 1986 and 1998. The mechanism of herbicide resistance was altered metabolism, although more than one mechanism is possible (H. Beckie, unpublished data). By the spring of 1998 prior to herbicide application, HR wild oat covered a large proportion of the 64-ha field and also occurred in other fields on the farm. Glyphosate-resistant canola was grown in 1998 and controlled HR wild oat.

Table 2. Cropping history and grass herbicide use associated with the occurrence of intergroup herbicide-resistant wild oat in a 64-ha field on a farm in northwestern Manitoba (adapted from Beckie and Gill 2006).

Year	Crop	Herbicide	Group
1998	Canola (*Brassica napus* L.)	Glyphosate	9
1997	Spring wheat (*Triticum aestivum* L.)	Imazamethabenz[a]	2
		Fenoxaprop	1
1996	Canola	Sethoxydim	1
1995	Spring wheat	Difenzoquat	26
1994	Spring wheat	Imazamethabenz	2
1993	Canola	Sethoxydim	1
1992	Spring wheat	Triallate + trifluralin	8 + 3
1991	Spring wheat	Diclofop	1
1990	Spring wheat	Diclofop	1
1989	Spring wheat	Diclofop	1
1988	Spring wheat	Difenzoquat	26
1987	Flax (*Linum usitatissimum* L.)[b]	Sethoxydim	1
	Barley (*Hordeum vulgare* L.)	Difenzoquat	26
1986	Spring wheat	Diclofop	1

[a] Fenoxaprop was applied first and failed to control wild oat; imazamethabenz was subsequently applied.

[b] Flax and barley were grown on 32 ha each.

The farmer realized that a major change in his cropping system was required to sustain the economic viability of his farm. To manage resistance, the farmer altered his no-till cropping system from one based on near monoculture of cereals (spring wheat) to a 6-yr sequence of diverse crops (Figure 2). A short-term (3-yr) alfalfa stand has markedly reduced wild oat recruitment from the seed bank. Alfalfa is followed by fall-planted cereals (winter wheat or fall rye, *Secale cereale* L.), which have replaced spring wheat in the rotation. Winter cereals have eliminated the need for a wild oat herbicide application in the spring because of early season crop growth and competitiveness. Herbicide-resistant canola (glufosinate-resistant hybrid) follows the cereal crop in the rotation, and is planted as early as possible in spring to optimize yield potential and eliminate the need for a preplant glyphosate application. Zand and Beckie (2002)

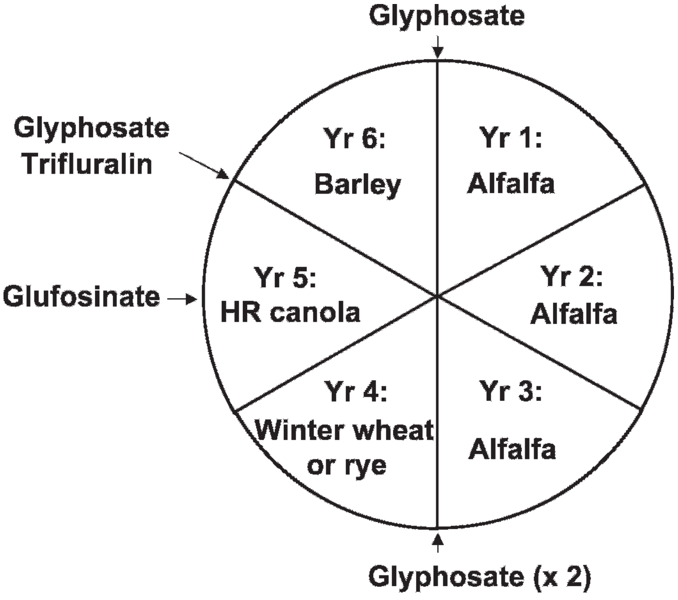

Figure 2. Cropping system used by a farmer in Manitoba in response to intergroup herbicide-resistant wild oat (*Avena fatua* L.) (adapted from Beckie and Gill 2006).

found that hybrid canola cultivars were twice as competitive against wild oat than open-pollinated cultivars when weed interference was relatively high. Barley (*Hordeum vulgare* L.), a competitive cereal crop, follows canola in the rotation, using trifluralin (group 3) applied preplant (fall-applied granular formulation) without incorporation in soil to control wild oat. Following barley harvest, alfalfa is planted in late summer. Seeding rates of cereals are typically 25 to 50% above recommended rates to increase stand density and aid crop competition against wild oat.

This cropping system has allowed the farmer to maintain or increase net returns and reduce economic risk compared with the previous system. By diversifying the crop rotation to include perennial forages and weed-competitive annual crops that differ in phenology (winter and spring) and type (monocot and dicot), and including agronomic practices such as increased crop seeding rates and precision fertilizer placement (i.e., banding fertilizer), the farmer has markedly reduced wild oat population densities. This change in farming system, in turn, has allowed a reduction in herbicide use. Herbicides used in the cropping system are rotated by site of action and pose a moderate (trifluralin) to low risk (glyphosate, glufosinate) of selecting for target-site based HR weed biotypes (Figure 1). Because these herbicides are not readily metabolized in plants, they pose a low risk for selecting for metabolic-based HR biotypes. Typical of no-till systems, the farmer relies heavily on glyphosate as a burnoff treatment before planting alfalfa and cereals, and for terminating the alfalfa stand; glyphosate is usually applied four times during the 6-yr crop rotation.

Approaches to integrated weed management differ, depending on agroecological conditions, biology and ecology of the weed species with evolved resistance, and agronomic and socioeconomic considerations by farmers. Although herbicides remain as the dominant weed control tool, diversification in cropping systems and practices can result in less herbicide used and thus a reduction in selection pressure for resistance. Even serious weed resistance problems can be managed successfully if farmers are receptive to changes in their cropping systems. The increasing incidence and complexity of herbicide resistance in these two grass weeds will inevitably require farming systems with a reduced dependence on herbicides.

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Received April 28, 2006, and approved August 14, 2006.