HERBICIDE-RESISTANT WEEDS: THE NEED FOR AN INTEGRATED MANAGEMENT APPROACH

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Introduction

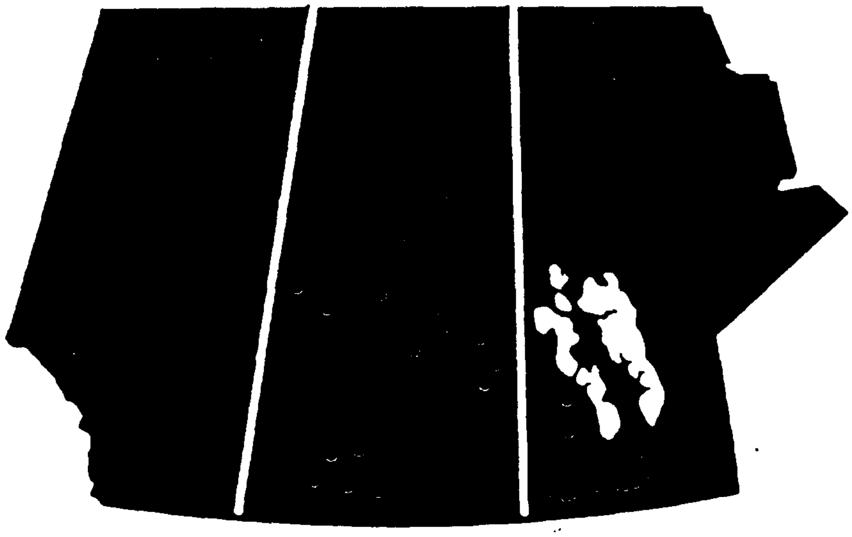
Herbicide-resistant (R) weeds are becoming increasingly common on the Canadian prairies. These are weeds that survive herbicide application, at rates that usually give effective control (LeBardon and Gressel 1982). Resistant weed biotypes, having a genetic make-up different from susceptible (S) plants, are a consequence of basic evolutionary processes. Individuals within a species that are best adapted to a particular practice are selected for and will increase in the population. Once a weed population is exposed to a herbicide to which some plants are naturally resistant, the herbicide kills S plants, but allows R ones to survive, mature and produce seed. With repeated use of that herbicide or other herbicides that kill weeds the same way (same mechanism of action) over a number of years on the same field, R weeds that initially appear as patches in the field can quickly spread to dominate the population and the soil seed bank. Because R weeds generally are cross-resistant to herbicides having the same mechanism of action (Beckie and Morrison 1993a), the ***group*** concept was developed to assist farmers in herbicide rotation planning. However, weed populations that are resistant to herbicides belonging to different groups (multiple resistance), have recently been discovered in western Canada.

The Problem

Since the first confirmed case of herbicide resistance in 1968 (Ryan 1970), there were 113 R weed biotypes worldwide by 1990. These include 58 species (4 1 dicots and 17 monocots) resistant to triazine herbicides and 55 species (36 dicots and 19 monocots) resistant to 14 other groups of herbicides (LeBaron 199 1; Moss and Rubin 1993). By 1996, the number of R weed biotypes had risen to 18 1 (114 dicots and 67 monocots) (Heap 1996). Populations of six weed species (green foxtail, wild oat, chickweed, kochia, Russian thistle and wild mustard) that are resistant to herbicides belonging to at least one of seven groups, have been discovered in western Canada during the past 8 years (Figure 1). Most of the weeds that have developed resistance on the prairies are common species, ranking high in relative abundance. Green foxtail is the most abundant weed of cropland on the Canadian prairies. Weed surveys show that this species occurs on approximately 78, 53, and 20% of fields in Manitoba, Saskatchewan and Alberta, respectively (Thomas and Wise 1985, 1988; Thomas 1996, unpublished data). Wild oat, the most serious annual weed, ranks second in abundance, occurring on approximately 64, 67, and 49% of fields in Manitoba, Saskatchewan and Alberta, respectively. Those weeds that occur at the highest densities are more likely to be treated with herbicides. As well, the more individuals present, the greater the likelihood of the population containing a R biotype.

Green foxtail populations have been reported to be resistant to herbicides belonging to Group 1 (arloxyphenoxypropionates/ cyclohexanediones) and Group 3 (dinitroanilines); wild oat populations have been reported to be resistant to herbicides in either Group 1, 2 (sulfonylureas/imidazolinones), 3 or 8 (triallate/difenzoquat). Group 3-R green foxtail and group 1 -R wild oat constitute the majority of reported cases. In both instances, resistance developed after about 8-12 herbicide treatments in a field (Morrison et al. 1989; Heap et al. 1993). Group 3-R green foxtail is now estimated to occur in one of every four fields in SW Manitoba (Goodwin 1994a). Wild oat resistance to Group 1 herbicides is the most pressing problem because of the prevalence of high risk areas reported in Manitoba as a result of repeated Group 1 herbicide use, the number of confirmed sites (over 1000), as well as the continuing high frequency and extent of use of these herbicides on the prairies (Figure 2). Moreover, there are few alternative chemical control options, particularly use of postemergence herbicides in oilseed crops.

All Weeds
Confirmed Sites of Herbicide Resistance 1988



All Weeds
Confirmed Sites of Herbicide Resistance 1995

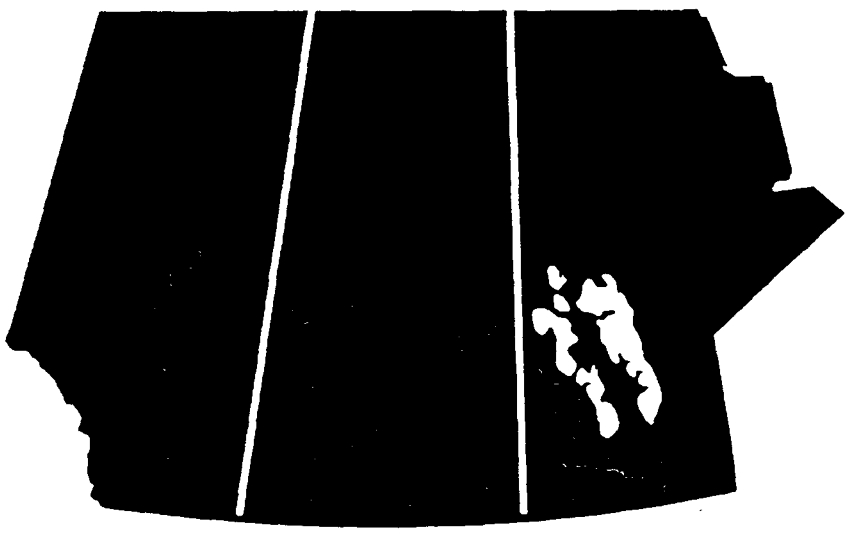


Figure 1. (Source: Cyanamid Canada Inc.)

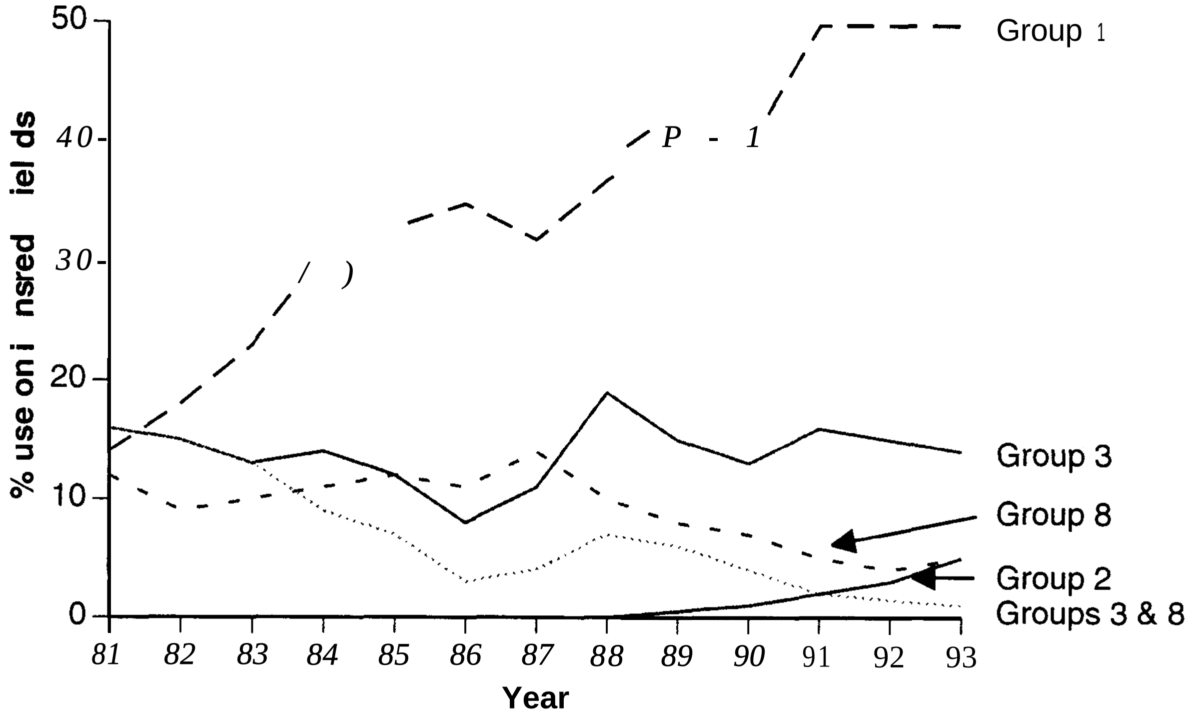


Figure 2. Proportion of sprayed fields in Manitoba treated with various wild oat herbicide groups, 198 1- 1993 (Source: Morrison *et al.* 1995).

A few populations of green foxtail and wild oat exhibit multiple resistance: green foxtail to herbicides belonging to Groups 1 and 3, and wild oat to herbicides in Groups 1, 2 and flamprop-methyl (Mataven®), which is in a group of its own (Morrison *et al.* 1995). Producers with Group 3-R green foxtail will tend to rely on Group 1 herbicides for control, thus increasing the risk of selecting for multiple-resistant biotypes. If so, the only remaining herbicides to control R foxtail is imazethapyr (Pursuit®),TCA and propanil (Stampede@). Pursuit is registered for use in field peas only; Stampede is limited for use in cereals and flax.

The costs of herbicide resistance in weeds can include fewer herbicide options, restricted crop rotations, increased dependence on tillage and associated risk of soil degradation, higher input costs, less weed control and lower yields, reduced land value and additional time and management skills needed (Cyanamid 1995). Clearly, it is simpler and more economical to use good agronomic practices now to prevent or delay the appearance of R weeds than to manage them after they infest an area.

The Short-Term Solution

The short-term solution to preventing, delaying or managing R weeds is meaningful herbicide rotation. A 'l-in-3' rule has been recommended, whereby herbicides in a particular group should not be used in a field more than once every 3 years. Accurate field records of crops grown and herbicides used will aid herbicide rotation planning. However, herbicide group rotation may be relatively ineffective in preventing the occurrence of multiple-resistant weed biotypes. Farmers with multiple-resistant wild oat previously had been rotating herbicides with the expectation that they could avert the resistance problem on their farms (Morrison et *al.* 1995).

Herbicide mixtures are recommended as a tactic to delay the development of resistance. However, to be effective, the mixing partners must belong to different herbicide groups and should be active on a similar spectrum of weeds and have similar persistence (Wrubel and Gressel 1994). Thus, tank-mixtures may be most useful for combating Group 2 resistance. This tactic will not be adopted, however, if costs are prohibitive. Furthermore, there is concern that herbicide mixtures may select for multiple-resistant biotypes. A final chemical strategy is to vary the time of herbicide application (e.g., preemergence or burnoff, in-crop, pre-harvest, post-harvest) within a field over time, so that the selection intensity on weed communities is varied (Derksen *et al.* 1994).

The Long-Term Solution

The appearance of multiple-resistant biotypes reinforces the need for an integrated weed management (IWM) approach, which is the long-term solution for reducing the risk of resistance development. The selection intensity (pressure) is the most important factor affecting the rate of evolution of resistance in weed biotypes (Gressel and Segel 1982). The selection intensity of the herbicide on the weed species is governed by the rate and frequency of use, its efficacy with particular weeds, and its persistence. The selection intensity is not determined by the initial reductions in density or biomass typically measured by weed scientists, but rather by determination of 'effective kill' (Beckie and Morrison 1993b). Effective kill is the reduction in weed seed yield due to the herbicide treatment. Traditionally, the selection intensity of soil residual herbicides, which control successive flushes of weeds over the growing season, was believed to be significantly greater than non-residual herbicides. However, the selection intensity exerted by highly effective, short or non-residual herbicides may be similar to soil residual herbicides under the relatively short growing season conditions on the Canadian prairies (Morrison and Devine 1994). The underlying principle of any management strategy is to reduce the selection intensity for the evolution of resistance (Holt and LeBaron 1990). This reduction in selection intensity can be accomplished by an IWM approach, including the judicious use of herbicides with the minimum selection intensity giving cost-effective weed control.

To reduce the selection intensity for resistance development, herbicide inputs in the cropping system need to be reduced. This means either lower rates with less effective kill, less frequency of application, or both. Reduced rate application is not recommended in Canada. However, significant research data exists to suggest that rates less than recommended can be effective when environmental conditions are ideal, optimum weed growth stage is present at application, the use of adjuvants, additives and adjustments to carrier volumes are related to specific water qualities and/or herbicide mechanisms of action (Kirkland 1995). However, research is required to determine if reduced rates of application lessens the risk of resistance development. To compensate for reduced herbicide inputs, effective cultural management practices need to be integrated into the cropping system to minimize both weed interference effects on crop productivity and quality, and weed seed production (Gorddard *et al.* 1995).

At present, farmers should spray only when necessary. For example, a light infestation of weeds that emerge after a competitive crop has emerged will likely not significantly reduce yield. Manitoba Agriculture (1996) has published economic threshold guidelines for wild oat and green foxtail in cereal and broadleaf crops. Is spot spraying an option, particularly in fields with topographic variation? The risk of resistance development is much greater with prophylactic weed control than increased weed seed production caused by skipping a herbicide application when not justified. In a conservation tillage, crop rotation study initiated in 1990 (Derksen and Lafond 1995), weed densities were similar or lower in the low-input (no grassy weed herbicides applied in the cereal crop plus a reduced broadleaf weed herbicide approach) compared to high-input rotations for the weed seed bank, weed seedling and mature weed community. There were more wild oats in the low-input rotations, but these did not influence crop yield.

Biological control constitutes the second component of IWM. Research in weed biocontrol with pathogens has been ongoing for over 25 years in the United States and Canada. In spite of much research in both countries, only two bioherbicides have been registered in the U.S.; BioMal® was the only one in Canada. However, none of these products are currently commercially available (Auld and Morin 1995). Nevertheless, scientists at Agriculture & Agri-Food Canada in Saskatoon are researching promising isolates of foliar and soil-borne microorganisms or their phytotoxins as potential biocontrol agents for some of our major weeds, such as green foxtail, wild oat and Canada thistle. Even so, it will be a few years before a bioherbicide can be commercially available.

If one holds the premise that weed species present in a field will always *be* present in that field, then IWM practices that minimize weed interference with the crop and weed seed production should be emphasized, rather than achieving high weed control efficacy by strictly chemical means. To compensate for reduced herbicide use as a means of preventing or delaying resistance, increased reliance on effective cultural management practices is needed. Giving an advantage to the crop at the expense of the weeds is the primary objective of IWM strategies. The key elements of cultural weed management are outlined below.

Tillage:

Timely tillage can be an effective control option in conservation tillage systems, particularly when hard-to-control weeds such as dandelion are pervasive. Crop rotation generally has a bigger impact on weed communities than tillage system (Derksen 1994). Derksen *et al.* (1993) concluded that changes in weed communities over a 4-year study in Saskatchewan were more likely to depend on species, location and environment, rather than solely on tillage systems. Similarly, Thomas and Frick (1993) found little difference among surveyed conventional, reduced and zero tillage fields in SW Ontario. A reduction in tillage, however, tends to cause an increase in wind-dispersed species (e.g. dandelion, foxtail barley) and volunteer crops, but a decrease in certain summer annual species, such as green foxtail (Derksen et *al. 1993).* The fact that weed communities are relatively similar among tillage systems may be explained by a compensation of cropping and herbicide use practices in conservation tillage systems (Johnson 1995). Research is required to determine if low disturbance direct seeding systems have less weeds than high disturbance systems. Theoretically, if weed seed is restricted to the soil surface, there should be less stimuli for germination, poorer establishment and greater mortality by weathering. Combined with a strongly-competitive crop stand, assisted by shallow seeding and good surface soil moisture, a herbicide application may be unnecessary (Johnston 1995).

Crop Competition:

Seeding date

Altering seeding dates within a field can be a very effective cultural weed management practice. Weeds differ in their time of emergence. For example, wild oat germinates early under cool, moist conditions, whereas green foxtail emerges later, due to higher temperature requirements for germination. Thus, late-planted spring crops and early-planted fall crops generally have fewer wild oat plants than early-planted spring crops and late-planted fall crops (Chancellor and Peters 1976). Varying the seeding date of a field will reduce the selection of either early or late emerging weeds. Since seeding is normally spread out over a number of days or even weeks, altering dates to suit crop type (e.g., pulses generally are seeded early), previous crop (e.g., direct seeding low residue fields first in the spring because of low temperature or excessive soil moisture concerns), and prevalent weed species (e.g., wild oat problem) gives an advantage to the crop. This may eliminate the need for a herbicide application. Pre-seeding burnoff treatments are less important for early-seeded crops, whereas in-crop treatments have greater impact on weed densities. As seeding date is delayed, the importance of the pre-seeding burnoff treatment in direct seeding systems increases, whereas the need for in-crop treatment lessens (Derksen 1994).

The influence of seeding date on crop competitiveness against weeds was examined in a crop rotation study initiated in 1990 (Derksen and Lafond 1995). Weed densities were similar or lower in the low-input (no grassy weed herbicides applied in the cereal crop plus a reduced broadleaf weed herbicide approach) compared to high-input rotations. The fact that weeds have not dramatically increased in the low input rotation was due to a combination of varied seeding dates and varied selection intensity due to the 'rotational effect' in the spring wheat-canola-spring wheat-lentil rotation.

Seeding rate and row spacing

Seeding rate is generally more effective than row spacing in promoting crop competition against weeds (Thill *et al.* 1994). The current seeding rate recommendations are too low and should be increased for yield and weed control purposes (Lafond 1993). Most of the recommendations were based on research done under relatively weed-free conditions. Thicker crop stands hasten maturity and improves uniformity of development, usually without yield loss due to moisture stress. When barley was seeded in the absence of herbicides, increasing the seeding rate resulted in higher barley yields and lower biomass production of wild oat, wild mustard and volunteer canola (Kirkland 1993). When barley seeding rate was increased from 94 to 188 kg ha^{-1}, wild oat seed production was reduced 52% (Elliot 1972). A similar reduction was achieved when winter wheat density was increased from 60 to 195 plants m-2 (Wright 1993). Higher crop plant densities alone may not eliminate herbicide use, but could make herbicides more effective and enable farmers to obtain satisfactory weed control at lower than recommended herbicide rates (Kirkland 1995).

Row spacing is more of a controversial issue. Narrowly-spaced rows of crop plants are equally or more competitive with weeds than widely-spaced rows (Kirkland 1993; Thill et *al.* 1994; Brandt and Beckie 1995). However, crops grown in 30-cm rows in low-disturbance direct seeding cropping systems with precision fertilizer placement may not have greater weed problems than crops grown in narrower rows (Lafond 1993). However, crops such as lentils, which are slow to cover the ground, will be more adversely affected by row width (Johnson 1995).

Promoting rapid and uniform crop emergence

Maximize early crop seedling vigour. Seed as shallow as possible as shallow-seeded crops emerge quicker, branch or tiller earlier and are less prone to root rots than deeper- seeded crops (Rourke and Hargrave 1993). Use seed treatments to control injury from disease and insects. Root rots, wireworm and damping off can cause major plant stand losses or decreased vigour. As a rule, the first plant to emerge from the soil wins. If the crop gets ahead of the weeds by one week, within-crop herbicide treatments often can be reduced or eliminated (Derksen 1994). Generally, early emerging weeds are most competitive and more likely to survive and produce the most seed (Blackshaw *et al.* 1981; O'Donovan *et al.* 1985). Field experiments with wild oat densities ranging from 50 to 100 plants m-2 showed that grain yield loss increased by about 3% for every day wild oat plants emerged before wheat or barley (O'Donovan *et al.* 1985). Yield loss gradually diminished by the same amount for every day wild oats emerged after the crops. Therefore, wild oat plants that emerge late relative to strongly competitive crops such as barley may not require control with herbicides. Manitoba Agriculture (1996) has shown that 25 wild oats m^2, which are one leaf stage ahead of the crop, can reduce yields 22% compared to the same weed density causing 8% damage if the crop is ahead of the wild oats by one leaf stage. Good seed-to-soil contact is achieved by placing the seed in contact with moist soil and providing adequate cover and packing to ensure rapid germination and emergence. In direct seeding systems, adequate chaff and straw spreading is critical to achieving rapid and uniform germination and emergence (Rourke and Hargrave 1993). On-row packing is preferred over random coil packing to create an undesirable environment for weed seed germination in the interrow area. Using vigorous, high-quality seed will favor quick crop emergence. On-going research indicates that large seed size has a significant effect on the competitive ability of the crop against weeds because of enhanced seedling vigour (Townley-Smith, unpublished data).

*Fertilizer rate **and** placement*

Ensuring the crop is supplied with adequate and balanced levels of essential nutrients (nitrogen, phosphorus and sulphur in particular) will favor crop growth and development and thus its competitive ability against weeds. Fertilize the crop and not the weeds. Subsurface banding of nitrogen with or near the seed compared to broadcast applications can substantially reduce weed densities and the seed bank, particularly for green foxtail (O'Donovan, unpublished data). Starter fertilizer, such as seedplaced P, can be very effective in promoting rapid seedling emergence and vigour. However, excessive levels of seed-placed fertilizer can injure crops and reduce their competitive ability against weeds. Biological seed treatments, such as legume inoculants or products, can be beneficial in further enhancing nutrient availability to the crop relative to the weeds (Rourke and Hargrave 1993).

Competitive crops and cultivars

Crops vary in their competitive ability against weeds. In general, cereals are more competitive than broadleaf crops, and winter cereals are more competitive than spring cereals (Chancellor and Peters 1976; Derksen and Lafond 1995). Fall-seeded crops such as winter wheat and fall rye can be highly competitive with spring-germinated weeds such as green foxtail and wild oat. Barley is the most efficient competitor; spring rye, oats, canola and wheat rank as less efficient competitors, followed by field pea, lentil and flax, which are the least competitive crops. Competitive crops are the ones to reduce herbicide use in (Derksen and Lafond 1995).

Differences in competitive ability against weeds also exist among crop cultivars. Varieties that are tall and tend to cover the ground earlier in the growing season (more rapid canopy closure) are generally the most competitive with weeds. Significant differences in days to canopy closure exist among Argentine canola varieties (Manitoba Zero Tillage Research Farm; Domitruk, unpublished data). Research is needed to determine if these differences are significantly correlated with competitiveness against weeds. Kirkland and Hunter (1991) noted that semi-dwarf wheat varieties are more susceptible to yield losses due to wild oat competition than some of the standard Hard Red Spring wheat varieties. Competitive differences among spring wheat genotypes also were related to stature, as well as tillering capacity and leaf area (Hue1 and Hucl 1993). The differences between the least competitive and most competitive spring wheat varieties were equal to the difference between barley and the best bread wheat varieties.

Crop Rotation:

The more diverse the rotation, the better. Rotating crops within a given field means that crop competitiveness, crop life cycles, seeding and maturity dates, the proportion of fallow, and herbicides are varied (Derksen and Lafond 1995). Varied selection intensity means that factors that suppress weeds are constantly changed to reduce the chances of a particular weed dominating the system. Summer annual crops select for summer annual weeds, winter annual crops select for winter annual weeds, and perennial crops select for perennial weeds (Derksen and Lafond 1995). Rotations reduce or prevent the buildup of high populations of certain weeds common to a particular crop, by altering the life cycle of the weed, particularly when crops with different growth habits are used, and/or if different herbicides can be used in different crops. Inclusion of crops with different phenologies, such as winter wheat or fall rye, or crops with greater competitive efficiencies, is especially important in ratarding the rate of evolution of resistance (Parochetti *et al.* 1982). The allelopathic effect of fall rye residues on weed germination and growth has been documented (Barnes and Putnam 1986). Sequencing crops with different competitive abilities is important for weed management (Derksen and Lafond 1995). Since many high value crops are broadleaved, rotating cereal and broadleaf crops is important. As a result of balancing broadleaf and cereal crops in rotation, you can also vary your chemical weed control program, avoiding frequent use of specific herbicide groups. Rotating annual crops with short-term perennial forages is particularly useful for reducing weed densities and inhibiting weed community changes (Entz *et al.* 1993). Underseeding forages, such as clover in cereals, can offer stiff competition to weeds. Herbicide-resistant crops can provide an additional tool to prevent and manage R weeds. However, reliance on these crops and associated herbicides in the crop rotation to the exclusion of conventional crops can increase the risk of occurrence of R weeds. Rotations also help increase crop vigour and competitiveness by decreasing disease and insect pressure (Rourke and Hargrave 1993). The use of snow trapping and reduced evaporative losses with zero tillage has been shown to effectively allow more extended and diverse rotations in some of the drier areas of the prairies.

Other Agronomic Practices:

About 33% of newly-shed wild oat seed on the soil surface can be destroyed by stubble burning immediately after harvest (Wilson and Cussans 1975). Although this practice is not recommended for soil and air quality reasons, it could be used to reduce initial weed seed populations in severely infested areas. Where dense stands of weeds exist in a field, cutting the crop for hay or silage before seed shed can greatly reduce seed rain. Concentrated straw and chaff rows left behind the combine provide an ideal environment for weed seed germination. Therefore, spreading of crop residues over the entire field is essential for successful direct seeding. Collecting chaff at harvest will remove a significant amount of weed seed from the field (Entz, unpublished data). Chaff is a very inexpensive feed for ruminants (Johnson 1995). Using weed-free seed, cleaning equipment between fields, covering transported seed or screenings and spraying or mowing the edges of fields are important sanitation measures to prevent weeds from being introduced and/or established.

Managing R Weeds

Cultural management practices that help prevent or delay resistance also are recommended to manage resistance after the fact. If R weeds are suspected, avoid spreading crop seed, weed seed, or crop residues from the affected area (Goodwin 1994a). Note the location of R weed patches and monitor their spread. If possible, prevent weed seed production by using herbicides, tillage or cutting, before or at anthesis. This can largely deplete the soil seed bank after a few years (Wilson and Phipps 1985). Managing R weeds will be more effective and successful if detected early. Therefore, routine field scouting to monitor the occurrence of R weeds, combined with the development of rapid bioassays to test for resistance (Beckie et *al.* 1990), can detect and confirm R weeds early, so that effective chemical and cultural management practices can be implemented promptly.

Conclusion

An IWM approach is the only long-term solution to preventing, delaying and managing R weeds, and thus for maintaining a competitive and sustainable agri-food sector in western Canada. Although herbicide group rotation can be an effective strategy to fight resistance, the appearance of multiple-R weed populations highlights the importance of using herbicides less. Farmers who use effective cultural management practices to advantage the crop over the weeds will more likely be able to reduce their dependence on herbicides. Only then will the probability of selecting for R weeds be stacked in the farmer's favor. In the future, the impetus for reduced herbicide inputs in agriculture will be driven not so much by environmental concerns, but by the increasing and more widespread occurrence of herbicide resistance in weeds.

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