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Authors: Beckie, Hugh J., Harker, K. Neil, Hall, Linda M., Holm, Frederick A., and Gulden, Robert H.

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Education/Extension

Risk Assessment of Glyphosate Resistance in Western Canada

Hugh J. Beckie, K. Neil Harker, Linda M. Hall, Frederick A. Holm, and Robert H. Gulden*

With increasing incidence of glyphosate-resistant weeds worldwide, greater farmer awareness of the importance of glyphosate stewardship and proactive glyphosate-resistance management is needed. A Web-based decision-support tool (http://www.weedtool.com) comprising 10 questions has been developed primarily for farmers in western Canada to assess the relative risk of selection for glyphosate-resistant weeds on a field-by-field basis. We describe the rationale for the questions and how a response to a particular question influences the risk rating. Practices with the greatest risk weighting in western Canadian cropping systems are lack of crop-rotation diversity (growing mainly oilseeds) and a high frequency of glyphosate-resistant crops in the rotation. Three case scenarios are outlined—low, moderate, and high risk of glyphosate-resistance evolution. Based on the overall risk rating, three best-management practices are recommended to reduce the risk of glyphosate resistance in weeds.
Nomenclature: Glyphosate.
Key words: Crop rotation, decision-support system, genetically modified crops, herbicide application frequency, herbicide resistance, integrated weed management.

Con la creciente incidencia en la maleza de resistencia a glifosato a nivel mundial, es necesario crear en los agricultores mayor conciencia sobre la importancia de la vigilancia en el uso glifosato y de su manejo proactivo para evitar la resistencia al herbicida antes mencionado. Se ha desarrollado, primordialmente para los agricultores en el occidente de Canadá, una herramienta en la web de apoyo a decisiones (http://www.weedtool.com) que comprende 10 preguntas para evaluar el riesgo relativo de selección para resistencia a glifosato en maleza, campo por campo. Describimos el porqué de las preguntas y cómo la respuesta a una pregunta en particular influye en la calificación del riesgo. Prácticas con la mayor ponderación de riesgo en los sistemas de cultivo en el occidente de Canadá son: la falta de diversidad en la rotación de cultivos (cultivar oleaginosas principalmente) y una alta frecuencia de cultivos resistentes al glifosato en la rotación. Tres escenarios se describen: evolución de resistencia al glifosato de bajo, moderado y alto riesgo. Basado en el nivel general de riesgo, se recomiendan tres mejores prácticas de manejo para reducir en la maleza, el riesgo de resistencia a glifosato.

The evolution of glyphosate resistance in numerous weed species in various countries is the most important global herbicide-resistance issue at this time (Powles 2008). Glyphosate-resistant weeds have evolved in both glyphosate-resistant and non–glyphosate-resistant crop production systems (Heap 2010). The actual or potential economic and environmental consequences of widespread glyphosate resistance in economically important weed species have even gained the attention of the mainstream (nonagricultural) media via television, Internet, or newspaper (e.g., Neuman and Pollack 2010; Osunsami 2009).

To date, however, glyphosate-resistant weeds have not been reported in western Canada (provinces of British Columbia, Alberta, Saskatchewan, and Manitoba). The principal annual field crops are grown on about 30 million ha (over 90% of national total); additionally, western Canada accounts for 86% of annual herbicide usage (Statistics Canada 2007, 2009). One case of glyphosate resistance was confirmed in 2010 in eastern Canada—giant ragweed (*Ambrosia trifida* L.) infesting a monoculture glyphosate-resistant soybean [*Glycine max* (L.) Merr.] field near Windsor, Ontario (Monsanto Canada, Inc. 2010).

From 1974 to 1995 in Canada, glyphosate was commonly applied preseeding (burn-off treatment), preharvest (primarily in cereals and pulses), or to a lesser extent, postharvest. With the introduction of glyphosate-resistant crops beginning in 1996, glyphosate usage increased markedly (Beckie et al. 2006). In 2009 in Canada, glyphosate-resistant canola (*Brassica napus* L.), soybean, and corn (*Zea mays* L.) comprised 48, 54, and 69% of the respective crop area (R. Ripley, Monsanto Canada, Inc., personal communication). Western Canada accounts for 99% (6.6 million ha) of the nation's canola area, 12% of soybean area (168,000 ha), and 12% of grain or fodder corn area (176,000 ha) (Statistics Canada 2009). In western Canada, soybean and corn are grown mainly in southern Manitoba because of sufficient heat units (i.e., growing degree days).

Canola is generally grown in rotation once every 3 or 4 yr (Statistics Canada 2007, 2009), primarily because of potential buildup of disease inoculum. However, a favorable net economic return in recent years from canola has resulted in some farmers growing the crop more frequently in their rotation than is recommended by agronomists. In general, there are limited herbicide options in canola. In addition to glyphosate used in glyphosate-resistant canola, glufosinate is

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* Weed Scientist, Agriculture and Agri-Food Canada (AAFC) Research Centre, Saskatoon, Saskatchewan, Canada S7N 0X2; Weed Scientist, AAFC Research Centre, Lacombe, Alberta, Canada T4L 1W1; Weed Scientist, University of Alberta, Edmonton, Alberta, Canada T6G 2P5; Professor, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A8; Weed Scientist, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2. Corresponding author's E-mail: hugh.beckie@agr.gc.ca

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applied POST in glufosinate-resistant cultivars, and acetolactate synthase (ALS) inhibitors are applied POST in imidazolinone-resistant cultivars. Ethametsulfuron can be applied POST in all canola cultivars, but controls only a few broadleaf weeds (Saskatchewan Ministry of Agriculture 2010). Although a number of acetyl-CoA carboxylase (ACCase) inhibitors can be applied POST in canola, their use is limited because of widespread ACCase-inhibitor resistance in wild oat (*Avena fatua* L.) and green foxtail [*Setaria viridis* (L.) Beauv.] populations; the PRE soil-applied herbicides ethalfluralin, trifluralin, or triallate are rarely used now in canola (Beckie et al. 2008a). Thus, three herbicides with different modes of action—glyphosate, glufosinate, and imazamox (or another imidazolinone herbicide)—are predominantly used in canola in western Canada.

Overall, selection pressure for weed-resistance evolution is greatest with in-crop herbicide application relative to other application timings (Beckie 2006). In most western Canadian cropping systems, glyphosate selection pressure is not considered high because of the relatively low frequency of canola in rotation or the moderate level of adoption of cultivars with this herbicide-resistance trait (48%). In southern Manitoba, however, farmers have the opportunity to grow glyphosate-resistant corn, soybean, and canola in their rotation. In this region, there is the potential for high glyphosate-resistant weed selection pressure if only glyphosate is used across a glyphosate-resistant crop rotation.

In the summer of 2009, a workshop was held in Winnipeg, Manitoba that was attended by a number of university and government weed scientists from across western Canada as well as Monsanto technology development personnel. The goal of the workshop was to promote glyphosate stewardship and proactive glyphosate-resistance management by developing a Web-based tool targeted primarily at farmers to assess the relative risk of glyphosate resistance in weeds on a field-by-field basis. The weed-resistance risk assessment was modeled after that developed for corn–soybean cropping systems in the Midwest region of the United States (Monsanto Company 2010). Herein, we describe the risk-assessment tool for western Canada and how it compares with that used for the corn-soybean cropping belt of the United States. Additionally, three case scenarios are presented to illustrate the risk-assessment tool—a low, moderate, and high risk of glyphosate-resistance evolution in weeds.

Materials and Methods

The Web site address of the weed-resistance risk assessment is http://www.weedtool.com (Monsanto Company 2010). On the home page, one can select ''Western Canada'' or ''United States.'' Even though the risk-assessment tool was developed for western Canada, some farmers in the northern Great Plain states such as Montana, North Dakota, or Minnesota may find it pertinent to their cropping systems.

The risk-assessment tool comprises 10 questions that ascertain the type of cropping and tillage system being used, as well as the timing and intensity of glyphosate usage in a particular field: preseeding (burn-off treatment), in-crop (i.e., glyphosate-resistant crops), and postharvest applications (Table 1). There is no question related to preharvest glyphosate application because perennial weeds, such as Canada thistle [*Cirsium arvense* (L.) Scop.] or perennial sowthistle (*Sonchus arvensis* L.), are mainly targeted. Perennial weeds are widely considered at lower risk for herbicide-resistance evolution than annuals because of fewer generations under selection pressure. It was decided to limit the number of questions to 10, similar to that for the corn–soybean weed-resistance risk assessment, to facilitate adoption or ease of use by farmers.

Each question and answer was run through analytical hierarchy software[1] to assign each relative risk-rating value. The questions and answers were then assessed and reviewed by university and government weed scientists (authors) and Monsanto technical staff (see Acknowledgment section). Based on their knowledge of the effect of cropping systems or practices on the risk of selection for herbicide resistance in weeds, a consensus score was derived for each of the answers.

When beginning an assessment, the profession of the user is identified for tracking purposes: farmer, seed or chemical dealer, crop consultant, university or government employee, or ''other.'' The general field location is ascertained from the required postal code. Users have the option of providing a field location or name for their future reference if they retain a hard copy of the assessment results. After the user completes the assessment, an overall relative glyphosate-resistance risk rating is depicted by the length and color of a horizontal bar (yellow for low risk ranging to red for high risk). Based on the overall risk rating, three best-management practices are recommended to mitigate the risk of glyphosate resistance in weeds. In addition to the situation-specific recommendations resulting from the assessment, users have access to additional information on weed-resistance management resources within the Web site.

Results and Discussion

The first two questions identify the type of cropping and tillage system (Table 1). The first question is related to the crop rotation generally used in the particular field: (a) mainly cereals, (b) mainly oilseeds, (c) mainly cereals and oilseeds, or (d) cereals, oilseeds, and pulses. The risk rating is greatest for mainly oilseeds (b) and least for mainly cereals (a), or cereals, oilseeds, and pulses (d); the risk rating for oilseeds (b) is about threefold greater than that for response (a) or (d). The main oilseed crop for a farmer is likely canola, with a 50% probability of being a glyphosate-resistant cultivar. Soybean was categorized as an oilseed crop, with most cultivars grown in southern Manitoba being glyphosate resistant. Although crop monoculture is a risk factor for weed resistance, there is no opportunity for in-crop glyphosate use in cereals (thus, the low risk rating for response [a]). Beckie et al. (2008b) showed that three or more crop types in rotation (e.g., response [d]) significantly reduce the risk of weed resistance.

The second question identifies the tillage system used in the field: (a) high, (b) minimum, (c) low1: high-soil-disturbance direct seeding, or (d) low2: low-soil-disturbance direct seeding. The risk rating is greater for low-soil-disturbance direct seeding (d) than the other responses. This tillage system

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Table 1. Ten questions, each with four possible responses, which comprise the risk-assessment tool for glyphosate resistance in weeds in western Canada.

1. The crop rotation generally used in this field could be described as
   (a) Mainly cereals
   (b) Mainly oilseeds
   (c) Mainly cereals and oilseeds
   (d) Cereals, oilseeds, and pulses
2. How would you describe the tillage intensity used in this field?
   (a) High (two or more high-soil-disturbance tillage operations before seeding)
   (b) Minimum (one high-soil-disturbance tillage operation before seeding)
   (c) Low1 (high-soil-disturbance direct seeding)
   (d) Low2 (low-soil-disturbance direct seeding)
3. In how many years did you apply a glyphosate (alone) burn-off treatment in this field?
   (a) None
   (b) 1–10 yr
   (c) 11–20 yr
   (d) More than 20 yr
4. When you use glyphosate (alone) in a burn-off treatment, the weed control in this field (not including crop volunteers) is:
   (a) Excellent—greater than 90% weed control
   (b) Good—80–90% weed control
   (c) Fair—60–80% weed control
   (d) Poor—less than 60% weed control
5. For the burn-off treatment, do you tank-mix glyphosate with another herbicide (or use a premix with the glyphosate)?
   (a) No
   (b) Occasionally
   (c) Usually
   (d) Always
6. How often do you grow a Roundup Ready® crop (e.g., canola, sugar beet, corn, soybean) in this field?
   (a) Never
   (b) Once every 3 or 4 yr on average
   (c) Once every 2 yr on average
   (d) Every year
7. Typically, how many times is in-crop glyphosate applied to a Roundup Ready® crop in this field?
   (a) None
   (b) One
   (c) Two
   (d) Three or more
8. When you use glyphosate in the Roundup Ready® crop, the weed control at harvest (not including crop volunteers) is
   (a) Excellent—greater than 90% weed control
   (b) Good—80–90% weed control
   (c) Fair—60–80% weed control
   (d) Poor—less than 60% weed control
9. In past years, how often did you apply a postharvest glyphosate application in this field?
   (a) Never
   (b) Occasionally (fewer than half the years)
   (c) Most years
   (d) Every year
10. Over the past few years, how would you describe the weed problem in this field?
   (a) No change from year to year
   (b) Fewer weeds than I used to have
   (c) More weeds than I used to have
   (d) Shifting to different weed species

was most often associated with occurrence of herbicide-resistant weeds, attributed mainly to greater seedbank turnover rate and therefore less buffering against herbicide-resistance allele enrichment (Beckie et al. 2008b). However, the risk rating for low-soil-disturbance direct seeding is about half that assigned to oilseed crop monoculture, reflecting the consensus view that cropping system generally has a greater impact on weed communities, and particularly the risk of glyphosate resistance, than tillage system. For the corn–soybean weed-resistance risk tool, there are similar questions related to frequency of tillage and frequency of corn and soybean crops in the rotation.

The remaining eight questions are designed to estimate glyphosate selection pressure, based on application timing and frequency of use within and across growing seasons in the field. Questions 3 to 5 focus on glyphosate applied preseeding. Question 3 asks how many years glyphosate (alone) has been applied as a burn-off treatment: (a) none, (b) 1 to 10 yr, (c) 11 to 20 yr, or (d) more than 20 yr. The risk rating gradually increases from response (a) through (d). For this application timing, glyphosate selection pressure would be greatest on winter annual or early-spring–emerging summer annual weeds. Model simulations suggest that glyphosate selection pressure for a preseeding application in western Canada would generally be markedly less than for an in-crop application (H. Beckie, unpublished data; Diggle et al. 2008).

As a follow-up to Question 3, the next question focuses on the level of weed control (poor to excellent) from the burn-off glyphosate treatment. The risk rating for most scenarios is generally insensitive to the level of weed control for the

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preseeding glyphosate application. However, for some scenarios, e.g., when the user indicates a weed species shift in the field (Question 10), a higher risk rating is assigned for excellent vs. poor control, as herbicide efficacy is a component of selection pressure. Poor preseeding weed control is likely related to an application problem or environmental conditions, not resistance.

The final question (5) related to the preseeding glyphosate application determines how frequently the user tank-mixes glyphosate with another herbicide or utilizes a premixture with glyphosate. Increasing availability to farmers of glyphosate tank mixtures for the burn-off treatment (Saskatchewan Ministry of Agriculture 2010) is in response to a need to control glyphosate-resistant crop volunteers or provide some residual control of economically important weed species. The risk rating is greatest when glyphosate is not mixed with another mode-of-action herbicide, declining marginally as the frequency of use of burn-off glyphosate mixtures increases.

Questions 6 to 8 focus on frequency of glyphosate-resistant crops in the rotation and frequency of in-crop glyphosate application within the crop. Question 6 asks how often a glyphosate-resistant crop is grown: (a) never, (b) once every 3 or 4 yr on average, (c) once every 2 yr on average, or (d) every year. The risk rating increases threefold from response (a) through (d), with the greatest increase in risk rating from response (c) to (d). The risk rating assigned for growing glyphosate-resistant crops every year was similar to that for growing mainly oilseeds in rotation (question 1). Monoculture glyphosate-resistant cropping when only glyphosate is used for weed management can result in high selection pressure for rapid enrichment of initially rare glyphosate-resistance alleles (Duke and Powles 2009). In some regions of North and South America, the evolution of glyphosate-resistant weeds is a consequence of intensive glyphosate usage in monoculture glyphosate-resistant cropping systems such as soybean (VanGessel 2001; Vila-Aiub et al. 2007) or cotton (*Gossypium hirsutum* L.) (Culpepper et al. 2006).

Question 7 determines the number of in-crop glyphosate applications—ranging from zero to three or more. For canola, glyphosate is usually applied twice in-crop (Beckie et al. 2006, unpublished data). The risk rating increases slightly from response (b) through (d). The risk rating associated with the frequency of in-crop glyphosate application is not weighted as highly as that for frequency of glyphosate-resistant crops in the rotation. In a weed-competitive crop such as hybrid canola, a second in-crop glyphosate application generally provides little or no additional weed control or crop yield benefit (Clayton et al. 2002; O'Donovan et al. 2006). Nevertheless, the interaction of these two factors impacts the overall risk rating.

Similar to Question 4 on weed control achieved from a preseeding glyphosate application, Question 8 determines the level of weed control at harvest time. A similar question is included in the corn–soybean weed-resistance risk assessment. The risk rating is slightly less for poor weed control vs. fair to excellent weed control for the same reason given for preseeding weed control.

Question 9 determines the frequency of postharvest glyphosate application in previous years in the field. The risk rating increases only slightly with increasing frequency of postharvest glyphosate application, similar to the rationale outlined for frequency of preseeding glyphosate application. The final question, copied from the corn–soybean risk-assessment tool, gauges the user's perception of changes in the weed population in the field over the past few years: (a) no change from year to year, (b) fewer weeds than before, (c) more weeds than before, or (d) shifting to a different weed species. The risk rating is markedly greater for response (d) than the other responses, as weed shifts may portend the evolution of weed resistance (Beckie 2006). Harker et al. (2005) detected weed shifts after only 3 yr of continuous glyphosate-resistant wheat (*Triticum aestivum* L.; nonregistered cultivar) at several western Canada sites.

In contrast to the herbicide-resistant weed risk assessment used in the United States (corn–soybean cropping), the assessment for western Canada lacks questions related to early-season soil-residual herbicide application or glyphosate rate. Soil-residual herbicides are not commonly used in western Canada because of inconsistent efficacy related to soil environmental conditions and the dominance of direct-seeding (no-till) practices. A question on glyphosate rate was deemed unnecessary, as field management questionnaires have shown that western Canadian farmers typically apply glyphosate at labeled rates (Leeson et al. 2004, 2005; Thomas et al. 2003).

Case Scenarios of Glyphosate-Resistance Risk. Three case scenarios are presented that illustrate the risk-assessment tool (Table 2). A low-risk scenario may be exemplified by a diverse crop rotation, minimum tillage, low to moderate frequency of glyphosate (alone) applied preseeding, glyphosate-resistant crops grown once every 3 or 4 yr, an in-crop glyphosate application, and occasional postharvest glyphosate application. The resultant risk rating is 0.15. Although the overall risk rating provided to the user is qualitative, not quantitative, this value indicates the proportion of the maximum risk of glyphosate-resistance evolution (0 to 1.0 scale with 0 = nil risk and 1.0 = maximum risk) as determined by the length of

Table 2. Case scenarios resulting in a low, moderate, and high risk assessment for glyphosate-resistance evolution in weeds.

	Answer (refer to Table 1)		
Question	Low	Moderate	High
1	d	c	b
2	b	d	d
3	b	d	d
4	b	b	b
5	b	b	b
6	b	c	d
7	b	c	c
8	b	b	b
9	b	b	b
10	b	b	b
Risk rating[a]	0.15	0.39	0.87

[a] Although the overall risk rating provided to the user is qualitative, not quantitative, these values indicate the proportion of the maximum risk of glyphosate-resistance evolution (0–1.0 scale with 0 = nil risk and 1.0 = maximum risk) as determined by the length of the horizontal bar depicting relative risk.

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Table 3. Best-management practices, in order listed, recommended for the high-risk-assessment scenario (described in Table 2).

1. In response to the answer to Question 1:
   - Crop rotation allows for diversification with crops with different competitive abilities and life cycles that keep weeds off balance and helps prevent weed species from becoming established, competitive, or dominant in a field.
   - Rotations consisting of cereals, oilseeds, and pulses, including winter annual (winter wheat) or perennial crops (forages), would be considered highly diverse and sustainable.
2. In response to the answer to Question 6:
   - A high frequency of glyphosate-resistant crops in the rotation can increase selection pressure for glyphosate-resistant weeds.
   - Be sure to include other crops in rotation with glyphosate-resistant crops to allow greater opportunity for the inclusion of other modes of action.
3. In response to the answer to Question 3:
   - A high frequency of herbicide applications applied alone (not tank-mixed) in a field will increase the selection pressure for herbicide-resistant weeds.
   - Although glyphosate is considered a low-risk mode of action with regards to the development of herbicide resistance, the inclusion of an alternative mode of action in a tank mix would serve to slow the rate of resistance evolution further through early removal of any rare glyphosate-resistant individuals in the population.
   - Early removal of weeds is an effective strategy to help manage weed populations and maintain high yield potential.
   - Where possible, use tank mixes with other herbicide groups to reduce the weed-resistance selection pressure of your glyphosate preseed burn-off application.
   - To be successful, both the glyphosate and the tank-mix partner need to be effective on the target weeds in the field.
   - Periodic tillage can substitute for glyphosate-based burn-down programs.

the horizontal bar depicting relative risk. In contrast, a high-risk scenario may be exemplified by mainly oilseeds grown in rotation, a low-soil-disturbance direct-seeding system, more than 20 yr of glyphosate applied alone as a burn-off treatment, and a glyphosate-resistant crop grown every year with two in-crop glyphosate applications. This scenario results in a risk rating of 0.87.

Once the risk assessment is completed, three best-management practices are recommended to the user. For the high-risk scenario (Table 2), the recommended practices address the user's response to Questions (in order) 1, 6, and 3 (Table 3). The order of the three recommended practices reflect the relative risk weighting of the questions and the user's response to those questions.

''Real'' integrated weed management systems that are not simply integrated herbicide management —''the other IPM'' (Ehler 2006), are essential (Blackshaw et al. 2008; O'Donovan et al. 2007). Combining optimal agronomic practices with judicious herbicide use can lead to successful weed management and reduce the selection pressure for herbicide resistance in weeds (Harker et al. 2009). Overwhelming scientific evidence indicates that cropping-system diversity is the foundation and long-term solution for proactive herbicide-resistant weed management (Beckie 2006; Beckie et al. 2006).

The low cost of glyphosate is not conducive to promoting glyphosate stewardship. The fear of glyphosate-resistant weeds is likely the only motivation for judicious use of the herbicide. It is hoped that this glyphosate-resistance risk-assessment tool will be widely used by farmers or land managers, and will help to preserve the utility of this very important herbicide for future generations of crop producers in western Canada.

Sources of Materials

[1] Expert Choice software version 11.5, Expert Choice Inc., 1501 Lee Highway, Suite 302, Arlington, VA 22209.

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