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Environmental Impact of Glyphosate-Resistant Weeds in Canada

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Glyphosate-resistant (GR) giant ragweed, horseweed, and common ragweed were confirmed in southwestern Ontario, Canada in 2008, 2010, and 2011, respectively. In the western prairie provinces of Alberta and Saskatchewan, GR (plus acetolactate synthase inhibitor-resistant) kochia was discovered in 2011. This symposium paper estimates the environmental impact (EI) of the top herbicide treatments or programs used to manage these GR weed species in the major field crops grown in each region. For each herbicide treatment, EI (per ha basis) was calculated as the environmental impact quotient (EIQ), which quantifies the relative potential risk of pesticide active ingredients on human and ecological health based on risk components to farm workers, consumers, and the environment, multiplied by the application rate (kg ai ha^{-1}). Total EI is defined as EI (per ha basis) multiplied by the application area (i.e., land area affected by a GR weed). It was assumed that all herbicide treatments would supplement the continued usage of glyphosate because of its broad spectrum weed control. For the control of these GR weeds, most treatments contain auxinic or protoporphyrinogen oxidase (PPO)-inhibiting herbicides. The majority of auxinic herbicide treatments result in low (EI $\leq$ 10) to moderate (11 to 20) EI, whereas all treatments of PPO inhibitors have low EI. Total EI of GR horseweed and kochia will generally be greater than that of giant or common ragweed because of rapid seed dispersal. For recommended herbicide treatments to control GR weeds (and herbicide-resistant weeds in general), EI data should be routinely included with cost and site of action in weed control extension publications and software, so that growers have the information needed to assess the EI of their actions.

Nomenclature: Glyphosate; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; giant ragweed, *Ambrosia trifida* L. AMBTR; horseweed, *Conzya canadensis* (L.) Cronq. ERICA; kochia, *Kochia scoparia* (L.) Schrad. KCHSC, synonym: *Bassia scoparia* (L.) A.J. Scott.

Key words: ALS-inhibitor resistance, environmental health, glyphosate resistance, herbicide resistance, multiple resistance, pesticide toxicity.

From 1974 to 1995 in Canada, glyphosate was commonly applied preseeding (burndown treatment), preharvest (primarily in cereals and pulses), or to a lesser extent, postharvest. With the introduction of glyphosate-resistant (GR) crops beginning in 1996, glyphosate usage increased markedly (Beckie et al. 2011). During the 7-yr period from 2005 to 2011, glyphosate usage tripled from 30.2 to 89.7 million L (standardized to 360 g ae L^{-1}) in western Canada, and from 3.8 to 12.3 million L in eastern Canada (S. Dilk, personal communication). In 2012, in Canada, GR canola (*Brassica napus* L.), soybean [*Glycine max* (L.) Merr.], and corn (*Zea mays* L.) comprised 47, 79, and 90% of the respective crop area (R. Ripley, personal communication). Western Canada accounts for 99% (8.5 million ha) of the nation's canola area, 20% of soybean area (344,000 ha), and 9% of grain corn area (122,000 ha) (Statistics Canada 2012). In western Canada, soybean and corn are grown mainly in southern Manitoba because of sufficient heat units (i.e., growing degree-days). In Ontario, soybean and corn (grain) are grown on 1.1 and 0.9 million ha, respectively (Ontario Ministry of Agriculture, Food and Rural Affairs [OMAFRA] 2012a). In eastern Canada in 2012, glyphosate was applied on 3.5 million ha of soybean and corn (single or multiple applications per field) (M. Reidy, personal communication).

In Canada, the first report of a GR weed was giant ragweed in 2008 in GR soybean in eastern Canada (southwestern Ontario); a survey conducted in 2009 and 2010 documented the GR weed in 47 new locations in three counties in the province (Vink et al. 2012). In southwestern Ontario, GR horseweed (referred to as Canada fleabane in Canada) and GR common ragweed were first documented in 2010 and 2011, respectively (Heap

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2013). To date, there are 71 sites (populations) with confirmed GR giant ragweed in six southwestern Ontario counties, 84 sites with GR horseweed in five counties, and one site with GR common ragweed (Sikkema et al. 2013). In the area where GR giant ragweed or horseweed is found, there tends to be a very high percentage of soybean fields (mainly GR cultivars). For example, some growers will have one to four crops of soybean, followed by winter wheat (*Triticum aestivum* L.), then back to soybean. However, some of the confirmed GR horseweed sites had a very diverse crop and herbicide rotation, e.g., corn-soybean-wheat-processing tomato (*Solanum lycopersicum* L.)-sweet corn, suggesting weed seed dispersal as a contributing factor in occurrence of GR weed populations.

The environmental impact (EI) of different weed control strategies should be considered when developing weed management programs. Based on toxicological and physicochemical properties of the pesticides, the environmental impact quotient (EIQ) measures the relative potential risk of pesticide active ingredients on human and ecological health based on risk components to farm workers, consumers, and the environment (Kovach et al. 1992, 2012). The EIQ was designed to provide growers and other decision-makers with one number that indicates the magnitude of relative risk of different pesticides or production systems (Brimner et al. 2005; Edwards-Jones and Howells 2001; Fernandez-Cornejo 1998; Gallivan et al. 2001; Ziegler et al. 2002). The EIQ of individual pesticides is the average value of the farm worker, consumer, and ecological components; equation variables include dermal toxicity, chronic toxicity, systemicity, fish toxicity, leaching potential, surface loss potential, bird toxicity, soil half-life, bee toxicity, beneficial arthropod toxicity, and plant surface half-life (Kovach et al. 1992). The EI of a particular pesticide treatment is obtained by multiplying the EIQ by the application rate. Thus, a higher EI indicates a greater risk of detrimental impact.

Worldwide, GR kochia was first reported in Kansas in 2007, followed by South Dakota in 2009, and Nebraska in 2011; these populations were selected primarily in GR corn and soybean fields (Heap 2013). In Warner county in southern Alberta, Canada in 2011, GR kochia was discovered in 10 chemical fallow (chem-fallow) or spring wheat fields (Beckie et al. 2013a). In a survey of 309 fields in southern Alberta in 2012, 13 sites (fields or ruderal areas) in three counties (Warner, Vulcan, and Taber) had GR kochia (Hall et al. 2013). Moreover, GR kochia was confirmed at nine sites in four counties (Warner, Lethbridge, Forty mile, and Cypress) in southern Alberta and 10 sites in southern and central Saskatchewan, Canada in 2012 based on samples submitted by growers (Hall et al. 2013). To date, all Canadian GR kochia populations are also resistant to acetolactate synthase (ALS)-inhibiting herbicides (Beckie et al. 2013a; Hall et al. 2013).

The primary issue in managing these GR weed species in Canada has been their economic impact on crop production and cost of herbicidal control (but see Egan et al. 2011 and Mortensen et al. 2012). In contrast, little attention has been given to the EI of herbicides used to manage GR weeds. Glyphosate continues to be used in fields with GR weeds because of its broad spectrum weed control; however, an additional herbicide(s) must be tank-mixed or applied sequentially with glyphosate to control the GR weed biotype (Beckie 2012). This symposium paper estimates the EI of the top herbicide treatments or programs used by growers or recommended by weed scientists to manage GR giant ragweed, common ragweed, and horseweed in southwestern Ontario, and GR plus ALS inhibitor-resistant kochia in Alberta and Saskatchewan.

EI Assessment: Methodology

The EI of managing the four GR weed species by various prescribed herbicide treatments (programs) was assessed using a commonly used methodology. For each herbicide treatment, EI (per ha basis) was calculated by multiplying the EIQ (Kovach et al. 1992, 2012) by the application rate (kg ai ha^{-1}) (OMAFRA 2012b; Saskatchewan Ministry of Agriculture 2012). The EI value for products or treatments with more than one active ingredient was obtained by summing the relative proportion of each active ingredient. The EIQ value for trifluralin was used for ethalfluralin because no value was listed for the latter herbicide (Kovach et al. 2012), and their toxicological properties are similar (Ahrens 1994). However, bromoxynil/pyrasulfotole ("/" denotes a herbicide mixture) treatment in cereal crops was omitted because no EIQ value is listed yet for pyrasulfotole. It was assumed that all herbicide treatments would supplement the continued use of glyphosate because of its broad spectrum weed control.

Application area is defined by the total field area (ha) with a GR weed infestation (with infestation defined as the actual area occupied by a GR weed), based on survey results or grower-reported cases.

Table 1. Environmental impact quotient (EIQ) and environmental impact (EI) of weed management treatments or programs for the control of glyphosate-resistant giant ragweed in Ontario, Canada.

Active ingredient(s)[a]	Individual EIQ values[b]	Product rate	EI[c]
		g ai/ae ha^{-1}	
Glyphosate, 9	15.3	900	13.8
Corn[d]			
Dicamba, 4	26.33	600	15.8
Dicamba/diflufenzopyr, 4	26.33/17.52	200	4.8
Dicamba, 4/atrazine, 5	26.33/22.85	1,800	43.2
Saflufenacil, 14/dimethenamid-p, 15	22.29/12.02	735	9.6
Mesotrione, 27 + atrazine, 5	18.67/22.85	140 + 1,500	36.9
Soybean			
2,4-D (PP), 4[e]	15.33	500	7.7
Amitrole (PP), 11	31.80	2000	63.6
Linuron (PP), 7	19.32	2250	43.5
Cloransulam (PRE), 2	15.33	35	0.54
DR Soybean			
Dicamba (PP or PRE) fb dicamba, 4	26.33 *fb* 26.33	300 *fb* 300	15.8
Dicamba (PP or PRE), 4	26.33	600	15.8
Wheat			
2,4-D ester, 4	15.33	528	8.1
MCPA, 4	36.67	630	23.1
2,4-D/dichlorprop, 4	15.33/17.41	740	11.9
Clopyralid , 4	18.12	200	3.6
Dicamba, 4	26.33	140	3.7
Dicamba/MCPA, 4	26.33/36.67	525	18.2
Dicamba/MCPA/mecoprop, 4	26.33/36.67/15.33	600	19.0

[a] Weed Science Society of America site of action number: 2 = acetolactate synthase inhibitors; 4 = synthetic auxins; 5 to 7 = photosystem-II inhibitors; 9 = glyphosate; 11 = carotenoid biosynthesis inhibitors; 14 = protoporphyrinogen oxidase inhibitors; 15 = very long-chain fatty acid synthesis inhibitors; 27 = hydroxyphenylpyruvate dioxygenase inhibitors (Mallory-Smith and Retzinger 2003).

[b] EIQ values for each ai obtained from Kovach et al. (1992, 2012).

[c] EI values for products with more than one ai were obtained by summing the relative proportion of each ai; EI is calculated as EIQ × application rate in kg ai ha^{-1}, expressed on a per ha basis.

[d] Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; winter wheat, *Triticum aestivum* L.

[e] Abbreviations: DR soybean, dicamba-resistant soybean; fb, followed by; PP, preplant.

Total EI is defined as EI (per ha basis) multiplied by the application area (ha). In addition to the actual application area, two hypothetical scenarios were included—1 yr (i.e., 2013), and 5 yr into the future (2017)—based on estimated annual rate of increase in the number of reported sites of each GR weed.

The EI was estimated for the top herbicide treatments used by growers or recommended by weed scientists to manage each GR weed in the major field crops grown in each region. In southwestern Ontario, the field crops included in the analysis were soybean, corn, and winter wheat. In Alberta and Saskatchewan, EI was estimated for the top herbicide treatments used in chem-fallow; the cereal crops spring wheat and barley (*Hordeum vulgare* L.) (both crops considered together); the oilseed crops canola, mustard (white mustard, *Sinapis alba* L. or Indian mustard, *Brassica juncea* [L.] Czern.), and flax (*Linum usitatissimum* L.); and the pulse (annual legume) crops field pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.). Herbicide treatments with EI values ≤ 10 were classified as "low," values from 11 to 20 as "moderate," and values > 20 as "high."

EI Assessment: Herbicides to Manage GR Weed Species in Eastern Canada

Glyphosate at 900 g ae ha^{-1} has an EI of 13.8 (Table 1). For the control of GR giant ragweed in corn, the supplemental herbicide treatments dicamba/diflufenzopyr, saflufenacil/dimethenamid-p, dicamba, mesotrione plus atrazine, and dicamba/atrazine increase the EI by a factor of 1.4 ([4.8 + 13.8]/13.8), 1.7, 2.1, 3.7, and 4.1, respectively. In soybean, the EI of cloransulam applied PRE is only 0.54. Preplant

Table 2. Environmental impact quotient (EIQ) and environmental impact (EI) of weed management treatments or programs for the control of glyphosate-resistant horseweed (Canada fleabane) in Ontario, Canada.

Active ingredient(s)[a]	Individual EIQ values[b]	Product rate	EI[c]
		g ai/ae ha^{-1}	
Glyphosate, 9	15.3	900	13.8
Corn[d]			
Dicamba, 4	26.33	600	15.8
Dicamba/diflufenzopyr , 4	26.33/17.52	200	4.8
Dicamba, 4/atrazine, 5	26.33/22.85	1,800	43.2
Flumetsulam, 2	15.61	50	0.78
Saflufenacil, 14/dimethenamid-p, 15	22.29/12.02	735	9.6
Mesotrione, 27 + atrazine, 5	18.67/22.85	140 + 1,500	36.9
Soybean			
Saflufenacil (PP), 14[e]	22.29	25	0.56
Metribuzin (PP), 5	28.37	1,120	31.8
Flumetsulam (PP), 2	15.61	70	1.1
DR Soybean			
Dicamba (PP or PRE) fb dicamba, 4	26.33 *fb* 26.33	300 *fb* 300	15.8
Dicamba (PP or PRE), 4	26.33	600	15.8
Wheat			
2,4-D ester, 4	15.33	528	8.1
Dicamba, 4	26.33	140	3.7
Dicamba/MCPA, 4	26.33/36.67	525	18.2
Dicamba/MCPA/mecoprop, 4	26.33/36.67/15.33	600	19.0

[a] Weed Science Society of America site of action number: 2 = acetolactate synthase inhibitors; 4 = synthetic auxins; 5 to 7 = photosystem-II inhibitors; 9 = glyphosate; 11 = carotenoid biosynthesis inhibitors; 14 = protoporphyrinogen oxidase inhibitors; 15 = very long-chain fatty acid synthesis inhibitors; 27 = hydroxyphenylpyruvate dioxygenase inhibitors (Mallory-Smith and Retzinger 2003).

[b] EIQ values for each ai obtained from Kovach et al. (1992, 2012).

[c] EI values for products with more than one ai were obtained by summing the relative proportion of each ai; EI is calculated as EIQ × application rate in kg ai ha^{-1}, expressed on a per ha basis.

[d] Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; winter wheat, *Triticum aestivum* L.

[e] Abbreviations: DR soybean, dicamba-resistant soybean; fb, followed by; PP, preplant.

(PP) treatments include 2,4-D, linuron, or amitrole, which increase the EI by a factor of 1.6, 4.2, and 5.6, respectively. In dicamba-resistant (DR) soybean, either dicamba treatment doubles the EI. In winter wheat, clopyralid or dicamba have the lowest EI (3.6 and 3.7, respectively), whereas EI for dicamba/MCPA (18.2), dicamba/MCPA/mecoprop (19.0), and MCPA (23.1) are the greatest.

For the control of GR horseweed in corn, the EI of flumetsulam is only 0.78, whereas the treatment with the highest EI is dicamba/atrazine at 43.2 (4.1 times that of glyphosate alone) (Table 2). Treatments with saflufenacil or flumetsulam in soybean have low EI; in contrast, metribuzin applied PP has a high EI (31.8). Dicamba in DR soybean has an EI (15.8) half that of metribuzin. In wheat, EI for dicamba, 2,4-D ester, dicamba/MCPA, and dicamba/MCPA/mecoprop is greater than glyphosate by a factor of 1.3, 1.6, 2.3, and 2.4, respectively.

For the control of GR common ragweed in corn, the EI range of herbicide treatments is similar to those for the control of giant ragweed in corn (Table 3). Dicamba/atrazine and mesotrione plus atrazine have the greatest EI (43.2 and 36.9, respectively). In soybean, EI of herbicide treatments to control GR common ragweed range from 0.54 (cloransulam) to 14.1 (acifluorfen). In wheat, clopyralid has the lowest EI (3.6), whereas MCPA has the greatest EI (23.1).

Although ALS-inhibiting herbicides such as cloransulam and flumetsulam have low EI, the increasing occurrence of GR plus ALS inhibitor-resistant biotypes of giant ragweed and horseweed will limit their future effectiveness. To date, there are four sites with these multiple-resistant giant ragweed populations in three counties and 12 sites with multiple-resistant horseweed in four counties (Sikkema et al. 2013). Increased usage of ALS-inhibiting herbicides to manage GR populations of these species will quickly select for multiple-resistant biotypes. In contrast, protoporphyrinogen oxidase (PPO) inhibitors (group 14) have both low EI

Table 3. Environmental impact quotient (EIQ) and environmental impact (EI) of weed management treatments or programs for the control of glyphosate-resistant common ragweed in Ontario, Canada.

Active ingredient(s)[a]	Individual EIQ values[b]	Product rate	EI[c]
		g ai/ae ha^{-1}	
Glyphosate, 9	15.3	900	13.8
Corn[d]			
Dicamba, 4	26.33	600	15.8
Dicamba/diflufenzopyr, 4	26.33/17.52	200	4.8
Dicamba, 4/atrazine, 5	26.33/22.85	1,800	43.2
Flumetsulam, 2	15.61	50	0.78
Isoxaflutole, 27 + atrazine, 5	24.00 + 22.85	79 + 800	20.2
Saflufenacil, 14/dimethenamid-p, 15	22.29/12.02	735	9.6
Mesotrione, 27 + atrazine, 5	18.67/22.85	140 + 1,500	36.9
Soybean			
Cloransulam, 2	15.33	35	0.54
Imazethapyr, 2 + metribuzin, 5	19.57 + 28.37	75 + 425	13.5
Acifluorfen, 14	23.57	600	14.1
Fomesafen, 14	24.46	240	5.9
Wheat			
2,4-D ester, 4	15.33	528	8.1
MCPA, 4	36.67	630	23.1
2,4-D/dichlorprop, 4	15.33/17.41	740	11.9
Clopyralid, 4	18.12	200	3.6
Bromoxynil, 6/MCPA, 4	17.00/36.67	560	15.0

[a] Weed Science Society of America site of action number: 2 = acetolactate synthase inhibitors; 4 = synthetic auxins; 5 to 7 = photosystem-II inhibitors; 9 = glyphosate; 11 = carotenoid biosynthesis inhibitors; 14 = protoporphyrinogen oxidase inhibitors; 15 = very long-chain fatty acid synthesis inhibitors; 27 = hydroxyphenylpyruvate dioxygenase inhibitors (Mallory-Smith and Retzinger 2003).

[b] EIQ values for each ai obtained from Kovach et al. (1992, 2012).

[c] EI values for products with more than one ai were obtained by summing the relative proportion of each ai; EI is calculated as EIQ × application rate in kg ai ha^{-1}, expressed on a per ha basis.

[d] Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; winter wheat, *Triticum aestivum* L.

($\leq$ 10) and low herbicide resistance risk; herbicides with this site of action will play an increasingly important role in GR weed management (Beckie 2012; Beckie and Tardif 2012). Although a few auxinic herbicide (group 4) treatments can have high EI ($>$ 20), most of these treatments have a low or moderate EI; combined with their low risk of selecting for herbicide resistance in weeds, these site-of-action herbicides will be the cornerstone of long-term GR weed management. Indeed, over 60% of the herbicide treatments listed in Tables 1 to 3 contain a synthetic auxin herbicide. There is concern that the introduction of auxinic-resistant crops will rapidly accelerate the evolution of auxinic-resistant weeds (Mortensen et al. 2012). Therefore, as with any technology, moderation in their usage is imperative for their sustainable deployment. Herbicide treatments containing atrazine or metribuzin have high EI because of both high EIQ values and high application rates. Triazine herbicides are banned or severely restricted in European Union countries because of environmental concerns.

In 2012, it was estimated that GR giant ragweed and horseweed each affected 3,000 ha in southwestern Ontario, whereas only one field had GR common ragweed. By 2013 (1 yr hence), we estimate GR giant ragweed, horseweed, and common ragweed will affect 4,000, 10,000, and 200 ha, respectively. The rapid spread of GR horseweed seed by wind has been well documented (Shields et al. 2006). If we assume that rate of increase is linear over time, in 5 yr from the 2012 baseline year (2017), 8,000, 38,000, and 1,000 ha of land will be affected by GR giant ragweed, horseweed, and common ragweed, respectively. Therefore, depending upon the treatment used by growers, the potential total EI (EI per ha basis multiplied by the number of ha) of GR horseweed will likely be substantially greater than that of GR giant or common ragweed.

Table 4. Environmental impact quotient (EIQ) and environmental impact (EI) of weed management treatments or programs for the control of glyphosate plus acetolactate synthase inhibitor-resistant kochia in Alberta and Saskatchewan, Canada.

Active ingredient(s)[a]	Individual EIQ values[b]	Product rate	EI[c]
		g ai/ae ha^{-1}	
Glyphosate (burndown or in-crop), 9	15.3	450	6.9
Chemical fallow			
Dicamba, 4	26.33	288	7.6
Dicamba/diflufenzopyr, 4	26.33/17.52	100	2.4
Dicamba/MCPA/mecoprop, 4	26.33/36.67/15.33	800	25.4
Saflufenacil, 14	22.29	18	0.4
Spring wheat and barley[d]			
Saflufenacil (PRE), 14	22.29	18	0.4
Dicamba, 4	26.33	140	3.7
Dicamba/fluroxypyr, 4	26.33/36.67	122	3.9
MCPA/mecoprop/dichlorprop, 4	36.67/15.33/17.41	1,480	32.7
2,4-D/fluroxypyr, 4	15.33/36.67	505	9.4
Mustard			
Ethalfluralin (PRE), 3[e]	18.83	1,100	20.7
Carfentrazone (PRE), 14	20.18	9	0.2
Glufosinate-resistant canola			
Carfentrazone (PRE), 14	20.18	9	0.2
Amitrole (PRE), 11	31.80	970	30.8
Glufosinate, 10 + clethodim, 1	20.20/17.00	400 + 15	8.4
Flax			
Sulfentrazone (PRE), 14	11.73	140	1.6
Carfentrazone/sulfentrazone (PRE), 14	20.18/11.73	149	1.8
MCPA, 4/bromoxynil, 6	36.67/17.00	550	14.7
Field pea			
Ethalfluralin (PRE), 3	18.83	1,100	20.7
Saflufenacil (PRE), 14	22.29	18	0.4
Sulfentrazone (PRE), 14	11.73	140	1.6
Carfentrazone/sulfentrazone (PRE), 14	20.18/11.73	149	1.8
Bentazon, 6	18.67	840	15.7
Lentil			
Ethalfluralin (PRE), 3	18.83	1,100	20.7
Saflufenacil (PRE), 14	22.29	18	0.4

[a] Weed Science Society of America site of action number: 1 = acetyl-CoA carboxylase inhibitors; 3 = dinitroanilines; 4 = synthetic auxins; 5 to 7 = photosystem-II inhibitors; 9 = glyphosate; 10 = glufosinate; 11 = carotenoid biosynthesis inhibitors; 14 = protoporphyrinogen oxidase inhibitors (Mallory-Smith and Retzinger 2003).

[b] EIQ values for each ai obtained from Kovach et al. (1992, 2012); the value for trifluralin was used for ethalfluralin because no value was listed.

[c] EI values for products with more than one ai were obtained by summing the relative proportion of each ai; EI is calculated as EIQ × application rate in kg ai ha^{-1}, expressed on a per ha basis.

[d] Barley, *Hordeum vulgare* L.; canola, *Brassica napus* L.; field pea, *Pisum sativum* L.; flax, *Linum usitatissimum* L.; mustard, *Sinapis alba* L. (yellow) or *Brassica juncea* L. (brown/oriental); wheat, *Triticum aestivum* L.

[e] Yellow mustard only.

EI Assessment: Herbicides to Manage Glyphosate- Plus ALS Inhibitor-Resistant Kochia in Western Canada

The baseline EI of glyphosate used alone as a burndown (PRE) treatment or in GR crops in the Canadian prairies is 6.9 (per ha basis; Table 4). In chem-fallow, saflufenacil or dicamba/diflufenzopyr increase the EI only marginally, whereas dicamba doubles the baseline EI value ([7.6 + 6.9]/6.9) and dicamba/MCPA/mecoprop increase the EI by a factor of 4.7. In the cereal crops spring wheat and barley, saflufenacil (PRE), dicamba or dicamba/fluroxypyr, 2,4-D/fluroxypyr, and MCPA/mecoprop/dichlorprop increase the EI by a factor of 1.1, 1.5, 1.6, and 5.7, respectively (Table 4).

Mustard growers have no in-crop herbicide treatments to control GR plus ALS inhibitor-resistant kochia (Table 4). The EI of carfentrazone PRE is only marginally greater than glyphosate alone, whereas ethalfluralin quadruples the EI. In glufosinate-resistant canola, carfentrazone PRE results in a much lower EI than amitrole (0.2 vs. 30.8, respectively). Glufosinate plus clethodim treatment has an EI of 8.4, slightly greater than glyphosate alone (6.9). However, a majority of GR canola growers apply glyphosate PRE and twice in-crop (Beckie et al. 2013b). Therefore, this alternative herbicide treatment actually reduces the EI by 25%. In the other oilseed crop, flax, the EI of sulfentrazone PRE or carfentrazone/sulfentrazone PRE is only 1.6 and 1.8, respectively. In contrast, MCPA/bromoxynil increases the EI by a factor of 3.1.

In field pea, saflufenacil, sulfentrazone, or carfentrazone/sulfentrazone applied PRE increase the EI only marginally, whereas bentazon or ethalfluralin increase the EI by a factor of 3.3 and 4, respectively (Table 4). Similarly, in lentil, saflufenacil PRE has an EI of only 0.4, whereas the ethalfluralin treatment quadruples the EI compared with glyphosate alone.

To date, we conservatively estimate that the total field area affected by GR kochia in 2012 is 3,000 ha. Therefore, the total EI of each of the above-mentioned herbicide treatments is 3,000 times the listed EI values (per ha basis). If we assume the area infested with GR kochia doubles every year, the application area would equal 6,000 ha in 2013 (yr 1) and 96,000 ha in 2017 (yr 5). Therefore, the total EI projected into the future to manage GR kochia may be relatively high for treatments such as dicamba/MCPA/mecoprop in chem-fallow, MCPA/mecoprop/dichlorprop in wheat or barley, ethalfluralin PRE for mustard or pulse crops, and MCPA/bromoxynil in flax.

The PPO-inhibiting herbicides (group 14) and auxinic herbicides (group 4) comprise the majority of the herbicide treatments listed in Table 4. Except for dicamba/MCPA/mecoprop used in chem-fallow or MCPA/mecoprop/dichlorprop used in wheat or barley, the remaining auxinic herbicide treatments result in a low EI (≤ 10). All PPO-inhibiting herbicide treatments confer a very low EI. In contrast, ethalfluralin, a dinitroaniline herbicide, and amitrole, a carotenoid biosynthesis inhibitor, both have a high EI (> 20).

Conclusions

The presence of GR weeds will increase the EI of weed management in two ways. First, additional herbicides (tank-mixes or sequential applications) will be required to control these weeds. In addition, some growers will resort to tillage to control these weed biotypes, resulting in deterioration in soil quality (e.g., increased soil erosion) and increased fossil fuel consumption. For example, GR kochia in a number of chem-fallow fields in Saskatchewan in 2012 were well advanced beyond the herbicide application window. Those growers, who had not tilled their fields in many years, had to resort to tillage to control their GR kochia population.

Growers are advised to implement a diverse crop rotation with multiple herbicide sites of action over time—whether GR weeds are present or not (Beckie 2012). Growers must reduce their reliance on glyphosate. However, substitution of glyphosate with repeated use of another herbicide site of action may accelerate the evolution of multiple-resistant weed biotypes (Mortensen et al. 2012). Other herbicide-resistant crops should be included where appropriate, i.e., glufosinate-resistant corn, soybean, or canola. Conventional crops (i.e., nonherbicide-resistant) have a place in weed management and should also be employed.

Growers choose their herbicide treatments based on price and perceived efficacy. They also place great importance on environmental stewardship of their land. Therefore, if two recommended treatments to control their GR weed have similar cost and efficacy, their EI values may influence their decision of which treatment to apply. Accordingly, EI data should be routinely included in weed control extension publications/guides and software/APPs for herbicide treatments recommended for the control of GR and other herbicide-resistant weeds.

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