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Economic impact of glyphosate-resistant weeds on major field crops grown in Ontario

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Research Article

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Nomenclature:
Common ragweed; *Ambrosia artemisiifolia* L.; giant ragweed; *Ambrosia trifida* L.; horseweed; *Erigeron canadensis* L.; waterhemp; *Amaranthus tuberculatus* (Moq.) Sauer; barley; *Hordeum vulgare* L.; canola; *Brassica rapa* L.; corn; *Zea mays* L.; oats; *Avena sativa* L.; soybean; *Glycine max* (L.) Merr.; wheat; *Triticum aestivum* L.; white bean; *Phaseolus vulgaris* L.

Keywords:
Field crops; economic loss; glyphosate-resistant; herbicides; optimal agronomic practices; yield; weed control strategies

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Abstract

Limited information exists on the global economic impact of glyphosate-resistant (GR) weeds. The objective of this manuscript was to estimate the potential yield and economic loss from uncontrolled GR weeds in the major field crops grown in Ontario, Canada. The impact of GR weed interference on field crop yield was determined using an extensive database of field trials completed on commercial farms in southwestern Ontario between 2010 and 2021. Crop yield loss was estimated by expert opinion (weed scientists and Ontario government crop specialists) when research data were unavailable. This manuscript assumes that crop producers adjust their weed management programs to control GR weeds, which increases weed management costs but reduces crop yield loss from GR weed interference by 95%. GR volunteer corn, horseweed, waterhemp, giant ragweed, and common ragweed would cause an annual monetary loss of (in millions of Can$) $172, $104, $11, $3, and $0.3, respectively, for a total annual loss of $290 million if Ontario farmers did not adjust their weed management programs to control GR biotypes. The increased herbicide cost to control GR volunteer corn, horseweed, waterhemp, giant ragweed, and common ragweed in the major field crops in Ontario is estimated to be (in millions of Can$) $17, $9, $2, $0.1, and $0.02, respectively, for a total increase in herbicide expenditures of $28 million annually. Reduced GR weed interference with the adjusted weed management programs would reduce farm-gate monetary crop loss by 95% from $290 million to $15 million. This study estimates that GR weeds would reduce the farm-gate value of the major field crops produced in Ontario by Can$290 million annually if Ontario farmers did not adjust their weed management programs, but with increased herbicide costs of Can$28 million and reduced crop yield loss of 95% the actual annual monetary loss in Ontario is estimated to be Can$43 million annually.

Introduction

The agriculture sector is an important part of the Canadian economy and contributes nearly Can $110 billion annually to the gross domestic product (GDP), which is equivalent to the total national GDP of more than two-thirds of countries worldwide (Anonymous 2019). The contribution of the farm sector to the economy of Ontario is estimated to be Can$27 billion (OMAFRA 2021). One of the greatest challenges facing field crop producers in Ontario is the control of weeds, especially glyphosate-resistant (GR) weeds. Since 2008, GR giant ragweed, horseweed, common ragweed, and waterhemp have been confirmed in Ontario, and the geographic area affected by them continues to increase (Byker et al. 2013; Schryver et al. 2017; Van Wely et al. 2015; Vink et al. 2012). In addition, volunteer GR corn is present in GR soybean when the two crops are grown in rotation. The increase in GR weeds is directly correlated with the overreliance on glyphosate for weed management.

The reasons for the overreliance on glyphosate are many, including the introduction of GR (Roundup Ready) crops, the use of glyphosate as a burndown method in no-till cropping systems, excellent weed control efficacy, low cost, wide margin of crop safety, relatively low environmental impact, and safety to the applicator (Nandula et al. 2005; Norsworthy et al. 2012). GR biotypes have been confirmed across a wide geographic area because of repeated use of glyphosate, wind-blown weed seeds, the resistance gene being carried by pollen, movement of contaminated farm machinery, and transport by migratory birds (Farmer et al. 2017; Heap 2022; Norsworthy et al. 2012). This has resulted in the movement of GR weeds from field to field, farm to farm, and county to county across Ontario (Heap 2022).

Giant ragweed was the first GR weed found in Ontario, confirmed from seed collected in 2008 (Vink et al. 2012). Subsequently, GR horseweed (Byker et al. 2013), common ragweed (Van Wely et al. 2015), and waterhemp (Schryver et al. 2017) were confirmed from seeds

collected in 2010, 2011, and 2014, respectively. GR common ragweed, giant ragweed, waterhemp, and horseweed are currently confirmed in 2, 6, 15, and 30 counties in Ontario, respectively; in addition, those weeds are estimated to be on 5%, 1%, 0.1%, and 0.01%, respectively, of the hectares where the major field crops are grown (Byker et al. 2013; Schryver et al. 2017; Van Wely et al. 2015; Vink et al. 2012). In addition to the aforementioned weeds, GR volunteer corn has become a major issue in soybean in Ontario (Deen et al. 2006; Soltani et al. 2015).

The major field crops grown in Ontario (averaged between 2013 and 2017) and their farm-gate values include the following (in thousands of hectares and millions of Can$, respectively): grain corn, 823, $1,613; fodder corn, 104, $190; soybean, 1,159, $1,695; winter wheat, 351, $499; spring barley, 39, $28; spring oats, 28, $20; spring wheat, 37, $32; spring mixed grain, 30, $16; white bean, 24, $43; colored dry bean, 24, $54; and canola, 17, $20 (Table 1), with a total value of Can$4.1 billion (OMAFRA 2021).

The presence of GR weeds can dramatically decrease crop yield when not controlled, increase weed management costs, and reduce net returns for affected producers. The yield loss of uncontrolled weeds varies depending on weeds species, weed density, the relative time of crop and weed emergence, soil characteristics, soil nutrient status, and weather conditions (Nandula et al. 2005; Norsworthy et al. 2012). Currently, no comprehensive study has been carried out to determine crop yield loss and associated monetary loss from GR weed interference in various field crops in Ontario. Earlier studies with non-GR weeds have shown that if weeds were left uncontrolled a percentage yield loss and value (in millions of US$) for the major crops grown in Ontario would be as follows: corn, 51%, $781; soybean, 38%, $425; wheat, 8%, $367; and dry bean, 64%, $85 (Flessner et al. 2021; Soltani et al. 2016, 2017, 2018). It is critically necessary that policymakers in government and regulatory agencies, individuals in grower groups, and industry personnel have accurate information on the impact of GR weeds when prioritizing and allocating funding for weed science research (Bridges 1992; Swanton et al. 1993).

The purpose of this manuscript is to estimate the potential yield and monetary loss due to GR weed interference on the main field crops grown in Ontario in the absence of any changes in weed management practices. Crop producers adjust their weed management programs to control GR weeds on their farms; the increase in weed management costs will be estimated based on expert opinion and crop yield loss due to GR weeds will be assumed to be reduced by 95%. The true monetary loss after these adjustments will be estimated.

Materials and Methods

The average number of hectares, yield per hectare, price, and total value of field crops for the 2013 to 2017 growing seasons were obtained from the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA 2021). Crop yield loss due to GR weeds was based on replicated trials conducted on commercial farms in southwestern Ontario or expert opinion (weed scientists and OMAFRA crop specialists) as indicated in the footnotes of Tables 1 through 5. The area in Ontario conservatively estimated to be infested with GR horseweed is 5%; waterhemp, 1%; giant ragweed, 0.1%; and common ragweed, 0.01%. The total value for each crop was multiplied by the percent of area infested and multiplied by the percent of crop yield loss from GR weed interference to calculate the estimated provincial monetary loss in the absence of any changes in weed management practices.

Table 1. Estimated economic impact of GR volunteer corn in Ontario, assuming GR volunteer corn is present on 50% and 10% of soybean and dry bean hectares, respectively.[a–f]

Crop	Average (2013-2017) hectares in Ontario	Total value	Yield loss due to GR weeds	Monetary loss from GR Weeds	Total monetary loss in Ontario	Herbicide cost before GR weeds	Herbicide cost after GR weeds	Increase in herbicide cost	Increase in herbicide cost	5% Yield loss	Net loss for Ontario farmers * increase in herbicide cost * 5% yield loss
		$ ha^{-1}	%	$ ha^{-1}	$	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ in province	$ in province	$ in province
Soybean	1,158,620	$1,463	20 [a]	$293	$169,529,278	$91 [c]	$121 [e]	$30	$17,414,059	$8,476,464	$25,890,523
White bean	23,720	$1,799	25 [b]	$450	$1,067,080	$228 [d]	$228 [d]	$0	$0	$53,354	$53,354
Colored bean	23,900	$2,255	25 [b]	$564	$1,347,363	$228 [d]	$228 [d]	$0	$0	$67,368	$67,368
Total					$171,943,721				$17,414,059	$8,597,186	$26,011,245

[a]Soybean yield loss due to GR volunteer corn interference from eight trials conducted in Ontario,
[b]Estimated crop yield loss due to GR volunteer corn interference based on expert opinion.
[c]Cost of glyphosate applied POST1 fb glyphosate applied POST2 (includes application costs).
[d]Cost of trifluralin + halosulfuron applied PPI fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[e]Cost of glyphosate applied POST1 fb glyphosate + quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[f]Abbreviations: fb, followed by; GR, glyphosate-resistant; POST, postemergence; PPI, preplant incorporated.

Table 2. Estimated economic impact of GR horseweed in Ontario during 2013 to 2017 (averaged), assuming GR horseweed is present on 5% of the field crop hectares.[a–m]

Crop	Average (2013-2017) hectares in Ontario	Total value	Yield loss due to GR Weeds	Monetary loss from GR Weeds	Total monetary loss in Ontario	Total herbicide cost before GR weed	Total herbicide cost after GR weed	Increase in herbicide cost	Increase in herbicide cost	5% yield loss	Net loss for Ontario farmers * increase in herbicide cost * 5% yield loss
	ha	$ ha^{-1}	%	$ ha^{-1}	$	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ in province	$ in province	$ in province
Grain corn	823,160	$1,960	51.5 [a]	$1,009	$41,537,678	$91 [e]	$200 [h]	$109	$4,504,743	$2,076,884	$6,581,627
Fodder corn	104,160	$1,833	51.5 [a]	$944	$4,916,326	$91 [e]	$200 [h]	$109	$570,016	$245,816	$815,832
Soybean	1,158,620	$1,463	61.4 [b]	$898	$52,045,488	$91 [e]	$151 [i]	$60	$3,480,205	$2,602,274	$6,082,479
Wheat, winter	351,260	$1,278	7.6 [c]	$97	$1,705,619	$48 [f]	$58 [j]	$9	$162,019	$85,281	$247,300
Barley, spring	39,420	$703	10 [d]	$70	$138,553	$48 [f]	$58 [j]	$9	$18,182	$6,928	$25,110
Oats, spring	27,500	$716	10 [d]	$72	$98,456	$48 [f]	$58 [j]	$9	$12,684	$4,923	$17,607
Spring wheat	37,480	$854	10 [d]	$85	$160,058	$48 [f]	$58 [j]	$9	$17,288	$8,003	$25,291
Spring mixed grain	29,780	$536	10 [d]	$54	$79,857	$48 [f]	$58 [j]	$9	$13,736	$3,993	$17,729
White bean	23,720	$1,799	65 [d]	$1,170	$1,387,204	$292 [g]	$303[k]	$12	$13,847	$69,360	$83,207
Colored bean	23,900	$2,255	65 [d]	$1,466	$1,751,571	$292 [g]	$303 [k]	$12	$13,952	$87,579	$101,530
Canola	16,920	$1,199	25 [d]	$300	$253,563	$91 [e]	$136 [l]	$45	$38,070	$12,678	$50,748
Total					$104,074,374				$8,844,741	$5,203,719	$14,048,460

[a]Corn yield loss due to GR horseweed interference from 41 trials conducted in Ontario.
[b]Soybean yield loss due to GR horseweed interference from 91 trials conducted in Ontario.
[c]Winter wheat yield loss due to GR horseweed interference from 13 trials conducted in Ontario.
[d]Estimated crop yield loss due to GR horseweed interference based on expert opinion.
[e]Cost of glyphosate applied PP fb glyphosate applied POST (includes application costs).
[f]Cost of bromoxynil/MCPA applied POST (includes application cost).
[g]Cost of glyphosate applied PP fb pendimethalin + halosulfuron applied PRE fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[h]Cost of glyphosate + dimethenamid-p/saflufenacil applied PP fb glyphosate + mesotrione + atrazine applied POST (includes adjuvant and application costs).
[i]Cost of glyphosate + saflufenacil + metribuzin applied PP fb glyphosate applied POST (includes adjuvant and application costs).
[j]Cost of bromoxynil/pyrasulfotole applied POST (includes adjuvant and application costs).
[k]Cost of glyphosate + 2,4-D applied PP fb pendimethalin + halosulfuron applied PRE fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[l]Cost of glyphosate applied PP fb glyphosate + clopyralid applied POST (includes application costs).
[m]Abbreviations: fb, followed by; GR, glyphosate-resistant; POST, postemergence; PP, preplant.

Farmers adjust their weed management programs to address GR weeds on their farms. Herbicide programs before and after GR weeds were determined, and the cost of herbicide, adjuvants (AGRIS Co-operative Ltd., Chatham, ON), and application costs were based on the currently recommended herbicide programs for each GR weed in each major field crop in Ontario (OMAFRA 2020). For the purposes of this manuscript, the weed control program prior to the evolution of GR weeds was two applications of glyphosate in corn and soybean. For this manuscript, after implementing revised herbicide programs to control GR weeds, crop yield loss from GR weeds is estimated to be reduced by 95%.

Results and Discussion

GR Volunteer Corn

GR volunteer corn is present across all areas in Ontario where soybean and dry bean are grown and is estimated to be present on 50% and 10% of soybean and dry bean hectares, respectively (Table 1). Uncontrolled GR volunteer corn is not expected to cause any yield loss in grain and fodder corn, winter wheat, spring barley, spring oats, spring wheat, spring mixed grain, and canola. In soybean, white bean, and colored bean GR volunteer corn interference causes an estimated yield loss of 20%, 25%, and 25% (Table 1, column 4) and a monetary loss of (in millions of Can$) $170, $1.1, and $1.3, respectively (Table 1, column 6). The total farm-gate loss from GR volunteer corn interference is estimated to be approximately $172 million per year in Ontario (Table 1).

The increased cost to control GR volunteer corn in soybean is Can$30 ha^{-1} (Table 1, column 9); there is no increase in herbicide cost in white and colored bean crops because a postemergence graminicide is usually applied to control annual and perennial grasses. The increase in herbicide cost to control GR volunteer corn in Ontario is $17 million (Table 1, column 10) and the crop monetary loss is reduced to $9 million (Table 1, column 11). In summary, GR volunteer corn has the potential to cause an annual loss of $172 million in Ontario, but with changes in weed management practices that amount would be reduced to $26 million (Table 1, column 13).

GR Horseweed

GR horseweed is present in 30 Ontario counties and is estimated to be present on 5% of all field crop hectares. Potential yield loss and monetary loss (as a percent and in millions of Can$, respectively) from GR horseweed interference are estimated to be as follows: grain corn, 52%, $42; fodder corn, 52%, $5; soybean, 61%, $52; winter wheat, 8%, $1.7; spring barley, 10%, $0.14; spring oats, 10%, $0.10; spring wheat, 10%, $0.16; spring mixed grain, 10%, $0.08; white bean, 65%, $1.4; colored dry bean, 65%, $1.8; and canola, 25%, $0.25, for a total farm-gate loss of $104 million per year in Ontario (Table 2).

Table 3. Estimated economic impact of GR waterhemp in Ontario during 2013 to 2017 (averaged), assuming GR waterhemp is present on 1% of the field crop hectares.[a–l]

Crop	Average (2013-2017) hectares in Ontario	Total value	Yield loss due to GR Weeds	Monetary loss from GR Weeds	Total monetary loss in Ontario	Total herbicide cost before GR weed	Total herbicide cost after GR weed	Increase in herbicide cost	Increase in herbicide cost	5% yield loss	Net loss for Ontario farmers * increase in herbicide cost * 5% yield loss
	Ha	$ ha^{-1}	%	$ ha^{-1}	$	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ in province	$ in province	$ in province
Grain corn	823,160	$1,960	19 [a]	$372	$3,064,916	$91 [f]	$173 [i]	$82	$675,403	$153,246	$828,649
Fodder corn	104,160	$1,833	19 [a]	$348	$362,758	$91 [f]	$173 [i]	$82	$85,463	$18,138	$103,601
Soybean	1,158,620	$1,463	41.9 [b]	$613	$7,103,277	$91 [f]	$178 [j]	$87	$1,011,186	$355,164	$1,366,349
Wheat, winter	351,260	$1,278	2.9 [c]	$37	$130,166	$48 [g]	$48 [g]	$0	$0	$6,508	$6,508
Barley, spring	39,420	$703	12.3 [d]	$86	$34,084	$48 [g]	$48 [g]	$0	$0	$1,704	$1,704
Oats, spring	27,500	$716	12.3 [d]	$88	$24,220	$48 [g]	$48 [g]	$0	$0	$1,211	$1,211
Spring wheat	37,480	$854	12.3 [d]	$105	$39,374	$48 [g]	$48 [g]	$0	$0	$1,969	$1,969
Spring mixed grain	29,780	$536	12.3 [d]	$66	$19,645	$48 [g]	$48 [g]	$0	$0	$982	$982
White bean	23,720	$1,799	50 [e]	$900	$213,416	$228 [h]	$228 [h]	$0	$0	$10,671	$10,671
Colored bean	23,900	$2,255	50 [e]	$1,128	$269,473	$228 [h]	$228 [h]	$0	$0	$13,474	$13,474
Canola	16,920	$1,199	15 [e]	$180	$30,428	$91 [f]	$155 [k]	$65	$10,939	$1,521	$12,460
Total					$11,291,756				$1,782,990	$564,588	$2,347,578

[a]Corn yield loss due to GR waterhemp interference from 63 trials conducted in Ontario.
[b]Soybean yield loss due to GR waterhemp interference from 37 trials conducted in Ontario.
[c]Winter wheat yield loss due to weed interference from 21 trials conducted in Ontario.
[d]Spring cereal yield loss due to weed interference from 16 trials conducted in Ontario.
[e]Estimated crop yield loss due GR waterhemp interference based on expert opinion.
[f]Cost of glyphosate applied POST1 fb glyphosate applied POST2 (includes application costs).
[g]Cost of bromoxynil/MCPA applied POST (includes application cost).
[h]Cost of trifluralin + halosulfuron applied preplant PPI fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[i]Cost of *S*-metolachlor/mesotrione/bicyclopyrone/atrazine applied PRE fb glufosinate applied POST (includes application costs).
[j]Cost of pyroxasulfone/flumioxazin applied PRE fb glyphosate/dicamba applied POST (includes application costs).
[k]Cost of glyphosate applied PP fb glyphosate + ethametsulfruon applied POST (includes adjuvant and application costs).
[l]Abbreviations: fb, followed by; GR, glyphosate-resistant; POST, postemergence; PP, preplant; PPI, preplant incorporated; PRE, preemergence.

To control GR horseweed the increase in weed management costs (in Can$) per hectare and for the province (in thousands of Can$), respectively, are estimated to be as follows: grain corn, $109, $4,504; fodder corn, $109, $570; soybean, $60, $3,480; winter wheat, $9, $162; spring barley, $9, $18; spring oats, $9, $13; spring wheat, $9, $17; spring mixed grain, $12, $14; white bean, $12, $14; colored dry bean, $12, $14; and canola, $45, $38, for a total of Can $8.8 million in the province. Assuming a reduction in crop yield loss of 95% from GR horseweed interference following the use of appropriate weed management programs there would be a farm-gate loss (in thousands of Can$) as follows: grain corn, $2,076; fodder corn, $245; soybean, $2,602; winter wheat, $85; spring barley, $7; spring oats, $5; spring wheat, $8; spring mixed grain, $; white bean, $69; colored dry bean, $88; and canola, $13; for an annual total of $5.2 million for the province. In summary, GR horseweed has the potential to cause a $104 million monetary loss each year in Ontario but with changes in management practices that could be reduced to Can$14 million (Table 2).

GR Waterhemp

GR waterhemp is present in 15 Ontario counties and is estimated to be present on 1% of the field crop hectares in the province. If GR waterhemp is not controlled, the potential yield loss and resulting monetary loss (in thousands of Can$) are estimated to be as follows: grain corn, 19%, $3,064; fodder corn, 19%, $362; soybean, 42%, $7,103; winter wheat, 3%, $130; spring barley, 12%, $34; spring oats, 12%, $24; spring wheat, 12%, $39; spring mixed grain, 12%, $20; white bean, 50%, $213; colored dry bean, 50%, $269; and canola, 15%, $30, for a total potential loss of Can$11.3 million per year in Ontario (Table 3).

Based on herbicide programs for GR waterhemp control in Ontario it is estimated that there would be an increase of $82, $87, and $65 per hectare for corn, soybean, and canola, respectively, for a total increase in herbicide cost of Can$1.8 million in the province. No adjustments were made in weed management costs for cereals and dry bean because current weed control programs control GR waterhemp, but there would still be a 5% crop yield loss from GR waterhemp interference. The farm-gate monetary loss from GR waterhemp interference after changes in weed management programs are expected to be as follows (in thousands of Can$): grain corn, $153; fodder corn, $18; soybean, $355; winter wheat, $7; spring barley, $2; spring oats, $1; spring wheat, $2; spring mixed grain, $1; white bean, $11; colored dry bean, $13; and $2 canola (Table 3) for a loss across the province of $564,000. In summary, GR waterhemp has the potential to cause Can$11.3 million in losses for Ontario farmers, but with changes in management practices that amount can be reduced to $2.3 million (Table 3).

GR Giant Ragweed

GR giant ragweed is present in six Ontario counties and is estimated to be present on 0.1% of field crop hectares. If GR giant ragweed is not controlled the potential yield loss and resulting monetary loss (in thousands of Can$) would be as follows: grain

Table 4. Estimated economic impact of GR giant ragweed in Ontario during 2013to 2017 (averaged), assuming GR giant ragweed is present on 0.1% of the field crop hectares.[a–n]

Crop	Average (2013-2017) hectares in Ontario	Total value	Yield loss due to GR Weeds	Monetary loss from GR Weeds	Total monetary loss in Ontario	Total herbicide cost before GR weed	Total herbicide cost after GR weed	Increase in herbicide cost	Increase in herbicide cost	5% yield loss	Net loss for Ontario farmers * increase in herbicide cost * 5% yield loss
	ha	$ ha^{-1}	%	$ ha^{-1}	$	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ in province	$ in province	$ in province
Grain corn	823,160	$1,960	72.4 [a]	$1,419	$1,167,894	$91 [f]	$194 [i]	$104	$85,279	$58,395	$143,674
Fodder corn	104,160	$1,833	72.4 [a]	$1,327	$138,230	$91 [f]	$194 [i]	$104	$10,791	$6,911	$17,702
Soybean	1,158,620	$1,463	74.4 [b]	$1,089	$1,261,298	$91 [f]	$122 [j]	$31	$35,685	$63,065	$98,750
Wheat, winter	351,260	$1,278	8.7 [c]	$111	$39,050	$48 [g]	$73 [k]	$24	$8,474	$1,952	$10,427
Barley, spring	39,420	$703	12.3 [d]	$86	$3,408	$48 [g]	$73 [k]	$24	$951	$170	$1,121
Oats, spring	27,500	$716	12.3 [d]	$88	$2,422	$48 [g]	$73 [k]	$24	$663	$121	$785
Spring wheat	37,480	$854	12.3 [d]	$105	$3,937	$48 [g]	$73 [k]	$24	$904	$197	$1,101
Spring mixed grain	29,780	$536	12.3 [d]	$66	$1,964	$48 [g]	$73 [k]	$24	$718	$98	$817
White bean	23,720	$1,799	80 [e]	$1,440	$34,147	$292 [h]	$303 [l]	$12	$277	$1,707	$1,984
Colored bean	23,900	$2,255	80 [e]	$1,804	$43,116	$292 [h]	$303 [l]	$12	$279	$2,156	$2,435
Canola	16,920	$1,199	30 [e]	$360	$6,086	$91 [f]	$136 [m]	$45	$761	$304	$1,066
Total					$2,701,552				$144,784	$135,078	$279,862

[a]Corn yield loss due to GR giant ragweed interference from 41 trials conducted in Ontario.
[b]Soybean yield loss due to GR giant ragweed interference from 91 trials conducted in Ontario.
[c]Winter wheat yield loss due to giant ragweed interference from 13 trials conducted in Ontario.
[d]Estimated crop yield loss due to GR giant ragweed interference based on expert opinion.
[e]Cost of glyphosate applied PP fb glyphosate applied POST (includes application costs).
[f]Cost of bromoxynil/MCPA applied POST (includes application cost).
[g]Cost of glyphosate applied PP fb pendimethalin + halosulfuron applied PRE fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[h]Cost of glyphosate + dimethenamid-p/saflufenacil applied PP fb glyphosate + mesotrione + atrazine applied POST (includes adjuvant and application costs).
[i]Cost of glyphosate + isoxaflutole + atrazine applied PP fb dicamba/atrazine applied POST (includes application costs).
[j]Cost of glyphosate DMA/2,4-D choline applied PP fb glufosinate applied POST (includes application costs).
[k]Cost of clopyralid applied POST (includes application cost).
[l]Cost of glyphosate + 2,4-D applied PP fb pendimethalin + halosulfuron applied PRE fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[m]Cost of glyphosate applied PP fb glyphosate + clopyralid applied POST (includes adjuvant and application costs).
[n]Abbreviations: fb, followed by; GR, glyphosate-resistant; POST, postemergence; PP, preplant; PRE, preemergence.

corn, 72%, $1,168; fodder corn, 72%, $138; soybean, 74%, $1,261; winter wheat, 9%, $39; spring barley, 12%, $3; spring oats, 12%, $2; spring wheat, 12%, $4; spring mixed grain, 12%, $2; white bean, 80%, $34; colored dry bean, 80%, $43; and canola, 30%, $6. The loss of farm-gate income from GR giant ragweed interference in crops is estimated to be approximately $2.7 million per year in Ontario (Table 4).

The increased herbicide cost to control GR giant ragweed is estimated to be (in Can$ ha^{-1}) as follows: grain corn, $104; fodder corn, $104; soybean, $31; winter wheat, $24; spring barley, $24; spring oats, $24; spring wheat, $24; spring mixed grain, $24; white bean, $12; colored dry bean, $12; and canola, $12, for a total cost of $144,000 in the province. Assuming a 95% reduction in crop yield loss from GR giant ragweed interference using the adjusted weed management program the farm-gate loss (in thousands of Can$) would be as follows: grain corn, $58; fodder corn, $7; soybean, $63; winter wheat, $2; spring barley, $0.2; spring oats, $0.1; spring wheat, $0.2; spring mixed grain, $0.1; white bean, $2; colored dry bean, $2; and canola $0.3, for a total farm-gate cost of $135,000. GR giant ragweed causes substantially greater yield and economic loss in soybean, corn (grain and fodder), and dry bean (white and color) than the other field crops evaluated in Ontario. In summary, GR giant ragweed interference has the potential to cause Can$2.7 million in losses for Ontario farmers, but with changes in management practices that amount is reduced to $0.3 million (Table 4).

GR Common Ragweed

GR common ragweed is present in two Ontario counties and is estimated to be present on 0.01% of field crop hectares. If GR common ragweed is not controlled the potential yield loss would be grain corn, 75%; fodder corn, 75%; soybean, 74%; winter wheat, 3%; spring barley, 12%; spring oats, 12%; spring wheat, 12%; spring mixed grain, 12%: white bean, 75%; colored dry bean, 75%; and canola, 25%, resulting in a monetary loss of Can$270,000 across Ontario (Table 5). The increase in herbicide cost to control GR common ragweed would be $18,000 and yield loss could be reduced to $14,000. In summary, GR common ragweed has the potential to cause Can$271,000 in annual losses for Ontario farmers, but with changes in management practices that amount can be reduced to $32,000 (Table 5).

In conclusion, the annual loss of farm-gate income from GR volunteer corn would be Can$175 million, $104 million from horseweed, $11 million from waterhemp, $3 million from giant ragweed, and $0.3 million from common ragweed, if these are left uncontrolled in the main field crops grown in Ontario, for a total of $290 million. The cost of changing herbicide programs to provide effective control of GR volunteer corn, horseweed, waterhemp, giant ragweed, and common ragweed in the aforementioned field corps would be Can$28 million annually. Assuming a 95% reduction in crop yield loss due to GR weeds with the implementation of revised, efficacious weed management programs for the

Table 5. Estimated economic impact of GR common ragweed in Ontario during 2013 to 2017 (averaged), assuming GR common ragweed is present on 0.01% of the field crop hectares. [a–l]

Crop	Average (2013-2017) hectares in Ontario	Total value	Yield loss due to GR weeds	Monetary loss from GR weeds	Total monetary loss in Ontario	Total herbicide cost before GR weed	Total herbicide cost after GR weed	Increase in herbicide cost	Increase in herbicide cost	5% yield loss	Net loss for Ontario farmers * increase in herbicide cost * 5% yield loss
	Ha	$ ha^{-1}	%	$ ha^{-1}	$	$ ha^{-1}	$ ha^{-1}	$ ha^{-1}	$ in province	$ in province	$ in province
Grain Corn	823,160	$1,960	74.6 [a]	$1,462	$120,338	$91 [f]	$176 [i]	$86	$7,059	$6,017	$13,076
Fodder Corn	104,160	$1,833	74.6 [a]	$1,367	$14,243	$91 [f]	$176 [i]	$86	$893	$712	$1,605
Soybean	1,158,620	$1,463	74.3 [b]	$1,087	$125,960	$91 [f]	$178 [j]	$87	$10,112	$6,298	$16,410
Wheat, winter	351,260	$1,278	2.9 [c]	$37	$1,302	$48 [g]	$48 [g]	$0	$0	$65	$65
Barley, spring	39,420	$703	12.3 [d]	$86	$341	$48 [g]	$48 [g]	$0	$0	$17	$17
Oats, spring	27,500	$716	12.3 [d]	$88	$242	$48 [g]	$48 [g]	$0	$0	$12	$12
Spring wheat	37,480	$854	12.3 [d]	$105	$394	$48 [g]	$48 [g]	$0	$0	$20	$20
Spring mixed grain	29,780	$536	12.3 [d]	$66	$196	$48 [g]	$48 [g]	$0	$0	$10	$10
White bean	23,720	$1,799	75 [e]	$1,350	$3,201	$228 [h]	$228 [h]	$0	$0	$160	$160
Colored Bean	23,900	$2,255	75 [e]	$1,691	$4,042	$228 [h]	$228 [h]	$0	$0	$202	$202
Canola	16,920	$1,199	25 [e]	$300	$507	$91 [f]	$136 [k]	$45	$76	$25	$101
Total					$270,767				$18,140	$13,538	$31,678

[a]Corn yield loss due to GR common ragweed interference from 41 trials conducted in Ontario.
[b]Soybean yield loss due to GR common ragweed interference from 91 trials conducted in Ontario.
[c]Winter wheat yield loss due to common ragweed interference from 13 trials conducted in Ontario.
[d]Estimated crop yield loss due to GR common ragweed interference based on expert opinion.
[e]Cost of glyphosate applied PP fb glyphosate applied POST (includes application costs).
[f]Cost of glyphosate applied POST1 fb glyphosate applied POST2 (includes application costs).
[g]Cost of bromoxynil/MCPA applied POST (includes application cost).
[h]Cost of trifluralin + halosulfuron applied PPI fb fomesafen applied POST1 fb quizalofop-p-ethyl applied POST2 (includes adjuvant and application costs).
[i]Cost of isoxaflutole + atrazine applied PRE fb dicamba/atrazine applied POST (includes application costs).
[j]Cost of pyroxasulfone/flumioxazin applied PRE fb glyphosate/dicamba applied POST (includes application costs).
[k]Cost of glyphosate applied PP fb glyphosate + clopyralid applied POST (includes adjuvant and application costs).
[l]Abbreviations: fb, followed by; GR, glyphosate-resistant; POST, postemergence; PP, preplant; PPI, preplant incorporated; PRE, preemergence.

control of GR weed biotypes there would still be a farm-gate loss of $15 million. This study concludes that the presence of GR weeds results in an annual increase in weed management costs of $28 million and yield loss of $15 million, resulting in an annual loss to Ontario field crop producers of $43 million. This study reemphasizes the need for more weed science research on developing diversified, sustainable crop/weed management programs to minimize the selection intensity for herbicide-resistant weeds.

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