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PROJECT FINAL REPORT

Section A: Project overview

1. Project number: 2013F008R	
2. Project title: Biology and Management of Glyphosate-Resistant Kochia	
3. Abbreviations: GR = glyphosate resistant	
4. Project start date: (2013/04/01)	
5. Project completion date: (2016/03/31)	
6. Final report submission date: (2016/03/31)	
7. Research and development team data	
a) Principal Investigator:	
Name	**Institution**
Dr. Bob Blackshaw	Agriculture and Agri-Food Canada Lethbridge
b) Research team members	
Name	**Institution**
Dr. Linda Hall (Collaborator)	University of Alberta
Dr. Hugh Beckie (Collaborator)	Agriculture and Agri-Food Canada Saskatoon

Section B: Non-technical summary

Kochia was identified as the first glyphosate-resistant weed in western Canada in 2011 and is now present in 7 counties in Alberta, 14 municipalities in Saskatchewan, and 2 municipalities in Manitoba. This development of glyphosate-resistant kochia sparked many questions from farmers and the agricultural industry about how to minimize its spread and what best management practices could be employed for its control. A research study was conducted to determine the timing of seed maturity, seed production potential, and seed dormancy

characteristics of glyphosate-resistant kochia and identify effective alternative herbicides to control glyphosate-resistant kochia in preseed/chemfallow and in-crop applications.

Study results indicate that kochia readily emerges in early spring and it is those early emerging plants that produce the most seed. In the absence of crop competition and at densities ranging from 75-150 plants m^{-2}, kochia emerging in April and May produced up to 2.4 million seeds m^{-2} in Edmonton and up to 5.2 million seeds m^{-2} in Lethbridge. Kochia emerging in mid-to-late July in Edmonton and mid-August in Lethbridge were capable of producing viable seed before a killing fall frost. Thus producers must be diligent in controlling kochia that emerges as late in the growing season as late July or early August to stop seed production. Kochia seed was found to possess short-term dormancy (a few weeks) after maturity but subsequently germinated at high levels. Overall results indicate that kochia will likely germinate or die within 1-2 years so growers can quickly reduce the soil seedbank if they also prevent new introductions.

Glyphosate-resistant and glyphosate-susceptible kochia were both included in the herbicide experiments to determine if they responded differently to herbicides other than glyphosate. Results indicated that the glyphosate resistance trait did not confer resistance to any other class of herbicides. This is good news for farmers; if the herbicide they are using is currently effective on kochia then it should remain so on glyphosate-resistant kochia.

The majority of glyphosate-resistant kochia populations in western Canada were selected for in chemfallow fields due to the repeated sole use of glyphosate. Thus farmers required immediate advice on effective herbicides that could be tank-mixed with glyphosate for use on fallow. Results indicated that dicamba (Banvel) at higher rates of 290-580 g ai ha^{-1}, dicamba/diflufenzopyr (Distinct), saflufenacil (Heat), MCPA/dichlorprop-p/mecoprop-p (Optica Trio), and carfentrazone (Aim) are the best tank-mix partners with glyphosate to control kochia in chemfallow.

In wheat, any herbicide product containing fluroxypyr (e.g. Pulsar, OcTTain, Enforcer D) gave consistent kochia control with excellent crop tolerance. Pyrasulfotole/bromoxynil (Infinity), dicamba/2,4-D/mecoprop (Dyvel Dsp), and MCPA/dichlorprop-p/mecoprop-p (Optica Trio) also provided a high level of kochia control. In field peas, the combination of carfentrazone/sulfentrazone (Authority Charge) applied preplant provided superior kochia control**.** Imazamox/bentazon (Viper ADV) also provided reasonable in-crop kochia control and this was improved when saflufenacil (Heat) was applied preplant to control early germinating plants. Kochia control will be problematic in Roundup Ready or Clearfield canola but our study found that glufosinate (Liberty) applied once or twice in Liberty Link canola consistently controlled kochia over sites and years. Other effective treatments were preplant ethalfluralin (Edge) followed by postemergence glufosinate and the three-way combination of preplant ethalfluralin, preemergence carfentrazone (Aim), and postemergence glufosinate. Farmers were advised of these results and they were also provided information on how best to rotate herbicides from different herbicide groups to manage existing herbicide-resistant kochia and prevent development of additional herbicide resistance.

Several unregistered herbicides were evaluated and a few showed good potential to control glyphosate-resistant kochia. Fluthiacet (Cadet) and pyroxasulfone (Focus) both provided selective control in field peas. Sulfentrazone (Authority) is not currently registered for use in spring wheat but our research indicated that wheat tolerance is acceptable and it was among the very best treatments in terms of kochia control. The respective companies selling these herbicides have been informed of these results and are proceeding with new herbicide registrations. These Group 14 and 15 herbicides will be beneficial in terms of rotating with the widely used Group 2 and Group 4 herbicides in many of our prairie field crops.

Lessons learned in these research studies and extension efforts will aid in preventing/delaying the onset of glyphosate resistance in other weed species and will allow a faster, more informed response if further resistance occurs.

Section C: Project details

1. **Background**

   Worldwide, glyphosate-resistant (GR) kochia was reported in Kansas in 2007, Colorado and South Dakota in 2009, Nebraska in 2011, North Dakota in 2012, and Montana in 2013 (Heap 2015). GR kochia has spread rapidly in those states since the initial discovery.

   Our investigations into GR kochia in Alberta began in the summer of 2011. Dr. Blackshaw received a farmer call regarding poor kochia control and our research group subsequently investigated suspected GR kochia in three chemfallow fields (each farmed by a different grower) in the Warner-Milk River area. In greenhouse dose-response experiments, the three kochia populations exhibited a resistance factor ranging from 4 to 7 based on survival and biomass data. In October of 2011, we surveyed an additional 46 fields within a 20-km radius of the original three chemfallow fields and found 7 of 46 populations were glyphosate-resistant. Subsequent field surveys in 2012-2014 indicate that glyphosate-resistant kochia is now present in 7 counties in Alberta, 14 municipalities in Saskatchewan, and 2 municipalities in Manitoba. The tumbleweed seed dispersal mechanism (Beckie et al. 2011) results in rapid spread of glyphosate-resistant kochia.

   Research conducted by Dr. Westra (Colorado State University) indicates that the resistance mechanism is likely gene amplification; 3 to 12 extra copies of the gene coding for the target enzyme (EPSPS) of glyphosate activity has been found in the initial GR kochia populations in the USA and Canada. Subsequent work in Canada by Dr. Sara Martin has found up to 27 EPSPS gene copies in some Canadian kochia populations and higher EPSPS copy number confers a higher level of glyphosate resistance.

   Our project will provide growers with new information on alternative herbicides to control GR kochia. Knowledge on the most effective existing herbicides will be conveyed to farmers. Unregistered herbicides showing good kochia efficacy were identified and this information has been provided to the crop protection companies to help support future registrations.

New information on kochia biology will help target best herbicide application timings as well as aid in devising longer term integrated control strategies (Blackshaw et al. 2008).

2. Objectives and deliverables

a) Objectives

1. Determine seed production potential, timing of viable seed development, and seed dormancy status of glyphosate-resistant kochia.
2. Identify effective herbicides to control glyphosate-resistant kochia in preseed/chemfallow situations and in-crop applications in the major field crops wheat, canola, and field pea.

b) Key deliverables

1. Provide information on seed production potential and time required for glyphosate-resistant kochia to reach seed maturity. Knowledge on timing of viable seed production will allow optimal timing of herbicides applied during the chemfallow year and postharvest.
2. Identify effective alternative herbicides to be tank-mixed with glyphosate to control GR kochia in preseed and chemfallow applications. Identify effective in-crop herbicides to control GR kochia in wheat, canola and field pea. This new information will be critical to growers as a first measure in controlling glyphosate-resistant kochia on their farms.
3. Train a M.Sc. student (University of Alberta).

There were no modifications to the objectives or deliverables during this 3-year project.

3. Research design and methodology

Objective 1: Determine kochia seed production potential, timing of viable seed development, and initial seed dormancy status.

Field experiments were conducted at the AAFC Lethbridge Research Centre and at the University of Alberta Research Farm. Treatments consisted of various kochia seeding dates (planted every two weeks from April until mid-August) and were organized in a randomized complete block design with four replicates. Kochia was harvested at maturity or when growth was terminated due to a killing fall frost. Data collection included emergence date, initiation of flowering, maturity date, aboveground biomass production, seed production, initial seed dormancy, and seed viability. Air temperature data were collected throughout the growing season to allow calculation of growing degree days (GDD) for each kochia emergence and harvest date. The field portion of this experiment was conducted at Lethbridge in 2014 and 2015 (flooded out in 2013) and Edmonton in 2013 and 2014. Seed dormancy and viability evaluations were conducted in the winter months in the lab and greenhouse at the University of Alberta. Data were analyzed using appropriate statistical models within SAS.

Objective 2: Identify effective herbicides to control glyphosate resistant (GR) kochia in preseed/chemfallow treatments and in-crop herbicide applications.

Field experiments were conducted in chem-fallow, spring wheat, field pea, and canola to identify the most effective herbicides to control glyphosate-resistant kochia. A factorial experimental design was utilized with Factor A being various registered and unregistered herbicides and Factor B being glyphosate-susceptible versus glyphosate-resistant kochia. Treatments were organized in a strip-block design (kochia biotypes) within a randomized complete block design with four replicates. The four experiments were conducted at Lethbridge in 2013-2015, Coalhurst in 2013-2014, and Edmonton in 2015 (glyphosate-susceptible kochia only). Data collection included visual crop injury ratings, visual kochia control ratings, and crop yield at maturity. Experiments were desiccated at crop maturity to minimize any viable kochia seed set and sites will be monitored for two years to ensure no kochia survivors. Data were statistically analyzed using appropriate models within SAS and treatments separated using the LSD test at the 5% significance level.

See Appendix for a complete list of herbicides evaluated.

4. Results, discussion and conclusions

Objective 1

Our study confirmed that kochia readily emerges in early spring and it is those early emerging plants that produce the most seed (see Appendix). In the absence of crop competition and at densities ranging from 75-150 plants m^{-2}, kochia emerging in April and May produced up to 2.4 million seeds m^{-2} in Edmonton and up to 5.2 million seeds m^{-2} in Lethbridge. Kochia seed production progressively declined as kochia emergence was delayed until July and August. This result of reduced seed set with later emergence times occurs for most weed species but is even more evident for a species such as kochia that requires a relatively longer time period to reach maturity.

A major question that farmers asked was how late in the growing season could kochia emerge and still produce viable seed before a killing fall frost. Visual observations indicated that temperatures below -5 C are required to kill kochia and thus they often continue growing later in the fall than other weed species. Edmonton results indicated that kochia planted on July 22, 2013 and July 16, 2014 (emerged in late July) was capable of producing viable seed (see germination data in Appendix). The Lethbridge 2014 experiment found that kochia planted July 23 (emerged early August) produced viable seed but no seed production occurred when kochia was planted August 6 (emerged mid-August). Lethbridge 2015 results indicated that kochia planted August 4 (emerged mid-August) produced viable seed but kochia planted on August 17 did not. Thus our study suggests that producers must be diligent in controlling kochia that emerges as late in the growing season as mid-August to stop viable seed production. Germination tests conducted 2-3 months after harvest indicated that dormancy levels are generally low in kochia and thus its persistence in the soil seed bank will be shorter than a species such as wild oat with high innate dormancy. Related studies at Lethbridge found that kochia seed has short-term dormancy (a few weeks) after maturity but subsequently germinates at high levels. Overall results indicate that kochia will likely germinate or die within 1-2 years so growers can quickly reduce the soil seedbank if they also prevent new introductions.

Objective 2

We evaluated both glyphosate-resistant and glyphosate-susceptible kochia in the herbicide experiments to determine if they responded differently to herbicides other than glyphosate. Results clearly indicated that the glyphosate resistance trait did not confer resistance to any other class of herbicides. This is good news for farmers; if the herbicide they are using is currently effective on kochia then it should remain so on glyphosate-resistant kochia.

Fallow

The majority of glyphosate-resistant kochia populations in western Canada were selected for in chemfallow fields due to the repeated sole use of glyphosate (applied 3-4 times per growing season). Thus it was imperative that farmers be provided with advice on effective herbicides that could be tank-mixed with glyphosate for use on fallow. Results indicate that dicamba (Banvel) at higher rates of 290-580 g ai ha^{-1}, dicamba/diflufenzopyr (Distinct), saflufenacil (Heat), MCPA/dichlorprop-p/mecoprop-p (Optica Trio), and carfentrazone (Aim) are the best tank-mix partners with glyphosate to control kochia in chemfallow (see Appendix). Kochia was poorly controlled with 2,4-D ester and this herbicide should not be used for that purpose. Sulfentrazone controlled kochia well but there are some cropping restrictions after its use and it might be better utilized in crops such as field peas to manage kochia. Flumioxazin showed potential to control kochia but again is likely better utilized in a cropping situation. The unregistered herbicide fluthiacet (Cadet) did not provide consistent kochia control on fallow but may have potential as an in-crop application.

Wheat

There are many registered herbicides to selectively control kochia in wheat but several do not provide the high level of consistent control needed to manage glyphosate-resistant kochia (see Appendix). Any herbicide product containing fluroxypyr (e.g. Pulsar, OcTTain, Enforcer D) gave consistent kochia control with excellent crop tolerance (see Appendix). Prasulfotole/bromoxynil (Infinity), dicamba/2,4-D/mecoprop (Dyvel Dsp), and MCPA/dichlorprop-p/mecoprop-p (Optica Trio) also provided a high level of kochia control over sites and years. Sulfentrazone (Authority) is not currently registered for use in spring wheat but our research indicated that wheat tolerance is acceptable and it was among the very best treatments in terms of kochia control. The company selling sulfentrazone in

Canada has indicated that they will proceed with adding spring wheat to the Canadian sulfentrazone label, thereby adding a Group 14 herbicide for in-crop use in wheat. This will be beneficial in terms of rotating with the widely used Group 2 and Group 4 herbicides used in many cereal crops.

Field pea

Field pea is not a highly competitive crop and there are fewer selective broadleaf herbicides to choose from compared with wheat. Additionally, most kochia populations in western Canada are resistant to Group 2 herbicides (e.g. Pursuit, Odyssey). Thus, glyphosate-resistant kochia control in field pea will be a challenge for some producers. Fall-applied ethalfluralin (Edge), propyzamide (Kerb), and flumioxazin (Valor) applied alone and in combination did not consistently control kochia (see Appendix). The combination of carfentrazone/sulfentrazone (Authority Charge) applied preplant provided superior kochia control at Lethbridge and Coalhurst. However, sulfentrazone efficacy on kochia decreased considerably in the higher organic Edmonton soils. Imazamox/bentazon (Viper ADV) provided reasonable in-crop kochia control and this was improved when saflufenacil (Heat) was applied preplant to control early germinating weeds. Metribuzin (Sencor) did not adequately control kochia without injuring field peas. The unregistered products pyroxasulfone (Focus) and fluthiacet (Cadet) showed good potential to selectively control kochia in field pea and the respective companies are proceeding with future registrations. They will likely need to be utilized in combination with other herbicides to give higher levels of kochia control but they will be very useful in terms of herbicide rotation diversity (fluthiacet is a Group 14 and pyroxasulfone is a Group 15 herbicide).

Canola

Management of glyphosate-resistant kochia will be problematic in canola. Obviously, using glyphosate in Roundup Ready canola will not be effective and Clearfield canola is not a very viable option as greater than 90% of kochia in western Canada is resistant to Group 2 herbicides. Thus, our research team decided to focus on Liberty Link canola in our field experiments to determine glufosinate (Liberty) efficacy when applied once or twice postemergence. Additionally, we evaluated some other potential herbicides for use in canola that could be used alone or in combination with glufosinate. Study findings clearly indicate that glufosinate applied early postemergence (2-3 leaf stage of canola) at either 500 or 590 g ai ha^{-1} consistently controlled kochia over sites and years (see Appendix). Repeated glufosinate applications (2-3 and 5-6 leaf stage) resulted in slightly higher levels of kochia control and would have the biggest benefit in years where multiple kochia flushes occurred. Glufosinate providing a consistent and high level of kochia control is very good news for farmers and the entire canola industry.

Ethalfluralin (Edge) can be used in all canola types but our study found that kochia control was generally inadequate; ranging from 40-70%. However, ethalfluralin could still be a useful treatment if used in conjunction with other herbicides. For example, fall-applied ethalfluralin followed by postemergence glufosinate was quite effective and the three-way combination of fall-applied ethalfluralin, preemergence carfentrazone (Aim), and postemergence glufosinate provided a high and consistent level of kochia control over sites and years. Postemergence carfentrazone was evaluated in 2013 but canola injury was very high and this treatment was not tested in subsequent years. Sulfentrazone is registered at rates of 105 and 140 g ai ha^{-1} in field peas and sunflower and at those rates it causes unacceptable canola injury. However, we decided to evaluate low sulfentrazone rates (27 and 53 g ai ha^{-1}) to determine if there was any potential to suppress or control kochia with minimal canola injury. Results indicated that there may be potential to use preemerge sulfentrazone at the lowest rate of 27 g ai ha^{-1} especially when combined with preplant ethalfluralin, preemerge carfentrazone, or preemerge carfentrazone followed by postemergence glufosinate (see Appendix). Visual canola injury was usually <10% and canola yield was not reduced. The company selling sulfentrazone in Canada has been informed of these results and are further considering its use in canola considering that there are so few other herbicide options. Our overall recommendation would be for farmers to grow Liberty Link canola if they know they have glyphosate-resistant kochia in their fields and to also consider using ethalfluralin or carfentrazone to get other herbicide modes of action in their weed control program.

See Appendix for data by site and year. Two published scientific manuscripts are also included in Appendix.

5. Literature cited

Beckie, H. J., S. I. Warwick, C. A. Sauder, C. Lozinski, and S. Shirriff. 2011. Occurrence and molecular characterization of acetolactate synthase (ALS) inhibitor-resistant kochia (*Kochia scoparia*) in western Canada. Weed Technology 25:170-175.

Blackshaw, R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian prairies. Weed Science 56:146-150.

Heap, I. M. 2015. International Survey of Herbicide Resistant Weeds. **http://www.weedscience.org.**

6. Project team

<u>Dr. Bob Blackshaw (project lead)</u>: Develop research protocols, prepare data collection templates, overall study management, distribute budget to collaborators, conduct statistical analyses, write annual and final reports, disseminate research findings. Manage Lethbridge field site.

Dr. Linda Hall (collaborator): Manages the Edmonton site of Objective 1 (kochia biology). Supervises M.Sc. student at the University of Alberta. Collaborator on developing research protocols, writing reports, and distributing extension messages.

Dr. Hugh Beckie (collaborator): Conducted initial seed increases of glyphosate-resistant and glyphosate-susceptible kochia populations used in the studies. Collaborator on developing research protocols, writing reports, and distributing extension messages.

7. Benefits to the industry

a) Describe the impact of the project results on the Alberta or western Canadian agriculture and food industry (results achieved and potential short-term, medium-term and long-term outcomes).

The main beneficiary of this research will be farmers. Growers asked questions about how late can kochia emerge in the growing season and still produce viable seed? How dormant is kochia seed? We had no answers to those questions; thus the kochia biology study was conducted in the heart of kochia country (Lethbridge) and at a more northerly site with a shorter growing season (Edmonton). Our studies found that kochia emerging as late as mid-July in Edmonton and mid-August in Lethbridge could produce viable seed before a killing fall frost. This is later in the season than we would have estimated and thus we have informed farmers that they must be diligent in controlling late kochia flushes in fallow and in-crop situations. Our study confirmed that kochia seed dormancy is quite short (only a few weeks) and thus effective control programs for as little as two years should markedly reduce the soil seed bank (as long as there are no new introductions).

We evaluated both glyphosate-resistant and glyphosate-susceptible kochia in the herbicide experiments to determine if they responded differently to herbicides other than glyphosate. Results indicated that the glyphosate resistance trait did not confer resistance to any other class of herbicides. This is good news for growers; if the herbicide they are using is currently effective on kochia then it should remain so on glyphosate-resistant kochia.

The herbicide studies identified the most effective herbicides (and rates of those herbicides) to control glyphosate-resistant kochia in chemfallow/preseed situations, wheat, field pea, and canola. Effective herbicide control measures are a critical first step in managing this weed problem and minimizing its spread to new areas. Farmers were also provided advice on how to rotate herbicides from different Herbicide Groups to manage existing herbicide-resistant kochia and prevent development of additional herbicide resistance. For example, growers in the USA switched en masse to using dicamba (Banvel) to control kochia with the result that kochia is now also resistant to dicamba in Montana, Nebraska and North Dakota.

The herbicide experiments also identified several unregistered herbicides that exhibit good potential for kochia control. Crop Protection companies have been informed of these results and at least a couple of these new herbicides (fluthiacet, pyroxasulfone) are moving forward to registration in Canada. Our data will help support these registrations. Identification of effective kochia herbicides from several Herbicide Groups will markedly reduce the risk of selecting for further resistance in kochia.

Lessons learned in our research studies and extension efforts will aid in preventing/delaying the onset of glyphosate resistance in other weed species and will allow a faster, more informed response if further resistance occurs.

b) Quantify the potential economic impact of the project results (e.g., cost-benefit analysis, potential size of market, improvement in efficiency, etc.).

Kochia is a large, competitive weed species capable of causing major reductions in crop yield. Additionally, due to it often being green at harvest time, it can increase the need to use a desiccant, slow harvest operations, and increase grain moisture content to unsafe levels. Thus, kochia is a weed of high economic importance and the presence of glyphosate-resistant biotypes only makes it more problematic. Glyphosate-resistant kochia is now present in 7 counties in Alberta, 14 municipalities in Saskatchewan, and 2 municipalities in Manitoba. Results obtained in this study will help farmers manage kochia in a timely and cost-effective manner.

8. Contribution to training of highly qualified personnel

One student and one technician were involved in this research project each year at Lethbridge (2013-2015). One student was involved each year at Coalhurst (2013-2014). One student and one technician were involved each year at Edmonton (2013-2015). Additionally, the M.Sc. student Alysha Torbiak was involved in conducting these studies each year.

9. Knowledge transfer/technology transfer/commercialisation

a) Scientific publications

Beckie, H. J., Blackshaw, R. E., Low, R., Hall, L. M., Sauder, C. A., Martin, S., Brandt, R. N., and Shirriff, S. W. 2013. Glyphosate- and acetolactate synthase inhibitor-resistant kochia (*Kochia scoparia*) in western Canada. Weed Science 61:310-318.

Hall, L. M., Beckie, H. J., Low, R., Shirriff, S.W., Blackshaw, R. E., Kimmel N., and Neeser, C. 2014. Survey of glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Alberta. Canadian Journal of Plant Science 94:127-130.

b) Industry-oriented publications

Dika, R. and Blackshaw, R. E. 2013. Dealing with glyphosate resistance. Top Crop Manager (Canola Issue – January 2013). p. 12-13

Barker, B., Blackshaw, R. E., and Hall, L. M. 2013. Targeting glyphosate-resistant kochia. Top Crop Manager (Western Edition, March 2013). p. 22-24

Barker, B., Blackshaw, R. E., and Beckie, H. J. 2015. Controlling group 2/9-resistant kochia. Top Crop Manager (Western Edition, mid-March Edition). p. 50-54.

c) Scientific presentations

Beckie, H. J., Blackshaw, R. E., Low, R., Hall, L. M., Sauder, C. A., Martin, S., Brandt, R. N., and Shirriff, S. W. 2013. Glyphosate- and acetolactate synthase inhibitor-resistant kochia (*Kochia scoparia*) in western Canada. Proc. Weed Science Society of America Conference, Baltimore, USA. 1 p.

Beckie, H. J., Blackshaw, R. E., Low, R., Hall, L. M., Sauder, C. A., Martin, S., Brandt, R. N., and Shirriff, S. W. 2013. Glyphosate- and acetolactate synthase inhibitor-resistant kochia (*Kochia scoparia*) in western Canada. Proc. Global Herbicide Resistance Challenge Conference, Perth, Australia. 1 p.

Blackshaw, R. E., Beckie, H. J., Low, R., and Hall, L. M. 2013. Glyphosate-resistant kochia on the Canadian Prairies. Proc. Western Society of Weed Science Conference, San Diego, CA, USA. p. 91-92

Hall, L. M., Beckie, H., Blackshaw, R. E., Low, R., Kimmel, N., and Shirriff, S. 2014. Survey of glyphosate resistant kochia in western Canada. Proc. Weed Science Society of America, Vancouver, BC. 1 p.

Blackshaw, R. E., Torbiak, A., Hall, L. M., and Beckie, H. J. 2014. Glyphosate-resistant kochia management. Proc. Canadian Weed Science Society Conference, Montreal, QC. p. 33

Hall, L. M. and Beckie, H. J. 2015. Western Canada herbicide resistance. Global Herbicide Resistance Workshop, Paris, France. 1 p.

d) Industry-oriented presentations

Blackshaw, R. E., Torbiak, A., Hall, L. M., and Beckie, H. J. 2015. Glyphosate-resistant kochia update. Proc. Agronomy Update Conference, Lethbridge, AB. 1 p.

Hall, L. M. 2015. Herbicide resistance weeds in western Canada. FarmTech Conference, Edmonton, AB. 1 p.

Hall, L. M. 2016. Defence mechanisms. Herbicide Resistance Summit, Saskatoon, SK. 2 p.

Dr. Blackshaw made grower presentations hosted by Crop Production Services in Milk River and Foremost in 2013, a presentation hosted by BASF Canada in Lethbridge in 2014, a presentation hosted by FMC Canada in Lethbridge in 2015, and a presentation hosted by Farming Smarter in Medicine Hat in 2015.

e) Media activities - Nil

f) Any commercialisation activities or patents - Nil

N.B.: Any publications and/or presentations should acknowledge the contribution of each of the funders of the project, as per the investment agreement.

Section D: Project resources

1. **Provide a detailed listing of all cash revenues to the project and expenditures of project cash funds in a separate document certified by the organisation's accountant or other senior executive officer, as per the investment agreement.**

   Provided in a separate document as stipulated.

2. **Provide a justification of project expenditures and discuss any major variance (*i.e.*, ± 10%) from the budget approved by the funder(s).**

   Salary: M.Sc. student, summer student, and technical help at the University of Alberta and one student in summer and one part-time student in fall at AAFC, Lethbridge annually. One part-time student at Coalhurst in 2013-2014.
   Travel: Travel costs include the M.Sc. student travelling between field sites at Lethbridge and University of Alberta, Dr. Hall visiting the Lethbridge field sites, and all collaborators speaking at grower and industry meetings.
   Supplies: Seed, stakes, fertilizer, herbicides, harvest bags, and pots needed for the field and greenhouse components of this study plus land rental and greenhouse usage fees which are mandatory at AAFC and the University of Alberta.
   CDL: Partial coverage of conference travel (Canadian Weed Science Society and Weed Science Society of America) for Dr. Blackshaw and Dr. Hall to make scientific presentations on glyphosate-resistant kochia distribution and management. Travel costs for Dr. Blackshaw and Dr. Hall to speak at Grower/Industry meetings.
   Government in-kind support: Time commitment spent on this project by the three scientists and use of field/lab equipment at AAFC, Lethbridge and the University of Alberta.

   There were no variances in project expenditures from approved budget.

3. **Resources:**
   Provide a list of all external cash and in-kind resources which were contributed to the project.

Total resources contributed to the project		
Source	**Amount**	**Percentage of total project cost**
Agriculture Funding Consortium	$147,000	26%
Other government sources: Cash	$0	0%
Other government sources: In-kind	$285,000	50%
Industry: Cash	$99,000	18%
Industry: In-kind	$36,000	6%
Total Project Cost	**$567,000**	**100%**

External resources (additional rows may be added if necessary)		
Government sources		
Name (no abbreviations unless stated in Section A3)	Amount cash	Amount in-kind
Agriculture and Agri-Food Canada	$0	$180,000
University of Alberta	$0	$105,000
Industry sources		
Name (no abbreviations unless stated in Section A3)	Amount cash	Amount in-kind
Dow AgroSciences Canada Inc.	$45,000	$30,000
BASF Canada	$30,000	$3,000
Valent Canada Inc.	$15,000	$1,500
NuFarm Agriculture Inc.	$9,000	$1,500

Section E: Research Team Signatures and Authorised Representative's Approval

By signing as an authorised representative of the Principal Investigator's employing organisation and/or the research team member's(s') employing organisation(s), the undersigned hereby acknowledge submission of the information contained in this final report to the funder(s).

Principal Investigator

Principal Investigator	
Name: **Dr. Robert Blackshaw**	**Title/Organisation:** **Agriculture and Agri-Food Canada**
Signature: R.E. Blackshaw	**Date:** March 22, 2016
Principal Investigator's Authorised Representative's Approval	
Name: **Dr. Francois Eudes**	**Title/Organisation:** **Agriculture and Agri-Food Canada**
Signature:	**Date:** March 22, 2016

Research Team Members (add more tables as needed)

1. Team Member	
Name: HUGH BECKIE	**Title/Organisation:** AAFC
Signature: [signature]	**Date:** Mar 23, 2016
Team Member's Authorised Representative's Approval	
Name: BRUCE MCARTHUR	**Title/Organisation:** AAFC, ACTING RDT DIRECTOR
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Appendix

A) **Kochia Seed Date Study**

Edmonton 2013

Seed date	Days from seeding to harvest	Biomass g/m^2	Seed number per m^2	Percent of earliest seed date	Germination %
May 2	182	1490	2,396,277	100	72
May 15	169	895	1,437,664	56	76
May 30	154	995	1,711,201	72	74
June 13	140	938	1,289,822	53	75
June 27	126	493	1,042,656	48	69
July 10	113	258	561,681	24	66
July 22	101	68	140,986	6	54

Kochia densities ranged from 75-150 plants m^{-2}.

Edmonton 2014

Seed date	Days from seeding to harvest	Biomass g/m^2	Seed number per m^2	Percent of earliest seed date	Germination %
April 9	173	1373	1,939,470	100	83
April 23	159	1368	2,212,192	112	78
May 7	145	1678	2,296,946	119	87
May 21	131	418	788,216	30	77
June 4	117	403	631,661	26	78
June 18	103	140	73,479	9	62
July 2	89	30	9,173	1	27
July 16	75	5	3,515	0	26

Kochia densities ranged from 75-150 plants m^{-2}.

Lethbridge 2014

Seed date	Days from seeding to harvest	Biomass g/m^2	Seed number per m^2	Percent of earliest seed date	Germination %
April 21	165	4608	4,012,360	100	89
May 9	147	4090	4,048,441	60	82
May 22	134	2413	2,965,202	59	88
June 6	119	2108	2,712,167	57	84
June 25	105	1800	1,971,347	19	85
July 10	97	473	640,564	6	78
July 23	93	185	259,241	2	43
August 6	86	120	0	0	0

Kochia densities ranged from 100-125 plants m^{-2}.

Lethbridge 2015

Seed date	Days from seeding to harvest	Biomass g/m^2	Seed number per m^2	Percent of earliest seed date	Germination %
April 9	182	8970	5,227,059	100	84
May 7	144	5223	3,681,304	71	79
May 26	128	5438	4,353,560	83	80
June 8	120	2763	2,835,058	54	83
June 22	107	2238	2,650,371	51	84
July 6	102	989	646,619	12	82
July 20	98	1127	655,975	13	65
August 4	83	368	26,676	1	49
August 17	70	119	0	0	0
September 1	58	18	0	0	0

Kochia densities ranged from 100-125 plants m^{-2}.

B) **Kochia Herbicide Studies**

Fallow – Lethbridge (2014)	Rate	Kochia control	
		GR	Gp2
Herbicide treatment	g ai/ha	---------%--------	
1. Untreated control	---	0	0
2. Glyphosate alone	450	0	95
3. Fluthiacet (Cadet)	8	55	95
4. Fluthiacet	10	60	95
5. 2,4-D ester	560	40	78
6. Carfentrazone (Aim)	18	85	100
7. Dicamba (Banvel)	290	63	98
8. Dicamba	580	80	99
9. Dicamba/diflufenzopyr (Distinct)	100	73	95
10. Dicamba/diflufenzopyr	200	85	95
11. Florasulam + dicamba	5 + 115	50	95
12. Flumioxazin (Valor) + 2,4-D ester	80 + 560	96	100
13. Saflufenacil (Heat)	18	90	100
14. Saflufenacil	50	100	100
15. Carfentrazone + sulfentrazone (Authority)	9 + 53	95	100
16. Carfentrazone + sulfentrazone	9 + 105	99	100
17. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	80	98
18. Fluroxypyr/bromoxynil/2,4-D ester (Enforcer D)	306	50	80

All treatments were tank-mixed with glyphosate applied at 450 g ai/ha. Herbicides were applied postemergence when kochia was 10-15 cm tall. Agsurf at 0.25% v/v was added to fluciacet. Merge at 1% v/v was added to carfentrazone, dicamba/diflufenzopyr, saflufenacil, and carfentrazone/sulfentrazone treatments.
In all tables, GR = glyphosate-resistant kochia; Gp2 = group 2 resistant kochia (but glyphosate-susceptible).

Note: The fallow experiment in 2013 was lost at both Lethbridge and Coalhurst due to early spring flooding and subsequent repeated hail storms.

<u>Fallow</u> – Coalhurst (2014)	Rate	Kochia control	
		GR	Gp2
Herbicide treatment	g ai/ha	---------%--------	
1. Untreated control	---	0	0
2. Glyphosate alone	450	0	99
3. Fluthiacet (Cadet)	8	90	99
4. Fluthiacet	10	85	99
5. 2,4-D ester	560	70	98
6. Carfentrazone (Aim)	18	90	99
7. Dicamba (Banvel)	290	94	99
8. Dicamba	580	98	99
9. Dicamba/diflufenzopyr (Distinct)	100	95	98
10. Dicamba/diflufenzopyr	200	98	99
11. Florasulam + dicamba	5 + 115	90	98
12. Flumioxazin (Valor) + 2,4-D ester	80 + 560	98	98
13. Saflufenacil (Heat)	18	99	99
14. Saflufenacil	50	95	99
15. Carfentrazone + sulfentrazone (Authority)	9 + 53	95	99
16. Carfentrazone + sulfentrazone	9 + 105	99	99
17. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	95	98
18. Fluroxypyr/bromoxynil/2,4-D ester (Enforcer D)	306	90	98

<u>All treatments were tank-mixed with glyphosate applied at 450 g ai/ha.</u> Herbicides were applied postemergence when kochia was 10 cm tall. Agsurf at 0.25% v/v was added to fluciacet. Merge at 1% v/v was added to carfentrazone, dicamba/diflufenzopyr, saflufenacil, and carfentrazone/sulfentrazone treatments.

<u>Fallow</u> – Lethbridge (2015)	Rate	Kochia control	
		GR	Gp2
Herbicide treatment	g ai/ha	---------%--------	
1. Untreated control	---	0	0
2. Glyphosate alone	450	0	92
3. Fluthiacet (Cadet)	8	50	91
4. Fluthiacet	10	50	91
5. 2,4-D ester	560	35	80
6. Carfentrazone (Aim)	18	70	92
7. Dicamba (Banvel)	290	77	95
8. Dicamba	580	90	100
9. Dicamba/diflufenzopyr (Distinct)	100	75	91
10. Dicamba/diflufenzopyr	200	87	95
11. Florasulam + dicamba	5 + 115	60	95
12. Flumioxazin (Valor) + 2,4-D ester	80 + 560	70	88
13. Saflufenacil (Heat)	18	70	90
14. Saflufenacil	50	80	93
15. Carfentrazone + sulfentrazone (Authority)	9 + 53	80	90
16. Carfentrazone + sulfentrazone	9 + 105	92	95
17. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	88	99
18. Fluroxypyr/bromoxynil/2,4-D ester (Enforcer D)	306	60	90
19. Bromoxynil + fluthiacet	280 + 8	63	78
20. Bromoxynil + fluthiacet	280 + 10	65	80

<u>All treatments were tank-mixed with glyphosate applied at 450 g ai/ha.</u> Herbicides were applied postemergence when kochia was 10-15 cm tall. Agsurf at 0.25% v/v was added to fluciacet. Merge at 1% v/v was added to carfentrazone, dicamba/diflufenzopyr, saflufenacil, and carfentrazone/sulfentrazone treatments.

<u>Fallow</u> – Coalhurst (2015)	Rate	Kochia control	
		GR	Gp2
Herbicide treatment	g ai/ha	---------%--------	
1. Untreated control	---	--	--
2. Glyphosate alone	450	8	88
3. Fluthiacet (Cadet)	8	75	95
4. Fluthiacet	10	75	95
5. 2,4-D ester	560	75	95
6. Carfentrazone (Aim)	18	90	96
7. Dicamba (Banvel)	290	93	97
8. Dicamba	580	95	97
9. Dicamba/diflufenzopyr (Distinct)	100	90	94
10. Dicamba/diflufenzopyr	200	92	95
11. Florasulam + dicamba	5 + 115	88	96
12. Flumioxazin (Valor) + 2,4-D ester	80 + 560	85	96
13. Saflufenacil (Heat)	18	90	95
14. Saflufenacil	50	91	96
15. Carfentrazone + sulfentrazone (Authority)	9 + 53	90	97
16. Carfentrazone + sulfentrazone	9 + 105	96	98
17. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	95	96
18. Fluroxypyr/bromoxynil/2,4-D ester (Enforcer D)	306	83	94
19. Bromoxynil + fluthiacet	280 + 8	89	92
20. Bromoxynil + fluthiacet	280 + 10	91	96

<u>All treatments were tank-mixed with glyphosate applied at 450 g ai/ha.</u> Herbicides were applied postemergence when kochia was 10-15 cm tall. Agsurf at 0.25% v/v was added to fluciacet. Merge at 1% v/v was added to carfentrazone, dicamba/diflufenzopyr, saflufenacil, and carfentrazone/sulfentrazone treatments.

<u>Spring wheat</u> – Lethbridge (2013)	Rate	Wheat injury	Kochia control	
			GR	Gp2
Herbicide treatment	g ai/ha	-- %--	--------%-------	
1. Untreated control	---	0	0	0
2. Dicamba + 2,4-D amine	110 + 420	0	79	75
3. Bromoxynil + 2,4-D ester (Thumper)	280 + 280	0	81	80
4. Fluroxypyr/2,4-D ester (OcTTain)	500	0	99	96
5. Florasulam/fluroxypyr + MCPA	102 + 350	0	90	86
6. Fluroxypyr + dicamba (Pulsar)	110 + 80	0	96	97
7. Fluroxypyr + clopyralid + MCPA (Prestige)	110 + 75 + 420	0	93	93
8. Fluroxypyr + bromoxynil + 2,4-D ester (Enforcer D)	306	0	95	96
9. Fluroxypyr + bromoxynil + 2,4-D ester (Enforcer D)	612	0	100	99
10. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	0	98	99
11. MCPA/mecoprop/dicamba (Target)	400	0	83	82
12. Pyrasulfotole/bromoxynil (Infinity)	200	0	90	88
13. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	412	0	86	86
14. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	545	0	96	95
15. Diclorprop/2,4-D (Estaprop XT)	1070	0	80	78

All herbicides were applied at the 4-5 leaf stage of wheat. Ammonium sulphate at 1% v/v was added to Infinity. <u>Wheat, field pea, and canola yield data is not available in 2013 due to repeated hail damage at both the Lethbridge and Coalhurst sites.</u>

<u>Spring wheat</u> – Coalhurst (2013) Herbicide treatment	Rate g ai/ha	Wheat injury -- %--	Kochia control GR	Kochia control Gr2
			-------%-------	
1. Untreated control	---	0	0	0
2. Dicamba + 2,4-D amine	110 + 420	2	78	80
3. Bromoxynil + 2,4-D ester (Thumper)	280 + 280	3	93	88
4. Fluroxypyr/2,4-D ester (OcTTain)	500	5	91	86
5. Florasulam/fluroxypyr + MCPA	102 + 350	0	90	87
6. Fluroxypyr + dicamba (Pulsar)	110 + 80	3	93	89
7. Fluroxypyr + clopyralid + MCPA (Prestige)	110 + 75 + 420	2	85	92
8. Fluroxypyr + bromoxynil + 2,4-D ester (Enforcer D)	306	3	83	87
9. Fluroxypyr + bromoxynil + 2,4-D ester (Enforcer D)	612	3	96	96
10. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	10	94	93
11. MCPA/mecoprop/dicamba (Target)	400	0	86	86
12. Pyrasulfotole/bromoxynil (Infinity)	200	0	96	96
13. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	412	7	90	92
14. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	545	6	95	93
15. Diclorprop/2,4-D (Estaprop XT)	1070	6	95	90

All herbicides were applied at the 4-5 leaf stage of wheat. Ammonium sulphate at 1% v/v was added to Infinity.

<u>Spring wheat</u> – Lethbridge (2014)	Rate	Wheat injury	Kochia control		Wheat yield	
			GR	Gp2	GR	Gp2
Herbicide treatment	g ai/ha	-- %--	-------%-------		------kg/ha-----	
1. Untreated control	---	0	0	0	4220a	4393a
2. Dicamba + 2,4-D amine	110 + 420	5	65	70	4208a	4285a
3. Bromoxynil + 2,4-D ester (Thumper)	280 + 280	0	65	65	4460a	4250a
4. Fluroxypyr/2,4-D ester (OcTTain)	500	0	80	85	4505a	4453a
5. Florasulam/fluroxypyr + MCPA	102 + 350	0	80	78	4220a	4540a
6. Fluroxypyr + dicamba (Pulsar)	110 + 80	5	85	85	4283a	4403a
7. Fluroxypyr + clopyralid + MCPA	110 + 75 + 420	0	75	75	4650a	4773a
8. Fluroxypyr + bromoxynil + 2,4-D ester	306	0	70	65	4463a	4185a
9. Fluroxypyr + bromoxynil + 2,4-D ester	612	5	90	93	4315a	4470a
10. MCPA/dichlorprop-p/mecoprop-p	1480	5	85	85	4580a	4585a
11. MCPA/mecoprop/dicamba (Target)	400	0	70	70	4435a	4693a
12. Pyrasulfotole/bromoxynil (Infinity)	200	0	95	95	4135a	4400a
13. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	412	5	75	80	4358a	4215a
14. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	545	8	85	95	4550a	4793a
15. Diclorprop/2,4-D (Estaprop XT)	1070	5	70	70	4505a	4168a
16. Fluroxypyr-methyl/Arylex + MCPA ester	82 + 350	0	75	80	4640a	4610a
17. Sulfentrazone (Authority) – Pre-emerge	105	5	98	99	4358a	4263a

All herbicides (except sulfentrazone) were applied at the 4-5 leaf stage of wheat. Ammonium sulphate at 1% v/v was added to Infinity. **In all Tables**, values within a column followed by the same letter are not significantly different according to the LSD test at the 5% significance level.

<u>Spring wheat</u> – Coalhurst (2014)	Rate	Wheat injury	Kochia control		Wheat yield	
			GR	Gp2	GR	Gp2
Herbicide treatment	g ai/ha	-- %--	-------%-------		-------kg/ha------	
1. Untreated control	---	0	0	0	3110a	2770a
2. Dicamba + 2,4-D amine	110 + 420	5	85	90	3260a	3030a
3. Bromoxynil + 2,4-D ester (Thumper)	280 + 280	0	80	85	3240a	3320a
4. Fluroxypyr/2,4-D ester (OcTTain)	500	0	90	90	2960a	2670a
5. Florasulam/fluroxypyr + MCPA	102 + 350	0	88	90	2990a	2890a
6. Fluroxypyr + dicamba (Pulsar)	110 + 80	10	90	90	3240a	3130a
7. Fluroxypyr + clopyralid + MCPA	110 + 75 + 420	0	85	90	3050a	2850a
8. Fluroxypyr + bromoxynil + 2,4-D ester	306	0	90	95	3220a	2940a
9. Fluroxypyr + bromoxynil + 2,4-D ester	612	0	94	93	2980a	2960a
10. MCPA/dichlorprop-p/mecoprop-p	1480	5	90	95	3140a	2650a
11. MCPA/mecoprop/dicamba (Target)	400	5	78	90	3250a	2610a
12. Pyrasulfotole/bromoxynil (Infinity)	200	0	95	94	3030a	2720a
13. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	412	10	90	90	3550a	2990a
14. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	545	15	85	93	3140a	2770a
15. Diclorprop/2,4-D (Estaprop XT)	1070	0	90	85	3270a	2740a
16. Fluroxypyr-methyl/Arylex	82 + 350	0	84	88	3240a	2970a
17. Sulfentrazone (Authority) – Pre-emerge	105	0	95	95	3310a	3210a

All herbicides (except sulfentrazone) were applied at the 4-5 leaf stage of wheat. Ammonium sulphateat 1% v/v was added to Infinity.

Spring wheat – Lethbridge (2015)

Herbicide treatment	Rate	Wheat injury	Kochia control		Wheat yield	
			GR	Gp2	GR	Gp2
	g ai/ha	-- %--	------%-------		---------kg/ha-------	
1. Untreated control	---	0	0	0	4130a	4270a
2. Dicamba + 2,4-D amine	110 + 420	8	68	70	4390a	4330a
3. Bromoxynil + 2,4-D ester (Thumper)	280 + 280	0	70	70	4210a	4310a
4. Fluroxypyr/2,4-D ester (OcTTain)	500	0	75	80	4680a	4640a
5. Florasulam/fluroxypyr + MCPA	102 + 350	0	80	77	4370a	4450a
6. Fluroxypyr + dicamba (Pulsar)	184	5	85	90	4320a	4240a
7. Fluroxypyr + clopyralid/MCPA (Prestige)	100 + 495	0	75	80	4390a	4200a
8. Fluroxypyr + bromoxynil + 2,4-D ester	306	0	75	70	4540a	4520a
9. Fluroxypyr + bromoxynil + 2,4-D ester	612	3	96	93	4880a	4460a
10. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	10	90	90	4370a	4250a
11. MCPA/mecoprop/dicamba (Target)	400	0	73	70	4390a	4600a
12. Pyrasulfotole/bromoxynil (Infinity)	200	0	93	90	4590a	4480a
13. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	412	5	77	80	4530a	4820a
14. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	545	10	90	90	4530a	4270a
15. Diclorprop/2,4-D (Estaprop XT)	1070	5	70	70	4880a	4530a
16. Fluroxypyr-methyl/Arylex + MCPA ester	82 + 350	0	70	75	4450a	4770a
17. Sulfentrazone (Authority) – Pre-emerge	105	0	99	100	4490a	4760a
18. Fluroxypyr-methyl/Arylex + MCPA ester	107 + 455	0	82	80	4810a	4710a
19. Fluthiacet + bromoxynil	6 + 280	3	90	93	4810a	4800a
20. Dicamba (Banvel II)	300	10	83	85	4730a	4510a
21. Dicamba	600	20	91	96	3640a	3830a

All herbicides (except sulfentrazone) were applied at the 4-5 leaf stage of wheat. Ammonium sulphate at 1% v/v was added to Infinity.

<u>Spring wheat</u> – Edmonton (2015)	Rate	Wheat injury	Kochia control	Wheat yield
Herbicide treatment	g ai/ha	---%---	---%---	Kg/ha
1. Untreated control	---	0	0	5000a
2. Dicamba + 2,4-D amine	110 + 420	5	75	5334a
3. Bromoxynil + 2,4-D ester (Thumper)	280 + 280	0	63	5020a
4. Fluroxypyr/2,4-D ester (OcTTain)	500	0	60	4890a
5. Florasulam/fluroxypyr + MCPA	102 + 350	3	60	5020a
6. Fluroxypyr + dicamba (Pulsar)	184	5	80	4880a
7. Fluroxypyr + clopyralid/MCPA (Prestige)	100 + 495	0	75	5320a
8. Fluroxypyr + bromoxynil + 2,4-D ester (Enforcer D)	306	3	80	5110a
9. Fluroxypyr + bromoxynil + 2,4-D ester (Enforcer D)	612	5	88	5420a
10. MCPA/dichlorprop-p/mecoprop-p (Optica Trio)	1480	3	83	4750a
11. MCPA/mecoprop/dicamba (Target)	400	4	78	5110a
12. Pyrasulfotole/bromoxynil (Infinity)	200	3	83	4910a
13. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	412	8	78	5260a
14. Dicamba/2,4-D/mecoprop (Dyvel Dsp)	545	5	75	5080a
15. Diclorprop/2,4-D (Estaprop XT)	1070	0	45	5240a
16. Fluroxypyr-methyl/Arylex (Pixxaro) + MCPA ester	82 + 350	0	60	5170a
17. Sulfentrazone (Authority) – Pre-emerge	105	0	75	5570a
18. Fluroxypyr-methyl/Arylex + MCPA ester	107 + 455	0	80	5460a
19. Fluthiacet + bromoxynil	6 + 280	3	25	5080a
20. Dicamba (Banvel II)	300	11	65	4490a
21. Dicamba	600	20	75	4690a

All herbicides (except sulfentrazone) were applied at the 4-5 leaf stage of wheat. Ammonium sulphate at 1% v/v was added to Infinity.

Kochia was glyphosate-susceptible (but Group 2 resistant) at the Edmonton site.

<u>Field peas</u> – Lethbridge (2013)			Rate	Pea injury	Kochia control	
Herbicide treatment		Timing	g ai/ha	--%--	GR	Gp2
					-------%------	
1.	Untreated control	---	---	0	0	0
2.	Ethalfluralin (Edge)	Preplant	850	0	65	65
3.	Propyzamide (Kerb)	Preplant	450	0	30	30
4.	Ethalfluralin + propyzamide	Preplant	850 + 225	0	60	65
5.	Ethalfluralin + propyzamide	Preplant	850 + 450	0	73	75
6.	Carfentrazone + propyzamide	Preplant	9 + 450	0	40	40
7.	Carfentrazone + sulfentrazone	Preplant	9 + 105	0	100	100
8.	Pyroxasulfone (Focus)	Preplant	125	10	73	65
9.	Flumioxazin (Valor)	Preplant	80	16	90	90
10.	Ethalfluralin + imazamox/bentazon	Preplant, post	850 + 440	14	90	88
11.	Saflufenacil + imazamox/bentazon	Preplant, post	50 + 440	20	99	100
12.	Fluthiacet (Cadet)	Post	4	10	90	90
13.	Imazamox/bentazon (Viper ADV)	Post	440	15	92	95
14.	Imazamox/bentazon + fluthiacet	Post	440 + 4	16	98	100
15.	MCPA sodium salt	Post	270	10	25	20

All postemergence treatments were applied at the 3-6 node stage of field pea.
Merge at 1% v/v was added to carfentrazone (Aim) and saflufenacil (Heat). BASF UAN (28-0-0) at 2% v/v was added to Viper ADV. AgSurf non-ionic surfactant at 0.25% v/v was added to fluthiacet. Sulfentrazone = Authority.

<u>Field peas</u> – Coalhurst (2013)			Rate	Pea injury	Kochia control	
Herbicide treatment		Timing	g ai/ha	--%--	GR	Gp2
					-------%------	
1.	Untreated control	---	---	0	0	0
2.	Ethalfluralin (Edge)	Preplant	850	3	78	63
3.	Propyzamide (Kerb)	Preplant	450	0	69	80
4.	Ethalfluralin + propyzamide	Preplant	850 + 225	3	59	74
5.	Ethalfluralin + propyzamide	Preplant	850 + 450	3	75	72
6.	Carfentrazone + propyzamide	Preplant	9 + 450	2	73	70
7.	Carfentrazone + sulfentrazone	Preplant	9 + 105	3	75	90
8.	Pyroxasulfone (Focus)	Preplant	125	3	85	80
9.	Flumioxazin (Valor)	Preplant	80	2	78	88
10.	Ethalfluralin + imazamox/bentazon	Preplant, post	850 + 440	1	93	95
11.	Saflufenacil + imazamox/bentazon	Preplant, post	50 + 440	2	86	92
12.	Fluthiacet (Cadet)	Post	4	1	91	92
13.	Imazamox/bentazon (Viper ADV)	Post	440	3	82	83
14.	Imazamox/bentazon + fluthiacet	Post	440 + 4	3	91	91
15.	MCPA sodium salt	Post	270	3	69	74

All postemergence treatments were applied at the 3-6 node stage of field pea.
Merge at 1% v/v was added to carfentrazone (Aim) and saflufenacil (Heat). BASF UAN (28-0-0) at 2% v/v was added to Viper ADV. AgSurf non-ionic surfactant at 0.25% v/v was added to fluthiacet.

Field peas – Lethbridge (2014)

Herbicide treatment	Timing	Rate g ai/ha	Pea injury --%--	Kochia control GR	Kochia control Gp2	Pea yield GR	Pea yield Gp2
				-------%------		-------kg/ha------	
1. Untreated control	---	---	0	0	0	3610b	3703a
2. Ethalfluralin (Edge)	Fall	1100	0	50	45	3568b	3733a
3. Propyzamide (Kerb)	Fall	900	0	20	25	3660b	3878a
4. Pyroxasulfone (Focus)	Fall	125	0	60	55	4258ab	4120a
5. Flumioxazin (Valor)	Fall	80	0	35	40	3525b	3383a
6. Flumioxazin	Fall	125	0	45	57	3758b	3858a
7. Ethalfluralin + propyzamide	Fall	1100 + 900	0	55	50	3990ab	4063a
8. Ethalfluralin + pyroxasulfone	Fall	1100 + 125	0	80	79	4273ab	3840a
9. Ethalfluralin + flumioxazin	Fall	1100 + 80	0	60	65	3915ab	3950a
10. Ethalfluralin + imazamox/bentazon	Fall, Post	1100 + 440	0	93	95	4268ab	3608a
11. Carfentrazone + sulfentrazone	Preplant	9 + 105	0	100	100	5103a	4180a
12. Saflufenacil + imazamox/bentazon	Preplant, Post	50 + 440	0	98	100	4410ab	4363a
13. Fluthiacet (Cadet)	Post	6	10	87	85	4480ab	3923a
14. Imazamox/bentazon (Viper ADV)	Post	440	0	93	95	4415ab	4103a
15. Imazamox/bentazon + fluthiacet	Post	440 + 6	10	95	96	4520ab	3698a

All postemergence treatments were applied at the 3-6 node stage of field pea.
Merge at 1% v/v was added to carfentrazone (Aim) and saflufenacil (Heat). BASF UAN (28-0-0) at 2% v/v was added to Viper ADV.
AgSurf non-ionic surfactant at 0.25% v/v was added to fluthiacet.

Field peas – Coalhurst (2014)

Herbicide treatment	Timing	Rate g ai/ha	Pea injury --%--	Kochia control GR	Kochia control Gp2	Pea yield GR	Pea yield Gp2
				-------%------		-------kg/ha------	
1. Untreated control	---	---	0	0	0	3690a	3260a
2. Ethalfluralin (Edge)	Fall	1100	0	65	55	3360a	3990a
3. Propyzamide (Kerb)	Fall	900	0	40	40	3220a	3770a
4. Pyroxasulfone (Focus)	Fall	125	0	50	60	4110a	3590a
5. Flumioxazin (Valor)	Fall	80	0	20	15	2600a	2860a
6. Flumioxazin	Fall	125	0	35	60	3510a	3320a
7. Ethalfluralin + propyzamide	Fall	1100 + 900	0	35	50	3070a	3110a
8. Ethalfluralin + pyroxasulfone	Fall	1100 + 125	0	75	76	3960a	4080a
9. Ethalfluralin + flumioxazin	Fall	1100 + 80	0	60	50	3540a	3800a
10. Ethalfluralin + imazamox/bentazon	Fall, Post	1100 + 440	0	65	70	3800a	3630a
11. Carfentrazone + sulfentrazone	Preplant	9 + 105	0	85	90	3870a	3520a
12. Saflufenacil + imazamox/bentazon	Preplant, Post	50 + 440	0	82	85	3360a	3780a
13. Fluthiacet (Cadet)	Post	6	5	82	80	2740a	2830a
14. Imazamox/bentazon (Viper ADV)	Post	440	0	85	80	3200a	3600a
15. Imazamox/bentazon + fluthiacet	Post	440 + 6	5	80	80	3400a	3220a

All postemergence treatments were applied at the 3-6 node stage of field pea.
Merge at 1% v/v was added to carfentrazone (Aim) and saflufenacil (Heat). BASF UAN (28-0-0) at 2% v/v was added to Viper ADV.
AgSurf non-ionic surfactant at 0.25% v/v was added to fluthiacet.

<u>Field peas</u> – Lethbridge (2015)		Rate	Pea injury	Kochia control		Pea yield	
Herbicide treatment	Timing	g ai/ha	--%--	GR	Gp2	GR	Gp2
				-------%------		-------kg/ha------	
1. Untreated control	---	---	0	0	0	5130abc	5060abc
2. Ethalfluralin (Edge)	Fall	1100	0	55	55	4560abc	5420abc
3. Propyzamide (Kerb)	Fall	900	0	10	5	4460abc	5210abc
4. Pyroxasulfone (Focus)	Fall	125	0	68	67	5740ab	6580a
5. Flumioxazin (Valor)	Fall	80	0	25	15	5280abc	5110abc
6. Flumioxazin	Fall	125	0	45	50	6310a	6610ab
7. Ethalfluralin + propyzamide	Fall	1100 + 900	0	65	60	5870ab	5740abc
8. Ethalfluralin + pyroxasulfone	Fall	1100 + 125	0	80	84	6310a	5990ab
9. Ethalfluralin + flumioxazin	Fall	1100 + 80	0	65	78	4930abc	4120bc
10. Ethalfluralin + imazamox/bentazon	Fall, Post	1100 + 440	2	85	88	5690ab	5580abc
11. Carfentrazone + sulfentrazone	Preplant	9 + 105	0	100	99	6290a	6520ab
12. Saflufenacil + imazamox/bentazon	Preplant, Post	50 + 440	2	95	95	5650ab	6040ab
13. Fluthiacet (Cadet)	Post	6	8	88	90	5970a	5460abc
14. Imazamox/bentazon (Viper ADV)	Post	440	5	78	75	5100abc	5690abc
15. Imazamox/bentazon + fluthiacet	Post	440 + 6	6	92	90	5450ab	5950ab
16. Metribuzin (Sencor)	Post	280	5	70	70	5640ab	5880ab
17. Metribuzin	Post	560	15	90	94	3740bc	4060bc
18. Flumioxazin	Post	70	0	60	55	3400c	3350c

All postemergence treatments were applied at the 3-6 node stage of field pea.
Merge at 1% v/v was added to carfentrazone (Aim) and saflufenacil (Heat). BASF UAN (28-0-0) at 2% v/v was added to Viper ADV.
AgSurf non-ionic surfactant at 0.25% v/v was added to fluthiacet. Sulfentrazone = Authority.

Field peas – Edmonton (2015) Herbicide treatment	Timing	Rate g ai/ha	Pea injury --%--	Kochia control ---%---	Pea yield --kg/ha--
1. Untreated control	---	---	0	0	5750ab
2. Ethalfluralin (Edge)	Fall	1390	0	35	6110ab
3. Propyzamide (Kerb)	Fall	900	0	15	6010ab
4. Pyroxasulfone (Zidua)	Fall	125	0	30	5670ab
5. Flumioxazin (Valor)	Fall	80	0	15	4940ab
6. Flumioxazin	Fall	125	0	25	4340b
7. Ethalfluralin + propyzamide	Fall	1390 + 900	0	35	7280ab
8. Ethalfluralin + pyroxasulfone	Fall	1390 + 125	0	70	6550ab
9. Ethalfluralin + flumioxazin	Fall	1390 + 80	0	25	7070ab
10. Ethalfluralin + imazamox/bentazon	Fall, Post	1390 + 440	0	80	7660a
11. Carfentrazone + sulfentrazone	Preplant	9 + 105	0	20	5240ab
12. Saflufenacil + imazamox/bentazon	Preplant, Post	50 + 440	0	96	6340ab
13. Fluthiacet (Cadet)	Post	6	0	75	5770ab
14. Imazamox/bentazon (Viper ADV)	Post	440	0	94	7350ab
15. Imazamox/bentazon + fluthiacet	Post	440 + 6	0	99	7270ab
16. Metribuzin (Sencor)	Post	280	0	85	6880ab
17. Metribuzin	Post	560	0	90	5290ab
18. Flumioxazin	Post	70	0	60	6260ab

All postemergence treatments were applied at the 3-6 node stage of field pea.
Merge at 1% v/v was added to carfentrazone (Cleanstart) and saflufenacil (Heat). BASF UAN (28-0-0) at 2% v/v was added to Viper ADV. AgSurf non-ionic surfactant at 0.25% v/v was added to fluthiacet. Sulfentrazone = Authority.
Kochia was ghyphosate-susceptible (but Group 2 resistant) at the Edmonton site.

<u>Liberty Link Canola</u> – Lethbridge (2013) Herbicide treatment		Timing	Rate g ai/ha	Canola injury ----%----	Kochia control GR	 Gp2
					-------%-------	
1.	Untreated control	---	---	0	0	0
2.	Ethalfluralin (Edge)	Preplant	850	0	56	60
3.	Ethalfluralin	Preplant	1100	0	70	68
4.	Ethalfluralin + glufosinate	Preplant, Post (2-3 1f)	850 + 500	0	88	90
5.	Ethalfluralin + carfentrazone	Preplant, Post (5-6 1f)	850 + 18	60	93	91
6.	Carfentrazone + sulfentrazone	Preemerge	9 + 53	18	91	93
7.	Carfentrazone + sulfentrazone	Preemerge	9 + 105	58	100	100
8.	Carfentrazone + sulfentrazone + glufosinate	Preemerge Post (2-3 1f)	9 + 105 500	55	100	100
9.	Glufosinate	Post (2-3 1f)	500	0	85	85
10.	Glufosinate	Post (2-3 1f)	590	0	88	89
11.	Glufosinate + glufosinate	Post (2-3 + 5-6 1f)	500 + 500	0	96	95
12.	Carfentrazone	Post (5-6 1f)	18	56	84	88

Merge adjuvant at 1% v/v was added to all carfentrazone treatments. Glufosinate = Liberty; Carfentrazone = Aim; Sulfentrazone = Authority.

<u>Liberty Link Canola</u> – Coalhurst (2013)		Rate	Canola injury	Kochia control	
Herbicide treatment	Timing	g ai/ha	----%----	GR	Gp2
				------%------	
1. Untreated control	---	---	0	0	0
2. Ethalfluralin (Edge)	Preplant	850	0	70	70
3. Ethalfluralin	Preplant	1100	3	61	65
4. Ethalfluralin + glufosinate	Preplant, Post (2-3 1f)	850 + 500	0	59	64
5. Ethalfluralin + carfentrazone	Preplant, Post (5-6 1f)	850 + 18	15	88	94
6. Carfentrazone + sulfentrazone	Preemerge	9 + 53	0	85	75
7. Carfentrazone + sulfentrazone	Preemerge	9 + 105	5	90	91
8. Carfentrazone + sulfentrazone +	Preemerge	9 + 105	3	96	97
glufosinate	Post (2-3 1f)	500			
9. Glufosinate	Post (2-3 1f)	500	4	97	97
10. Glufosinate	Post (2-3 1f)	590	1	94	80
11. Glufosinate + glufosinate	Post (2-3 + 5-6 1f)	500 + 500	0	97	97
12. Carfentrazone	Post (5-6 1f)	18	14	80	85

Merge adjuvant at 1% v/v was added to all carfentrazone treatments. Glufosinate = Liberty; Carfentrazone = Aim; Sulfentrazone = Authority.

<u>Liberty Link Canola</u> – Lethbridge (2014)		Rate	Canola injury	Kochia control		Canola yield	
Herbicide treatment	Timing	g ai/ha	----%----	GR	Gp2	GR	Gp2
				-------%-------		--------kg/ha--------	
1. Untreated control	---	---	0	0	0	3550a	3585a
2. Ethalfluralin (Edge)	Fall	1100	0	50	55	3933a	3618a
3. Ethalfluralin + carfentrazone + glufosinate	Fall, Preemerge Post (2-3 1f)	1100 + 9 500	0	95	95	3865a	3598a
4. Ethalfluralin + sulfentrazone	Fall, Preemerge	1100 + 27	0	92	93	3640a	3560a
5. Ethalfluralin + glufosinate	Fall, Post (2-3 1f)	1100 + 500	0	92	90	3515a	3818a
6. Carfentrazone + sulfentrazone	Preemerge	9 + 27	5	93	95	3930a	3773a
7. Carfentrazone + sulfentrazone	Preemerge	9 + 53	20	100	100	3873a	3800a
8. Carfentrazone + sulfentrazone + glufosinate	Preemerge Post (2-3 1f)	9 + 27 500	7	98	99	3878a	3750a
9. Glufosinate	Post (2-3 1f)	500	0	88	90	3738a	3770a
10. Glufosinate	Post (2-3 1f)	590	0	93	94	3950a	3880a
11. Glufosinate + glufosinate	Post (2-3 + 5-6 1f)	500 + 500	0	100	99	3943a	3543a

Merge adjuvant at 1% v/v was added to all carfentrazone (Aim) treatments. Glufosinate = Liberty; Sulfentrazone = Authority.

<u>Liberty Link Canola</u> – Coalhurst (2014)		Rate	Canola injury	Kochia control		Canola yield	
Herbicide treatment	Timing	g ai/ha	----%----	GR	Gp2	GR	Gp2
				-----------%----------		-----------kg/ha-----------	
1. Untreated control	---	---	0	0	0	1190a	1750a
2. Ethalfluralin (Edge)	Fall	1100	0	30	25	1680a	2310a
3. Ethalfluralin + carfentrazone + glufosinate	Fall, Preemerge Post (2-3 1f)	1100 + 9 500	5	95	94	1850a	2040a
4. Ethalfluralin + sulfentrazone	Fall, Preemerge	1100 + 27	0	60	40	1720a	1860a
5. Ethalfluralin + glufosinate	Fall, Post (2-3 1f)	1100 + 500	0	95	90	1780a	2020a
6. Carfentrazone + sulfentrazone	Preemerge	9 + 27	5	50	35	1520a	1810a
7. Carfentrazone + sulfentrazone	Preemerge	9 + 53	5	75	80	1120a	1230a
8. Carfentrazone + sulfentrazone + glufosinate	Preemerge Post (2-3 1f)	9 + 27 500	10	95	95	1720a	1760a
9. Glufosinate	Post (2-3 1f)	500	5	95	94	1780a	1450a
10. Glufosinate	Post (2-3 1f)	590	5	95	94	1760a	1860a
11. Glufosinate + glufosinate	Post (2-3 + 5-6 1f)	500 + 500	5	95	99	1920a	2070a

Merge adjuvant at 1% v/v was added to all carfentrazone (Aim) treatments. Glufosinate = Liberty; Sulfentrazone = Authority.

Liberty Link Canola – **Lethbridge (2015)**		Rate	Canola injury	Kochia control		Canola yield	
Herbicide treatment	Timing	g ai/ha	----%----	GR	Gp2	GR	Gp2
				-----------%----------		--------kg/ha--------	
1. Untreated control	---	---	0	0	0	1080c	1510c
2. Ethalfluralin (Edge)	Fall	1100	0	45	40	1290c	1930c
3. Ethalfluralin + carfentrazone + glufosinate	Fall, Preemerge Post (2-3 1f)	1100 + 9 500	0	90	90	3200a	3310ab
4. Ethalfluralin + sulfentrazone	Fall, Preemerge	1100 + 27	0	93	88	2760ab	3040ab
5. Ethalfluralin + glufosinate	Fall, Post (2-3 1f)	1100 + 500	0	86	88	3130a	3290ab
6. Carfentrazone + sulfentrazone	Preemerge	9 + 27	8	85	85	2260b	2670b
7. Carfentrazone + sulfentrazone	Preemerge	9 + 53	25	100	98	2790ab	2670b
8. Carfentrazone + sulfentrazone + glufosinate	Preemerge Post (2-3 1f)	9 + 27 500	10	100	98	2880ab	3090ab
9. Glufosinate	Post (2-3 1f)	500	0	82	83	3050a	3210ab
10. Glufosinate	Post (2-3 1f)	590	0	87	90	3190a	2970ab
11. Glufosinate + glufosinate	Post (2-3 + 5-6 1f)	500 + 500	0	94	96	3510a	3740a

Merge adjuvant at 1% v/v was added to all carfentrazone (Aim) treatments. Glufosinate = Liberty; sulfentrazone = Authority.

<u>Liberty Link Canola</u> – Edmonton (2015) Herbicide treatment		Timing	Rate g ai/ha	Canola injury ----%----	Kochia control -----%-----
1.	Untreated control	---	---	0	0
2.	Ethalfluralin (Edge)	Fall	1390	0	40
3.	Ethalfluralin + carfentrazone + glufosinate	Fall, Preemerge Post (2-3 1f)	1390 + 9 500	0	99
4.	Ethalfluralin + sulfentrazone	Fall, Preemerge	1390 + 27	0	50
5.	Ethalfluralin + glufosinate	Fall, Post (2-3 1f)	1390 + 500	0	100
6.	Carfentrazone + sulfentrazone	Preemerge	9 + 27	0	55
7.	Carfentrazone + sulfentrazone	Preemerge	9 + 53	0	70
8.	Carfentrazone + sulfentrazone + glufosinate	Preemerge Post (2-3 1f)	9 + 27 500	0	95
9.	Glufosinate	Post (2-3 1f)	500	0	99
10.	Glufosinate	Post (2-3 1f)	590	0	97
11.	Glufosinate + glufosinate	Post (2-3 + 5-6 1f)	500 + 500	0	100

Merge adjuvant at 1% v/v was added to all carfentrazone (Aim) treatments. Glufosinate = Liberty; sulfentrazone = Authority. Kochia was glyphosate-susceptible (but Group 2 resistant) at the Edmonton site. Extreme drought prevented collecting canola yield at Edmonton in 2015.

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Glyphosate- and Acetolactate Synthase Inhibitor–Resistant Kochia (*Kochia scoparia*) in Western Canada

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In summer, 2011, we investigated suspected glyphosate-resistant (GR) kochia in three chem-fallow fields (designated F1, F2, F3, each farmed by a different grower) in southern Alberta. This study characterizes glyphosate resistance in those populations, based on data from dose–response experiments. In a greenhouse experiment, the three populations exhibited a resistance factor ranging from 4 to 6 based on shoot biomass response (GR_{50} ratios), or 5 to 7 based on survival response (LD_{50} ratios). Similar results were found in a field dose–response experiment at Lethbridge, AB, in spring 2012 using the F2 kochia population. In fall 2011, we surveyed 46 fields within a 20-km radius of the three chem-fallow fields for GR kochia. In the greenhouse, populations were screened with glyphosate at 900 g ae ha^{-1}. Seven populations were confirmed as GR, the farthest site located about 13 km from the three originally confirmed populations. An additional GR population more than 100 km away was later confirmed. Populations were screened for acetolactate synthase (ALS)–inhibitor (thifensulfuron : tribenuron) and dicamba resistance in the greenhouse, with molecular characterization of ALS-inhibitor resistance in the F1, F2, and F3 populations. All GR populations were resistant to the ALS-inhibiting herbicide, but susceptible to dicamba. ALS-inhibitor resistance in kochia was conferred by Pro_{197}, Asp_{376}, or Trp_{574} amino acid substitutions. Based upon a simple empirical model with a parameter for selection pressure, calculated from weed relative abundance and glyphosate efficacy, and a parameter for seedbank longevity, kochia, wild oat, and green foxtail were the top three weeds, respectively, predicted at risk of selection for glyphosate resistance in the semiarid Grassland region of the Canadian prairies; wild oat, green foxtail, and cleavers species were predicted at greatest risk in the subhumid Parkland region. This study confirms the first occurrence of a GR weed in western Canada. Future research on GR kochia will include monitoring, biology and ecology, fitness, mechanism of resistance, and best management practices.

Nomenclature: Dicamba; glyphosate; thifensulfuron; tribenuron; cleavers: false cleavers, *Galium spurium* L. or catchweed bedstraw, *Galium aparine* L.; green foxtail, *Setaria viridis* (L.) Beauv.; kochia, *Kochia scoparia* (L.) Schrad. KCHSC, synonym: *Bassia scoparia* (L.) A.J. Scott.; wild oat, *Avena fatua* L.

Key words: ALS-inhibitor resistance, glyphosate resistance, herbicide resistance, multiple resistance, target-site mutation.

Kochia is an annual broadleaf weed species native to Eurasia, and introduced as an ornamental to the Americas in the mid- to late 1800s (reviewed in Friesen et al. 2009). This naturalized species is a common and economically important weed in crop production systems and ruderal (noncrop disturbed) areas in semiarid to arid regions of North America. It is one of the top 10 most abundant agricultural weeds in the Canadian prairies (Leeson et al. 2005). Kochia is reported to have the highest rate of spread among 40 alien weed species in the northwestern United States (Forcella 1985), and has expanded northward in the Canadian prairies during the past 40 yr (Beckie et al. 2012; Thomas and Leeson 2007). Kochia, a C_4 species, is highly competitive in cropping systems because of its ability to germinate at low soil temperatures and emerge early; grow rapidly; tolerate heat, drought, and salinity; and exert allelopathic effects on neighboring species (Friesen et al. 2009).

In cereal or pulse (annual legume) crops in western Canada, ALS-inhibiting herbicides or synthetic auxins (e.g., dicamba) are commonly used to control kochia (Saskatchewan Ministry of Agriculture 2012). ALS-inhibitor herbicide-resistant (HR) populations of the species were first reported in the United States in 1987 (Primiani et al. 1990; Saari et al. 1990; Thompson et al. 1994), and in Canada (prairies) in 1988 (Morrison and Devine 1994). Target-site mutations at Pro_{197} with Thr, Ser, Arg, Leu, Glu, and Ala substitutions were reported for chlorsulfuron-HR kochia populations from Kansas (Guttieri et al. 1992, 1995). A Trp_{574}Leu mutation of the *ALS* gene was identified in ALS-inhibitor–HR populations from Illinois (Foes et al. 1999) and the Czech Republic (Salava et al. 2004). A field survey in Manitoba, Canada, in 2004 found widespread, broad cross-resistance (across ALS-inhibitor classes) in 102 of 114 kochia populations collected (B. Murray and L. Friesen, unpublished data). The broad cross-resistance in those populations suggested a target mutation, such as Trp_{574}Leu, which imparts plants with high-level, broad-spectrum resistance (Beckie and Tardif 2012).

The molecular basis for ALS-inhibitor resistance was determined for 24 HR kochia populations from western Canada (Warwick et al. 2008). *ALS* gene sequences revealed three target-site mutations (Pro_{197}, Asp_{376}, and Trp_{574}). The Trp_{574}Leu mutation was found in 70% of plants, whereas the remaining plants had the highly variable residue Pro_{197}, with substitution by one of nine amino acids, or Asp_{376}Glu and Trp_{574}Arg substitutions. This study also reported the first field-selected presence of two *ALS* target-site mutations in individual kochia plants. These included combinations Pro_{197} + Trp_{574} (23 HR plants) and Pro_{197} + Asp_{376} (7 HR plants). Kochia is predominantly selfed but capable of outcrossing, with pollen-mediated gene flow documented to a distance of 29 m (Stallings et al. 1995). The detection of Pro_{197}, Asp_{376},

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and Trp_{574} mutations, as well as both combinations, from geographically separate regions suggested multiple origins of these mutations. A more recent survey of 109 fields was conducted across western Canada to determine the extent of ALS-inhibitor and dicamba resistance in kochia (Beckie et al. 2009, 2011b). All kochia populations were susceptible to dicamba. ALS-inhibitor–HR kochia was found in 85% of the fields surveyed in western Canada. *ALS* sequence data (Pro_{197} and Asp_{376} mutations) and genotyping data (Trp_{574} mutation) confirmed the presence of all three target-site mutations as well as two mutational combinations (Pro_{197} + Trp_{574}, Asp_{376} + Trp_{574}) in HR individuals.

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 GR crops beginning in 1996, glyphosate usage increased markedly (Beckie et al. 2011a). In 2011 in Canada, GR canola (*Brassica napus* L.), soybean [*Glycine max* (L.) Merr.], and corn (*Zea mays* L.) comprised 47, 72, and 90% of the respective crop area (R. Ripley, B. Senft, M. Reidy, 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, GDD). In Canada, the first report of a GR weed was giant ragweed (*Ambrosia trifida* L.) in 2008 in GR soybean in eastern Canada (southwestern Ontario); a survey conducted in 2009 and 2010 documented the HR biotype in 47 new locations in three counties in the province (Vink et al. 2012). In 2010, GR horseweed (referred as Canada fleabane in Canada; *Conzya canadensis* Cronq.) was documented in the same region (Sikkema et al. 2013).

Worldwide, GR kochia was first reported in Kansas in 2007, followed by South Dakota in 2009, and Nebraska in 2011; these HR populations were selected primarily in GR corn and soybean fields (Heap 2012). In August 2011, we investigated suspected GR kochia in three chem-fallow fields (each farmed by a different grower) in southern Alberta. This study characterizes glyphosate resistance in those populations, based on data from dose–response experiments. We also describe the results of a GR kochia survey comprising 46 fields within a 20-km radius of those three chem-fallow fields, which was conducted in the fall of 2011. Confirmed GR kochia populations were screened for ALS-inhibitor and dicamba resistance in the greenhouse, with molecular characterization of ALS-inhibitor resistance in populations in the three chem-fallow fields. Looking ahead, we estimate the GR risk for the most abundant weed species in the semiarid Grassland and subhumid Parkland regions of the Canadian prairies (Agriculture and Agri-Food Canada 2003) using a simple empirical model.

Materials and Methods

Plant Material. In August 2011, 15 kochia plants (vegetative stage) were randomly selected throughout each of three chem-fallow fields (surveyed using a ''W'' pattern; fields labeled F1, F2, F3), which were located within 3.5 km of each other in the County of Warner in southern Alberta. The no-till cropping systems used in the fields were wheat (*Triticum aestivum* L.) or mustard [*Sinapis alba* L. or *Brassica juncea* (L.) Czern.] alternating with chem-fallow. For the latter, glyphosate (alone) was applied periodically over the 2011 growing season at 1.5 to two times the recommended (1×) rate (450 g ae ha^{-1}). GR crops had not been grown in the three fields. Plants were transplanted into 10-L pots, watered, and transported to Saskatoon, SK. In the greenhouse, plants were covered with pollen bags (Chantler Packaging, Mississauga, ON) and grown to maturity, at which time the selfed seeds were harvested over a 3-wk period. For the dose–response experiments, seeds from each plant collected in a field were combined into a composite sample (total of three samples or populations F1, F2, and F3).

Greenhouse Dose–Response Experiment. The dose–response experiment was conducted in the greenhouse at Saskatoon, SK, in November 2011, and repeated the following month. The experiment was arranged in a completely randomized design with four replications (one pot per replicate) per treatment. In addition to the suspected Alberta populations—F1, F2, and F3—two known herbicide-susceptible (HS) populations from Hanley, SK, and Hays, KS, and three known GR populations from Phillip, Scott, and Russell, KS, were included in the experiment. Five seeds were planted 1 cm deep in 10-cm square pots containing a mixture of soil, peat, vermiculite, and sand (3 : 2 : 2 : 2 by volume) plus a controlled-release fertilizer (15–9–12, 150 g 75 L^{-1}; Scotts Osmocote PLUS, Mississauga, ON). The experiment was conducted under a 20/16 C day/night temperature regime with a 16-h photoperiod supplemented with 230 μmol m^{-2} s^{-1} illumination. Pots were watered daily to field capacity.

Glyphosate (Roundup WeatherMax, K+ salt 540 g ae L^{-1} formulation, Monsanto Canada Inc., Winnipeg, MB) was applied to seedlings when 7 to 8 cm tall. The herbicide was applied using a moving-nozzle cabinet sprayer equipped with a flat-fan nozzle tip (TeeJet 8002VS, Spraying Systems Co., Wheaton, IL) calibrated to deliver 200 L ha^{-1} of spray solution at 275 kPa in a single pass over the foliage. Glyphosate was applied at one-eighth (0.125×), one-quarter, one-half, one (450 g ae ha^{-1}), two, three, four, and five times the field-recommended rate, plus a nontreated control. Three weeks after treatment (WAT), plant response to herbicide application was visually scored as HS: dead (0) or nearly dead (1); or GR: some injury but new growth (level 2) or no injury (level 3). Assessments were made relative to herbicide-treated and -untreated HS and GR check populations. Although the scoring system is likely related to dose, rating levels were distinct when visually evaluating plants in the greenhouse. Following herbicide injury rating, shoot biomass was harvested. Harvested biomass was immediately weighed (fresh weight), dried at 60 C for 3 d, then weighed again.

GR Kochia Survey. A field survey was conducted in late September and October 2011 in the County of Warner, Alberta, in an area within a 20-km radius of fields F1, F2, and F3. An approximately similar number of sites (total of 46) in each of the cardinal directions were surveyed (Figure 1). Fields with kochia were randomly selected when driving along primary or secondary roads. Between 15 and 20 mature kochia plants (i.e., target of 1,000 viable seeds) were collected from each field, bulked in a cotton bag, and air-dried. Plants from a site were hand-threshed to avoid sample cross-contamination.

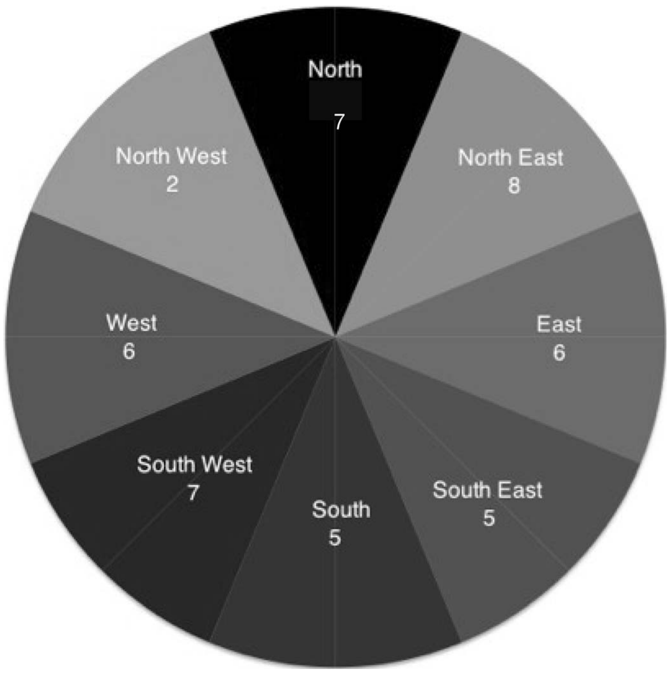

Figure 1. Number of fields sampled for kochia, by cardinal direction sector, in a survey conducted in fall 2011 in the County of Warner, Alberta, in an area within a 20-km radius of fields F1, F2, and F3 (total of 46 fields).

In February 2012, seeds were planted in 52 by 26 by 5–cm flats containing a potting mixture as described previously. A minimum total of 100 F_1 seedlings (3 to 5 cm tall) per population (three flats or replicates per experiment run and repeated) were sprayed with glyphosate at 900 g ae ha^{-1} according to procedures described previously. Plants were visually rated for survival 3 WAT using the above-mentioned scoring system. Known GR and HS populations served as positive and negative controls, respectively.

ALS-Inhibitor Resistance in GR Kochia Populations and Molecular Characterization. All kochia populations (F1, F2, F3, plus those surveyed) confirmed as GR were screened in March 2012 for resistance to a synthetic auxin herbicide, dicamba, and an ALS-inhibiting herbicide, thifensulfuron : -tribenuron premixture, using procedures described previously for the surveyed populations. Herbicides were sprayed to plants 3 to 5 cm tall using Banvel II (480 g L^{-1} dicamba, BASF Canada, Mississauga, ON) at 140 g ai ha^{-1} or Refine SG (thifensulfuron at 10 g ai ha^{-1} and tribenuron at 5 g ai ha^{-1}, E.I. duPont, Mississauga, ON) plus a nonionic surfactant (Agral 90, Norac Concepts Inc., Ottawa, ON) at 0.2% v/v. Known HR and HS controls were included in both experiment runs.

ALS Gene Sequencing. Sequence data of the entire *ALS* gene were generated for 20 kochia parental-generation plants of Alberta populations F1, F2, F3, and Kansas GR population Phillip (plus 10 plants of HS population Hanley). DNA was extracted from freeze-dried leaf tissue (10 to 20 mg) of glyphosate-treated (F1, F2, F3, Phillip) or untreated (Hanley) plants using Fast DNA SPIN kit (QBioGen, MP Biomedicals, Solon, OH) following the manufacturer's instructions.

Two sets of primers were used to amplify the entire *ALS* gene (Table 1). Polymerase chain reaction (PCR) amplifications of the *ALS* gene were performed using Ready-To-Go (GE Healthcare UK Limited, Little Chalfont, Buckinghamshire, UK) PCR beads with approximately 25 ng of genomic DNA and 400 nM of each primer in a total of 25 ml. PCR was performed under the following conditions: 2 min incubation at 95 C; 40 cycles of 30 s at 94 C, 90 s at 58 C, 90 s at 68 C; followed by 5 min at 72 C. PCR fragments were purified using the E-Gel iBase Power System with 0.8% CloneWell SYBR Safe gels (Invitrogen Corporation, Carlsbad, CA). Sequencing used ABI BigDye Terminator Reaction Mix (v. 3.1; PE Corporation, PE Biosystems, Foster City, CA). Primers used for sequencing were the same as those used for PCR amplification, and a further two internal primers were used to ensure complete coverage (Table 1). Polymorphisms or nucleotide heterozygosity was based on the appearance of two peaks at a single nucleotide position. Amino acid and nucleotide positions are numbered based on the amino acid sequence of *ALS* from *Arabidopsis* (Sathasivan et al. 1990).

Risk Assessment of Glyphosate Resistance in Canadian Prairie Weeds. We wanted to look ahead to try to identify other Canadian prairie weed species that may be at greatest risk to evolve glyphosate resistance. Because we have an extensive and unique weed survey database of thousands of prairie cropland fields spanning 40 yr, we utilized this data set in conjunction with an empirical model to estimate the top three weed species in the semiarid (southern) Grassland and subhumid (northern) Parkland regions of the prairies at potential risk of glyphosate resistance.

A classic model of herbicide resistance evolution was described by Gressel and Segel (1982):

$$N_n = N_o[1 + (f \times a/B)]^n \quad [1]$$

where N_n is the proportion of HR individuals in the population after n herbicide applications, N_o is the initial

Table 1. Primers for amplifying and sequencing kochia *ALS* gene fragments.

Primers	5′–3′	Region of homology
b1–f[a]	ATGGCGTCTACTGTGCAAATCCC	1–23
KGenFor[b]	CGGGCCGTGTTGGTGTCTG	449–467
RuTh-F-2b[c]	GAAGAATAAGCAACCCCATGTGTC	1194–1217
5-f[c]	AATTACTCTAGCTGGAGGG	1294–1312
RuTh-R[c]	GACACATGGGGTTGCTTATT TTC	1194–1217
RuTh-R-3[c]	AACTTGTTCTTCCATCACCTTCG	1974–1996
e–rev[a]	GAAATCTTTCAACAATATAGGAAGATC	2227–2200

[a] Foes et al. 1999.
[b] Warwick et al. 2008.
[c] Warwick et al. 2010.

frequency of HR plants prior to herbicide use, *f* is the relative fitness of HR vs. HS biotypes, *B* is the average weed seedbank longevity, and *a* is the selection pressure. Little is known about how N_o and *f* vary by weed species resistant to glyphosate; selection pressure and seedbank longevity can be better estimated.

Glyphosate selection pressure was estimated for the top 10 most abundant prairie weed species [excluding Canada thistle, *Cirsium arvense* (L.) Scop., but including wild mustard, *Sinapis arvensis* L.] in two main agroecological regions of the prairies (Agriculture and Agri-Food Canada 2003). Selection pressure was quantified as the product of (1) relative abundance of a weed in each region; (2) proportional weed emergence as a function of soil GDD base 0 C under conservation tillage (Bullied et al. 2003; Schwinghamer and Van Acker 2008) at glyphosate application at preseeding (early May, 250 GDD), twice in-crop (early June, 650 GDD; late June, 850 GDD), and postharvest (September, > 1,000 GDD); and (3) glyphosate efficacy for each weed based on expert opinion. Relative abundance of a weed is a composite index based on field frequency, field uniformity, and weed density; these data are collected in July and August after all herbicide treatments have been applied (Leeson et al. 2005). Total selection pressure is simply relative abundance multiplied by efficacy, since weed emergence in a growing season totals 1.0. Because of the spaced-out germination of weeds, glyphosate resistance risk rating for each species was calculated as total selection pressure divided by seedbank longevity (Equation 1) using data from Van Acker (2009).

Dose–Response Data Analysis. Greenhouse data were combined across runs upon confirmation of homogeneity of variances (Steel and Torrie 1980). Statistical analysis of shoot biomass (fresh or dry weight) dose–response curves followed the procedure detailed by Seefeldt et al. (1995). Data were fitted to the log-logistic model [Equation 2]:

$$y = c + (d - c)/(1 + \exp(b(\ln(x) - \ln(GR_{50})))) \quad [2]$$

where y = shoot fresh or dry weight (percentage of nontreated control), x = glyphosate dose (g ha^{-1}; a value of 1.0 was added to each dose to calculate natural logarithms, ln), c = lower limit (asymptote) of the response curve, d = upper limit, b = slope, and GR_{50} = dose (g ha^{-1}) of herbicide that reduced shoot fresh or dry weight by 50% relative to the nontreated control. However, the survival dose–response curves were best described using the quadratic (suspected or known GR populations) [Equation 3] or exponential decay model (HS populations) [Equation 4]:

$$y = cx^2 + bx + d \quad [3]$$

where y = survival (percentage of control), x = glyphosate dose (g ha^{-1}), d = intercept, b = linear coefficient, and c = curvilinear coefficient;

$$y = de^{-bx} \quad [4]$$

where y = survival (percentage of control), x = glyphosate dose (g ha^{-1}), d = intercept, and db = initial slope.

Data were fitted to the models using a derivative-free nonlinear regression procedure, provided with PROC NLIN (SAS 1999). Regression analyses were performed on treatment means averaged over replications as recommended by Gomez and Gomez (1984). Coefficients of determination (R^2) were

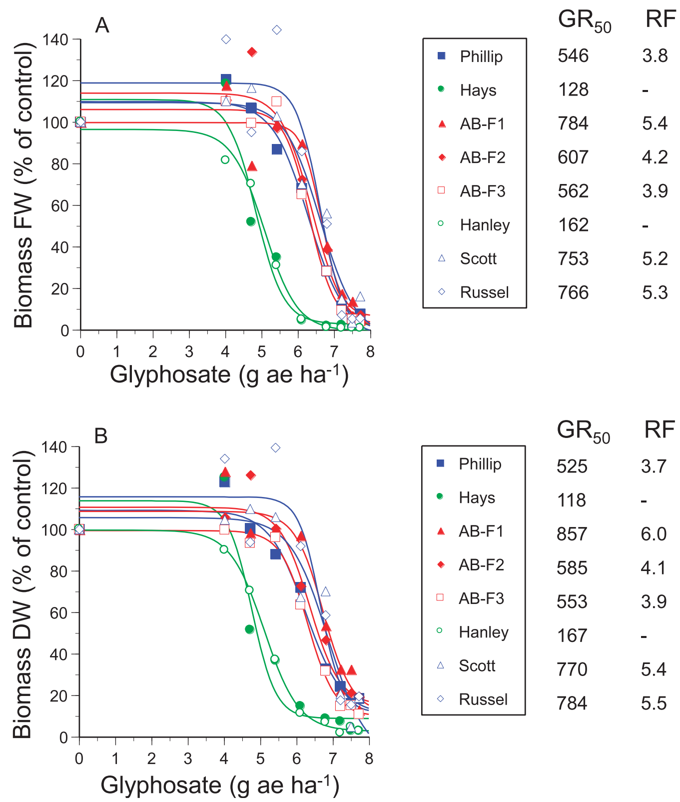

Figure 2. Kochia shoot biomass (fresh weight, FW [A] and dry weight, DW [B]) response to increasing dose of glyphosate in a greenhouse experiment: susceptible populations, Hanley and Hays; glyphosate-resistant (GR) populations from Kansas, Phillip, Scott, and Russell; and suspected GR populations from southern Alberta, F1, F2, and F3. Other abbreviations: GR_{50}, glyphosate dose resulting in a 50% reduction in biomass; RF, resistance factor, calculated as GR_{50} of a GR population divided by average GR_{50} of the susceptible populations. See text for regression equation and Table 2 for parameter estimates.

calculated as described by Kvalseth (1985) using the residual sum of squares value from the SAS output. Standard errors of the parameter estimates were calculated. Parameter estimates are considered significant at the 0.05 level if the standard error is less than one-half the value of the estimate (Koutsoyiannis 1977). Individual response curves were systematically compared for common parameters using the lack-of-fit *F* test at the 0.05 level of significance, as outlined by Seefeldt et al. (1995). The resistance index or factor (RF) was calculated as GR_{50} (biomass) or LD_{50} (survival) of a suspected or known GR population divided by average GR_{50} or LD_{50} of the two HS populations, where GR_{50} and LD_{50} is the dose resulting in a 50% reduction in aboveground biomass and survival, respectively, relative to the nontreated control.

Results and Discussion

Glyphosate Dose–Response Experiments. Based on shoot biomass (fresh weight) response to increasing doses of glyphosate, the three GR Kansas populations exhibited a RF of 4 to 5 (Figure 2A; Table 2). The three Alberta populations—F1, F2, and F3—responded to glyphosate similarly as the Kansas populations: RF of 4 to 5. Therefore, these three Alberta populations can be considered to have a low level of resistance to glyphosate, i.e., RF ≤ 5 (RF categorization detailed in Beckie and Tardif 2012). Similar results were obtained when shoot dry weight was regressed against

Table 2. Parameter estimates (standard errors in parentheses) of regression equations for shoot fresh and dry weight and plant survival response (% of nontreated control) of eight kochia populations (glyphosate-susceptible: Hays, Hanley; glyphosate-resistant: Phillip, Scott, Russell; suspected glyphosate-resistant: AB-F1, AB-F2, AB-F3) to increasing doses of glyphosate under greenhouse conditions. Refer to equations 2 to 4 in text for description of regression parameters.

Population	*d*	*c*	*b*	ED_{50}[a]	R^2	RF[b]
Fresh weight						
Hays, KS	110.6 (11.8)	2.6 (6.3)	2.64 (1.15)	128 (25)	0.95	—
Hanley, SK	96.3 (3.7)	0.1 (2.3)	2.22 (0.33)	162 (13)	0.99	—
Phillip, KS	109.6 (5.6)	0.2 (1.1)	2.01 (0.64)	546 (100)	0.98	3.8
Scott, KS	109.1 (7.5)	0.2 (3.4)	2.04 (1.03)	753 (241)	0.96	5.2
Russell, KS	116.5 (10.8)	1.0 (5.2)	2.94 (2.05)	766 (217)	0.90	5.3
AB-F1	99.5 (6.4)	6.1 (2.5)	3.65 (2.08)	784 (138)	0.95	5.4
AB-F2	113.7 (8.1)	0.1 (1.1)	2.30 (1.11)	607 (152)	0.96	4.2
AB-F3	105.8 (4.0)	2.8 (6.6)	2.93 (0.82)	562 (62)	0.99	3.9
Dry weight						
Hays, KS	113.5 (13.8)	8.7 (7.1)	3.06 (1.79)	118 (25)	0.93	—
Hanley, SK	99.5 (1.5)	2.5 (1.0)	2.11 (0.13)	167 (6)	0.99	—
Phillip, KS	108.9 (6.3)	10.3 (3.2)	1.95 (0.79)	525 (123)	0.97	3.7
Scott, KS	105.4 (9.3)	0.5 (4.2)	1.91 (1.39)	770 (227)	0.93	5.4
Russell, KS	115.4 (10.4)	11.3 (7.8)	3.37 (2.71)	784 (214)	0.90	5.5
AB-F1	108.5 (6.8)	10.8 (3.1)	2.51 (1.47)	857 (244)	0.94	6.0
AB-F2	110.4 (6.4)	14.9 (1.1)	2.39 (1.10)	585 (132)	0.96	4.1
AB-F3	99.2 (2.2)	9.5 (3.9)	2.63 (0.45)	553 (41)	0.99	3.9
Survival						
Hays, KS	101.8 (7.9)		−0.00221 (0.00050)	310	0.99	—
Hanley, SK	104.5 (6.8)		−0.00205 (0.00041)	340	0.99	—
Phillip, KS	101.9 (7.3)	−8.1E-6 (9.6E-7)	−0.012 (0.0021)	1900	0.83	5.8
Scott, KS	105.4 (4.6)	−2.4E-6 (6.0E-6)	−0.041 (0.013)	1260	0.97	3.9
Russell, KS	106.2 (7.0)	−4.9E-6 (9.1E-7)	−0.038 (0.020)	1280	0.94	3.9
AB-F1	100.5 (1.7)	−1.0E-5 (2.2E-6)	0.00013 (0.00007)	2250	0.99	6.9
AB-F2	101.5 (7.8)	−5.6E-6 (1.0E-7)	−0.020 (0.022)	1720	0.84	5.3
AB-F3	103.7 (7.5)	−1.0E-5 (9.8E-7)	−0.014 (0.0021)	1740	0.91	5.4

[a] Abbreviations: AB, Alberta; ED_{50}, effective dose reducing growth or survival by 50% compared with the nontreated control; KS, Kansas; RF, resistance factor (index); SK, Saskatchewan.

[b] ED_{50} of resistant population divided by ED_{50} mean of susceptible populations; standard error not available for survival regression models.

glyphosate dose (Figure 2B; Table 2). Both the Kansas GR populations and Alberta populations had a RF ranging from 4 to 6 (a low to moderate level of resistance). Based on survival response to increasing doses of glyphosate, RF for the three Kansas populations ranged from 4 to 6, whereas RF for the three Alberta populations ranged from 5 to 7 (Figure 3; Table 2). Seedlings of the three Alberta populations survived 900 g ha^{-1}, whereas there were no survivors from the two HS populations at that dose. Therefore, the three Alberta populations are indeed GR, responding similarly as the Kansas populations to increasing dose of glyphosate.

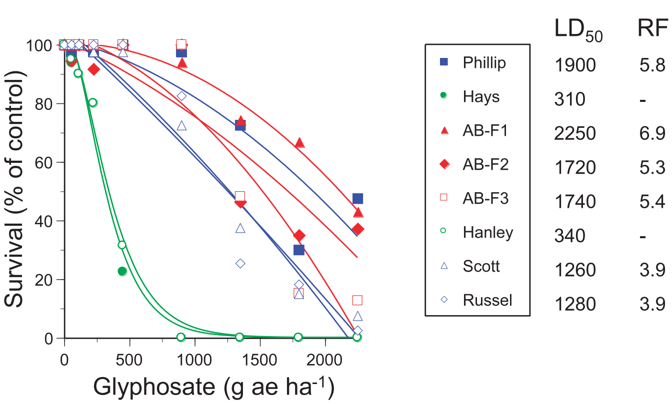

Figure 3. Kochia survival as a function of increasing dose of glyphosate in a greenhouse experiment: susceptible populations, Hanley and Hays; glyphosate-resistant (GR) populations from Kansas, Phillip, Scott, and Russell; and suspected GR populations from southern Alberta, F1, F2, and F3. Other abbreviation: RF, resistance factor, calculated as LD_{50} of a GR population divided by average LD_{50} of the susceptible populations). See text for regression equations and Table 2 for parameter estimates.

For other GR weed species, RF values generally are ≤ 10 (Beckie 2012). Target-site mutation generally confers a lower level of resistance to glyphosate than physiological processes resulting in reduced translocation, although levels can be similar in rigid ryegrass (*Lolium rigidum* Gaudin) (Preston et al. 2009). Regardless, the three Alberta populations would not be controlled in the field by realistic glyphosate application rates. When sampled in August 2011, it was apparent that the kochia populations in the glyphosate-treated chem-fallow fields were likely GR, with linear strips of surviving plants oriented in a southwest to northeast direction (prevailing winds from the southwest) (Figure 4). Kochia was the only weed species present, and it was common to observe live plants next to dead plants throughout the three fields. The three Alberta populations may indeed be a single genotype, with the tumbleweed dispersing seeds across the open landscape as observed previously with ALS-inhibitor–HR kochia. The relative roles of GR kochia seed immigration (gene flow) vs. evolution through glyphosate selection in each of the three fields is presently unknown.

To examine the response of GR kochia to increasing rates of glyphosate under field conditions, a dose–response trial was established in spring 2012 at Lethbridge, AB (the same trial at a site in Saskatchewan was terminated because of poor seedling emergence due to flooding). The trial was arranged in a split-block design with four replications, with glyphosate rate as main plot factor—the same rates as those in the greenhouse experiment plus 2,700 (6×) and 3,150 g ha^{-1} (7×), applied to seedlings 4 cm tall—and kochia population

Figure 4. Southern Alberta chem-fallow field in August 2011, where the F1 population was sampled; glyphosate had been applied earlier in the growing season at 670 g ae ha^{-1}.

(GR-F2 and a non-GR population) as split-block factor. The kochia populations were planted May 15 into fallow land at a 0.5-cm depth using a small-plot seeder. The exponential decay model best described the response of aboveground biomass of the two kochia populations to glyphosate (vegetative plants harvested 8 wk after planting). The RF equaled 6.2 based on aboveground biomass dose response of the F2 population (GR_{50} = 330 and 53 g ha^{-1} for GR and non-GR kochia populations, respectively). Although the trial was not successfully repeated in the field, the computed RF was similar to that determined in the greenhouse experiment (RF = 4.1).

GR Kochia Survey. Of the 46 populations screened for glyphosate resistance (900 g ha^{-1}), seven were confirmed as GR (Figure 5). The seven fields had been chem-fallowed or cropped to small-grain cereals in 2011. The frequency of GR plants in a population ranged from 18% (sample point [SP] 21) to 79% (SP22) (Table 3). The site (SP27) farthest from the chem-fallow fields (F1, F2, F3) was located about 13 km to the southeast. All of the sites were located east of the three chem-fallow fields. The same grower farmed fields F1 and SP23; another grower fields F2 and SP20, and another grower fields SP2 and SP22. Therefore, kochia seed may have been spread by farm equipment, in addition to wind. Molecular markers will be needed to determine the relative contribution of evolution through selection and gene flow, primarily seed dispersal.

In addition to the seven confirmed GR kochia populations found in this survey, an additional population more than

Figure 5. Seven sites (labeled SP) in the County of Warner in southern Alberta in fall, 2011 with confirmed glyphosate-resistant (GR) kochia; F01, F02, and F03 denote the chem-fallow fields where GR kochia was first confirmed.

Table 3. Frequency of glyphosate- and acetolactate synthase (ALS)-inhibitor–resistant plants in Alberta kochia populations.[a]

Population	Glyphosate resistance	ALS-inhibitor resistance
	%	
F1	100	13
F2	100	100
F3	100	90
SP2	71	52
SP14	53	100
SP20	66	85
SP21	18	100
SP22	79	100
SP23	61	90
SP27	65	89

[a] Glyphosate applied at 900 g ae ha^{-1} and thifensulfuron : tribenuron premixture applied at 15 g ai ha^{-1}. A minimum of 100 plants per population were screened with each herbicide.

100 km northwest of these survey populations was recently confirmed as GR. An expanded survey (300 sites) was completed in the fall of 2012 throughout southern Alberta to estimate the prevalence of GR kochia in the region. In the neighboring province of Saskatchewan in 2012, a number of GR kochia populations in chem-fallow fields covering a wide geographic area were confirmed (Beckie, unpublished data). Surveys will be conducted in central and southern Saskatchewan and southern Manitoba in 2013 to determine the incidence of GR kochia.

ALS-Inhibitor Resistance in GR Kochia Populations and Molecular Characterization. When the confirmed GR kochia populations were screened with thifensulfuron : tribenuron premixture at 15 g ha^{-1}, all of them were ALS-inhibitor HR (Table 3). These results were expected, as previous surveys had documented about 90% of Canadian prairie kochia populations exhibiting resistance to ALS-inhibiting herbicides (Beckie et al. 2011b). Most of the GR populations had a high frequency of ALS-inhibitor–HR plants, except sites F1 (13%) and SP2 (52%). However, all populations were susceptible to dicamba, an auxinic herbicide (data not shown). Dicamba-HR kochia has not yet been reported in Canada, although numerous populations are found in the northwestern United States (Heap 2012).

The following amino acid substitutions that previously were known to confer ALS-inhibitor resistance were found in this study: Pro$_{197}$, Asp$_{376}$, and Trp$_{574}$ sites (Table 4). Pro$_{197}$ mutations resulting in amino acid substitutions conferring resistance were the following: CCG Pro to CAG Gln, CCG Pro to TCG Ser, and CCG Pro to CGG Arg. At the Asp$_{376}$ site, a T to G mutation resulted in an amino acid substitution of GAT Asp to GAG Glu. At the Trp$_{574}$ amino acid site, a mutation of G to T resulted in an amino acid substitution of TGG Trp to TTG Leu.

In the Alberta F2 population, 11 of the 20 individuals tested had amino acid substitutions conferring ALS-inhibitor resistance (Table 4). One individual in the F2 population was homozygous for Leu$_{574}$, whereas eight individuals from that population revealed the target-site mutation T(T/G)G, resulting in a Trp/Leu$_{574}$ amino acid substitution. The polymorphism GA(T/G) results in the substitution Asp/Glu$_{376}$, and was found in two individuals in the F2 population. Three individuals possessed the Pro/Gln$_{197}$ substitution. Three individuals had two amino acid substitutions: two individuals with both Pro/Gln$_{197}$ and Trp/Leu$_{574}$ substitutions, and one individual with both Asp/Glu$_{376}$ and Trp/Leu$_{574}$ substitutions.

In the Alberta F3 population, five of the 20 individuals had the polymorphism C(C/A)G, resulting in the amino acid substitution Pro/Gln$_{197}$. One individual in the Kansas (Phillip) population had a polymorphism (T/C)CG, resulting in a Pro/Ser$_{197}$ substitution, whereas a polymorphism C(C/G)G resulting in a Pro/Arg$_{197}$ substitution was found in another individual. A third individual revealed the target-site mutation T(T/G)G, resulting in the amino acid substitution Trp/Leu$_{574}$. As expected, no target-site mutations were found in the 10 sequenced plants of the Hanley HS population (data not shown).

Unexpectedly, no target-site mutations were found in the 20 sequenced plants of the Alberta F1 population (data not shown). The low frequency of ALS-inhibitor–HR individuals in the Alberta F1 population (13%; Table 3) likely explains

Table 4. Acetolactate synthase (*ALS*) target-site mutations in glyphosate-resistant (GR) Alberta kochia populations F2 and F3, and a GR Kansas population, Phillip (total of 20 individuals per population sequenced).[a]

Population	Pro197	Asp376	Trp574
F2	CCG Pro197	GAT Asp	T(T/G)G Trp/**Leu**
F2	C(C/A)G Pro/**Gln**	GAT Asp	TGG Trp
F2	CCG Pro	GA(T/G) **Asp/Glu**	T(T/G)G Trp/**Leu**
F2	CCG Pro	GAT Asp	T(T/G)G Trp/**Leu**
F2	C(C/A)G Pro/**Gln**	GAT Asp	T(T/G)G Trp/**Leu**
F2	CCG Pro	GA(T/G) **Asp/Glu**	TGG Trp
F2	CCG Pro	GAT Asp	T(T/G)G Trp/**Leu**
F2	CCG Pro	GAT Asp	T**T**G **Leu**
F2	CCG Pro	GAT Asp	T(T/G)G Trp/**Leu**
F2	C(C/A)G Pro/**Gln**	GAT Asp	T(T/G)G Trp/**Leu**
F2	CCG Pro	GAT Asp	T(T/G)G Trp/**Leu**
F3	C(C/A)G Pro/**Gln**	GAT Asp	TGG Trp
F3	C(C/A)G Pro/**Gln**	GAT Asp	TGG Trp
F3	C(C/A)G Pro/**Gln**	GAT Asp	TGG Trp
F3	C(C/A)G Pro/**Gln**	GAT Asp	TGG Trp
F3	C(C/A)G Pro/**Gln**	GAT Asp	TGG Trp
Phillip	(T/C)CG Pro/**Ser**	GAT Asp	TGG Trp
Phillip	CCG Pro	GAT Asp	T(T/G)G Trp/**Leu**
Phillip	C(C/G)G Pro/**Arg**	GAT Asp	TGG Trp

[a] A slash (/) between nucleotides indicates that both nucleotides are present at that position, i.e., heterozygosity.

Table 5. Weed risk assessment of selection for glyphosate resistance in the semiarid Grassland and subhumid Parkland regions of the Canadian prairies (top three weeds in each region in bold font).

			Proportional emergence							
Weed species	RA[a]	Efficacy[b]	Preseed	In-crop1	In-crop-2	Postharvest	Total SP[c]	Seedbank (yr)[d]	SP: In-crop/ preseed	Risk rating: SP/seedbank
Grassland region										
Green foxtail[e]	68.8	0.95	0.00	0.85	0.15	0.0	65.4	10	> 60.0	**6.54**
Wild oat	47.3	0.95	0.10	0.80	0.10	0.0	44.9	4.5	9.0	**9.99**
Wild buckwheat	28.9	0.75	0.04	0.94	0.02	0.0	21.7	8	27.6	2.71
Common lambsquarters	10.7	0.90	0.0	1.00	0.0	0.0	9.6	14	> 10.0	0.69
Chickweed	0.4	0.95	0.05	0.90	0.05	0.0	0.4	7.5	19.0	0.05
Field pennycress	16.7	0.95	0.06	0.81	0.12	0.0	15.9	15	15.0	1.06
Redroot pigweed	14.0	0.95	0.0	0.35	0.50	0.15	13.3	15	> 10.0	0.89
Cleavers	1.5	0.90	0.05	0.90	0.05	0.0	1.4	2	19.0	0.69
Kochia	20.9	0.90	0.60	0.40	0.0	0.0	18.8	1	0.7	**18.8**
Wild mustard	2.9	0.95	0.05	0.90	0.05	0.0	2.8	25	19.0	0.11
Parkland region										
Green foxtail	43.0	0.95	0.00	0.85	0.15	0.0	40.9	10	> 40.0	**4.09**
Wild oat	37.1	0.95	0.10	0.80	0.10	0.0	35.2	4.5	9.0	**7.83**
Wild buckwheat	32.1	0.75	0.04	0.94	0.02	0.0	24.1	8	27.6	3.01
Common lambsquarters	13.8	0.90	0.0	1.00	0.0	0.0	12.4	14	> 13.0	0.89
Common chickweed	16.0	0.95	0.05	0.90	0.05	0.0	15.2	7.5	19.0	2.03
Field pennycress	9.2	0.95	0.06	0.81	0.12	0.0	8.7	15	15.0	0.58
Redroot pigweed	7.4	0.95	0.0	0.35	0.50	0.15	7.0	15	> 6.0	0.47
Cleavers	9.0	0.90	0.05	0.90	0.05	0.0	8.1	2	19.0	**4.05**
Kochia	1.9	0.90	0.60	0.40	0.0	0.0	1.7	1	0.7	1.71
Wild mustard	3.7	0.95	0.05	0.90	0.05	0.0	3.5	25	19.0	0.14

[a] RA, relative abundance (derived from Leeson et al. 2005); see text for description.
[b] Based on expert opinion (see Acknowledgments)" preseeding (early May), in-crop1(early June), in-crop2 (late June), postharvest (September).
[c] SP, selection pressure, calculated as RA × efficacy.
[d] Derived from Van Acker (2009).
[e] Green foxtail, *Setaria viridis* (L.) Beauv.; wild oat, *Avena fatua* L.; wild buckwheat, *Polygonum convolvulus* L.; common lambsquarters, *Chenopodium album* L.; common chickweed, *Stellaria media* (L.) Vill.; field pennycress, *Thlaspi arvense* L.; redroot pigweed, *Amaranthus retroflexus* L.; cleavers, *Galium spurium* L (false cleavers). or *G. aparine* L. (catchweed bedstraw); wild mustard, *Sinapis arvensis* L.

the lack of detection of target-site mutations in tissue-sampled GR plants.

Risk Assessment of Glyphosate Resistance in Prairie Weeds. Kochia, which emerges early in the growing season, was the only weed examined in which preseed glyphosate selection pressure was greater than in-crop selection pressure (Table 5: column SP: In-crop/preseed = 0.7). In the Grassland region of the prairies, the top three weeds predicted at greatest risk of glyphosate resistance were kochia, wild oat, and then green foxtail. In the Parkland region, wild oat and green foxtail, followed by cleavers species were the top three species. Based on numerous surveys of HR weeds in the prairies since 1988, weed population abundance is a key HR risk factor. The risk rating for kochia was twice that of any other species. Those predictions were originally presented in a poster presented at the 2010 Canadian Weed Science Society annual meeting (Beckie 2010) in response to repeated questions of prairie weeds at greatest risk of glyphosate resistance.

For predicting invasive weed species, a history of invasion elsewhere is probably the best indicator. Thus, the risk of GR kochia in the prairies was elevated following the report of GR kochia in Kansas in 2007 (Heap 2012). Regardless of whether the predictions prove accurate or not (other than kochia), the simple empirical modeling exercise was successful in raising awareness among all regional stakeholders, via the media, of the risk of selection of GR weeds and the urgency of proactive management—which was the original intent of the project.

Herbicides to control ALS-inhibitor (group 2)–HR kochia or group 2 plus glyphosate (group 9)–HR kochia in field crops in Canada are listed in Appendix Table 1—at preseeding (burndown), in-crop, or in chem-fallow situations. Based on previous survey results, growers must assume kochia populations are group 2–HR. There are sufficient alternative herbicides to control group 2 + 9–HR kochia in most cereal crops. However, there currently are no registered in-crop herbicides to control the multiple-HR biotype in mustard, sunflower (*Helianthus annuus* L.), lentil (*Lens culinaris* Medik), chickpea (*Cicer arietinum* L.), dry bean (*Phaseolus vulgaris* L.), soybean, or potato (*Solanum tuberosum* L.). Broadleaf crops with very few alternative herbicides include sugar beet (*Beta vulgaris* L.; phenmedipham + desmedipham, a group 5 herbicide); field pea (*Pisum sativum* L.; MCPA, group 4); and canola (glufosinate, group 10). We are presently exploring various herbicide treatments to control GR kochia under field conditions.

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SHORT COMMUNICATION

Survey of glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Alberta

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Hall, L. M., Beckie, H. J., Low, R., Shirriff, S. W., Blackshaw, R. E., Kimmel, N. and Neeser, C. 2014. **Survey of glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Alberta**. Can. J. Plant Sci. **94**: 127–130. Glyphosate-resistant (GR) kochia was identified in Warner county in southern Alberta in 2011. To determine the scale of the distribution and frequency of GR kochia, a randomized stratified survey of more than 300 locations (one population per location) in southern Alberta was conducted in the fall of 2012. Mature plants were collected, seed separated, and F_1 seedlings screened by spraying with glyphosate at 900 g a.e. ha^{-1} under greenhouse conditions. Screening confirmed 13 GR kochia sites: seven in Warner county, five in Vulcan county, and one in Taber county. The frequency of GR individuals in a population ranged from 0.3 to 98%. GR kochia were found in arid areas where chemical fallow is a significant component of the rotation. Economic and agronomic impact of this GR weed biotype is compounded because of multiple resistance to acetolactate synthase-inhibiting herbicides.

Key words: Chemical fallow, *Kochia scoparia* (L.) Schrad., glyphosate resistance, multiple herbicide resistance

Hall, L. M., Beckie, H. J., Low, R., Shirriff, S. W., Blackshaw, R. E., Kimmel, N. et Neeser, C. 2014. **Étude de la kochie (*Kochia scoparia* L. Schrad.) résistante au glyphosate en Alberta**. Can. J. Plant Sci. **94**: 127–130. En 2011, des plants de kochie résistants au glyphosate (RG) étaient identifiés dans le comté de Warner, dans le sud de l'Alberta. Pour avoir une meilleure idée de l'importance de la distribution et de la fréquence de la kochie RG, les auteurs ont procédé à une étude stratifiée randomisée à plus de 300 emplacements (une population par emplacement) du sud de l'Alberta, à l'automne 2012. Ils ont recueilli des plants adultes, ont séparé les graines puis sélectionné les plantules en les aspergeant avec 900 g de matière active de glyphosate par hectare, en serre. La sélection a confirmé l'existence de 13 sites où pousse la kochie RG, soit sept dans le comté de Warner, cinq dans le comté de Vulcan et un dans le comté de Taber. La fréquence des plants RG au sein de la population varie de 0,3 à 98 %. La kochie RG a été découverte dans les lieux arides où on recourt abondamment à la jachère chimique dans les assolements. L'impact économique et agronomique de cette adventice RG est d'autant plus important que celle-ci résiste aussi aux herbicides qui inhibent l'acétolactate synthase.

Mots clés: Jachère chimique, *Kochia scoparia* (L.) Schrad., résistance au glyphosate, résistance multiple aux herbicides

Glyphosate is a key herbicide for weed control in chemical fallow in arid to semiarid regions of the prairies, pre-seeding in direct-seeding systems, pre- and post-harvest control, and in glyphosate-resistant (GR) canola (*Brassica napus* L.), soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), and sugar beet (*Beta vulgaris* L.). Glyphosate was first introduced in 1974, and is the most widely used herbicide in the world. Frequent glyphosate use has selected for GR weeds – over 20 weed species in several countries, including eastern Canada (Vink et al. 2012; Heap 2013). Until 2011, GR weeds had not been identified in western Canada.

Kochia is a competitive tumbleweed with early emergence (Schwinghamer and Van Acker 2008), abundant seed production, and tolerant of stress (Friesen et al. 2009). It is one of the most common weeds of southern Alberta, being the fourth most abundant weed in the Mixed and Moist Mixed Grassland ecoregions (Leeson et al. 2005). A C_4 plant, it continues to grow under hot, dry conditions. Kochia is morphologically plastic, and occurs in agricultural areas, waste lands,

Abbreviations: **ALS**, acetolactate synthase; **GR**, glyphosate-resistant and rangelands. Kochia also matures later than many other weeds, usually after annual crop harvest. Kochia resistant to acetolactate synthase (ALS) inhibitors in the prairies was reported in 1989. Beckie et al. (2011b, 2013b) reported that about 90% of the prairie populations tested were resistant. Resistant genes may be transmitted through pollen movement (Stallings et al. 1995). However, long-distance transport of resistant genes occurs via seed dispersal from mature plants tumbling across the landscape.

GR kochia was first identified in Kansas in 2007 (Waite 2008; Waite et al. 2013), followed by South Dakota in 2009, and Nebraska in 2011; it was selected primarily in GR corn and soybean fields (Heap 2013). In 2011, kochia resistant to glyphosate and ALS inhibitors (multiple herbicide-resistant) was discovered in southern Alberta (Beckie et al. 2013a). Initially, three populations were identified in chemical-fallow fields. A 20-km survey around these sites confirmed an additional seven populations. Resistance level was considered low to moderate, with a resistance factor (ratio of the rates required for 50% control of the resistant and susceptible populations) of 4 to 7. However, resistant plants could not have been controlled in the field by a reasonable rate of glyphosate. To determine the frequency and distribution of GR kochia in southern Alberta, a random survey, stratified by cropped area, was conducted in the fall of 2012.

MATERIALS AND METHODS

Survey Methodology

A random survey of GR kochia was conducted in fall, 2012. The number of populations collected was stratified, proportional to cultivated land area per ecodistrict within the Southern Alberta agricultural extension region, covering four agricultural ecoregions (Leeson et al. 2005). Therefore, the proportional allocation of collection sites in each county was the same as that of the general weed survey. Surveyors drove to 309 predetermined sites during a 3-wk post-harvest survey period in September and October, 2012. Approximately 20 mature kochia plants were randomly collected at each site, and placed in a cotton bag to form a composite sample. A survey form was completed on-site for each population, and a photograph taken with GPS reference. Populations were sampled in field border areas and ruderal areas such as roadsides/ditches, railway rights-of-way, and oil well sites.

Sample Processing and Resistance Screening

Samples were threshed under contained conditions at the University of Alberta in Edmonton, and seed samples sent for screening to Agriculture and Agri-Food Canada, Saskatoon, SK. All remaining material was autoclaved to prevent distribution of kochia on the University of Alberta research station. Samples were also received from growers in Alberta and Saskatchewan who had experienced poor kochia control and were included in screening. From each population, a minimum of 100 seeds were planted in flats filled with potting soil in a greenhouse, and glyphosate, tribenuron/thifensulfuron, or dicamba was applied at 900, 15 (5 + 10), and 480 g a.e./ a.i. ha^{-1}, respectively, when seedlings were 3 to 5 cm tall, using a moving-nozzle cabinet sprayer equipped with a flat-fan nozzle tip (TeeJet 8002VS, Spraying Systems Co., Wheaton, IL) calibrated to deliver 200 L ha^{-1} of spray solution at 275 kPa (Beckie et al. 2013a). Three weeks after treatment, plant response to herbicide application was visually scored as susceptible: dead or nearly dead, or resistant: some injury but new growth, or no injury (Beckie et al. 2013a). Assessments were made relative to known herbicide-treated and -untreated susceptible and resistant populations.

RESULTS AND DISCUSSION

Kochia resistant to glyphosate was identified at 13 of 309 sites surveyed (4.2% of fields) (Fig. 1). Seven sites were located in Warner county, where GR kochia was previously confirmed at 10 other sites in a fall, 2011 survey (Beckie et al. 2013a). Five sites were located in Vulcan county to the north, and one site to the east in Taber county. Besides these 13 confirmed sites, 9 sites were also confirmed in Alberta in 2012 from samples submitted by growers: three sites in Warner county, one site in Lethbridge county, four sites in Forty Mile county, and one site in Cypress county (Fig. 2). Moreover, 10 kochia samples submitted by growers in west-central and southwestern Saskatchewan that year were confirmed as GR (Fig. 2). In this survey, two of the locations where GR kochia was found were non-agricultural areas (ditch and railway rights-of-way) adjacent to agricultural areas (Table 1). Kochia can be an abundant weed in ruderal areas of southern Alberta where glyphosate may be used for non-selective weed control.

The frequency of glyphosate resistance in confirmed populations varied from 0.3 to 98% (Table 1). Differences may be due to the time since glyphosate resistance was selected or introduced (either via seed or pollen), the amount of glyphosate selection that occurred in that population over time, or the amount of selection that had occurred in 2012 to reduce the frequency of susceptible individuals in the population. It should be noted that even though glyphosate resistance was at low levels in some samples, that frequency would be expected to increase with the use of glyphosate applied alone.

Only three populations tested were < 50% resistant to the ALS-inhibiting herbicide tribenuron/thifensulfuron (Table 1). High frequency of resistance to ALS inhibitors in kochia populations had been previously reported in Alberta (Beckie et al. 2011b). None of the GR populations were resistant to dicamba, suggesting that dicamba can control GR kochia prior to seeding of most cereal crops and in chemical fallow. Dicamba-resistant kochia has not been identified previously in

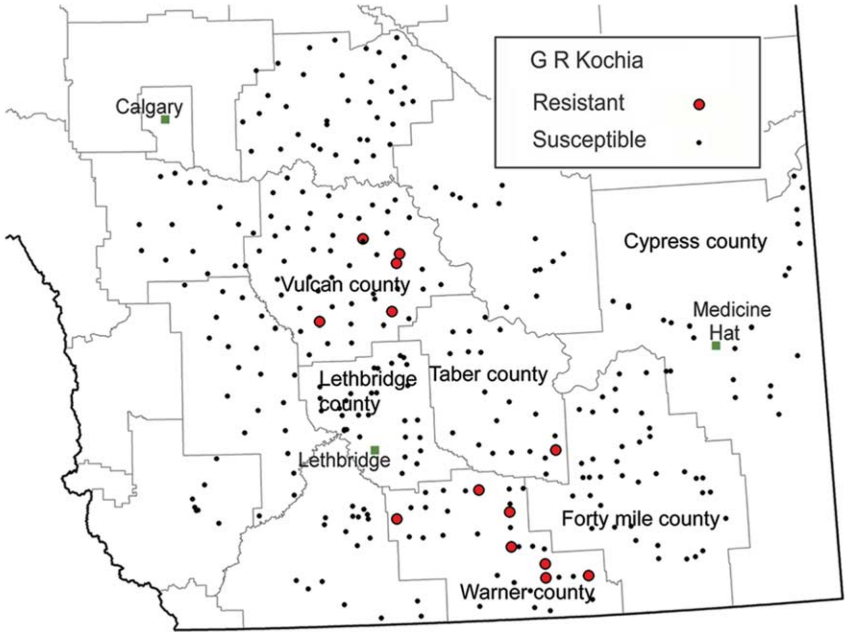

Fig. 1. Location of glyphosate-resistant (GR) (large red circle) and glyphosate-susceptible (small black circle) kochia, surveyed in fall, 2012: seven populations in Warner county, five populations in Vulcan county, and one population in Taber county.

Alberta, but has been reported in the midwestern USA (Cranston et al. 2001; Preston et al. 2009).

In Vulcan, Taber, and Warner counties, where resistant populations were located, frequent chemical fallow (strip cultivation) is practiced. In chemical fallow, glyphosate is typically applied alone, and at multiple times during the fallow year to control vegetation. Kochia is a very abundant weed in these arid locations. The combination of frequent applications of a single herbicide on an abundant weed population has led to selection of herbicide resistance in other parts of the world. Unfortunately, kochia will not be confined to

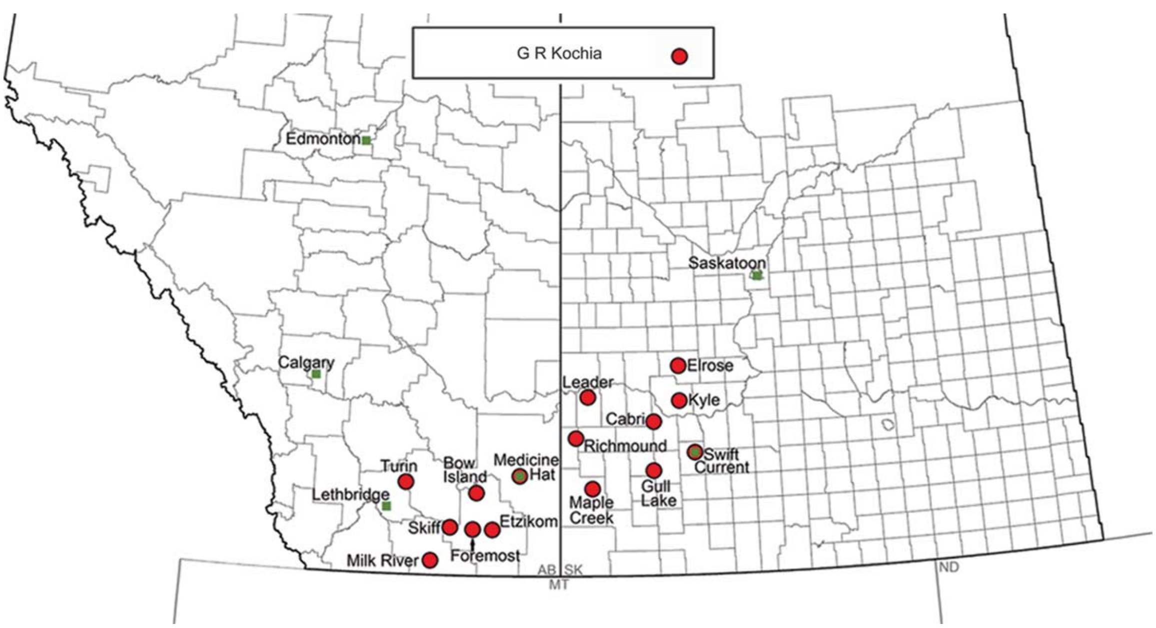

Fig. 2. Glyphosate-resistant (GR) kochia confirmed in 2012 from samples submitted by growers. Note: the site at Milk River, Alberta, represents three confirmed fields; the site at Cabri and Kyle, Saskatchewan represent two confirmed fields each.

Table 1. Percentage of plants in a population resistant (R) to glyphosate, dicamba, or tribenuron/thifensulfuron, and the habitat and Alberta county where populations were located

Site	County	Habitat	Glyphosate-R	Dicamba-R	Tribenuron/ thifensulfuron-R
1	Warner	Field	98	0	20
2	Vulcan	Field	95	0	1
3	Vulcan	Ditch	85	0	98
4	Vulcan	Field	85	0	75
5	Warner	Field	80	0	70
6	Vulcan	Field	80	0	80
7	Warner	Field	70	0	15
8	Taber	Field	50	NA[z]	NA
9	Warner	Field	50	0	98
10	Warner	Field	50	0	98
11	Vulcan	RR[y]	10	0	55
12	Warner	Field	0.7	0	98
13	Warner	Field	0.3	0	50

[z]NA, data not available due to limited sample size.
[y]Railway right-of-way.

areas where it was selected, as it is capable of moving long distances and infesting other areas – agricultural, industrial, and waste areas.

This survey shows that GR kochia has established in discontinuous areas in southern Alberta where chemical fallow (strip cultivation) is practiced. Because of wind dispersal, GR kochia is an imminent threat for growers in southern Alberta who practice chemical fallow, direct-seeding, or grow GR sugar beet, corn, or canola. All GR populations tested for ALS-inhibitor resistance were resistant to the sulfonylurea herbicide tribenuron/thifensulfuron; cross-resistance would probably occur to triflusulfuron, marketed as Upbeet®, the only other herbicide that effectively controls kochia in sugar beet. In areas where GR kochia may already be present, glyphosate should not be used alone for pre-seeding or chemical fallow weed control.

Kochia was the first of several species predicted to be at risk for glyphosate resistance (Beckie et al. 2011a, 2013a). Other abundant species, selected during pre-seeding applications or present in large numbers in chemical-fallow fields are also at risk, including wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* L. Beauv.), and wild buckwheat (*Polygonum convolvulus* L.) (Beckie et al. 2013a). Like kochia, these weeds have already been selected for resistance to herbicides with different modes of action used in-crop. Worldwide, the incidence of multiple-resistant weed biotypes is increasing at an alarming rate. Across the prairies, multiple-resistant weeds will continue to challenge growers and agronomists, especially when one of those modes of action is glyphosate.

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