Agriculture Development Fund (ADF)
Project Progress Report

Completed reports must be returned by email to Evaluation.Coordinator@gov.sk.ca

Project Title:	Understanding, mitigating, and managing PPO inhibitor (Group 14)-resistant kochia
ADF File Number:	20230188
Reporting Period:	April 2024 – March 2025

Principal Investigator

Full Name:	Charles Geddes
Organization:	Agriculture and Agri-Food Canada
Mailing Address:	5403 1st Avenue South, Lethbridge, Alberta, T1J 4B1
Phone Number:	403-360-2466
E-mail:	Charles.Geddes@agr.gc.ca

Collaborators and Co-Investigators *(add additional lines as needed)*

Name	Organization	Mailing Address	Phone Number	Email
Gagagnpreet Dhariwal	Agriculture and Agri-Food Canada	5403 1st Ave South, Lethbridge AB T1J 4B1	403-715-1777	Gaganpreet.Dhariwal@agr.gc.ca
Benjamin Ellert	Agriculture and Agri-Food Canada	5403 1st Ave South, Lethbridge AB T1J 4B1	403-317-2230	Benjamin.Ellert@agr.gc.ca
Henry Chau	Agriculture and Agri-Food Canada	5403 1st Ave South, Lethbridge AB T1J 4B1	403-327-4561	Henry.Chau@agr.gc.ca
Shaun Sharpe	Agriculture and Agri-Food Canada	107 Science Place, Saskatoon, SK S7N 0X2	306-385-9398	Shaun.Sharpe@agr.gc.ca
Prabhath Lokuruge	Agriculture and Agri-Food Canada	Hwy 374, Scott, SK S0K 4A0	306-247-2011	Prabhath.Lokuruge@agr.gc.ca

Abstract *(no more than 250 words)*

Describe in lay language the progress towards the project objectives over the last reporting period. Include any key findings and any interim conclusions. Include any deviations from the original methodology.

In 2024, we completed the dose-response and molecular diagnostics to assess cross-/multiple-resistance in the Group 14-resistant kochia population from Saskatchewan (Objectives 1 and 2). We determined the mechanism conferring Group 14 resistance in kochia (Objective 3) and are developing a rapid genetic test to identify it using leaf tissue. We screened through 214 of the 281 kochia samples collected from Saskatchewan in 2024 (Objective 4) and completed two site-years of the burndown experiment (Objective 5). Two site-years of the residual preemergence herbicide experiment were initiated in fall 2024. Weeds and soil health were assessed in the tenth year of the long-term strategic tillage experiment (Objective 6) and two site-years of the experiment assessing timing and implement/depth of soil disturbance were initiated in fall 2024 (Objective 7). Finally, the sixth year of the crop rotation experiment was completed as proposed (Objective 8). While all results are considered preliminary, resistance assessments suggest that Group 14-resistant kochia exhibits resistance to most Group 14 active ingredients used in western Canada except the diphenyl ether family (which currently has limited use in the region). The Group 14-resistant kochia population from Saskatchewan was also resistant to Groups 2 and 9, but not 4 and 5. Non-residual burndown options varied in efficacy for kochia control among site-years with glufosinate being the most consistent. After ten years, strategic tillage (once every 3 years) and conventional tillage reduced kochia plant densities compared with no tillage. Of the soil health parameters assessed so far, few were impacted the tillage treatments.

Introduction *(maximum 1,500 words)*

Provide a brief project background and rationale.

Kochia has grown to be one of the worst agricultural weed problems on the southern Canadian Prairies where its impact on crop production has been exacerbated by warm dry summers over the past half decade. Kochia is a tumbleweed that thrives in conditions of drought, salinity, and heat stress, allowing it to compete with crops for essential resources, resulting in substantial crop yield losses (Geddes and Sharpe 2022). High genetic diversity combined with protogynous flowering result in rapid evolution and selection for resistance in response to herbicides followed by efficient transfer of herbicide resistance traits through pollen (Beckie et al. 2016). Prolific seed production and tumbleweed seed dispersal also allow the plant to disperse seeds among multiple fields in a single year, further spreading resistant biotypes across farmlands.

Kochia on the Canadian Prairies can exhibit resistance to up to four herbicide modes of action, including Groups 2, 4, 9, and 14. Acetolactate synthase inhibitor (Group 2)-resistant kochia was documented first on the Canadian Prairies in 1988, and after about two decades, all kochia populations tested in this region were Group 2-resistant (Hall et al. 2014; Beckie et al. 2015). Glyphosate (Group 9)-resistant kochia was confirmed in Canada in 2011, where it was found in chemical fallow fields located in southern Alberta (Beckie et al. 2013). Recent surveys of Manitoba (2018), Saskatchewan (2019), and Alberta (2021) found glyphosate-resistant kochia in 59%, 87%, and 78% of the kochia populations tested, respectively (Geddes et al. 2022a, 2023; Sharpe et al. 2023). Synthetic auxin (Group 4)-resistant kochia was confirmed in Saskatchewan in 2015, and since spread to an estimated 1%, 45%, and 45% of kochia populations tested in Manitoba, Saskatchewan, and Alberta, respectively. However, we have documented variable overlap between fluroxypyr and dicamba resistance in kochia populations where a population may exhibit resistance to one, the other, or both of these auxin mimics (Geddes et al. 2022b).

Protoporphyrinogen oxidase (PPO) inhibitor (Group 14)-resistant kochia has been documented in a single kochia population from west-central Saskatchewan (Geddes et al. 2025a). Group 14 resistance in kochia drastically limits the herbicide options available to manage this weed using a preplant burndown before crop emergence. In response to wide-spread glyphosate resistance in kochia, many farmers switched to mixing a group 14 product (e.g., Heat, Aim, Authority, Valtera, etc. and the main kochia-active component of several others such as Fierce, Focus, Blackhawk, Goldwing, etc.) with glyphosate to regain efficacy of the pre-plant burndown treatment. However, if the kochia present were glyphosate-resistant, this resulted in widespread use of only a single herbicide mode of action for kochia control during this management window, and unfortunately substantial selection pressure for group 14 resistance. Very few herbicide options remain to control group 2, 4, 9, and 14-resistant kochia, and the ones that are available have rather limited use cases (Geddes et al. 2025a). For example, every option registered for pre-plant or in-crop application in small grain cereals includes bromoxynil (Group 6) either alone or mixed with a Group 27 active ingredient. Diquat (Group 22) may be another option because it is registered for foliar-application to promote a stale seedbed prior to crop emergence, however, kochia is not listed explicitly on the label. There is a need to understand which of the remaining herbicide options are available for kochia management, especially before crop planting, and also what approach can lead to better stewardship of these remaining active ingredients to mitigate further selection for resistance to new modes of action.

We recently confirmed protoporphyrinogen oxidase (PPO) inhibitor (Group 14)-resistant kochia in a mustard crop grown in west-central Saskatchewan in 2021 (Geddes et al. 2025a). So far, we have shown that the kochia seed collected from this field survived 32X the standard field rate (25 g ai/ha) of foliar-applied saflufenacil (Heat LQ). We also documented that the resistance trait was passed on to the next generation of kochia which exhibited 63- to 82-fold resistance to saflufenacil in greenhouse dose-response bioassays. Single-dose screening of 882 kochia samples collected from Manitoba (2018), Saskatchewan (2019), and Alberta (2021) did not find group 14-resistant kochia, suggesting that this biotype exists currently at low abundance in this region (Geddes et al. 2025b). However, we are working with colleagues from North Dakota State University who found a few kochia populations in North Dakota in 2022 that appear to be Group 14-resistant (Geddes et al. 2025a). As we have learned from Group 2, 4 and 9 resistance in kochia, an new herbicide resistance trait in this species is typically widespread across the region within 5-10 years after its discovery. It is therefore critical to characterize cross-resistance to the range of foliar- and soil-applied PPO-inhibiting herbicides available in western Canada (**Objective 1**). It is also important to understand if there is cross- or multiple-resistance to other herbicide modes of action in this biotype (**Objective 2**).

Knowledge of the mechanism conferring Group 14 resistance in kochia could help to determine how the trait may spread, and if there are management practices that could mitigate its spread (**Objective 3)**. In addition, understanding the status, impact, and distribution of this biotype (**Objective 4**) will be critical to inform regional implementation of best management practices. It will be important to understand which herbicide options are available for farmers to manage kochia populations that are resistant Group 2, 4, 9, and 14 herbicides, and to develop herbicide stewardship strategies to help prolong the efficacy of the remaining herbicide options for kochia control (**Objective 5**).

Few herbicide options for Group 2, 4, 9, and 14-resistant kochia control pre-plant, and soil incorporation required for either of the soil-applied residual options for kochia control, will cause some conservation tillage farmers to reconsider tillage as a viable option to control kochia prior to crop planting. However, it is well-known that conventional tillage can result in soil erosion and degrade soil health especially in the semi-arid region of the Canadian Prairies where kochia tends to thrive. There is a need to understand the value of occasional/strategic tillage (e.g., once in every 3 years) for kochia management as part of an integrated weed management program, while also maintaining the use of this practice at a low frequency in the crop rotation such that soil health can be maintained (**Objective 6**). Further, since the judicious use of tillage for weed control will be essential to maintain the soil health benefits of conservation tillage systems, it will be important to optimize the timing and implement/depth of the limited number of tillage passes that farmers do implement such that they achieve the greatest management of multiple herbicide-resistant kochia (**Objective 7**). Past research has shown that kochia seed in the soil seedbank persists for the same duration whether it is on the soil surface, buried at 2.5 cm or 10 cm depth (Beckie et al. 2018). In addition, kochia seedlings do not emerge from the soil when the seed is buried below 8 cm depth (Schwinghamer and Van Acker 2008). Therefore, tillage can be a viable tool to manage kochia populations without aiding in their seedbank persistence, however, it will be important to take a systems approach to assessing this tool to balance implications for soil health, productivity, and weed management.

Cultural weed management options will become increasingly important as kochia continues to overcome more herbicide modes of action. Our previous research showed that crop rotations including winter wheat resulted in 74% decline in kochia densities and 64% lower kochia biomass by the third year of the crop rotation compared with rotations consisting solely of summer-annual crops. A perennial alfalfa/meadow brome forage treatment reduced kochia densities and biomass by 89% and 99%, respectively, by the third year of growth. The initial results from this four-year crop rotation study were promising, but it is important to also understand mid/long-term implications of these practices on kochia management, crop yields, profitability, and other pest dynamics (**Objective 8**).

This project is designed to tackle the impending threat that is PPO inhibitor (Group 14)-resistant kochia, and the stacking of 4-way resistance (Group 2, 4, 9, and 14) in kochia populations on the Canadian Prairies. The research will span lab, greenhouse, and small-plot studies that will provide practical insights into PPO inhibitor resistance and how to mitigate and manage it moving forward.

Objectives and Progress *(add additional lines as needed)*

Please list the original objectives and/or revised objectives if ministry-approved revisions have been made to original objectives. A justification is needed for any deviation from original objectives.

Objective	**Progress** *(i.e., completed/in progress)*
1) Determine cross-resistance to PPO-inhibiting (Group 14) herbicides in PPO inhibitor-resistant kochia confirmed in SK	Dose-response studies will be conducted in the greenhouse to determine whether PPO inhibitor-resistant kochia confirmed in Saskatchewan is cross-resistant to foliar and soil-applied activity of the range of PPO-inhibiting herbicides available in western Canada.
2) Determine cross- or multiple-resistant to other herbicide modes of action in PPO inhibitor (Group 14)-resistant kochia	Dose-response studies and molecular diagnostics (where available) will be used to determine whether PPO inhibitor-resistant kochia confirmed in Saskatchewan is resistant to other herbicide modes of action, including Groups 2, 4 and 9.

3) Determine the mechanism conferring resistance to PPO-inhibiting (Group 14) herbicides in kochia	Molecular diagnostics and genetic sequencing will be used to identify the mechanism conferring PPO inhibitor resistance in kochia, and if possible, develop a rapid molecular diagnostic test to confirm PPO inhibitor resistance using a leaf tissue sample. This will help to inform mitigation strategies and may also result in a rapid test that could confirm Group 14 resistance in-season, thereby informing additional management in the same growing season.
4) Continue monitoring kochia survey samples for PPO inhibitor (Group 14) resistance across the Canadian Prairies	Kochia survey samples to be collected in detailed surveys of 400 fields in Saskatchewan (2024/2025), 150 fields in Manitoba (2026), and 250 fields in Alberta (2027) will be screened for resistance to the PPO-inhibiting herbicide saflufenacil. This monitoring will be critical to understand the status, impact, and spread of Group 14-resistant kochia across the Canadian Prairies, and inform regional implementation of best management practices.
5) Assess the efficacy of alternative herbicides to manage multiple herbicide-resistant kochia prior to crop seeding	Field and greenhouse studies will be used to assess alternative herbicides and herbicide mixtures for pre-plant burndown and residual control of multiple herbicide-resistant and -susceptible kochia.
6) Determine the mid/long-term utility and sustainability of strategic tillage for kochia management	An ongoing cropping systems study comparing conventional tillage, strategic tillage (once every ~4 years), and no tillage initiated in 2014 will be used to determine the utility of occasional/strategic tillage for kochia management, and the impact on crop yields, profitability, and soil health after 10 years.
7) Assess the impact of timing and implement/depth of soil disturbance on kochia emergence, density, and the soil seedbank	A field study will be conducted to determine the impact of strategic timing and implement/depth of soil disturbance on kochia emergence, plant density, and seedbank density, as well as impact on the subsequent cash crop.
8) Determine the mid/long-term impact of winter cereals and perennials in crop rotations on multiple herbicide-resistant kochia	An ongoing crop rotation study established in 2019 will be continued to assess the mid/long-term impact of crop rotation diversity and crop life cycle diversity for management of multiple herbicide-resistant kochia, and the impact on crop productivity and crop rotation profitability.

Project Changes *(400 words or less)*

Briefly explain new challenges faced during this reporting period and the impact on the work plan or the budget.

No challenges were faced during the 2024/2025 reporting period. No project changes are proposed.

Methodology *(maximum of five pages)*

Specify project activities undertaken during this reporting period. Include approaches, experimental design, tests, materials, sites, etc. Please note that any significant changes from the original work plan will require written approval from the ministry.

1) Determine cross-resistance to PPO-inhibiting (Group 14) herbicides in PPO inhibitor-resistant kochia confirmed in SK

Whole-plant dose-response bioassays (10 different experiments) were conducted in the greenhouse to determine resistance to various PPO-inhibiting herbicides. The herbicides (listed below) cover a range of products and all PPO-inhibiting chemical families available in western Canada, including: aryl triazones, dicarboximides, pyrazoles, pyrimidinediones, and diphenyl ethers. The dose-response experiments included two susceptible kochia populations and the Group 14-resistant population collected from Saskatchewan (same as those reported in Geddes et al. 2025a). Each herbicide was a separate randomized complete block design (RCBD) experiment.

Foliar-applied dose-response experiments

Saflufenacil (Heat) (0, 0.25, 2.5, **25**, 79, 250, 790, 2500 g ai ha^{-1})

Carfentrazone (Aim) (0, 0.175, 1.75, **17.5**, 55.3, 175, 553, 1750 g ai ha^{-1})

Pyraflufen-ethyl (part of Blackhawk) (0, 0.09, 0.9, **9**, 28.44, 90, 284.4, 900 g ai ha^{-1})

Tiafenacil (Insight) (0, 0.5, 5, **50**, 158, 500, 1580, 5000 g ai ha^{-1})

Acifluorfen (Ultra Blazer) (0, 3, 30, **300**, 948, 3000, 9480, 30000 g ai ha^{-1})

Oxyfluorfen (Goal 2XL) (0, 2.4, 24, **240**, 758.4, 2400, 7584, 24000 g ai ha^{-1})

Trifludimoxazin + saflufenacil (Voraxor) (0, 0.06+0.12, 0.6+1.2, **6+12**, 19+38, 60+120, 190+380, 600+1200 g ai ha^{-1})

Note: "**field rates**" are in bold and underlined.

The foliar-applied dose-response experiments consisted of 9 replications and were repeated over 2 runs in the greenhouse. The treatment structure was a 2-way factorial of kochia population (3) and herbicide rate (8), for a total of 216 experimental units in each run (3 kochia populations x 8 herbicide rates x 9 replicates). Each experimental unit was a 9 x 9 cm plastic greenhouse pot with 1 kochia seedling. Each kochia population was seeded in greenhouse flats with inserts of 1 cm cells filled with Cornell soilless potting mixture. When the kochia seedlings reach 1-2 cm in height, a single seedling was transplanted into each greenhouse pot. When the kochia seedlings reach 5-8 cm in height, the herbicide treatments were applied using a moving-nozzle cabinet sprayer equipped with a flat-fan nozzle calibrated to deliver 200 L/ha spray volume. The treated pots were placed back in the greenhouse and watered daily to field capacity. Visible control of each experimental unit was evaluated at 1 and 3 weeks after treatment (WAT) following the Canadian Weed Science Society methodology (http://weedscience.ca/cwss_scm-rating-scale). Plant survival and biomass fresh weight (FW) and dry weight (DW) were determined at 3 WAT.

Soil-applied dose-response experiments

Sulfentrazone (Authority) (0, 3.28 6.56, 13.13, 26.25, 52.5, **105**, 210, 420, 840 g ai ha^{-1})

Flumioxazin (Valtera) (0, 4.375, 8.75, 17.5, 35, **70**, 140, 280, 560, 1120 g ai ha^{-1})

Trifludimoxazin + saflufenacil (Voraxor) (0, 0.78+1.56, 1.56+3.125, 3.125+6.25, 6.25+12.5, **12.5+25**, 25+50, 50+100, 100+200, 200+400 g ai ha^{-1})

Note: "**field rates**" are in bold and underlined.

The soil-applied dose-response experiments consisted of 6 replications and were repeated over 2 runs in the greenhouse. The treatment structure was a 3-way factorial of soil type (2), kochia population (3), and herbicide rate (10), for a total of 360 experimental units in each run (2 soils x 3 kochia populations x 10 herbicide rates x 6 replicates). Each experimental unit was a 9 x 9 cm plastic greenhouse pot filled with field soil. The fields soils were chosen based on contrasting properties to account for the interaction of soil residual herbicides with soil properties such as clay content, pH and organic matter. One soil was a clay loam, while the other soil was a sandy loam. The soil was supplemented with added N/P/K fertilizer. The viability of seed was determined for each kochia population using a petri-dish germination assay, and kochia seeds were added to each experimental unit at a rate of 20 viable seeds per pot. The seeds were covered with a thin layer (2 mm) of soil and each experimental unit was watered to field capacity. The pots were treated with herbicide using the moving-nozzle cabinet sprayer described above. Each experimental unit was enclosed in a plastic bag immediately following treatment to prevent volatilization and maintain soil moisture to activate the herbicide. The pots were placed back in the greenhouse and the plastic bags were removed after 48 hrs. Each pot was watered daily. Visible control and kochia seedling density was evaluated at 2, 4, and 6 WAT, and biomass FW and DW were determined at 6 WAT.

Statistical analyses

The response variables were analyzed using the 'drc' package of R statistical environment to fit nonlinear dose-response models to the data. The best fitting non-linear regression model was selected based on the Akaike Information Criterion and lack of fit test. The effective dose of each herbicide resulting in 50% control (ED50) was extracted and the ratio of ED50 values was used to determine whether the putative-resistant population is resistant compared with the two susceptible control populations. Following the guidelines from the Global Herbicide Resistance Action Committee (HRAC), the putative resistant population were considered susceptible if the ratio of ED50 values (resistance index) was <4, while low-level resistance was 4-10 and high resistance was >10.

2) Determine cross- or multiple-resistant to other herbicide modes of action in PPO inhibitor (Group 14)-resistant kochia

Separate whole-plant bioassays were conducted in the greenhouse to determine whether the Group 14-resistant kochia population from Saskatchewan exhibited resistance to herbicide Groups 2, 4, 5, and 9. Each experiment included three kochia populations, 3 herbicide rates, 9 replicates and 2 runs arranged in a completely randomized design. Separate experiments were conducted for thifensulfuron + tribenuron (Refine SG; Group 2), dicamba (Xtendimax 2; Group 4), fluroxypyr (Prestige XCA; Group 4), metribuzin (Squadron II; Group 5), and glyphosate (RoundUp WeatherMAX; Group 9). The populations consisted of the Group 14-resistant kochia from Saskatchewan and two susceptible control accessions. The herbicide rates included an untreated control, and 1X and 2X field rates (see below). The other methodology followed that described for the foliar-applied dose-response experiments under objective 1. Plant survival was determined at 3 (Groups 2, 5, and 9) or 4 weeks (Group 4) after treatment.

Foliar-applied screening experiment to determine cross/multiple-resistance

Thifensulfuron + Tribenuron (Refine SG) = 0 + 0, 10 + 5, 20 + 10 g ai ha^{-1}

Dicamba (Xtendimax 2) = 0, 280, 540 g ae ha^{-1}

Fluroxypyr (Prestige XCA) = 0, 140, 280 g ae ha^{-1}

Metribuzin (Squadron II) = 0, 563, 1125 g ai ha^{-1}

Glyphosate (RoundUp WeatherMAX) = 0, 900, 1800 g ae ha^{-1}

Where kochia plants survived 1X or 2X field dates in the initial screening experiment (described above), subsequent research was conducted to confirm resistance (excluding Group 2, which is safe to assume resistance). Glyphosate resistance was confirmed using a molecular assay. qPCR was used to determine glyphosate resistance by assessing EPSPS gene copy number following the delta-delta CQ method compared with known resistant and susceptible controls. Fluroxypyr resistance was studied further using a dose-response experiment following the foliar-applied methodlology outlined under Objective 1 with the following rates: 0, 17.5, 35, 70, **140**, 280, 560, 1120 g ae ha^{-1}. The dose-response experiment was analyzed following the approach described under Objective 1.

3) Determine the mechanism conferring resistance to PPO-inhibiting (Group 14) herbicides in kochia

A material transfer agreement was established with BASF. The Group 14-resistant kochia from Saskatchewan was analyzed in their global lab in Germany along with the Group 14-resistant kochia populations from North Dakota. The results were used to design a molecular test at AAFC Lethbridge to rapidly identify Group 14 resistance in kochia using plant leaf tissue.

4) Continue monitoring kochia survey samples for PPO inhibitor (Group 14) resistance across the Canadian Prairies

214 of the 281 kochia samples collected as part of the post-harvest herbicide-resistant weed survey of Saskatchewan in 2024 were evaluated for PPO inhibitor resistance using single-dose population screening in the greenhouse. Kochia seeds from each sample were planted in a 24 x 24 cm greenhouse flat filled with Cornell soilless potting mixture and watered daily. Each flat was treated with saflufenacil at 50 g ai ha when the plants reach 5-8 cm in height. Treated and untreated flats of known resistant and susceptible control populations were included in each run in the greenhouse. The response of each plant within each population was evaluated visually as resistant (living with new regrowth) or susceptible (dead or nearly dead) relative to the control populations 3 WAT following the methods described by Geddes et al. (2025b). Plant survival (percent of individuals with the resistance trait in each sample) and resistance frequency (percentage of samples with the resistance trait in each jurisdiction of interest) was quantified.

5) Assess the efficacy of alternative herbicides to manage multiple herbicide-resistant kochia prior to crop seeding

The loss of efficacy of PPO-inhibiting herbicides to control kochia will have the greatest impact on the preplant burndown window for weed management. Alternative herbicides and herbicide strategies (e.g., mixtures) were evaluated based on control of multiple (Group 2+9) herbicide-resistant kochia prior to crop planting. Group 2+9-resistant kochia was used with the assumption that Group 14-resistant kochia will respond similarly to alternative herbicides with the exception of PPO inhibitors. This assumption was confirmed in the greenhouse under objectives 1 and 2. We are unable to work with Group 14-resistant kochia in the field because at current it remains at low abundance on the Canadian Prairies, and planting it in the field would be a biosecurity risk.

Two RCBD small-plot field studies were used to evaluate (a) pre-plant burndown using non-residual non-PPO active ingredients, and (b) residual preemergence kochia control using fall- and spring-applied non-PPO active ingredients. Treatments included in each experiment are described in Tables 1 and 2:

Table 1. Treatment description used for Test 81 to determine the efficacy of pre-plant burndown (non-PPO-inhibiting) herbicides for kochia control at Lethbridge and Scott in 2024/2025 and 2025/2026.

Trt	Active ingredient	Rate[a] (g ai/ae ha^{-1})	Trade name	Concentration	Rate (product/ha)	Company
1	Untreated control					
2	Glyphosate	900	RoundUp WeatherMAX	540 g ae/L	1.67 L/ha	Bayer
3	Bromoxynil	280	Pardner	280 g ai/L	1 L/ha	Bayer
4	Bromoxynil	350	Pardner	280 g ai/L	1.25 L/ha	Bayer
5	Glyphosate +	900 +	RoundUp WeatherMAX	540 g ae/L	1.67 L/ha	Bayer
	Bromoxynil	280	Pardner	280 g ai/L	1 L/ha	Bayer
			Agral 90 @ 0.35% v/v	92%	350 ml/ha	Syngenta
6	Glyphosate +	900 +	RoundUp WeatherMAX	540 g ae/L	1.67 L/ha	Bayer
	Bromoxynil	350	Pardner	280 g ai/L	1.25 L/ha	Bayer
			Agral 90 @ 0.35% v/v	92%	350 ml/ha	Syngenta
7	Bromoxynil +	6 +	Certitude A	336 g ai/L	17 ml/ha	BASF
	Topramezone	140	Certitude B	235 g ai/L	600 ml/ha	BASF
			Merge @ 0.5% v/v	50% blend	500 ml/ha	BASF
8	Glyphosate +	900 +	RoundUp WeatherMAX	540 g ae/L	1.67 L/ha	Bayer
	Topramezone +	6 +	Certitude A	336 g ai/L	17 ml/ha	BASF
	Bromoxynil	140	Certitude B	235 g ai/L	600 ml/ha	BASF
			Merge @ 0.5% v/v	50% blend	500 ml/ha	BASF
9	Diquat	550	Reglone	240 g ai/L	5.7 L/ha	Syngenta
10	Diquat	1100	Reglone	240 g ai/L	11.4 L/ha	Syngenta
11	Glufosinate	400	Liberty 150 SN	150 g ai/L	2.7 L/ha	BASF
12	Glufosinate	600	Liberty 150 SN	150 g ai/L	4.0 L/ha	BASF

[a]Abbreviations: ae, acid equivalence; ai, active ingredient; Trt, treatment.

Sustainable Canadian Agricultural Partnership
Saskatchewan
Canada

Table 2. Treatment description used for Test 82 to determine the efficacy of residual preemergence (non-PPO-inhibiting) herbicides for kochia control at Lethbridge and Scott in 2024/2025 and 2025/2026.

Trt	Active ingredient	Rate (g ai ha^{-1})	Trade name	Timing[a]	Rate (product/ha)	Company
1	Untreated control					
2	Fall harrow			Fall		
3	Spring harrow			Spring		
4	Triallate + Trifluralin	1400 + 560	Fortress MicroActiv	Fall PPI	14 kg/ha	Gowan
5	Triallate + Trifluralin	1400 + 560	Fortress MicroActiv	Spring PPI	14 kg/ha	Gowan
6	Ethalfluralin	1100	Edge MicroActiv	Fall PPI	11 kg/ha	Gowan
7	Ethalfluralin	850	Edge MicroActiv	Spring PPI	8.5 kg/ha	Gowan
8	Ethalfluralin	1100	Edge MicroActiv	Spring PPI	11 kg/ha	Gowan
9	Ethalfluralin fb. Metribuzin	1100 fb. 336	Edge MicroActiv fb. Sencor 480F	Fall PPI fb. Fall	11 kg/ha 0.7 L/ha	Gowan fb. Bayer
10	Ethalfluralin fb. Metribuzin	1100 fb. 264	Edge MicroActiv fb. Sencor 480F	Spring PPI fb. Spring	11 kg/ha 0.55 L/ha	Gowan fb. Bayer
11	Trifluralin fb. Metribuzin	1100 fb. 336	Treflan MicroActiv fb. Sencor 480F	Fall PPI fb. Fall	11 kg/ha 0.7 L/ha	Gowan fb. Bayer
12	Trifluralin fb. Metribuzin	1100 fb. 264	Treflan MicroActiv fb. Sencor 480F	Spring PPI fb. Spring	11 kg/ha 0.55 L/ha	Gowan fb. Bayer
13	Trifluralin + Metribuzin	1100 + 336	Treflan Liquid EC + Sencor 480F	Fall PPI	2.3 L/ha 0.7 L/ha	Gowan fb. Bayer
14	Tribluralin + Metribuzin	1100 + 264	Treflan Liquid EC + Sencor 480F	Spring PPI	2.3 L/ha 0.55 L/ha	Gowan fb. Bayer
15	Pyroxasulfone	90	Zidua SC	Fall	0.18 L/ha	BASF
16	Pyroxasulfone	120	Zidua SC	Fall	0.24 L/ha	BASF
17	Pyroxasulfone	150	Zidua SC	Fall	0.30 L/ha	BASF
18	Pyroxasulfone	60	Zidua SC	Spring	0.12 L/ha	BASF
19	Pyroxasulfone	90	Zidua SC	Spring	0.18 L/ha	BASF
20	Pyroxasulfone	120	Zidua SC	Spring	0.24 L/ha	BASF
21	Pyroxasulfone	150	Zidua SC	Spring	0.30 L/ha	BASF

[a]Abbreviations: fb. followed by; PPI, pre-plant incorporated.

The field experiments included four replicates and will be repeated over two runs in Lethbridge, AB and Scott, SK for a total of 4 site-years for each experiment. Plot sizes were 2 x 6 m. The herbicide treatments were applied using either a boom-mounted bicycle sprayer, or tractor-mounted CO sprayer calibrated to deliver 100 L/ha spray solution. Two sites of the non-residual burndown experiment (Test 81) were completed in 2024 and another two were initiated in 2025. Two sites of the residual experiment (Test 82) were initiated in fall 2024 and spring measurements are currently underway. For the non-residual burndown experiment, kochia density and visible control relative to the untreated treatment were evaluated at 1, 3, and 9 WAT. Kochia biomass FW and DW were determined at 9 WAT.

Data from the non-residual burndown experiment was analyzed using a generalized mixed model approach in the GLIMMIX procedure of SAS. Herbicide treatments, site and their interactions were fixed factors while replication nested within site was random. Tukey's HSD (alpha = 0.05) was used for post-hoc means comparison.

Sustainable Canadian Agricultural Partnership
Saskatchewan
Canada

6) Determine the mid/long-term utility and sustainability of strategic tillage for kochia management

The long-term strategic tillage experiment was initiated near Lethbridge, AB in 2014. It was initiated on larger plots that had been under no-till wheat production since 1968. This experiment follows a RCBD with three treatments and five replicates. Each plot is 1 acre of land. The three treatments include:

1. no tillage
2. strategic tillage (tillage once every 3 years; 2017, 2020, 2023)
3. conventional tillage (tillage every year)

The tillage treatments have been conducted using a heavy duty cultivator with (~16") sweeps and harrows. The cultivar selection, seeding rates, fertilizer application, seeding equipment, and pest control follow standard recommendations for the semi-arid prairie region. The experiment has been planted to wheat every year and a canola-wheat rotation is being established beginning in spring 2025 (year 11). The area where this experiment is located has a historical issue with herbicide-resistant kochia, and it is among the most abundant weeds in the study area along with green foxtail and some wild oat. Weed plant density by species was evaluated in ten 0.5 x 0.5 m quadrat areas within each plot after postemergence weed control in 2024. A 1.25” dia. soil corer was used to collect 30 cores per plot down to 15 cm. Each core was separated into 0-5 cm (0-2”), 5-10 cm (2-4”), and 10-15 cm (4-6”) depths and these depths bulked together for each plot. The soil was frozen at -20 C until evaluated in the greenhouse using repeated cycles of 1 month grow out in the greenhouse followed by 1 month cold stratification (-20 C) until seedbank exhaustion (Cardina and Sparrow 1996). During the grow out, all emerged weed seedlings were counted by species and removed after counting. 10 core samples were collected per plot following the same methodology and analyzed for soil properties at Down to Earth Labs (Lethbridge, AB).

Also in fall 2024, separate soil core samples were collected from each plot using a punch truck at 0-7.5 cm, 7.5- 15 cm, 15-30 cm, and 30-45 cm depths. Soil gravimetric moisture, bulk density, organic and inorganic C and N concentrations will be evaluated on these soil samples. Soil hardness was also evaluated using a field penetrometer. Surface soil (0-2 cm depth) samples were also collected to determine wet aggregate stability by wet sieving. Crop yield data was collected using the onboard weighing system on a Wintersteiger plot combine.

The weed density, seedbank density, and Down to Earth Labs soil property data , were analyzed using generalized linear mixed models in the GLIMMIX procedure of SAS to evaluate the utility of occasional/strategic tillage for kochia management as well as the sustainability of this practice from a crop productivity and soil health perspective. Tillage treatment and soil depth were fixed factors while replication was random. Tukey's HSD (alpha = 0.05) was used for post-hoc means comparison. The crop productivity, punch truck soil, soil hardness, and wet aggregate stability data are being compiled and prepared for analysis, which has not taken place yet. Upon further discussion with the soil scientist collaborators, it was determined that measurement of soil hydraulic conductivity could not be completed given the size of the plots, the large number of samples required for an accurate assessment, and temporal dynamic of this soil property. Therefore, this measurement was excluded from the comprehensive soil health assessment.

7) Assess the impact of timing and implement/depth of soil disturbance on kochia emergence, density, and the soil seedbank

An augmented factorial RCBD field experiment was established at Lethbridge and Scott in fall 2024 to determine the impact of timing and implement/depth of soil disturbance on kochia management. The experiment was established on land with previous kochia infestation. The experiment included 13 treatments and four replications and will be repeated over a total of six site-years. The first factor was timing of soil disturbance: (1) early fall (immediately after harvest), (2) late fall (1 month after early fall (3) early spring (April), and (4) late spring (one month after early spring). The second factor was implement, which varied between sites based on equipment availability. The implement used followed the categories: (1) heavy disturbance (e.g., disc), (2) moderate disturbance (e.g., cultivator), and (3) light disturbance (e.g., harrow). This two-way factorial treatment structure was augmented with a no-tillage control treatment for a total of 13 treatments overall (Table 3).

Table 3. Treatment description used for Test 83 to assess the impact of timing and implement/depth of soil disturbance on kochia emergence, density, and the soil seedbank at Lethbridge and Scott in 2024/2025, 2025/2026 and 2026/2027.

Treatment	Timing	Target tillage date	Level of soil disturbance	Primary tillage implement
1	N/A	N/A	No-till control (none)	
2	Early fall	ASAP after harvest	Light	Tine harrow
3	Early fall	ASAP after harvest	Moderate	Cultivator w/ tine harrow
4	Early fall	ASAP after harvest	Heavy	Offset disc[a]
5	Late fall	1 month after early fall	Light	Tine harrow
6	Late fall	1 month after early fall	Moderate	Cultivator w/ tine harrow
7	Late fall	1 month after early fall	Heavy	Offset disc
8	Early spring	ASAP in spring	Light	Tine harrow
9	Early spring	ASAP in spring	Moderate	Cultivator w/ tine harrow
10	Early spring	ASAP in spring	Heavy	Offset disc
11	Late spring	1 month after early spring	Light	Tine harrow
12	Late spring	1 month after early spring	Moderate	Cultivator w/ tine harrow
13	Late spring	1 month after early spring	Heavy	Offset disc

[a]Rototiller at Scott.

Following the soil disturbance treatments, the experiment will be seeded to a spring wheat cash crop (in spring 2025) using disc openers to maximize the soil disturbance treatment effect. Spring seedbank density (see soil core and growout procedure under Objective 6), weed density by species (before and after the postemergence herbicide), mid-season kochia biomass, and crop yield will be evaluated. The experiment will be repeated near Lethbridge, AB and Scott, SK for a total of six site-years (2024/2025, 2025/2026, and 2026/2027). Data analyses will follow that outlined for Objective 6 with the exception of the model structure. For this experiment, data will be analyzed following an augmented factorial where the no-till treatment will be considered a control treatment and the combination of (a) timing, and (b) implement/intensity of soil disturbance will be the nested factorial. Implement/intensity and timing of soil disturbance, site, year, and their interactions will be considered fixed factors while replicate nested within site-year will be random. Means will be separated based on Tukey's HSD (alpha = 0.05). These data will be used to optimize soil disturbance passes such that they may have the greatest efficacy for kochia management while having a minimal impact on soil health.

Since the first run of these experiments was established in fall 2024 and data collection continues into 2025, no data are available for analyses and presentation in this interim report.

8) Determine the mid/long-term impact of winter cereals and perennials in crop rotations on multiple herbicide-resistant kochia

A rainfed crop rotation experiment initiated in 2019 near Lethbridge, AB is being used to evaluate the mid/long-term impact of crop rotations on kochia management. Crop variety selection, fertilization rates and seeding practices follow those recommended for the semi-arid region of the Canadian Prairies. The herbicide program varies somewhat based on the crop rotation to account for recropping restrictions while also layering multiple effective herbicide modes of action targeting kochia throughout the crop rotation. The RCBD fully-phased crop rotation treatments (each with 4 replications) are outlined in Table 4. The experiment was initiated under the CAP-Integrated Crop Agronomy Cluster (covering years 2019- 2022). Group 2+9-resistant kochia was seeded across the experiment upon its establishment in 2019.

This project extended the crop rotation experiment by another four years (2023-2026). In 2024, weed density by species before and after the post-emergence herbicide application, mid-season crop, kochia, and other weed biomass, and crop yield data were collected as proposed. Data analyses follow that outlined for Objectives 6 and 7. These analyses will be used to determine which crop rotation treatments are most effective at managing herbicide-resistant kochia, while also determining weed community shifts in response to the various crop rotations. It is hypothesized that the crop rotations containing winter wheat will reduce kochia densities, however over time this will also result in greater densities of winter-annual weeds (e.g., downy brome or Japanese brome) in these treatments. Crop rotation, life cycle, year and their interactions will be considered fixed factors while replication will be considered random.

Table 4. Fully-phased crop rotation treatments included in the experiment used to understand the impact of crop rotation and crop life cycle diversity on kochia management near Lethbridge, AB.

Treatment	Rotation	Phase	Life cycle[a]	2019[b]	2020	2021	2022	2023	2024	2025	2026
1	1	A	SA	SW	C	SW	C	SW	C	SW	C
2	1	B	SA	C	SW	C	SW	C	SW	C	SW
3	2	A	SA	SW	L	SW	L	SW	L	SW	L
4	2	B	SA	L	SW	L	SW	L	SW	L	SW
5	3	A	SA	SW	C	SW	L	SW	C	SW	L
6	3	B	SA	C	SW	L	SW	C	SW	L	SW
7	3	C	SA	SW	L	SW	C	SW	L	SW	C
8	3	D	SA	L	SW	C	SW	L	SW	C	SW
9	4	A	SA/WA	WW	C	WW	C	WW	C	WW	C
10	4	B	SA/WA	C	WW	C	WW	C	WW	C	WW
11	5	A	SA/WA	WW	L	WW	L	WW	L	WW	L
12	5	B	SA/WA	L	WW	L	WW	L	WW	L	WW
13	6	A	SA/WA	WW	C	WW	L	WW	C	WW	L
14	6	B	SA/WA	C	WW	L	WW	C	WW	L	WW
15	6	C	SA/WA	WW	L	WW	C	WW	L	WW	C
16	6	D	SA/WA	L	WW	C	WW	L	WW	C	WW
17	7	N/A	P/SA	Alf/MB	Alf/MB	Alf/MB	Alf/MB	SW	L	SW	C

[a]Abbreviations: SA, summer-annual; WA, winter-annual; P, perennial; [b]Abbreviations: SW, spring wheat; C, liberty link canola; L, Clearfield lentil; WW, winter wheat; ALD, alfalfa; MB, meadow brome grass.

Results *(maximum of 20 pages (not including figures or tables))*

Describe research accomplishments during the reporting period under relevant objectives listed under "Objectives and Progress" section. Please accompany a written description of results with tables, graphs and/or other illustrations. Provide discussion necessary to the full understanding of the results. Where applicable, results should be discussed in the context of existing knowledge and relevant literature. Detail any major concerns or project setbacks.

All results presented below are considered preliminary until the final analysis and report are completed.

1) Determine cross-resistance to PPO-inhibiting (Group 14) herbicides in PPO inhibitor-resistant kochia confirmed in SK

Both runs of all foliar-applied and soil-applied dose-response experiments were completed in 2024/2025. The dose-response analyses indicated that the Group 14-resistant kochia population collected from Saskatchewan in 2021 exhibited resistance to foliar-applied saflufenacil, carfentrazone-ethyl (Figure 1), tiafenacil, saflufenacil + trifludimoxazin, and pyraflufen-ethyl and soil-applied flumioxazin, sulfentrazone (Figure 2), and saflufenacil + trifludimoxazin. However, the Group 14-resistant kochia was susceptible to foliar-applied acifluorfen (Figure 3) and oxyfluorfen. Therefore, the assessment of cross-resistance among Group 14 herbicides available in western Canada suggests that Group 14-resistant kochia was resistant to almost all Group 14 products used in the region, with the exception of those in the diphenyl ether family (Figure 4). Unfortunately, herbicides within this family currently have limited use in the region with registration in soybean and for some horticultural uses. However, these results suggest that label expansion for these products could help manage Group14-resistant kochia.

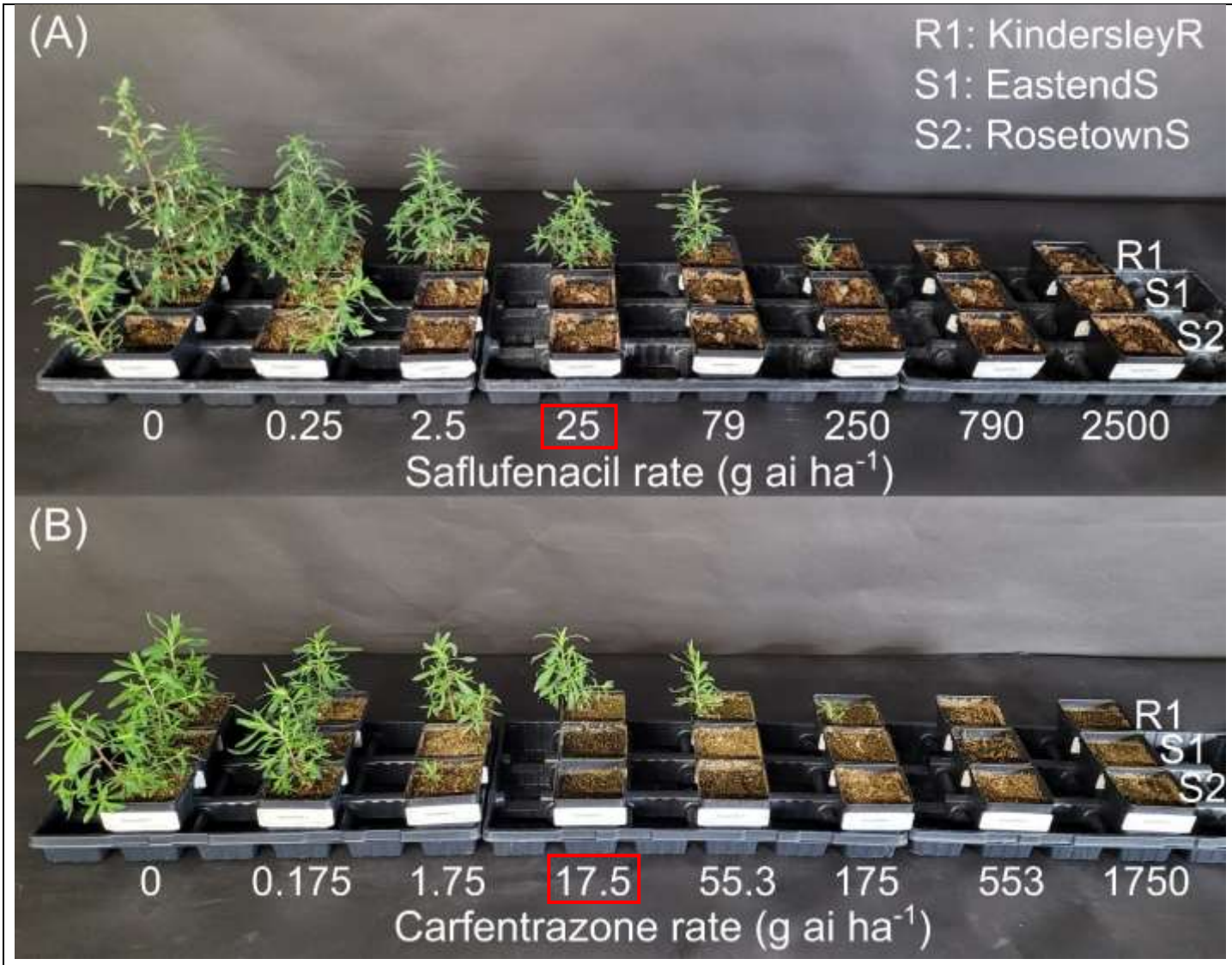

Figure 1. One replicate of the dose-response experiments with (A) saflufenacil, and (B) carfentrazone-ethyl showing the response of protoporphyrinogen oxidase inhibitor (Group 14)-resistant kochia (R1; back) compared with two susceptible control accessions (S1 and S2; middle and front) three weeks after foliar treatment. Rough field rates for each product are highlighted in red. Figure adapted from Geddes et al. (2025a).

Sustainable Canadian Agricultural Partnership
Saskatchewan
Canada

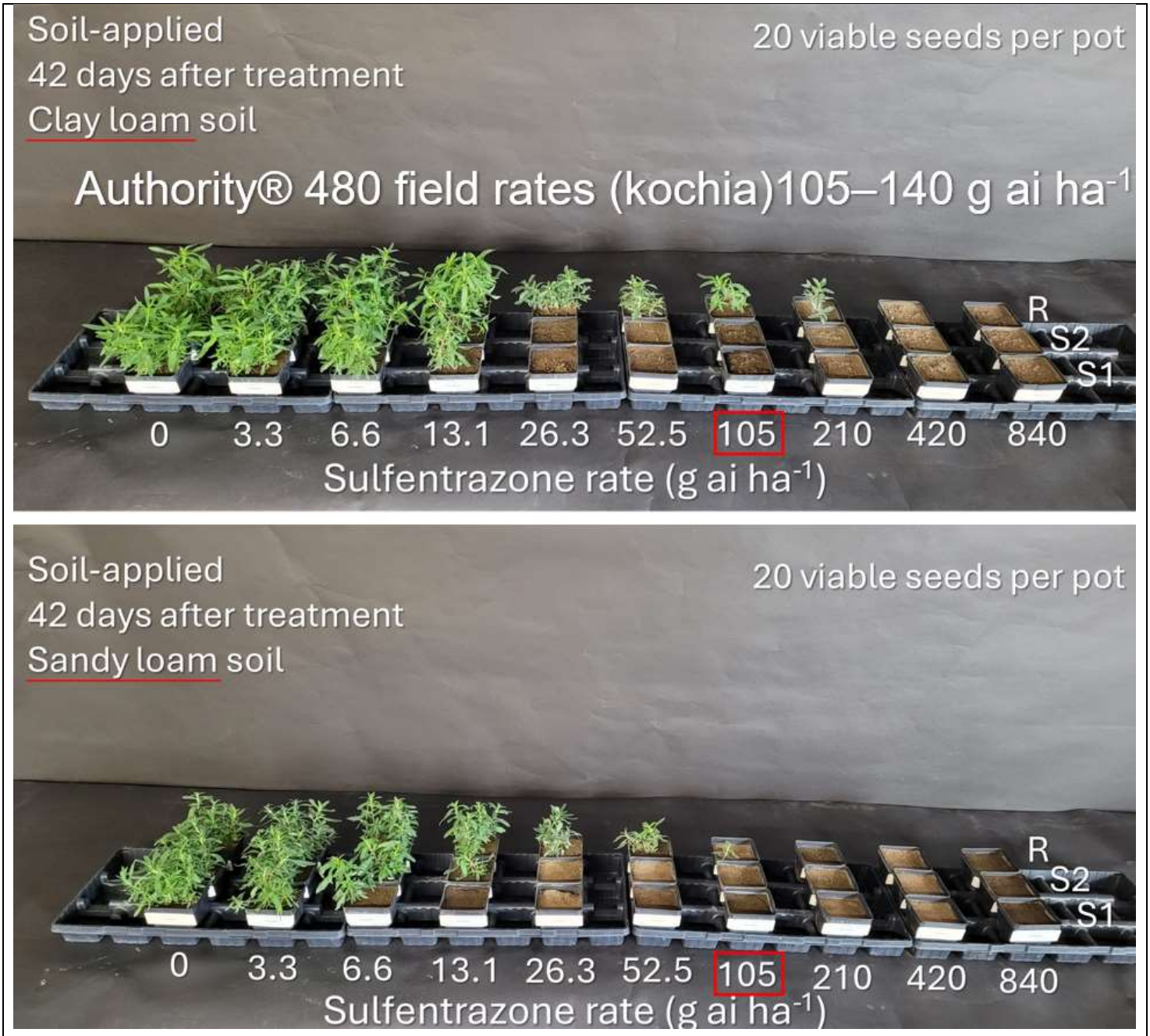

Figure 2. One replicate of the dose-response experiments with soil-applied sulfentrazone in clay loam (top), and sandy loam (bottom) soils showing the response of protoporphyrinogen oxidase inhibitor (Group 14)-resistant kochia (R; back) compared with two susceptible control accessions (S1 and S2, middle and front) six weeks after soil treatment. The field rate is highlighted in red.

Sustainable Canadian Agricultural Partnership
Saskatchewan
Canada

Figure 3. One replicate of the dose-response experiment with acifluorfen showing the response of protoporphyrinogen oxidase inhibitor (Group 14)-resistant kochia (R; back) compared with two susceptible control accessions (S1 and S2; middle and front) three weeks after foliar treatment. The field rate is highlighted in red.

Sustainable Canadian Agricultural Partnership
Saskatchewan
Canada

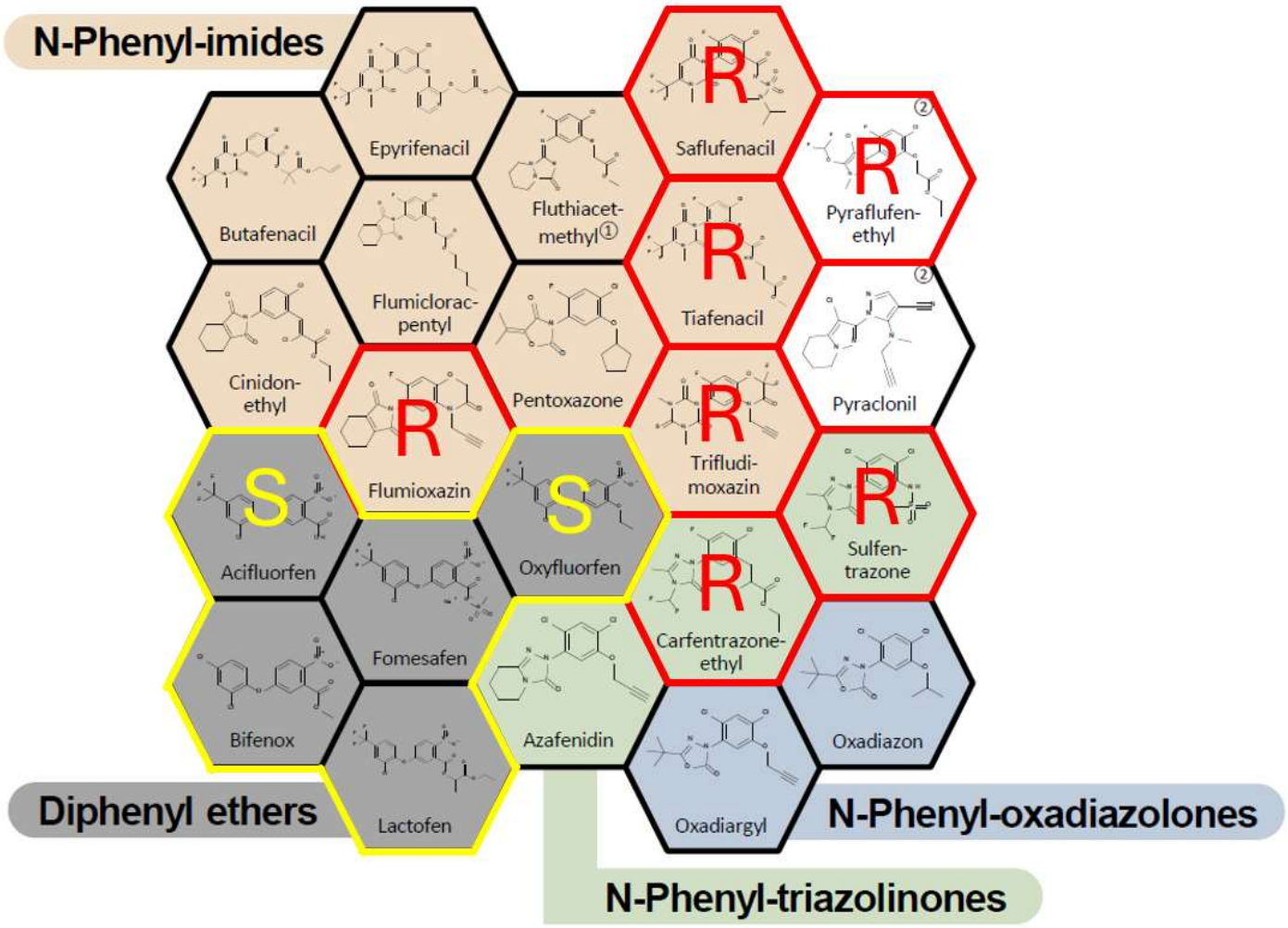

Figure 4. Diagram depicting PPO-inhibiting active ingredients separated into their chemical families. Active ingredients outlined in red indicate those to which the Group 14-resistant kochia population from Saskatchewan exhibits resistance, while those in yellow indicate susceptibility based on dose-response experiments.

2) Determine cross- or multiple-resistant to other herbicide modes of action in PPO inhibitor (Group 14)-resistant kochia

All experiments to determine cross- or multiple-resistance have been completed. In 3-rate screening experiment, the Group 14-resistant kochia population from Saskatchewan survived either 1X or 2X rates of thifensulfuron + tribenuron (Group 2), glyphosate (Group 9) and fluroxypyr (Group 4), but not dicamba (Group 4) or metribuzin (Group 5). The subsequent fluroxypyr dose-response experiment confirmed that the Group 14-resistant kochia population was susceptible to fluroxypyr (data not shown). qPCR analyses of the gene encoding EPSPS (the target site for glyphosate) revealed that the Group 14-resistant kochia had 22.5 ± 1.4 fold increase in EPSPS gene copy number relative to the susceptible control. Therefore, this suite of experiments confirmed that the Group 14-resistant kochia population from Saskatchewan exhibited multiple-resistance to herbicide Groups 2, 9, and 14.

3) Determine the mechanism conferring resistance to PPO-inhibiting (Group 14) herbicides in kochia

Molecular analyses revealed that the mechanism conferring Group 14 resistance in the kochia population from Saskatchewan was a novel target site mutation not known to occur in other weed species. Protein modelling revealed three potential amino acid substitutions at this location that could confer Group 14 resistance in kochia. Detailed results will be presented in future reports after the peer-reviewed article is published because some information is protected under the material transfer agreement. We are currently in the process of developing a molecular test that will be used to identify Group 14 resistance using kochia leaf tissue.

4) Continue monitoring kochia survey samples for PPO inhibitor (Group 14) resistance across the Canadian Prairies

The baseline survey (2018-2021) of Group 14-resistant kochia in western Canada was completed and published by Geddes et al. (2025b). No saflufenacil resistance was found among 882 survey samples collected across the region in 2018-2021 (data not shown). However, Group 14 resistance was confirmed in two of 14 grower-submitted samples: one was the original case from Saskatchewan in 2021 and the other from Forty Mile County, AB in 2023 (Figure 5). The subsequent assessment across the region is underway, beginning with 281 samples collected from 210 sites in Saskatchewan in fall 2024 (Figure 6). Single-dose screening with saflufenacil has been completed for 214 of the 281 samples. Preliminary results suggest that Group 14 resistance in kochia has increased substantially since 2021. Among the samples tested, 8% exhibited moderate or high resistance to saflufenacil (≥20% plant survival) while another 24% were developing resistance (>5% to <20% plant survival) (data not shown). Plants that survived saflufenacil treatment under controlled environment were sampled for DNA extraction and molecular identification using the assay being developed under objective 3. These preliminary results suggest that Group 14 resistance could be spreading rapidly among kochia populations in Saskatchewan.

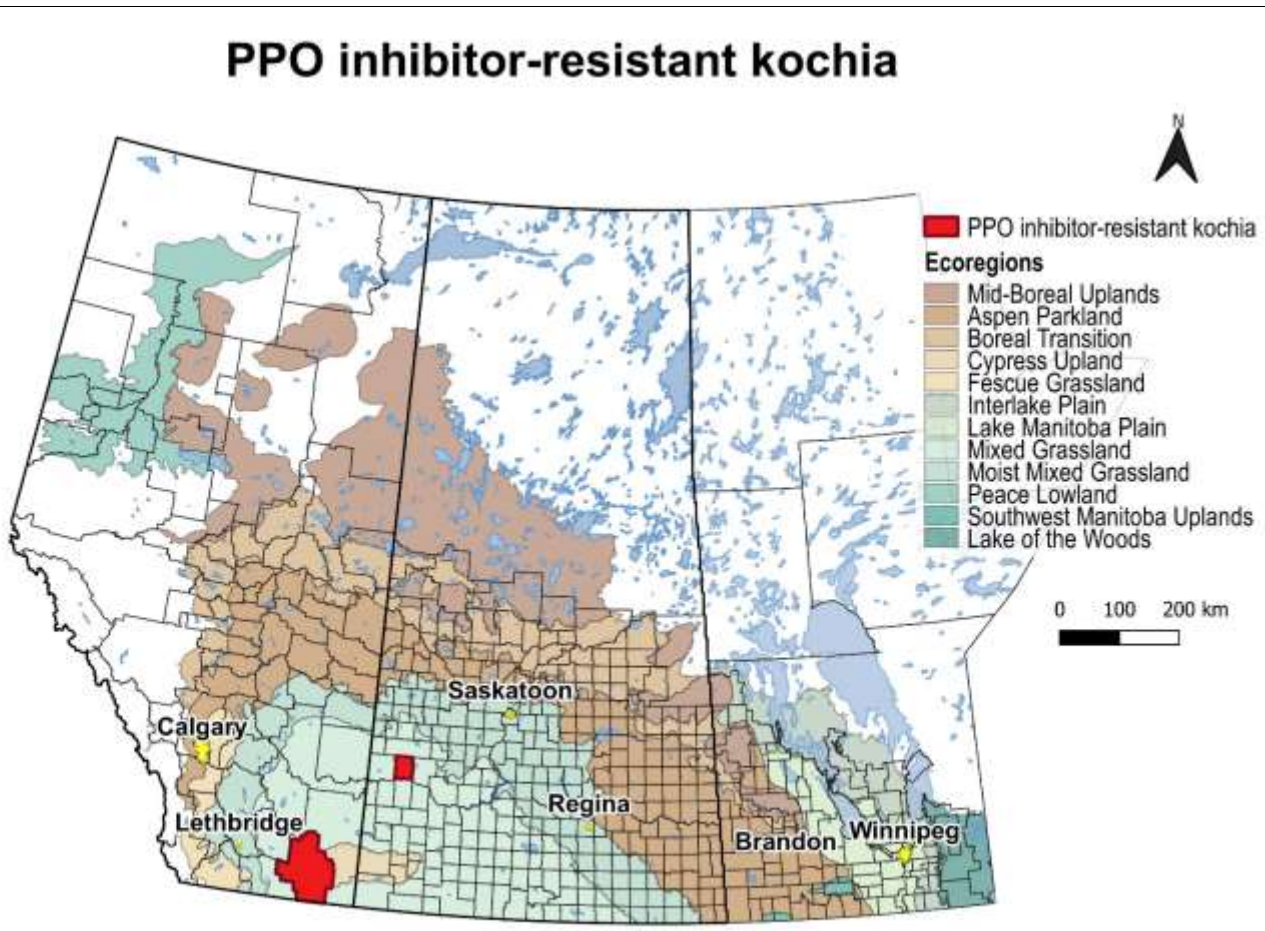

Figure 5. Map of the Canadian Prairies showing the locations of two fields where protoporphyrinogen oxidase inhibitor (Group 14)-resistant kochia was confirmed in west-central Saskatchewan (brown mustard field in 2021) and southern Alberta (seedling alfalfa field in 2023). Figure adapted from Geddes et al. (2025b).

Sustainable Canadian Agricultural Partnership
Saskatchewan
Canada

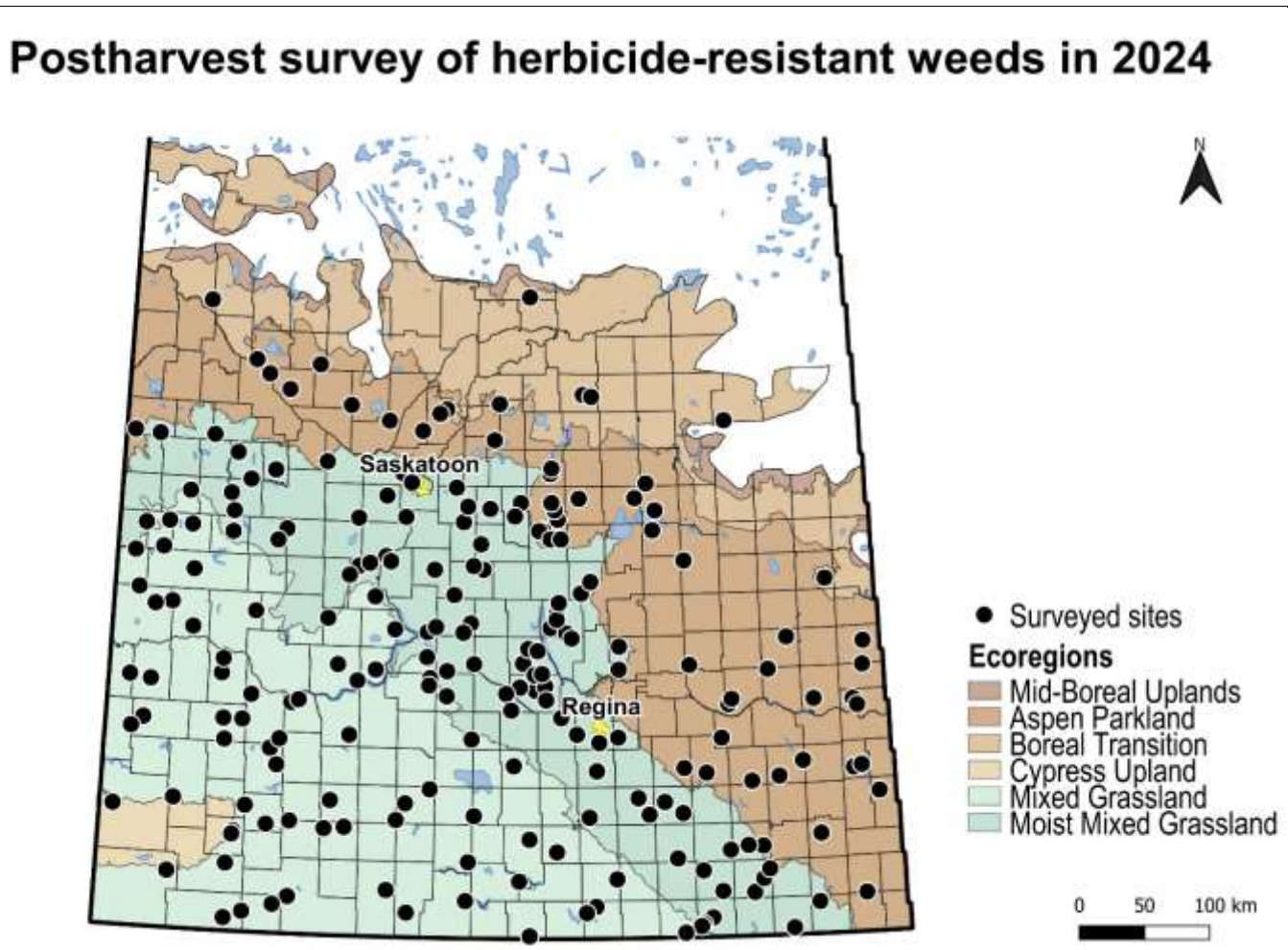

Figure 6. Fields sampled during the 2024 postharvest survey of herbicide-resistant weeds in Saskatchewan.

5) Assess the efficacy of alternative herbicides to manage multiple herbicide-resistant kochia prior to crop seeding

The first repeat of the pre-plant burndown experiment was conducted at Lethbridge, AB and Scott, SK in 2024. No differences in kochia density or biomass were observed at Lethbridge, perhaps due to the very high density of kochia present at this site (Table 5). Based on visible control, both rates of glufosinate resulted in the greatest control of the kochia at Lethbridge among the burndown treatments tested. As expected, control declined as time progressed after the burndown treatment. All herbicide treatments other than glufosinate resulted in poor control that was less than the 60% threshold considered "suppression" by the Pest Management Regulatory Agency. Far better control was observed at the Scott, SK site. Topramezone + bromoxynil (6 + 140 g ai ha^{-1}) alone or mixed with glyphosate (900 g ae ha^{-1}), and the high rate of diquat (1100 g ai ha^{-1}) resulted in a reduction in kochia biomass compared with the untreated control. Based on visible control ratings, bromoxynil (280 or 350 g ai ha^{-1}), topramezone + bromoxynil (6 + 140 g ai ha^{-1}) alone or mixed with glyphosate (900 g ae ha^{-1}), diquat (550 or 1100 g ai ha^{-1}) and glufosinate (400 or 600 g ai ha^{-1}) all provided adequate (≥80%) kochia control at either 1 or 3 weeks after treatment. While glufosinate consistently provided good kochia control as a burndown between sites, this is the only product tested that is not registered for this use window. Good control with several other treatments at Scott but not at Lethbridge suggests that the effectiveness of these burndown herbicide options may depend on the environment under which they are used.

The residual preemergence experiment was established at Lethbridge, AB and Scott, SK in fall 2024 and measurements are currently underway.

Table 5. Efficacy of pre-plant burndown herbicides for control of kochia assuming blanket resistance to HRAC Group 2, 4, 9 and 14 at Lethbridge, AB in 2024[a,b]

		Visible control				Biomass
Treatment	Rate	1 WAT	3 WAT	9 WAT	Density	DW
	g ai/ae ha^{-1}	*%*	*%*	*%*	*plants m^{-2}*	*g m^{-2}*
Untreated					1795	386
Glyphosate	900	15 d	20 bc	5 b	1372	449
Bromoxynil	280	18 d	13 bc	13 ab	1137	375
Bromoxynil	350	23 d	15 bc	13 ab	1085	370
Glyphosate + Bromoxynil	900 + 280	18 d	23 bc	10 ab	811	426
Glyphosate + Bromoxynil	900 + 350	23 d	13 bc	8 b	881	399
Topramezone + Bromoxynil	6 + 140	33 cd	20 bc	13 ab	878	442
Glyphosate + Topramezone + Bromoxynil	900 + 6 + 140	55 b	33 b	10 ab	976	398
Diquat	550	28 cd	10 c	15 ab	1318	415
Diquat	1100	44 bc	23 bc	13 ab	525	375
Glufosinate	400	79 a	73 a	33 ab	700	372
Glufosinate	600	84 a	78 a	40 a	480	359
P-value		< 0.0001	< 0.0001	0.0021	0.4213	0.1938

[a]Within columns, different letters indicate significant difference based on Tukey's HSD (α = 0.05).
[b]Abbreviations: DW, dry weight; WAT, weeks after treatment.

Table 6. Efficacy of pre-plant burndown herbicides for control of kochia assuming blanket resistance to HRAC Group 2, 4, 9 and 14 at Scott, SK in 2024[a,b]

		Visible control				Biomass
Treatment	Rate	1 WAT	3 WAT	9 WAT	Density	DW
	g ai/ae ha^{-1}	*%*	*%*	*%*	*plants m^{-2}*	*g m^{-2}*
Untreated					494 a	197 a
Glyphosate	900	71 a	69 c	40 d	297 ab	74 ab
Bromoxynil	280	74 a	85 abc	63 bcd	123 b	49 ab
Bromoxynil	350	82 a	94 ab	70 abcd	75 b	77 ab
Glyphosate + Bromoxynil	900 + 280	66 a	79 abc	55 cd	265 ab	113 ab
Glyphosate + Bromoxynil	900 + 350	61 a	70 bc	50 d	278 ab	106 ab
Topramezone + Bromoxynil	6 + 140	98 a	97 a	98 a	5 b	15 b
Glyphosate + Topramezone + Bromoxynil	900 + 6 + 140	98 a	100 a	95 a	1 b	25 b
Diquat	550	93 a	94 ab	83 abc	34 b	53 ab
Diquat	1100	99 a	99 a	90 ab	3 b	25 b
Glufosinate	400	99 a	97 a	90 ab	23 b	39 ab
Glufosinate	600	99 a	97 a	91 ab	14 b	32 ab
P-value		0.0079	< 0.0001	< 0.0001	< 0.0001	0.0133

[a]Within columns, different letters indicate significant difference based on Tukey's HSD (α = 0.05).
[b]Abbreviations: DW, dry weight; WAT, weeks after treatment.

6) Determine the mid/long-term utility and sustainability of strategic tillage for kochia management

After 10 years, both strategic tillage and conventional tillage resulted in substantially lower kochia plant densities following postemergence weed management in wheat grown in 2024 (Table 7). A similar trend was observed in the soil seedbank samples collected after harvest in 2024, however significant differences were absent at $P < 0.05$. Despite lower kochia densities in strategic and conventional tillage than no tillage, these differences were absent across all weed species together. The seedbank data were not separated into depth within the soil due to an abundance of 0 values that hindered frequentist statistical analyses, and so these data are presented for the combined 15 cm (6") depth of soil.

Table 7. Kochia and all weed plant density after postemergence weed management in wheat and postharvest seedbank density after ten years of no-till vs. strategic till (once every 3 years) vs. conventional till (every year) near Lethbridge, AB in 2024[a]

	Plant density (plants m^{-2})		Seedbank density (seeds m^{-2})	
Treatment	Kochia	All weeds	Kochia	All weeds
No-till	99 a	141	177	505
Strategic-till	23 b	156	25	345
Conventional-till	6 b	156	34	387
SE	*15*	*46*	*45*	*146*
P-value	*0.0018*	*0.9682*	*0.0691*	*0.4054*

[a]Within columns, different letters indicate significant difference based on Tukey's HSD ($\alpha = 0.05$).

Among soil health parameters analyzed alongside the seedbank samples, conventional tillage reduced the bulk density and K concentration but increased the NO_3-N compared with no tillage (Table 8). Likewise, strategic tillage resulted in higher NO_3-N and lower K than no tillage. Despite statistical differences for NO_3-N and K concentrations, the magnitude of these differences were so small that they have little biological meaning. There was an interaction between tillage treatment and surface soil depth for bulk density and organic matter. Despite a significant F-test effect for organic matter, there was no difference between each tillage treatment at each soil depth indicating than no differences in stratification of organic matter were observed. However, the bulk density of the 0-2" surface layer was lower under conventional tillage than strategic or no tillage.

Taken together, these initial preliminary results suggest that strategic tillage may be a viable option to help manage kochia while maintaining a healthy soil. However, further analyses will be required to reach this conclusion.

Table 8. Stratification of surface soil properties by depth (0-2”, 2-4”, 4-6”) after ten years of no-till vs. strategic till (once every 3 years) vs. conventional till (every year) near Lethbridge, AB in 2024[a,b]

Factor	BD	GWC	OM	ECEC	pH	NO_3-N	P	K	SO_4-S
	g cm^{-3}	%	%			kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Tillage									
No-till	1.47 a	15.2	2.88	21.8	7.37	3 b	19	280 a	9
Strategic-till	1.48 a	14.9	2.87	22.4	7.40	4 a	18	267 b	9
Conv-till	1.36 b	14.7	2.86	22.3	7.39	4 a	21	260 b	7
SE	*0.03*	*0.2*	*0.04*	*1.0*	*0.04*	*<1*	*2*	*11*	*2*
P-value	***<0.0001***	*0.2613*	*0.8595*	*0.7441*	*0.4949*	***<0.0001***	*0.1365*	***0.0003***	*0.3330*
Depth									
0-2”	1.30 c	13.0 b	3.23 a	20.6 b	7.26 c	5 a	33 a	348 a	9
2-4”	1.48 b	15.9 a	2.77 b	21.9 b	7.40 b	3 b	19 b	255 b	8
4-6”	1.52 a	15.9 a	2.61 c	24.0 a	7.51 c	3 b	6 c	204 c	8
SE	*0.03*	*0.2*	*0.04*	*1.0*	*0.04*	*<1*	*2*	*11*	*2*
P-value	***<0.0001***	***<0.0001***	***<0.0001***	***0.0010***	***<0.0001***	***<0.0001***	***<0.0001***	***<0.0001***	*0.6422*
Tillage × Depth									
No-till 0-2”	1.34 b	13.3	3.32 a	20.3	7.26	4	36	365	9
No-till 2-4”	1.56 a	16.1	2.72 bc	21.4	7.34	2	18	263	9
No-till 4-6”	1.51 a	16.2	2.60 c	23.8	7.50	2	4	212	9
Strategic-till 0-2”	1.36 b	13.2	3.22 a	20.6	7.26	5	32	345	9
Strategic-till 2-4”	1.54 a	15.8	2.72 bc	22.2	7.42	3	18	241	8
Strategic-till 4-6”	1.54 a	15.9	2.64 c	24.4	7.54	3	4	193	9
Conv-till 0-2”	1.21 c	12.5	3.14 a	21.0	7.26	5	33	335	9
Conv-till 2-4”	1.35 b	15.9	2.86 b	22.1	7.44	4	21	260	7
Conv-till 4-6”	1.52 a	15.8	2.60 c	23.9	7.48	4	10	208	7
SE	*0.03*	*0.4*	*0.05*	*1.3*	*0.05*	*<1*	*3*	*11*	*3*
P-value	***0.0001***	*0.8182*	***0.0149***	*0.9944*	*0.5852*	*0.5207*	*0.2887*	*0.0528*	*0.5910*

[a]Abbreviations: BD, bulk density; GWC, gravimetric water content; ECEC, estimated cation exchange capacity
[b]Within columns and factors, different letters indicate significant difference based on Tukey’s HSD (α = 0.05).

7) Assess the impact of timing and implement/depth of soil disturbance on kochia emergence, density, and the soil seedbank

No results to report yet.

8) Determine the mid/long-term impact of winter cereals and perennials in crop rotations on multiple herbicide-resistant kochia

The crop rotation study was continued as proposed for the sixth year in 2024. Crop yield under kochia interference differed by crop species grown in 2024 but not between crop sequences prior to the 2024 crop year (Table 9). The density of kochia present before and (3 weeks) after the in-crop herbicide treatment did not differ among the crop rotation treatments in year 6 of the crop rotation study. However, differences in kochia density were observed later in the growing season before crop harvest. Despite these differences, pre-harvest kochia densities all remained low (≤5 plants m^{-2}). The greatest late-season kochia densities were observed in either lentil or canola that followed either spring or winter wheat. A similar observation was made based on mid-season kochia biomass. Lack of difference between crop rotation treatments for some parameters in Table 9 could be due to low statistical power from only a single site-year of research. The final analyses across all years of the study will help improve model performance and reveal a more-comprehensive story.

Table 9. Kochia density, biomass and crop yield in year 6 of the crop rotation study (Test 1) used to understand the impact of crop diversity and crop life cycle diversity on management of multiple herbicide-resistant kochia[a]

	Kochia plant density				
Crop rotation[b]	Pre-spray	Post-spray	Pre-harvest	Kochia biomass	Crop yield
	plants m^{-2}			kg ha^{-1}	
SW-C-SW-C-SW-**C**	3	1	2 ab	379 bc	514 c
C-SW-C-SW-C-**SW**	<1	<1	<1 b	<1 c	2690 b
SW-L-SW-L-SW-**L**	<1	<1	1 b	5 c	586 c
L-SW-L-SW-L-**SW**	<1	<1	<1 b	1 c	2497 b
SW-C-SW-L-SW-**C**	2	1	1 b	4 c	646 c
C-SW-L-SW-C-**SW**	1	1	<1 b	4 c	2698 b
SW-L-SW-C-SW-**L**	3	2	3 ab	928 ab	551 c
L-SW-C-SW-L-**SW**	<1	<1	<1 b	<1 c	2594 b
WW-C-WW-C-WW-**C**	9	1	2 ab	266 bc	1046 c
C-WW-C-WW-C-**WW**	56	15	<1 b	<1 c	5196 a
WW-L-WW-L-WW-**L**	3	2	3 ab	1357 a	550 c
L-WW-L-WW-L-**WW**	5	1	<1 b	<1 c	5011 a
WW-C-WW-L-WW-**C**	6	3	3 ab	123 c	918 c
C-WW-L-WW-C-**WW**	25	2	<1 b	<1 c	5281 a
WW-L-WW-C-WW-**L**	7	3	5 a	590 abc	795 c
L-WW-C-WW-L-**WW**	8	2	<1 b	<1 c	4909 a
Alf/MB(x4)-SW-**L**	<1	<1	<1 b	<1 c	430 c
P-value	*0.2788*	*0.5330*	***<0.0001***	***<0.0001***	***<0.0001***

[a]Within columns, different letters indicate significant difference based on Tukey's HSD (α = 0.05).
[b]Abbreviations: ALF/MB, alfalfa/meadow brome grass; C, Liberty link canola; L, Clearfield lentil; SW, spring wheat; WW, winter wheat.

Interim Conclusions

Describe the interim conclusions.

All results presented in this report are considered preliminary until the final analyses and report are completed. Preliminary conclusions are as follows:

1) Group 14-resistant kochia exhibits resistance to a range of Group 14 active ingredient used in western Canada with the exception of the diphenyl ether family (currently registered in soybean and some horticultural crops).
2) The Group 14-resistant kochia population collected form Saskatchewan in 2021 exhibited multiple-resistance to Groups 2 and 9 but not 4 and 5.

3) Group 14 resistance in kochia is conferred by a novel PPO1 target-site mutation that is not known to occur in other species.
4) Preliminary screening of survey samples suggests that Group 14 resistance may be spreading rapidly among kochia populations in Saskatchewan, with 8% of those tested in 2024 exhibiting moderate or high resistance (≥20% plant survival).
5) Alternative pre-plant burndown options for Group 2, 4, 9 and 14 resistant kochia were inconsistent among sites. The most consistent of which was glufosinate, the only herbicide tested that is not currently registered for this use window.
6) After 10 years of no-till vs. strategic-till (once every 3 years) vs. conventional-till (every year), kochia plant densities were substantially reduced by strategic and conventional tillage compared with no tillage.
7) In the sixth year of the crop rotation study, late-season kochia densities and biomass were greatest in lentil or canola that followed either spring wheat or winter wheat.

Technology Transfer Activities

List any technology transfer activities undertaken in relation to this project. Include conference presentations, talks, papers published in science journals or other magazines etc.

Peer-reviewed articles published in science journals

1) Geddes, C.M., Law, Q.D., Jenks, B.M., Howatt, K.A., Ikley, J.T., Jaster, A., Pittman, M.M., Biggers, K., Meiners, I., and Porri, A. 2025. Protoporphyrinogen oxidase (PPO)-inhibitor resistance in kochia (*Bassia scoparia*). *Weed Science* **73**(e36):1-12. doi: 10.1017/wsc.2025.4
2) Geddes, C.M., Pittman, M.M., Sharpe, S.M., and Leeson, J.Y. 2025. Baseline survey of protoporphyrinogen oxidase inhibitor-resistant kochia (*Bassia scoparia*) in western Canada. *Canadian Journal of Plant Science* **105**:1-6. doi: 10.1139/cjps-2024-0219

Guest lectures

1) Kochia biology and management. Weed Science course. University of Alberta, AB, CA. Mar 31, 2025. Instructor: Nat Kav. *Invited lecture.*
2) Herbicide-resistant weeds in western Canada. Weed Science Short Course – Western Canada. Winnipeg, MB, CA. Jan 29, 2025. Instructor: Peter Sikkema and Kim Brown-Livingston. *Invited lecture.*
3) Kochia biology and management. Weed Science course. University of Alberta, AB, CA. Apr 03, 2024. Instructor: Nat Kav. *Invited lecture.*

Workshops, seminars, webinars or field days

1) Geddes, C.M. 2025. Managing Herbicide Resistance. Richardson Pioneer CropWatch Webinar. Virtual. Feb 19, 2025. (Oral Presentation). *~200 agronomists in attendance.*
2) Geddes, C.M. 2025. Wicked weeds of the west: How are the changing and what can you do about it? CropConnect Conference 2025. Winnipeg, MB. Feb 12-13, 2025. (Oral Presentation). *~200 farmers, agronomists, and industry members in attendance.*
3) Geddes, C.M. 2025. Creativity kills kochia. Manitoba Crop Alliance – All Crop Committee Delegates Meeting. Brandon, MB. Jan 30, 2025. (Oral Presentation). *~30 delegates and staff members in attendance.*
4) Geddes, C.M. 2025. Herbicide-resistant weeds and threats to no-till management. Sustaining Barley webinar series: Threats to no-till progress: Examining threats to progress on no-till adoption in barley production systems. American Malting Barley Association, Canadian Malting Barley Technical Centre, Brewing and Malting Barley Research Institute. Virtual. Jan 08, 2025. (Oral Presentation). Invited. *~40 industry members in*

attendance.

5) Geddes, C.M., Japp, M., and Ford, E. 2024. Weed management: Research insights and farmer perspectives. Expert Panel. Sponsored by Bayer CropScience Inc. Banff, AB. Nov 28, 2024. (Oral Presentation). Invited. *~200 farmers, agronomists, and industry members in attendance.*
6) Geddes, C.M., Palmier, M., and Cranston, R. 2024. Discussion on Western Canadian herbicide resistance. TopCrop Webinar. Sponsored by Bayer CropScience Inc. Virtual. Nov 14, 2024. (Oral Presentation). Invited. *~250 farmers, agronomists, and industry members in attendance.*
7) Geddes, C.M. 2024. Resistance monitoring and tailoring IPM. CropLife Canada Information Sharing Session on the Environmental Risks and Regulatory Oversight of Novel Herbicide Tolerant Traits. Ottawa, ON. Oct 17, 2024. (Oral Presentation). Invited by Jennifer Hubert, Executive Director, Plant Biotechnology, CropLife Canada. *~50 industry members in attendance.*
8) Geddes, C.M. 2024. Herbicide resistance testing and plot tour. Field tour with Saskatchewan Ministry of Agriculture delegates. Lethbridge, AB. Jul 09, 2024. (Oral Presentation). *~8 delegates in attendance.*

Media interviews

1) Bayer Crop Science. 2025. A deep dive into herbicide resistance. *Top Crop Manager*. Dec 04, 2024.
2) Barker, B. 2024. Top Crop Summit series: Herbicide resistant weeds in the Prairies. *Top Crop Manager*. Apr 15, 2024.

Contributions and Support

Identify any changes expected to industry contributions, in-kind support, collaborations or other resources.

No changes to report.

Appendices

Include any additional materials supporting the previous sections, e.g. detailed data tables, maps, graphs, specifications, literature cited (Use a consistent reference style throughout).

Literature cited

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

Beckie, H.J., Gulden, R.H., Shaikh, N., Johnson, E.N., Willenborg, C.J., Brenzil, C.A., Shirriff, S.W., Lozinski, C., and Ford, G. 2015. Glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Saskatchewan and Manitoba. *Canadian Journal of Plant Science* **95**:345-349.

Beckie, H.J., Blackshaw, R.E., Hall, S.M., and Johnson, E.N. 2016. Pollen- and seed-mediated gene flow in kochia (*Kochia scoparia*). *Weed Science* **64**:624-633.

Beckie, H.J., Blackshaw, R.E., Leeson, J.Y., Stahlman, P.W., Gaines, T.A., and Johnson, E.N. 2018. Seedbank persistence, germination and early growth of glyphosate-resistant *Kochia scoparia*. *Weed Research* **58**:177-187.

Cardina, J., and Sparrow, D.H. 1996. A comparison of methods to predict weed seedling populations from the soil seedbank. *Weed Science* **44**:46-41.

Geddes, C.M., and Sharpe, S.M. 2022. Crop yield losses due to kochia (*Bassia scoparia*) interference. *Crop Protection* **157**:105981.

Geddes, C.M., Law, Q.D., Jenks, B.M., Howatt, K.A., Ikley, J.T., Jaster, A., Pittman, M.M., Biggers, K., Meiners, I., and Porri, A. 2025a. Protoporphyrinogen oxidase (PPO)-inhibitor resistance in kochia (*Bassia scoparia*). *Weed Science* **73**(e36):1-12.

Geddes, C.M., Pittman, M.M., Sharpe, S.M., and Leeson, J.Y. 2025b. Baseline survey of protoporphyrinogen oxidase inhibitor-resistant kochia (*Bassia scoparia*) in western Canada. *Canadian Journal of Plant Science* **105**:1-6.

Geddes, C.M., Pittman, M.M., Hall, L.M., Topinka, A.K., Sharpe, S.M., Leeson, J.Y., and Beckie, H.J. 2023. Increasing frequency of multiple herbicide-resistant kochia (Bassia scoparia) in Alberta. *Canadian Journal of Plant Science* **103**:233-237.

Geddes, C.M., Pittman, M.M., Gulden, R.H., Jones, T., Leeson, J.Y., Sharpe, S.M., Shirriff, S.W., and Beckie, H.J. 2022a. Rapid increase in glyphosate resistance and confirmation of dicamba-resistant kochia (*Bassia scoparia*) in Manitoba. *Canadian Journal of Plant Science* **102**:459-464.

Geddes, C.M., Owen, M.L., Ostendorf, T.E., Leeson, J.Y., Sharpe, S.M., Shirriff, S.W., and Beckie, H.J. 2022b. Herbicide diagnostics reveal multiple patterns of synthetic auxin resistance in kochia (*Bassia scoparia*). *Weed Technology* **36**:28-37.

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

Sharpe, S.M., Leeson, J.Y., Geddes, C.M. Willenborg, C.J., and Beckie, H.J. 2023. Survey of glyphosate and dicamba-resistant kochia (*Bassia scoparia*) in Saskatchewan. *Canadian Journal of Plant Science* **103**:472-480.

Schwinghamer, T.D., and Van Acker, R.C. 2008. Emergence timing and persistence of kochia (*Kochia scoparia*). *Weed Science* **56**:37-41.

Sustainable Canadian Agricultural Partnership

Saskatchewan

Canada