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ARTICLE

Herbicide strategies for managing glyphosate-resistant and -susceptible kochia (*Bassia scoparia*) in spring wheat

Alysha T. Torbiak, Robert E. Blackshaw, Randall N. Brandt, Bill Hamman, and Charles M. Geddes

Abstract: Kochia [*Bassia scoparia* (L.) A.J. Scott] is a summer annual tumbleweed that is tolerant of heat, drought, and salinity and capable of causing large yield losses in spring wheat (*Triticum aestivum* L). Increased incidence of glyphosate- and acetolactate synthase (ALS) inhibitor-resistant kochia in western Canada warrants investigation of alternative herbicides to manage these biotypes. Herbicides applied pre- or post-emergence in spring wheat were evaluated based on crop tolerance and control of ALS inhibitor-resistant kochia accessions with and without the glyphosate resistance trait in five environments near Lethbridge and Coalhurst, Alberta, from 2013 to 2015. The most effective and consistent treatments for kochia management included sulfentrazone applied pre-emergence and fluroxypyr/bromoxynil/2,4-D or pyrasulfotole/bromoxynil applied post-emergence. All of these treatments resulted in ≥90% visible control in all environments and ≥90% kochia biomass reduction compared with the untreated control in Lethbridge 2014 and 2015. MCPA/dichlorprop-p/mecoprop-p, dicamba/2,4-D/mecoprop-p, and dicamba/fluroxypyr resulted in acceptable control among environments (≥80% visible control in all environments and ≥80% kochia biomass reduction in Lethbridge 2014 and 2015); however, the latter two options caused unacceptable (>10%) wheat visible injury in Coalhurst 2014. Recent confirmations of auxinic herbicide-resistant kochia in western Canada—due, in part, to use of synthetic auxins to manage glyphosate-resistant kochia in small-grain cereals—will limit kochia management options. When implemented with non-chemical tools as part of an integrated weed management program, alternative herbicide modes of action like protoporphyrinogen oxidase inhibitors before and photosystem II or 4-hydroxyphenylpyruvate dioxygenase inhibitor(s) within spring wheat could mitigate selection for multiple herbicide-resistant kochia.

Key words: Bassia scoparia, glyphosate resistance, herbicide resistance, herbicide stewardship, *Kochia scoparia*.

Résumé : La kochie [*Bassia scoparia* (L.) A.J. Scott] est une annuelle estivale qui tolère la chaleur, la sécheresse et la salinité. L'adventice entraîne parfois de lourdes pertes dans les cultures de blé de printemps (*Triticum aestivum* L). La présence d'un nombre croissant de spécimens résistants au glyphosate et à l'inhibiteur de l'acétolactate synthase (ALS) dans l'Ouest canadien justifie l'examen d'autres herbicides pour combattre ces biotypes. De 2013 à 2015, les auteurs ont évalué l'application d'herbicides avant ou après la levée dans les champs de blé de printemps selon la tolérance de la culture et la destruction des obtentions de kochie résistantes à l'inhibiteur de l'ALS, avec ou sans gène codant la résistance au glyphosate, à cinq endroits près de Lethbridge et de Coalhurst, en Alberta. Le traitement le plus efficace et le plus uniforme pour lutter contre la kochie consiste à appliquer du sulfentrazone avant la levée. Suivent l'application de fluroxypyr/bromoxynil/2,4-D ou de pyrasulfotole/bromoxynil après la levée. Ces traitements avaient supprimé ≥90% des plants de kochie visibles dans toutes les conditions et réduit la biomasse de l'adventice de ≥90%, comparativement aux parcelles témoins non traitées, à Lethbridge, en 2014 et en 2015. Le MCPA/dichlorprop-p/mecoprop-p, le dicamba/2,4-D/mecoprop-p et le dicamba/fluroxypyr demeurent acceptables pour combattre la kochie aux différents endroits testés (≥80% de plants visibles détruits dans tous les environnements et ≥80% de réduction de la biomasse à Lethbridge, en 2014 et en 2015). Cependant, les deux derniers traitements avaient causé des dommages manifestes et inacceptables (>10%) au blé à Coalhurst, en 2014. L'identification récente de kochies résistantes aux herbicides auxiniques dans l'ouest du Canada, en partie

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attribuable à l'usage d'auxines synthétiques pour combattre la kochie résistante au glyphosate dans les champs de céréales à paille, réduira le nombre de traitements envisageables contre l'adventice. Quand ils sont utilisés avec d'autres moyens non chimiques dans le cadre d'un programme de lutte intégré, les herbicides recourant à un autre mode d'action, comme les inhibiteurs de la protoporphyrinogène oxydase avant la levée et les inhibiteurs du photosystème II ou de la 4-hydroxyphénylpyruvate dioxygénase, pourraient ralentir la sélection des plants de kochie polyrésistants dans les champs de blé de printemps. [Traduit par la Rédaction]

Mots-clés : *Bassia scoparia*, résistance au glyphosate, résistance aux herbicides, gestion des herbicides, *Kochia scoparia*.

Introduction

Kochia [*Bassia scoparia* (L.) A.J. Scott] is a troublesome, summer annual C_4 tumbleweed that was introduced to North America as an ornamental garden forb in the late 1800s (Friesen et al. 2009). At present, kochia is widely disseminated among the prairie provinces of Canada and the western United States. While the range of kochia in North America continues to expand northward, its current northern distribution is limited by growing season length and thermal time requirements for successful reproduction (Beckie et al. 2012*b*). Despite these limitations, kochia remains the 15th most abundant weed species among annual crops in Alberta and Saskatchewan following post-emergence herbicide application, and the most abundant weed in the mixed grassland ecoregion of Alberta (Leeson 2016; Leeson et al. 2019).

Kochia is a problematic weed in agricultural lands including annual crops, perennial forages, hay fields, and rangeland, in addition to ruderal areas such as roadsides, railways, and oil well sites (Friesen et al. 2009). Several weedy traits allow kochia to thrive in such diverse environments. Kochia is tolerant of several abiotic stresses, including drought, heat, and salinity (Braidek et al. 1984; Friesen et al. 2009; Endo et al. 2014). In western Canada, it is among the first weed species to emerge in the spring, but prolonged emergence periodicity can result in emergence after pre- or post-emergence herbicide applications (Schwinghamer and Van Acker 2008; Dille et al. 2017; Kumar et al. 2018). Kochia plants produce a large number of seeds (up to 120 000 seeds·plant^{-1} in non-competitive environments), and these seeds can be dispersed over long distances when the stem of the senescing plant breaks at an abscission layer and the tumbleweed is blown by prevailing winds (Becker 1978; Stallings et al. 1995; Friesen et al. 2009; Beckie et al. 2016).

Herbicide resistance in kochia can spread rapidly due, in part, to protogynous flowering—where the stigmas emerge and are receptive to pollen before the anthers fully mature on the same plant—which causes initial outcrossing prior to self-pollination. Efficient pollen- and seed-mediated gene flow (Beckie et al. 2016) and short seedbank longevity (1–2 yr) (Beckie et al. 2018*a*) contribute to rapid population turnover and evolution of resistance in response to recurrent selection pressures, like herbicides. Acetolactate synthase (ALS) inhibitor-resistant kochia was reported first in Saskatchewan and Manitoba in 1988, and in Alberta in 1989 (Morrison and Devine 1994; Heap 2020). Two decades later, ALS inhibitor-resistant kochia was disseminated throughout western Canada, and present in 85% of surveyed populations (Beckie et al. 2011). Currently, all kochia populations in western Canada are considered ALS inhibitor-resistant (Beckie et al. 2019). Kochia was the first glyphosate-resistant (GR) weed reported in western Canada (in Alberta in 2011) (Beckie et al. 2013), following initial reports of this biotype in Kansas in 2007 (Kumar et al. 2019). Subsequent surveys in 2013 identified GR kochia in the prairie provinces of Saskatchewan and Manitoba (Beckie et al. 2015). In Alberta, glyphosate resistance in kochia spread rapidly from 4% to 50% of kochia populations sampled in 2012 and 2017, respectively (Hall et al. 2014; Beckie et al. 2019). The 2017 survey of Alberta also reported dicamba resistance in 18% of the kochia populations sampled, while 10% of the populations were triple herbicide-resistant to ALS inhibitors, glyphosate, and dicamba. Rapid spread of herbicide-resistant kochia in the Canadian Prairies over the past decade warrants investigation of alternative herbicide options in many crops, including small-grain cereals, pulses, and oilseeds.

Glyphosate is a non-selective herbicide that is touted for its several favorable qualities including systemic activity on a wide range of plant species, low mammalian toxicity, minimal impact on the environment, and low herbicide cost (Duke and Powles 2008). Farmers in the Great Plains of North America rely on glyphosate as a cost-effective option for pre-plant burndown weed control in place of tillage in no-till production systems (Geddes 2019). Widespread adoption of no-till cropping systems and production of GR crops contribute to increased glyphosate use pre-plant and post-emergence. In addition to these windows for weed control, farmers also use glyphosate to manage weeds pre- and post-harvest. As a result, glyphosate use in the Canadian Prairies tripled in the past decade (Blackshaw and Harker 2016), which undoubtedly increased selection pressure for GR weeds (Beckie et al. 2013). Greater abundance of GR weeds like kochia in the Great Plains of North America threatens the sustainability of no-till production systems because farmers may consider reverting to tillage for mechanical weed control (Geddes 2019).

Spring wheat (*Triticum aestivum* L.) (including durum) is the most grown crop in the Canadian Prairies based on seeded area, where it was grown on about 9.4 million ha in 2020 (Statistics Canada 2020). Kochia can be

Fig. 1. A kochia patch during spring wheat senescence in southwestern Saskatchewan. Photo credit: Dr. Charles M. Geddes © Her Majesty the Queen in Right of Canada, 2019. [Colour online].

difficult to manage in spring wheat, especially if it is controlled inadequately by, or emerges after, the pre-plant burndown herbicide application. Based on representative herbicide programs in the United States, GR kochia control varied among experimental sites to a greater extent in wheat compared with corn (*Zea mays* L.) or soybean [*Glycine max* (L.) Merr.] (Sbatella et al. 2019). Lower densities of glyphosate-susceptible (GS) kochia (14 and 21 plants·m^{-2}) reduced spring wheat yield by 10%–33% in Manitoba, while higher densities (195–520 plants·m^{-2}) reduced yield by 40%–73% (Friesen et al. 2009). In addition to yield loss, kochia can hinder harvest operations because indeterminate growth results in kochia plants which remain green long after spring wheat senescence (Fig. 1).

Due to the reliance on glyphosate for pre-plant weed control before growing wheat and the increased abundance of herbicide-resistant kochia in western Canada, there is a need to determine effective herbicide options for kochia control. The objective of this study was to determine which herbicide options remain effective for management of GR and GS kochia in spring wheat in western Canada.

Materials and Methods

Site description

Field experiments were conducted at the Agriculture and Agri-Food Canada Lethbridge Research and Development Centre located near Lethbridge, AB (49.69°N, −112.77°W), in 2013, 2014, and 2015, and at Hamman Ag Research Inc. located near Coalhurst, AB (49.79°N, −112.99°W), in 2013 and 2014. Soils at both locations were classified as dark brown chernozems. The soil at Lethbridge was a clay loam with 3.6% organic matter (OM) and pH 7.8, while the soil at Coalhurst was a loam with 2.5% OM and pH 8.3. In all years, the previous crop at Lethbridge was silage barley, while the previous crop at Coalhurst was chemical fallow.

Experimental design and treatment structure

The field experiment conducted within each of the five environments followed a split-block randomized complete block design with a two-way factorial treatment structure and four experimental replications (blocks). The main plot size was 2.5 m × 7.5 m in Lethbridge and Coalhurst 2013, 3.0 m × 7.5 m in Lethbridge 2014 and 2015, and 2.5 m × 6.0 m in Coalhurst 2014. Each block was split in half with two kochia accessions: one GR and the other GS. The kochia accession split-blocks were randomized among the experimental replications. A Fabro double-disk drill (or Fabro hoe-drill in Coalhurst 2014) (Fabro Enterprises Ltd., Swift Current, SK) was used to seed spring wheat 'AC Lillian' and kochia simultaneously along each experimental replication, perpendicular to the direction of the herbicide treatments. Each kochia accession was seeded in a different pass with the seeder. Each seeder pass included 10 rows of wheat spaced 23 cm apart with

9 rows of kochia seeded between the wheat rows. The wheat was planted at a depth of 3.5 cm, while the kochia seed was placed 0.3 cm below the soil surface and pressed into the soil with the seeder packing tires. Both wheat and kochia were seeded at a target rate of 300 viable seeds·m^{-2}. The wheat seed was treated with CruiserMaxx® Cereals (Syngenta Canada Inc., Guelph, ON), containing 2.8% thiamethoxam, 3.4% difenoconazole, and 0.6% metalaxyl-M, at 3.9 mL·kg^{-1} seed. Monoammonium phosphate or triple superphosphate fertilizer were placed within the seed-row and urea was placed in a side-row band (or ESN broadcast before seeding in Lethbridge 2015) based on soil test recommendations for spring wheat.

The kochia seed accessions were sourced from the Agriculture and Agri-Food Canada Lethbridge Research and Development Centre. The GR kochia accession was selected and maintained among successive generations following treatment with glyphosate (Roundup Transorb® HC, Monsanto Canada Inc., Winnipeg, MB) at 900 g a.e.·ha^{-1}. Both kochia accessions were ALS inhibitor-resistant, and the GS accession was selected and maintained among generations using thifensulfuron-methyl + tribenuron-methyl at 10 + 5 g a.i.·ha^{-1} (Refine® SG; FMC Corporation, Philadelphia, PA).

A pre-plant burndown was conducted in each environment with chemicals used based on the weed species that were present. In Lethbridge 2013 and Coalhurst 2013 and 2014, glyphosate was applied at 900 g a.e.·ha^{-1}. Glyphosate was applied at 1334 g a.e.·ha^{-1} at Lethbridge in 2014, while glyphosate + bromoxynil (Koril®, Nufarm Canada, Calgary, AB) were used at Lethbridge in 2015 at a rate of 1334 + 348 g a.e./a.i.·ha^{-1}.

Herbicide treatments were chosen because they were registered for control of kochia in spring wheat, or because they held potential for adequate kochia control with minimal wheat injury (Table 1). All herbicide treatments were applied post-emergence at the 4–5 leaf stage of wheat with the exception of sulfentrazone, which was applied pre-emergence (1–2 d before or after seeding). At Lethbridge, the herbicides were applied using a 2.0 m bicycle CO_2 sprayer equipped with Greenleaf Air Mix 110-010 nozzles (Greenleaf Technologies, Covington, LA) calibrated to deliver 100 L·ha^{-1} spray solution at 290 kPa when travelling at 5 km·h^{-1}. At Coalhurst, the herbicides were applied using a 2.0 m handheld propane-propelled sprayer equipped with John Deere LDX01 nozzles (John Deere, Moline, IL) calibrated to deliver 100 L·ha^{-1} spray solution at 242 kPa when travelling at 4 km·h^{-1}.

Data collection

Visible injury of wheat was assessed within each main plot as a percentage from 0% (visually similar to the untreated control) to 100% (complete necrosis) 3 wk after post-emergence herbicide application (WAA) (CWSS 2018). Wheat grain yield was determined by harvesting each subplot separately using a Wintersteiger Delta (Wintersteiger Inc., Saskatoon, SK) or Zürn 150 plot combine (Zürn Harvesting GmbH & Co. KG, Schöntal-Westernhausen, Germany), cleaning the seed using a clipper seed cleaner, and adjusting the clean seed weight to 14.5% moisture.

Kochia plant density was determined for each kochia accession 2 wk after emergence by counting all seedlings within a 0.25 m^2 quadrat placed randomly within each subplot. Visible control of kochia was assessed within each subplot as a percentage from 0% (visually similar to the untreated control) to 100% (complete necrosis) 3 WAA (CWSS 2018). Kochia shoot biomass fresh weight was determined 6 WAA by removing and weighing all kochia from a 0.5 m^2 area (3 rows × 0.71 m) within each subplot.

Statistical analysis

All data were analyzed using the GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). The wheat response variables included visible injury 3 WAA, and grain yield, while the kochia response variables included plant density, visible control 3 WAA, and shoot biomass. The analyses were separated by year due to the addition of two herbicide treatments in 2014 that were not present in 2013, and three treatments in 2015 that were not present in 2014. The main and interaction effects of herbicide treatment, kochia accession, and environment were considered fixed effects, while experimental replication nested within environment, the interaction of herbicide treatment and experimental replication nested within environment, and the interaction of kochia accession and experimental replication nested within environment were considered random effects.

Residual normality was assessed using the Shapiro–Wilk statistic, while homoscedasticity was assessed visually by plotting the residuals against the predicted values (Littell et al. 2006). Extreme outliers were removed based on Lund's test (Lund 1975). The covariance structure of residuals was adjusted to correct for heteroscedasticity based on minimization of the Akaike Information Criterion and visual assessment of the residuals vs. predicted values (Littell et al. 2006). For analyses of kochia visible control, the residual group option was set to environment, while the group option was set to the kochia accession by environment interaction for the other response variables. For kochia biomass, a lognormal distribution was fit with the identity link function to meet the assumptions of normality and homoscedasiticity. The F test was used to determine significant main and interaction effects, and means were compared using Tukey's HSD ($\alpha = 0.05$).

Results and Discussion

Annual weather variation

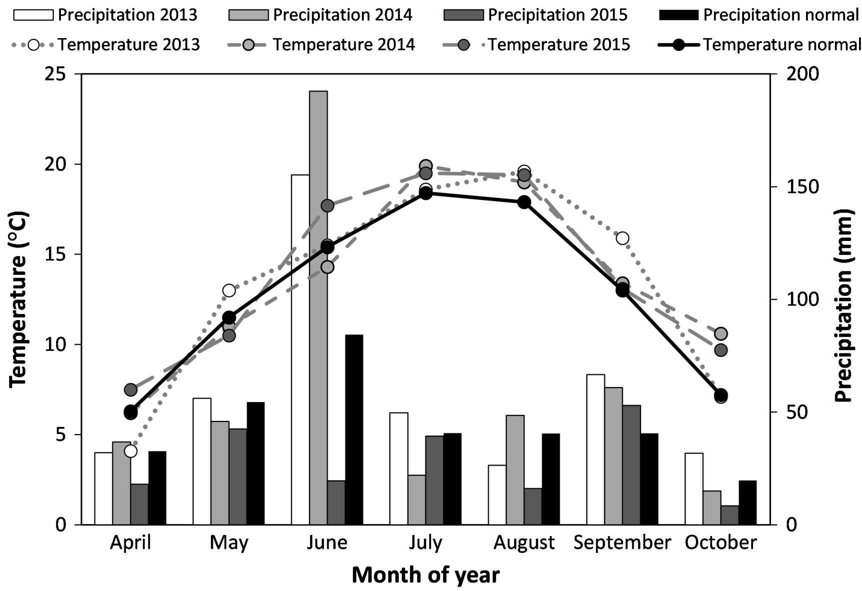
Temperatures during the growing season among the 3 yr of field experimentation in Lethbridge ranged on

Table 1. Herbicide treatments assessed based on control of glyphosate-resistant and glyphosate-susceptible kochia in spring wheat near Lethbridge and Coalhurst, AB, in 2013 and 2014, and Lethbridge in 2015.

Herbicide common name[a]	Herbicide trade name	Herbicide group	Concentration	Formulation (g a.e./a.i.·L^{-1})	Rate (g a.e./a.i.·ha^{-1})	Company
Dicamba + 2,4-D	Banvel® II + 2,4-D amine 600	4 + 4	480 + 560	SN + EC	110 + 420	BASF + Nufarm Agriculture
Bromoxynil/2,4-D	Thumper®	6/4	280/280	EC	280/280	Bayer CropScience
Fluroxypyr/2,4-D	OcTTain™ XL	4/4	90/360	EC	100/400	Corteva AgriScience
Florasulam/Fluroxypyr + MCPA	Stellar™ A + Stellar™ B	2/4 + 4	2.5/100 + 600	SC + EC	2.5/100 + 350	Corteva AgriScience
Dicamba/Fluroxypyr	Pulsar®	4/4	87/113	EC	80/104	Syngenta
Fluroxypyr + Clopyralid/MCPA	Prestige™ XCA + Prestige™ XCB	4 + 4/4	333 + 50/280	EC + EC	100 + 75/420	Corteva Agriscience
Fluroxypyr/Bromoxynil/2,4-D	Enforcer® D	4/6/4	80/190/240	EC	48/114/144	Nufarm Agriculture
Fluroxypyr/Bromoxynil/2,4-D	Enforcer® D	4/6/4	80/190/240	EC	96/228/288	Nufarm Agriculture
MCPA/Diclorprop-P/Mecoprop-P	Optica™ Trio	4/4/4	160/310/130	SN	395/765/320	Nufarm Agriculture
MCPA/Mecoprop-P/Dicamba	Target®	4/4/4	275/62.5/62.5	SN	275/62.5/62.5	Syngenta
Pyrasulfotole/Bromoxynil	Infinity® [b]	27/6	37.5/210	EC	30/170	Bayer CropScience
Dicamba/2,4-D/Mecoprop-P	DyVel® DS$_{P}$	4/4/4	110/295/80	SN	93/251/68	BASF
Dicamba/2,4-D/Mecoprop-P	DyVel® DS$_{P}$	4/4/4	110/295/80	SN	124/331/90	BASF
Dichlorprop-P/2,4-D	Estaprop® XT	4/4	210/400	EC	368/702	Nufarm Agriculture
Sulfentrazone	Authority® 480	14	480	SC	105	FMC Corporation
Fluroxypyr/Halauxifen + MCPA	Pixxaro™ A + Pixxaro™ B	4/4 + 4	250/16.25 + 600	EC + EC	77/5 + 350	Corteva Agriscience
Fluroxypyr/Halauxifen + MCPA	Pixxaro™ A + Pixxaro™ B	4/4 + 4	250/16.25 + 600	EC + EC	100/6.5 + 455	Corteva Agriscience
Dicamba	Banvel® II	4	480	SN	300	BASF
Dicamba	Banvel® II	4	480	SN	600	BASF

Note: EC, emulsifiable concentrate; SC, suspension concentrate; SN, solution.
[a]All herbicides were applied post-emergence at wheat 4–5 leaf stage with the exception of sulfentrazone, which was applied pre-emergence.
[b]Applied with ammonium sulfate at 1% *v*/*v*.

Fig. 2. Growing season monthly average temperature and precipitation at Lethbridge, AB, in 2013, 2014, and 2015 compared with the 30-yr average (normal) monthly temperature and precipitation for this region. In 2014, Coalhurst received 50 mm of supplemental irrigation in July and August. In 2015, Lethbridge received 6, 25, and 25 mm of supplemental irrigation in May, June, and July, respectively.



average from 0.6 °C to 1.1 °C warmer than the 30-yr climactic normal for this region (Fig. 2). The summers (July through September) were consistently warmer than normal; however, conditions during the spring months varied around climatic normal temperatures (Fig. 2). Cumulative growing season precipitation varied among years, and ranged from about one-third greater than normal in 2013 and 2014 to one-third less than normal in 2015 (418, 421, and 197 mm of precipitation received from April through October in 2013, 2014, and 2015, respectively, compared with the 30-yr climatic normal of 313 mm). The greatest variability in precipitation was experienced in June of each year, the month during which post-emergence herbicides were applied. During the month of June, precipitation was equivalent to 184%, 228%, and 23% of the climatic normal in 2013, 2014, and 2015, respectively (Fig. 2). Weather data were compiled for the Lethbridge site only due to lack of a weather station near the Coalhurst site, and the proximity of these two locations.

Herbicide treatments

Wheat injury and grain yield

Visible injury data did not conform to the assumptions of ANOVA due to an abundance of zero values, and were therefore presented as simple means (Supplementary Table S1[1]).Wheat visible injury was considered minor among the herbicide treatments in the majority of environments. Injury ratings from 0% to 10% were considered acceptable because the crop generally outgrows minor injury absent of yield penalty (PMRA 2016). Based on Pest Management Regulatory Agency (PMRA) standards, wheat visible injury was not acceptable in Coalhurst 2014 and Lethbridge 2015 for certain treatments where dicamba was applied alone or in mixture with other synthetic auxin active ingredients (Supplementary Table S1[1]). Visible injury ranged from 11% to 21% in Coalhurst 2014 for dicamba + 2,4-D (110 + 420 g a.e.·ha^{-1}), dicamba/fluroxypyr (80/104 g a.e.·ha^{-1}), MCPA/mecoprop-p/dicamba (275/62.5/62.5 g a.e.·ha^{-1}), and both high and low rates of dicamba/2,4-D/mecoprop-p (93/251/68 and 124/331/90 g a.e.·ha^{-1}). Treatments including higher rates of dicamba applied alone were tested in 2015 only, and the highest rate (600 g a.e.·ha^{-1}) was the only herbicide treatment in this environment that resulted in crop injury considered unacceptable (21% injury), while injury from dicamba applied at 300 g a.e.·ha^{-1} was considered just acceptable (10% injury).

Wheat yield remained the same among the kochia accessions, herbicide treatments, and the untreated weedy control in each of the environments tested (Table 2; Supplementary Table S2[1]). Lack of spring wheat yield response suggested that the densities of kochia present in the current study were too low to result in considerable yield reduction. This is unlikely considering the spring wheat yield loss values in response to low densities of GS kochia reported previously (Friesen et al. 2009).

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjps-2020-0303.

Table 2. ANOVA table showing the significance of main and interaction effects of herbicide treatment (H), glyphosate-resistant vs. glyphosate-susceptible kochia accession (A), and environment (E) on kochia visible control, density, biomass, and wheat yield in 2013 and 2014 (Lethbridge and Coalhurst, AB), and 2015 (Lethbridge only).

	2013				2014				2015[a]			
Fixed effect	Kochia control (%)	Kochia density[b] (plants·m^{-2})	Kochia biomass[c] (g·m^{-2})	Wheat yield (kg·ha^{-1})	Kochia control (%)	Kochia density (plants·m^{-2})	Kochia biomass (g·m^{-2})	Wheat yield (kg·ha^{-1})	Kochia control (%)	Kochia density (plants·m^{-2})	Kochia biomass (g·m^{-2})	Wheat yield (kg·ha^{-1})
Herbicide (H)	**<0.001**	0.824	—	0.289	**<0.001**	**<0.001**	**<0.001**	0.885	**<0.001**	**<0.001**	**<0.001**	0.164
Accession (A)	0.207	0.318	—	0.477	**<0.001**	**<0.001**	**0.002**	0.405	0.321	**0.007**	**0.039**	0.897
Environment (E)	0.942	—	—	0.130	**<0.001**	**<0.001**	0.650	**<0.001**	—	—	—	—
H × A	**0.026**	0.112	—	0.366	0.456	0.432	0.423	0.712	0.151	0.079	0.065	0.385
H × E	**<0.001**	—	—	0.950	**<0.001**	**<0.001**	0.359	0.174	—	—	—	—
A × E	0.669	—	—	0.982	0.100	**<0.001**	0.962	0.289	—	—	—	—
H × A × E	0.174	—	—	0.111	0.489	0.519	0.328	0.774	—	—	—	—

Note: Boldface text indicates significant effects at $P < 0.05$; dash (—) indicates absence of the effect from the ANOVA.

[a]The experiment in 2015 was conducted near Lethbridge only.

[b]Visible differences in kochia density were absent at Lethbridge in 2013, and thus density was measured in the untreated control treatment only; Lethbridge 2013 was excluded from the kochia density ANOVA.

[c]Kochia biomass was not sampled in 2013.

Alternatively, lack of yield difference following a range of herbicide treatments compared with that of the untreated weedy control could suggest that spring wheat yield loss manifests in response to kochia interference prior to the wheat 4–5 leaf stage. A true untreated weed-free control treatment would aid in this conjecture, however, this treatment was not present in the current study. The sulfentrazone (105 g a.i.·ha^{-1}) treatment applied pre-emergence could serve a similar purpose as the weed-free control due to minimal wheat visible injury (0%–5% among environments) and the very low density of kochia present in this treatment prior to the timing of the post-emergence herbicide treatments (6 plants and 1 plant·m^{-2} in 2014 and 2015, respectively; treatment not present in 2013). However, since kochia density was evaluated prior to the post-emergence herbicide timing only, we cannot rule out the possibility that late-emerging kochia caused wheat yield loss following the period of residual activity provided by sulfentrazone applied pre-emergence. Despite the lack of wheat yield response to herbicide treatments in the current study, the true benefit of herbicide treatment in the wheat phase of the crop rotation could manifest as a reduction in kochia biomass inhibiting harvest operations, and likely also reduced seed production and return to the soil seedbank.

Kochia plant density, visible control, and biomass

Kochia densities evaluated before post-emergence herbicide treatment remained the same among all post-emergence herbicide treatments in each environment (Tables 3–5). At Lethbridge 2013, kochia density was evaluated in the untreated control treatment only (85 ± 6.1 plants·m^{-2}) due to visual observation of consistent densities among plots. Sulfentrazone (105 g a.i.·ha^{-1}) applied pre-emergence reduced kochia density by 96% and 99% in Lethbridge 2014 and 2015, respectively; however, this effect was not observed in Coalhurst 2014 due to the low kochia densities present in this environment overall (27 ± 3.8 plants·m^{-2} in Coalhurst 2014 compared with 85–205 plants·m^{-2} among kochia accessions and herbicide treatments in the other environments) (Tables 4 and 5).

Several herbicide treatments controlled GR and GS kochia accessions effectively in spring wheat. The PMRA defines weed control as a visible control rating of ≥80% (PMRA 2016). Several herbicide treatments achieved ≥80% visible control in all environments in which they were tested, including dicamba/fluroxypyr (80/104 g a.e.·ha^{-1}), fluroxypyr/bromoxynil/2,4-D (96/288/288 g a.e./a.i.·ha^{-1}), MCPA/dichlorprop-p/mecoprop-p (395/765/320 g a.e.·ha^{-1}), pyrasulfotole/bromoxynil (30/170 g a.i.·ha^{-1}), dicamba/2,4-D/mecoprop-p (124/331/90 g a.e.·ha^{-1}), sulfentrazone (105 g a.i.·ha^{-1}) applied pre-emergence, fluroxypyr/halauxifen + MCPA (100/6.5 + 455 g a.e.·ha^{-1}), and both rates of dicamba (300 or 600 g a.e.·ha^{-1}); although the latter four treatments were only tested in 3, 1, 1, and 1 environment(s), respectively

Table 3. Visible control of glyphosate-resistant (GR) and glyphosate-susceptible (GS) kochia 3 weeks after post-emergence herbicide application in wheat in two environments near Lethbridge and Coalhurst, AB, in 2013.

		Density[b] (plants·m^{-2})	Visible control (%)					
					Among environments			
Herbicide treatment[a]	Rate (g a.e./a.i.·ha^{-1})	Coalhurst	Lethbridge	Coalhurst	GS	GR	GS vs. GR[c]	Among accessions
Untreated	—	131	—	—	—	—	—	—
Dicamba + 2,4-D	110 + 420	133	78e	79b	78d	78d	0.884	78g
Bromoxynil/2,4-D	280/280	153	81de	91ab	84cd	87b–d	0.052	86e–g
Fluroxypyr/2,4-D	40/160	125	97ab	90ab	91a–c	96ab	0.005	93a–d
Florasulam/Fluroxypyr + MCPA	2.5/100 + 350	190	88a–e	88ab	87b–d	89a–c	0.128	88c–f
Dicamba/Fluroxypyr	80/104	147	96ab	90ab	93a–c	94ab	0.559	93a–d
Fluroxypyr + Clopyralid/MCPA	100 + 75/420	173	93a–c	88ab	92a–c	89a–c	0.083	91a–f
Fluroxypyr/Bromoxynil/2,4-D	48/114/144	118	95ab	84ab	91a–c	88a–c	0.061	90a–f
Fluroxypyr/Bromoxynil/2,4-D	96/228/288	191	99a	96a	97a	97a	0.826	97a
MCPA/Dichlorprop-P/Mecoprop-P	395/765/320	179	98a	93a	96ab	96ab	0.826	96ab
MCPA/Mecoprop-P/Dicamba	275/62.5/62.5	124	83c–e	85ab	84cd	84cd	0.715	84fg
Pyrasulfotole/Bromoxynil	30/170	172	90a–d	96a	92a–c	93a–c	0.559	93a–e
Dicamba/2,4-D/Mecoprop-P	93/251/68	164	86b–e	91ab	89a–c	88a–d	0.308	88b–f
Dicamba/2,4-D/Mecoprop-P	124/331/90	140	95ab	94a	94a–c	95ab	0.466	94a–c
Dichlorprop-P/2,4-D	368/702	168	80de	92a	84cd	88a–d	0.027	86d–f

Note: Values are LS means. Within columns, different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$).
[a]Herbicides were applied post-emergence at wheat 4–5 leaf stage.
[b]Visual differences in kochia density were absent among treatments in Lethbridge 2013, and therefore density was evaluated in the untreated control only (data not shown).
[c]*P* value indicating significant difference in visible control between GS and GR kochia accessions.

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Table 4. Visible control 3 weeks after post-emergence herbicide application, density, and aboveground biomass of glyphosate-resistant (GR) and glyphosate-susceptible (GS) kochia in wheat in two environments near Lethbridge and Coalhurst, AB, in 2014.

		Lethbridge			Coalhurst			Among environments		
Herbicide treatment[a]	Rate (g a.e./a.i.·ha^{-1})	Visible control (%)	Density (plants·m^{-2})	Biomass (g·m^{-2})	Visible control (%)	Density (plants·m^{-2})	Biomass (g·m^{-2})	Visible control (%)	Density (plants·m^{-2})	Biomass (g·m^{-2})
Untreated	—	—	129a	138a	—	27	45	—	78a	78a
Dicamba + 2,4-D	110 + 420	67gh	140a	18a–c	91ab	24	26	79fg	82a	21a–c
Bromoxynil/2,4-D	280/280	63h	148a	5b–e	83b	36	12	73g	92a	8b–d
Fluroxypyr/2,4-D	40/160	83c–e	136a	48ab	90ab	21	13	86c–e	79a	25ab
Florasulam/Fluroxypyr + MCPA	2.5/100 + 350	78d–f	140a	23ab	90ab	22	14	84d–f	81a	18a–c
Dicamba/Fluroxypyr	80/104	83c–e	112a	11b–d	89ab	26	13	86c–e	69a	12bc
Fluroxypyr + Clopyralid/MCPA	100 + 75/420	74e–g	130a	43ab	89ab	34	32	81ef	82a	37ab
Fluroxypyr/Bromoxynil/2,4-D	48/114/144	68f–h	111a	8b–d	94a	39	19	81ef	75a	13a–c
Fluroxypyr/Bromoxynil/2,4-D	96/228/288	92a–c	129a	1c–e	93a	28	7	92a–c	78a	3cd
MCPA/Dichlorprop-P/Mecoprop-P	395/765/320	84b–d	121a	12b–d	93a	39	11	89b–d	80a	11bc
MCPA/Mecoprop-P/Dicamba	275/62.5/62.5	71f–h	144a	20a–c	90ab	26	26	80ef	85a	23a–c
Pyrasulfotole/Bromoxynil	30/170	94ab	140a	1de	94a	37	0	94ab	88a	0[b]
Dicamba/2,4-D/Mecoprop-P	93/251/68	76d–g	127a	10b–d	89ab	22	21	83d–f	74a	15a–c
Dicamba/2,4-D/Mecoprop-P	124/331/90	83c–e	145a	13a–d	89ab	22	12	86c–e	83a	13bc
Dichlorprop-P/2,4-D	368/702	71f–h	135a	21a–c	88ab	25	14	80f	80a	17a–c
Sulfentrazone	105	98a	5b	1e	95a	8	2	96a	6b	1d
Fluroxypyr/Halauxifen + MCPA	77/5 + 350	77d–g	146a	38ab	86ab	22	25	82ef	84a	30ab

Note: Values are LS means. Within columns, different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$).
[a]All herbicides were applied post-emergence at wheat 4–5 leaf stage except for sulfentrazone, which was applied pre-emergence.
[b]Non-estimable.

Table 5. Visible control 3 weeks after post-emergence herbicide application, density, and aboveground biomass of glyphosate-resistant (GR) and glyphosate-susceptible (GS) kochia in wheat in one environment near Lethbridge, AB, in 2015.

		Lethbridge		
Herbicide treatment[a]	Rate (g a.e./a.i.·ha^{-1})	Visible control (%)	Density (plants·m^{-2})	Biomass (g·m^{-2})
Untreated	—	—	246a	208a
Dicamba + 2,4-D	110 + 420	68g	210a	23b–d
Bromoxynil/2,4-D	280/280	71fg	235a	29bc
Fluroxypyr/2,4-D	40/160	79d–f	210a	33ab
Florasulam/Fluroxypyr + MCPA	2.5/100 + 350	79d–f	230a	27bc
Dicamba/Fluroxypyr	80/104	86b–d	219a	12b–g
Fluroxypyr + Clopyralid/MCPA	100 + 75/420	79d–f	217a	42ab
Fluroxypyr/Bromoxynil/2,4-D	48/114/144	73e–g	188a	18b–e
Fluroxypyr/Bromoxynil/2,4-D	96/228/288	94ab	212a	3e–g
MCPA/Dichlorprop-P/Mecoprop-P	395/765/320	89bc	198a	1g
MCPA/Mecoprop-P/Dicamba	275/62.5/62.5	72fg	227a	15b–f
Pyrasulfotole/Bromoxynil	30/170	92ab	216a	2fg
Dicamba/2,4-D/Mecoprop-P	93/251/68	78d–f	243a	2g
Dicamba/2,4-D/Mecoprop-P	124/331/90	89bc	227a	5b–g
Dichlorprop-P/2,4-D	368/702	71fg	177a	11b–g
Sulfentrazone	105	99a	1b	1d–g
Fluroxypyr/Halauxifen + MCPA	77/5 + 350	71fg	199a	42ab
Fluroxypyr/Halauxifen + MCPA	100/6.5 + 455	81de	198a	37ab
Dicamba	300	83cd	231a	5c–g
Dicamba	600	94ab	221a	2d–g

Note: Values are LS means. Within columns, different letters indicate significant differences based on Tukey's HSD ($\alpha = 0.05$).
[a]All herbicides were applied post-emergence at wheat 4–5 leaf stage except for sulfentrazone, which was applied pre-emergence.

(Tables 3–5). Among these treatments, sulfentrazone (105 g a.i.·ha^{-1}) applied pre-emergence, and fluroxypyr/bromoxynil/2,4-D (96/288/288 g a.e./a.i.·ha^{-1}), pyrasulfotole/bromoxynil (30/170 g a.i.·ha^{-1}), and the highest rate of dicamba (600 g a.e.·ha^{-1}) applied post-emergence resulted in excellent visible control (≥90% visible control) in all environments tested. While excellent kochia control was achieved by the high rate of dicamba (600 g a.e.·ha^{-1}) applied alone (Table 5), it also resulted in unacceptable wheat visible injury (21% visible injury) (Supplementary Table S1[1]), and therefore should not be considered for this purpose.

All of the herbicide treatments resulted in acceptable visible control of GR and GS kochia in Coalhurst, with the exception of dicamba + 2,4-D (110 + 420 g a.e.·ha^{-1}) in Coalhurst 2013, while greater variation in visible control was observed among treatments in Lethbridge. Variability in visible control estimates among experimental locations is common in herbicide research due to the subjectivity of visual ratings among different assessors (Duddu et al. 2019). While visible control estimates are subject to personal standards of herbicide efficacy, weed biomass estimates do not share these same biases.

Similar to the estimates of kochia visible control, several herbicide treatments resulted in acceptable kochia control based on aboveground shoot biomass evaluated 6 WAA. In particular, sulfentrazone (105 g a.i.·ha^{-1}) applied pre-emergence and pyrasulfotole/bromoxynil (30/170 g a.i.·ha^{-1}), or both rates of dicamba (300 or 600 g a.e.·ha^{-1}) applied post-emergence reduced kochia biomass by ≥90% compared with the untreated control among the environments in 2014 and 2015 (although the dicamba-only treatments were only tested in 2015) (Tables 4 and 5). Fluroxypyr/bromoxynil/2,4-D (96/288/288 g a.e.·ha^{-1}) reduced kochia biomass by ≥90% in Lethbridge 2014 and 2015, and 84% in Coalhurst 2014. The high rate of fluroxypyr/halauxifen + MCPA (100/6.5 + 455 g a.e.·ha^{-1}) reduced kochia biomass by 82% in Lethbridge 2015, the only environment in which it was tested (Table 5). It is important to note, however, that statistical differences in kochia biomass among herbicide treatments were absent in Coalhurst 2014 due to large variability in the biomass estimates likely as a result of lower kochia population densities (27 ± 3.8 plants·m^{-2}) (Table 4). Excluding the Coalhurst 2014 environment from consideration (due to lack of statistical difference), ≥90% reduction in kochia biomass in Lethbridge 2014 and 2015 was achieved also by dicamba/fluroxypyr (80/104 g a.e.·ha^{-1}), fluroxypyr/bromoxynil/2,4-D (48/114/114 g a.e./a.i.·ha^{-1}), MCPA/dichlorprop-p/mecoprop-p (395/765/320 g a.e.·ha^{-1}), and both rates of dicamba/2,4-D/mecoprop-p (93/251/68 and 124/331/90 g a.e.·ha^{-1}). Dicamba + 2,4-D (110 + 420 g a.e.·ha^{-1}), bromoxynil/2,4-D (280/280 g a.i./a.e.·ha^{-1}), florasulam/fluroxypyr + MCPA (2.5/110 + 350 g a.i./a.e.·ha^{-1}), MCPA/

mecoprop-p/dicamba (275/62.5/62.5 g a.e.·ha^{-1}), and dichlorpop-p/2,4-D (368/702 g a.e.·ha^{-1}) resulted in acceptable control and reduced kochia biomass by ≥80% in the Lethbridge 2014 and 2015 environments (Tables 4 and 5). Kochia shoot biomass was not evaluated in 2013.

The majority of herbicides evaluated in the current study were mixtures of synthetic auxins. Dicamba, fluroxypyr, 2,4-D, MCPA, clopyralid, dichlorprop-p, mecoprop-p, and halauxifen are synthetic auxins used (among other purposes) to manage broadleaf weeds selectively in small-grain cereal crops (Hall et al. 1999; Epp et al. 2016). The mechanism of weed control by synthetic auxin herbicides remains elusive, however, recent reports suggest that synthetic auxin herbicides result in a rapid increase in abscisic acid (ABA) through up-regulation of the rate-limiting step for ABA production which causes down-regulation of photosynthesis-related genes and a loss of photosynthesis (Gaines 2020). Some auxinic herbicides have soil residual activity which can be limited by rapid microbial degradation (Hall et al. 1999). For example, dicamba/2,4-D/mecoprop-p (124/331/90 g a.e.·ha^{-1}) and MCPA/dichlorprop-p/mecoprop-p (395/765/320 g a.e.·ha^{-1}) are synthetic auxin mixtures with little soil residual activity (Shaner 2014). Dicamba has low persistence in soil with a half-life of ≤14 d, while fluroxypyr persistence in soil can vary from a half-life of 11–68 d depending on whether it is present in formulation as an ester or acid (Shaner 2014). Fluroxypyr (70 g a.e.·ha^{-1}) alone or in combination with 2,4-D (70 + 560 g a.e.·ha^{-1}) resulted in excellent control of sulfonylurea-resistant kochia in Manitoba (92%–96% reduction in biomass 60 d after application) (Friesen et al. 1993), while dicamba (140 g a.e.·ha^{-1}) alone or in combination with fluroxypyr (53/69 g a.e.·ha^{-1}) reduced biomass of GR and GS kochia accessions by 76% and 82% 3 WAA in a controlled-environment study (Burton et al. 2014). A somewhat higher rate of dicamba/fluroxypyr (80/104 g a.e.·ha^{-1}) in the current study resulted in ≥83% visible control in all environments, and ≥92% kochia biomass reduction in Lethbridge 2014 and 2015 compared with the untreated control (Tables 3–5), and therefore correspond with previous observations under a controlled environment (Burton et al. 2014).

Herbicide mixtures with multiple modes of effective action are favorable because they can help mitigate or delay the development and spread of herbicide resistance (Beckie and Reboud 2009; Evans et al. 2016). Fluroxypyr/bromoxynil/2,4-D (96/228/288 g a.e./a.i.·ha^{-1}) includes a combination of rapid uptake of 2,4-D, slight soil residual activity of fluroxypyr, and contact activity of the photosystem II (PSII) inhibitor bromoxynil. Bromoxynil is readily absorbed into leaves (with little to no translocation) resulting in chlorosis within 1–2 d and necrosis within 3–6 d after foliar application (Shaner 2014). In a greenhouse study, Burton et al. (2014) showed excellent control of GR and GS kochia in response to MCPA/bromoxynil (275/275 g a.e./a.i.·ha^{-1}) (99% biomass reduction compared with the untreated control 3 WAA). However, due to the contact activity of bromoxynil, kochia control can diminish over time because of partial plant recovery or seedling recruitment following herbicide application (Kumar and Jha 2015). Thus, an effective strategy could be to mix bromoxynil with another active ingredient which provides more sustained control. Pyrasulfotole/bromoxynil (30/170 g a.i.·ha^{-1}) provides the contact activity of a PSII inhibitor (bromoxynil) with pyrasulfotole, which inhibits 4-hydroxyphenylpyruvate dioxygenase (HPPD). Pyrasulfotole causes tissue bleaching by inhibiting pigment biosynthesis, and remains active in the soil often for the duration of the growing season (van Almsick 2009). This is an important advantage for kochia management because prolonged emergence periodicity can result in flushes of emerged seedlings after treatment with a pre- or post-emergence herbicide (Schwinghamer and Van Acker 2008; Dille et al. 2017; Kumar et al. 2018).

Layering of effective herbicide modes of action pre- and post-emergence can be another way to mitigate or delay the selection for herbicide resistance. Sulfentrazone is a soil-applied herbicide that can be applied pre-plant or pre-emergence. Sulfentrazone is a protoporphyrinogen oxidase (PPO) inhibitor that is systemic and has moderate soil residual activity with a half-life ranging between 121 and 302 d (Shaner 2014). When applied 1–2 d before or after planting, sulfentrazone (105 g a.i.·ha^{-1}) resulted in excellent kochia management with almost no wheat visible injury (Tables 3–5; Supplementary Table S1[1]). Sulfentrazone provided excellent kochia control in the absence of crop competition when applied alone in Montana (≥91% visible control when applied at 210 g a.i.·ha^{-1}) or with glyphosate and carfentrazone in Alberta (≥91% visible control of GR kochia when applied at 105 g a.i.·ha^{-1}) (Kumar and Jha 2015; Torbiak et al. 2021). When applied prior to sunflower (*Helianthus annuus* L.) in Kansas, sulfentrazone alone (at 90–140 g a.i.·ha^{-1}) or mixed with S-metolachlor showed excellent kochia control (Reddy et al. 2012). Carfentrazone is another PPO inhibitor, and unlike sulfentrazone, it is registered for use prior to spring wheat in western Canada (Anonymous 2020). Carfentrazone is a contact herbicide with almost no residual activity in soil. Rapid necrosis and plant cell death can be observed within hours following carfentrazone application, however, little residual activity offered by carfentrazone can result in kochia regrowth (Torbiak et al. 2021). Consistent kochia control (Tables 3–5) and almost no wheat visible injury in response to sulfenrazone (Supplementary Table S1[1]) suggest that this herbicide should be considered for registration prior to wheat in western Canada.

Differences among kochia accessions

In general, the GR kochia accession was present at a greater density than the GS accession in all environments in 2014 and 2015 [GR kochia densities of 33 (± 4.3), 153 (± 7.1), and 248 (± 14.6) in Coalhurst 2014, Lethbridge 2014, and Lethbridge 2015, respectively, compared with GS kochia densities of 21 (± 4.0), 98 (± 6.3), and 162 (± 13.9) in the same environments]. A similar trend was observed in Coalhurst 2013 [159 (± 14.9) vs. 149 (± 15.9) plants·m^{-2} for GR and GS kochia, respectively], however, these kochia densities were not statistically different ($P = 0.318$) (Table 2).

There were differences in visible control among the kochia accessions in 2014 ($P < 0.001$), where the herbicide treatments overall resulted in greater control of the GS compared with the GR kochia accession (85% ± 0.5% vs. 83% ± 0.5% visible control of GS vs. GR kochia, respectively) (Table 2). It is likely that these differences were caused by the greater density of GR compared with GS kochia present in 2014, and not due to the presence vs. absence of the glyphosate resistance trait. The opposite was observed for some herbicide treatments in 2013, where fluroxypyr/2,4-D (40/160 g a.e.·ha^{-1}) (96% vs. 91% visible control of GR vs. GS kochia, respectively) and dichlorprop-p/2,4-D (368/702 g a.e.·ha^{-1}) (88% vs. 84% visible control of GR vs. GS kochia, respectively) resulted in slightly greater control of the GR compared with GS kochia accessions (Table 3), while differences in kochia density were absent (Table 2). This could be due to negative cross-resistance similar to that reported for ALS inhibitor resistant kochia and PPO- or HPPD-inhibiting herbicides (Beckie et al. 2012*a*), or more likely a statistical difference absent of biological significance since the differences observed were minimal (Table 3). Similar to visible control, a greater density of GR compared with GS kochia in 2014 and 2015 resulted in a greater biomass of GR than GS kochia among herbicide treatments. In 2014, GR kochia biomass averaged 19 (3.00 ± 0.16; natural logarithm-transformed mean ± SE) g·m^{-2} among herbicide treatments compared with 10 (2.3 ± 0.20) g·m^{-2} for GS kochia ($P = 0.002$) (Table 2). Likewise, GR kochia biomass in 2015 averaged 17 (2.9 ± 0.26) g·m^{-2} compared with 6 (1.8 ± 0.30) g·m^{-2} for GS kochia ($P = 0.039$). Despite these minor differences in visible control and biomass among kochia accessions, general observations from the current study agree with previous greenhouse research which showed similar response of GR and GS kochia to a range of alternative herbicide treatments (Burton et al. 2014).

Management implications

In addition to glyphosate and ALS inhibitor resistance in kochia, auxinic herbicide resistance is a major threat to small-grain cereal crops. Dicamba- and (or) fluroxypyr-resistant kochia were reported first in the United States in 1993/1994 (Cranston et al. 2001; Goss and Dyer 2003; Kumar et al. 2019). In Canada, auxinic herbicide-resistant kochia was reported first in 2015 in a spring wheat field in Saskatchewan (Heap 2020). A subsequent 2017 Alberta survey reported that 18% of the kochia populations tested were dicamba-resistant, and 10% were triple herbicide-resistant (resistant to ALS inhibitors, glyphosate, and dicamba) (Beckie et al. 2019). While synthetic auxin herbicides continue to play an important role in control of GR kochia in spring wheat, farmers must remain diligent and include alternative modes of action in their herbicide programs like PPO inhibitors applied pre-emergence, or pyrasulfotole (a HPPD inhibitor) and bromoxynil (a PSII inhibitor) applied post-emergence. The current research suggests that optimal control of glyphosate and ALS inhibitor-resistant kochia in spring wheat may be achieved by a combination of sulfentrazone (105 g a.i.·ha^{-1}) applied pre-emergence with fluroxypyr/bromoxynil/2,4-D (96/228/288 g a.e./a.i.·ha^{-1}) or pyrasulfotole/bromoxynil (30/170 g a.i.·ha^{-1}) applied post-emergence.

The sustainability of remaining herbicides for kochia control will depend on the successful implementation of integrated weed management; of which, a key foundational principle is crop diversity (integrated herbicide management is simply not enough) (Beckie and Harker 2017). Other potential tools for integrated management of kochia include: alternative crop life cycles (e.g., winter-annuals or perennials), competitive crop cultivars, cover crops, field scouting, resistance diagnostic testing, strategic and site-specific tillage, and potentially also harvest weed seed control (Beckie and Harker 2017; Beckie et al. 2018*b*; Kumar et al. 2019). If implemented alone, integrated herbicide strategies like those identified in the current research will remain a short-term solution at risk of resistance development, and for this reason, improved understanding of non-chemical weed control is required for sustainable kochia management in wheat production systems.

Conflict of Interest

The authors declare there are no competing interests.

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