Herbicide mixtures control glyphosate-resistant kochia (Bassia scoparia) in chemical fallow, but their longevity warrants careful stewardship

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ARTICLE

Herbicide mixtures control glyphosate-resistant kochia (*Bassia scoparia*) in chemical fallow, but their longevity warrants careful stewardship

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Abstract: Glyphosate-resistant kochia [*Bassia scoparia* (L.) A.J. Scott], the first known glyphosate-resistant weed in western Canada, was confirmed initially in chemical fallow fields located in Warner County, AB, in 2011. Further selection, lack of control, and rampant spread of this biotype contributed to its increased incidence, now present in about 50% of kochia populations sampled in Alberta. In 2014 and 2015, herbicide mixtures were evaluated based on control of glyphosate-resistant and susceptible kochia in chemical fallow fields near Lethbridge and Coalhurst, AB. The most consistent control (≥80% visual control in all environments with ≥80% biomass reduction in 2014) was observed with glyphosate + dicamba (450 + 580 g a.e.·ha^{-1}), glyphosate + dicamba/diflufenzopyr (450 + 150/50 g a.i./a.e.·ha^{-1}), glyphosate + saflufenacil (450 + 50 g a.i./a.e.·ha^{-1}), and glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g a.i./a.e.·ha^{-1}). Reduced efficacy was observed for several herbicide mixtures when they were applied to glyphosate-resistant compared with glyphosate-susceptible kochia accessions. Effective modes of action mixed with glyphosate include synthetic auxins (group 4), a combination of a synthetic auxin and an auxin transport inhibitor (group 19), or protoporphyrinogen oxidase inhibitors (group 14). In response to glyphosate-resistant kochia, many farmers in this region shifted their herbicide programs resulting in greater reliance on synthetic auxins; likely contributing to the recent discovery of auxinic herbicide-resistant kochia biotypes in Alberta in 2017. Careful herbicide stewardship is warranted to mitigate further selection of multiple herbicide-resistant kochia, suggesting an important role for integrated weed management.

Key words: Bassia scoparia, chemical fallow, glyphosate resistance, herbicide mixtures, herbicide resistance, herbicide stewardship.

Résumé : La présence de kochie [*Bassia scoparia* (L.) A.J. Scott] résistante au glyphosate, première adventice résistante à cet herbicide découverte dans l'Ouest canadien, a été découverte en 2011, dans des champs en jachère chimique du comté de Warner, en Alberta. Une sélection supplémentaire, l'absence de moyens de lutte et la propagation du biotype par traçage ont concouru à en accroître la fréquence, si bien qu'on le retrouve désormais dans près de la moitié des peuplements de kochie, en Alberta. En 2014 et 2015, les auteurs ont évalué des mélanges d'herbicides pour combattre la variété résistante ou sensible au glyphosate dans les champs en jachère chimique près de Lethbridge et de Coalhurst, en Alberta. Le meilleur résultat (destruction visuellement évidente ≥ 80 % dans tous les milieux avec réduction ≥ 80 % de la biomasse en 2014) a été obtenu avec les mélanges glyphosate + dicamba (450 + 580 g de m.a. par hectare), glyphosate + dicamba/diflufenzopyr

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(450 + 150/50 g de m.a. par hectare), glyphosate + saflufenacil (450 + 50 g de m.a. par hectare) et glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g de m.a. par hectare). Les auteurs ont remarqué que l'efficacité de divers mélanges diminue quand on les applique aux variétés de kochie résistantes au glyphosate plutôt que sensible à cet herbicide. Les mélanges dont le mode d'action demeure efficace après combinaison au glyphosate comprennent les auxines synthétiques (groupe 4), une combinaison d'auxine synthétique et d'inhibiteur du transport de l'auxine (groupe 19) et des inhibiteurs de la protoporphyrinogène oxydase (groupe 14). Face à la prolifération de la kochie résistante au glyphosate, beaucoup d'agriculteurs de la région ont modifié leurs programmes de désherbage pour recourir davantage aux auxines synthétiques, ce qui explique sans doute pourquoi on a découvert des biotypes de kochie résistants aux auxines en Alberta, en 2017. Il faut gérer avec soin l'usage des herbicides si on veut freiner une sélection encore plus grande de la résistance à de multiples herbicides chez la kochie, d'où le rôle important de la lutte intégrée contre les mauvaises herbes. [Traduit par la Rédaction]

Mots-clés : Bassia scoparia, jachère chimique, résistance au glyphosate, mélanges d'herbicides, résistance aux herbicides, gestion des herbicides.

Introduction

Kochia [*Bassia scoparia* (L.) A.J. Scott] is an abundant and troublesome weed throughout the Great Plains region. It is the most abundant weed in annual crops of the mixed grassland ecoregion of Alberta and the 15th most abundant weed among annual crops in Alberta and Saskatchewan (Leeson 2016; Leeson et al. 2019). Kochia is an invasive, summer annual weed that was introduced to the Americas in the late 1800s as an ornamental garden forb from central Europe and western Asia (Friesen et al. 2009). Its unique weedy characteristics, including early spring germination, prolonged emergence periodicity, rapid growth, prolific seed production, efficient pollen-mediated gene flow, and long-distance seed dispersal (Schwinghamer and Van Acker 2008; Beckie et al. 2016), contribute to its geographic spread. Forcella (1985) found that kochia had the highest rate of spread compared with 40 other invasive weed species in the northwestern United States.

Kochia is a competitive C4 plant that favors arid and semi-arid conditions, and is tolerant of drought, heat, and saline soils (Friesen et al. 2009). These traits enable kochia to be problematic in annual cropping systems, forage crops and hay fields, rangeland, roadsides, oil well sites, and waste areas.

Kochia has a high level of genetic diversity within and among populations (Mengistu and Messersmith 2002), and this diversity is maintained via seed- and pollen-mediated gene flow (Beckie et al. 2016). Protogynous flowering (where the stigmas emerge and are receptive to pollen before the anthers fully mature on the same plant) promotes initial outcrossing prior to self-pollination and increases the chance of pollen transfer to other kochia plants (Mulugeta et al. 1994; Stallings et al. 1995). Resistance alleles are spread among kochia plants and populations through pollen-mediated gene flow and seed dispersal resulting from abscised mature kochia plants tumbling in the wind (Beckie et al. 2016). Kochia seed longevity in soil lasts about 1–2 yr (Beckie et al. 2018), which can lead to the rapid evolution of herbicide resistance (Beckie et al. 2013).

Outcrossing of kochia increases the chance of spreading herbicide resistance and resistance to four herbicide modes of action, including photosystem II inhibitors (group 5) (not known to be present in Canada), acetolactate synthase (ALS) inhibitors (group 2), the 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) inhibitor glyphosate (group 9), and synthetic auxins (group 4), have been found; in some cases within the same kochia population (Heap 2020). In 1988 the first herbicide-resistant kochia population, resistant to the ALS inhibitor chlorsulfuron, was found in Manitoba and Saskatchewan, then in Alberta the following year (Morrison and Devine 1994). This type of resistance was found in 85% of the kochia populations surveyed across the three Canadian prairie provinces in 2007 (Beckie et al. 2011), and 100% of kochia populations in Alberta in 2017 (Beckie et al. 2019). The first synthetic auxin-resistant kochia in Canada was confirmed in Saskatchewan in 2015, and subsequently in 2017 the first triple-resistant kochia populations (to synthetic auxins, ALS inhibitors, and an EPSPS inhibitor) were found in Alberta (Beckie et al. 2019).

Glyphosate-resistant (GR) kochia was first reported in wheat fields in Kansas in 2007, and since then it has been identified in ten of the US American Great Plains states (Kumar et al. 2019; Heap 2020). In 2011, the first cases of GR kochia in Canada were confirmed in chemical fallow fields located in Warner County, AB (Beckie et al. 2013). This was the first GR weed confirmed in western Canada. Rapid spread of GR kochia was observed in Alberta, increasing from an estimated 4% of kochia populations in 2012 to 50% of kochia populations in 2017 (Beckie et al. 2019). This rapid spread of glyphosate resistance represents an unprecedented rate of herbicide resistance gene flow present among kochia populations.

Growers located in the semi-arid environment of the Canadian Prairies, east of the Rocky Mountains, include fallow in rotation with annual crops to improve soil water storage and water availability for subsequent cash crops (Campbell et al. 1990). There are about 1, 415, 600 ha of summer fallow left unseeded in western Canada per annum (10 yr average between 2011 and

2020) (Statistics Canada 2020*a*). About 59% of growers in western Canada practice zero tillage, while 24% practice reduced tillage (retaining most crop residue on the soil surface), and 17% use conventional tillage systems (incorporating most crop residue into the soil) (Statistics Canada 2020*b*). In reduced or zero tillage systems, growers use herbicides for weed control in place of tillage to maintain a weed-free environment while the field remains absent of a crop throughout the growing season (known as chemical fallow). Chemical fallow can help retain or build soil moisture, maintain crop residue on the soil surface, and allow for a period of mineralization making soil nutrients more available for plant uptake (Fenster et al. 1965; Lindwall and Anderson 1981). Summer fallow can also increase soil susceptibility to wind and water erosion, salinization, moisture storage inefficiencies, and result in the economic loss of a cash crop for one growing season. In winter wheat–fallow rotations, zero tillage chemical fallow can retain more soil moisture, maintain greater surface residue, and result in reduced weed growth compared with tilled fallow (Wicks and Smika 1973).

Kochia is difficult to control in chemical fallow because it continues to emerge after herbicide applications in early spring (Schwinghamer and Van Acker 2008), then grows aggressively in the absence of crop competition. The risk of selecting for herbicide resistance is greater in chemical fallow because uncontrolled weeds may grow and produce copious amounts of seed when they are uninhibited by plant competition. Many farmers rely on glyphosate for cost-effective non-selective weed control in chemical fallow systems, which can result in a large selection pressure for glyphosate resistance if this herbicide is used as the sole source of weed management. Including multiple effective modes of action in chemical fallow is essential to mitigate the selection for herbicide-resistant weeds. In western Canada, there are no research reports on alternative herbicide options for control of GR kochia in chemical fallow. Due to the reliance of glyphosate in chemical fallow systems and the increasing abundance and distribution of GR kochia, alternative control options are warranted to manage kochia effectively. The objective of this study was to determine herbicide mixtures including multiple modes of action to manage GR and glyphosate-susceptible (GS) kochia in chemical fallow fields.

Materials and Methods

Site description

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

Experimental design and treatment structure

The experiment used a randomized complete block design with four replications (blocks). The main plot size at Coalhurst was 2.5 m × 6.0 m, and at Lethbridge was 2.5 m × 5.5 m. Blocks were split randomly with GR and GS kochia accessions. Two seeder passes (2.1 m width) including nine seed rows of each kochia accession (a different accession in each pass) was seeded across each experimental replication (perpendicular to herbicide treatment) in early spring. One meter spacing was left between each kochia accession, for a subplot size of 2.5 m × 2.1 m. Kochia was seeded at a rate of 300 viable seeds·m^{-2} in all environments, with the exception of Lethbridge in 2015 where it was seeded at 400 viable seeds·m^{-2}. Seeds were placed on the soil surface using a Fabro cone seeder (Fabro Enterprises Ltd., Swift Current, SK, Canada) with double-disc seed-row openers spaced 23 cm apart. The seeder packer tires were left on the ground and packed the seed firmly into the soil.

Weeds were controlled at each experimental location prior to kochia seeding. Coalhurst used glyphosate at 900 g a.e.·ha^{-1} as a pre-seed burndown, while Lethbridge used glyphosate at 1334 g a.e.·ha^{-1} and glyphosate + bromoxynil (Koril®, Nufarm Canada, Calgary, AB, Canada) at 1334 + 348 g a.e./a.i.·ha^{-1} in 2014 and 2015, respectively.

Both kochia seed accessions were sourced from the Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre. The GR kochia accession was selected over multiple generations of in-field glyphosate use at 900 g a.e.·ha^{-1}. The GS kochia accession was ALS inhibitor–resistant and was selected in the field using recurrent applications of tribenuron-methyl + thifensulfuron-methyl (Refine® SG; FMC of Canada, Mississauga, ON, Canada) at 5 + 10 g a.i.·ha^{-1} over several years.

The herbicide treatments tested included an untreated control and glyphosate applied alone or in mixture with 13 other herbicide combinations, that were either registered for kochia management in chemical fallow or to determine whether they would be effective for this usage (Table 1). Herbicide treatments were applied post-emergence when kochia plants reached 10 cm in height. Coalhurst used a 2.0 m hand-held, propane-propelled sprayer equipped with John Deere LDX01 nozzles (John Deere, Moline, IL, USA). The sprayer applied the herbicide mixtures with 100 L·ha^{-1} water carrier at 242 kPa and a speed of 4 km·h^{-1}. Lethbridge used a 2.0 m bicycle CO_2 sprayer equipped with Greenleaf Air Mix 110-01 nozzles (Greenleaf Technologies, Covington, LA, USA). This sprayer applied herbicide mixtures with 100 L·ha^{-1} water carrier at 290 kPa and a speed of 5 km·h^{-1}.

Data collection

Kochia seedling emergence was determined for each kochia accession 2 wk after emergence by counting all

Table 1. Herbicide treatments used at Lethbridge and Coalhurst, AB, in 2014 and 2015 to manage glyphosate-resistant and glyphosate-susceptible kochia in chemical fallow.

Herbicide common names	Herbicide trade name	MOA	Concentration/ formulation	Rate ($g\ a.i./a.e.\cdot ha^{-1}$)	Merge adjuvant	Company
Glyphosate	Roundup WeatherMAX®	9	540 $g\cdot L^{-1}$ SN	450	—	Monsanto Canada Inc.
Glyphosate + dicamba	Roundup WeatherMAX® + Banvel® II	9 4	540 $g\cdot L^{-1}$ SN 480 $g\cdot L^{-1}$ SN	450 + 290	—	Monsanto Canada Inc. BASF Canada
Glyphosate + dicamba	Roundup WeatherMAX® + Banvel® II	9 4	540 $g\cdot L^{-1}$ SN 480 $g\cdot L^{-1}$ SN	450 + 580	—	Monsanto Canada Inc. BASF Canada
Glyphosate + dicamba/diflufenzopyr	Roundup WeatherMAX® + Distinct®	9 4/19	540 $g\cdot L^{-1}$ SN 70% WG	450 + 75/25	0.5% *v*/*v*	Monsanto Canada Inc. BASF Canada
Glyphosate + dicamba/diflufenzopyr	Roundup WeatherMAX® + Distinct®	9 4/19	540 $g\cdot L^{-1}$ SN 70% WG	450 + 150/50	0.5% *v*/*v*	Monsanto Canada Inc. BASF Canada
Glyphosate + saflufenacil	Roundup WeatherMAX® + Heat®	9 14	540 $g\cdot L^{-1}$ SN 70% WG	450 + 18	0.5% *v*/*v*	Monsanto Canada Inc. BASF Canada
Glyphosate + saflufenacil	Roundup WeatherMAX® + Heat®	9 14	540 $g\cdot L^{-1}$ SN 70% WG	450 + 50	0.5% *v*/*v*	Monsanto Canada Inc. BASF Canada
Glyphosate + carfentrazone	Roundup WeatherMAX® + Aim®	9 14	540 $g\cdot L^{-1}$ SN 240 $g\cdot L^{-1}$ EC	450 + 18	1.0% *v*/*v*	Monsanto Canada Inc. FMC of Canada
Glyphosate + carfentrazone + sulfentrazone	Roundup WeatherMAX® + Aim® + Authority®	9 14 14	540 $g\cdot L^{-1}$ SN 240 $g\cdot L^{-1}$ EC 480 $g\cdot L^{-1}$ SN	450 + 9 + 53	1.0% *v*/*v*	Monsanto Canada Inc. FMC of Canada FMC of Canada
Glyphosate + carfentrazone + sulfentrazone	Roundup WeatherMAX® + Aim® + Authority®	9 14 14	540 $g\cdot L^{-1}$ SN 240 $g\cdot L^{-1}$ EC 480 $g\cdot L^{-1}$ SN	450 + 9 + 105	1.0% *v*/*v*	Monsanto Canada Inc. FMC of Canada FMC of Canada
Glyphosate + MCPA/dichlorprop/mecoprop-p	Roundup WeatherMAX® + Optica Trio	9 4/4/4	540 $g\cdot L^{-1}$ SN 600 $g\cdot L^{-1}$ SN	450 + 395/765/320	—	Monsanto Canada Inc. Nufarm Agriculture Inc.
Glyphosate + 2,4-D ester	Roundup WeatherMAX® + 2,4-D ester LV 700	9 4	540 $g\cdot L^{-1}$ SN 660 $g\cdot L^{-1}$ EC	450 + 560	—	Monsanto Canada Inc. Nufarm Agriculture Inc.
Glyphosate + pyraflufen-ethyl/2,4-D ester	Roundup WeatherMAX® + Blackhawk®	9 14/4	540 $g\cdot L^{-1}$ EC 6.1/473 $g\cdot L^{-1}$ EC	450 + 188/167	—	Monsanto Canada Inc. Nufarm Agriculture Inc.
Glyphosate + pyraflufen-ethyl/bromoxynil	Roundup WeatherMAX® + Conquer® II	9 14/6	540 $g\cdot L^{-1}$ SN 25/235 $g\cdot L^{-1}$ EC	450 + 4.5/140	—	Monsanto Canada Inc. Nufarm Agriculture Inc.

Note: MOA, mode of action; EC, emulsifiable concentrate; SN, solution; WG, wettable granule.

kochia seedlings present within one 0.25 m^2 quadrat placed randomly within each subplot. Kochia control was visually assessed for herbicide efficacy as a percentage from 0% (visually similar to untreated control) to 100% (complete necrosis) 3 wk after herbicide application (WAA). Kochia aboveground biomass was sampled at 6 WAA. Kochia fresh weight was determined for each accession from a 0.34 m^2 area (three rows by 0.5 m) in each subplot in all locations and years with the exception of Coalhurst in 2014 where biomass was collected from a 0.45 m^2 area (two rows by 1 m).

Statistical analysis

Kochia density, visual control, and biomass data were analyzed using the GLIMMIX procedure in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Analyses were separated by year due to the addition of two herbicide treatments in 2015 that were not present in 2014 (Table 2). The main and interaction effects of kochia accession (GR vs. GS), herbicide treatment, and experimental location (Lethbridge vs. Coalhurst) were considered fixed effects. Random effects included experimental replication nested within location, herbicide treatment by replication nested within location, and kochia accession by replication nested within location. Outliers were removed according to Lund's test (Lund 1975). The distribution and link functions were optimized using visual assessment of predicted vs. residual values and the within-group covariance structure of residuals was fit based on minimization of the Akaike Information Criterion. The assumption of normality was assessed using the Shapiro–Wilk test, while homoscedasticity was evaluated using visual assessment of the residual vs. predicted values. Visual control estimates for the untreated control treatment were removed from the analyses to avoid heteroscedasticity induced by lack of variation in this treatment among locations, and experimental replications.

A Gaussian distribution was used with the identity link function and an unaltered covariance structure of residuals for analysis of kochia density. The same distribution and link functions were used to assess kochia visual control, but the covariance structure of residuals was adjusted based on the location main effect. For kochia biomass, the lognormal distribution was used with the identity link function and the covariance structure of residuals was adjusted based on the interaction effect of kochia accession and location. Significant main and interaction effects were determined according to the F test and treatment means were compared using Tukey's honestly significant difference ($\alpha = 0.05$). Kochia biomass means are presented on the original data scale following post-hoc back transformation.

Results and Discussion

GR kochia

Several herbicide mixtures controlled GR kochia effectively in chemical fallow (Tables 2 and 3) despite variable precipitation among years during the month of herbicide application (June) (Fig. 1). A greater number of treatments controlled GR kochia in Coalhurst compared with Lethbridge, based on visual assessments (≥80% control). These differences were likely due to the subjectivity of visual control estimates among locations and assessors or due to environmental differences between these two locations. The Pest Management Regulatory Agency defines weed control as ≥80% efficacy (Pest Management Regulatory Agency 2003). The best glyphosate mixture treatments that resulted in acceptable (≥80%) control of GR kochia among all environments were glyphosate + dicamba (450 + 580 g a.e.·ha^{-1}), glyphosate + dicamba/diflufenzopyr (450 + 150/50 g a.i./a.e.·ha^{-1}), glyphosate + saflufenacil (450 + 50 g a.i./a.e.·ha^{-1}), and glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g a.i./a.e.·ha^{-1}). The treatments that showed acceptable control at the majority of environments (three out of four environments) were glyphosate + saflufenacil (450 + 18 g a.i./a.e.·ha^{-1}), glyphosate + carfentrazone (450 + 18 g a.i./a.e.·ha^{-1}), glyphosate + carfentrazone + sulfentrazone (450 + 9 + 53 g a.i./a.e.·ha^{-1}), and glyphosate + MCPA/dichlorprop/mecoprop-p (450 + 395/765/320 g a.i./a.e.·ha^{-1}). Glyphosate + pyraflufen-ethyl/bromoxynil (450 + 4.5/140 g a.i./a.e.·ha^{-1}) (tested in 2015 only) showed acceptable control of GR kochia (84% visual control) at Coalhurst only (compared with 69% visual control at Lethbridge) (Table 2).

In 2014, GR kochia biomass supported the visual control estimates, resulting in a biomass reduction of ≥80% for all treatments that had acceptable visual control; with the exception of glyphosate + carfentrazone + sulfentrazone (450 + 9 + 53 g a.i./a.e.·ha^{-1}) at 72% biomass reduction and glyphosate + MCPA/dichlorprop/mecoprop-p, which resulted in the slightly less than acceptable control (79%) and a similar reduction in biomass (79%) (Table 3). One anomaly was glyphosate + carfentrazone (450 + 18 g a.i./a.e.·ha^{-1}), which showed acceptable visual control at 3 WAA (in three out of four environments at 85%, 89%, and 90%), but only a 37% reduction in biomass in 2014. This was likely due to the contact nature of carfentrazone (with little-to-no systemic action) resulting in control of top growth but little plant mortality, allowing for kochia regrowth prior to the biomass assessment (Table 3). Assessment of visual control at multiple time points (including 6 WAA) would aid this conjecture, however, these data were collected only at a single time point in the current study. The glyphosate + dicamba (450 + 290 g a.e.·ha^{-1}) treatment reduced kochia biomass by 88% among locations in 2014, but did not result in acceptable visual control. Differences in kochia biomass among herbicide treatments were not observed in 2015 due to large variability in the biomass measurement (Table 4).

Dicamba is a synthetic auxin (group 4) within the benzoic acid chemical family, and a systemic herbicide that is translocated in the xylem and phloem (Hall et al.

Table 2. Visual control (%) of glyphosate-resistant (GR) and glyphosate-susceptible (GS) kochia 3 wk after herbicide application in chemical fallow at Lethbridge and Coalhurst, AB, in 2014 and 2015.[a]

		Visual control in 2014						Visual control in 2015					
		Lethbridge			Coalhurst			Lethbridge			Coalhurst		
Herbicide treatment	Rate (g a.i./a.e.$\cdot$ha^{-1})	GR (%)	GS (%)	GR vs. GS	GR (%)	GS (%)	GR vs. GS	GR (%)	GS (%)	GR vs. GS	GR (%)	GS (%)	GR vs. GS
Glyphosate	450	0h	95a	***	55d	99	***	0e	93abc	***	0e	89	***
Glyphosate + dicamba	450 + 290	61f	97a	***	94ab	99	**	78abc	96ab	***	94ab	97	NS
Glyphosate + dicamba	450 + 580	80cde	98a	***	99a	99	NS	90a	99a	*	95ab	97	NS
Glyphosate + dicamba/diflufenzopyr	450 + 75/25	73e	96a	***	95ab	98	NS	75abc	91abc	***	89abc	94	*
Glyphosate + dicamba/diflufenzopyr	450 + 150/50	84cd	95a	***	98a	99	NS	86a	94abc	*	92abc	95	NS
Glyphosate + saflufenacil	450 + 18	89bc	99a	***	99a	99	NS	68bc	90abc	***	91abc	95	*
Glyphosate + saflufenacil	450 + 50	99a	99a	NS	95ab	99	*	80ab	93abc	***	91abc	96	*
Glyphosate + carfentrazone	450 + 18	85cd	99a	***	89b	99	***	69bc	91abc	***	90abc	97	***
Glyphosate + carfentrazone + sulfentrazone	450 + 9 + 53	95ab	99a	NS	96ab	99	NS	79ab	90abc	**	90abc	97	***
Glyphosate + carfentrazone + sulfentrazone	450 + 9 + 105	98ab	99a	NS	99a	99	NS	91a	95abc	NS	96a	98	NS
Glyphosate + MCPA/dichlorprop/mecoprop-p	450 + 395/765/320	79de	98a	***	96ab	99	NS	88a	98a	**	95ab	96	NS
Glyphosate + 2,4-D ester	450 + 560	36g	78b	***	76c	98	***	28d	79c	***	78d	95	***
Glyphosate + pyraflufen-ethyl/2,4-D ester	450 + 188/167	—	—	—	—	—	—	61c	85abc	***	79cd	87	**
Glyphosate + pyraflufen-ethyl/bromoxynil	450 + 4.5/140	—	—	—	—	—	—	69bc	80bc	**	84bcd	94	***

Note: Within columns, different letters indicate significant difference based on Tukey's honestly significant difference ($\alpha = 0.05$). GR vs. GS indicates the level of significant difference in visual control between GR and GS kochia accessions for each herbicide treatment. *, **, and *** indicate significant difference between means at $P < 0.05$, 0.01, and 0.001, respectively, while NS indicates lack of significant difference ($P \geq 0.05$).

[a]Analyses were separated by year due to the addition of two herbicide treatments in 2015 (glyphosate + pyraflufen-ethyl/2,4-D ester and glyphosate + pyraflufen-ethyl/bromoxynil).

Table 3. Biomass (kg·ha^{-1}) of glyphosate-resistant (GR) and glyphosate-susceptible (GS) kochia 6 wk after herbicide application in chemical fallow at Lethbridge and Coalhurst, AB, in 2014.

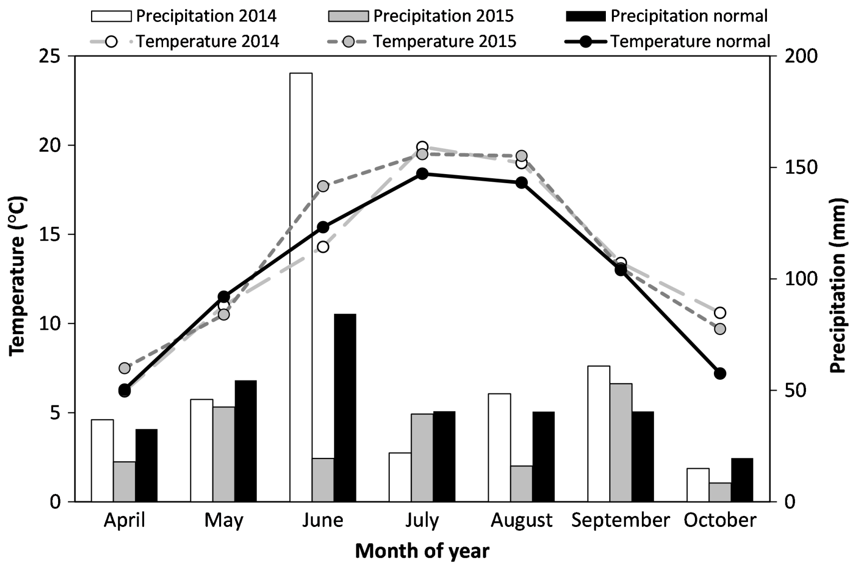
		Kochia biomass				
		Location[a]		Kochia accession[b]		
Herbicide treatment	Rate (g a.i./a.e.·ha^{-1})	Lethbridge (kg·ha^{-1})	Coalhurst (kg·ha^{-1})	GR (kg·ha^{-1})	GS (kg·ha^{-1})	GR vs. GS
Untreated control	—	2264a	980a	1701a	1304a	NS
Glyphosate	450	607bc	106abc	1590a	40b	***
Glyphosate + dicamba	450 + 290	291cde	34abc	200cde	49ab	NS
Glyphosate + dicamba	450 + 580	219de	8bc	116de	15b	**
Glyphosate + dicamba/diflufenzopyr	450 + 75/25	467bcd	139abc	582abcd	111ab	*
Glyphosate + dicamba/diflufenzopyr	450 + 150/50	474bcd	7c	166de	21b	***
Glyphosate + saflufenacil	450 + 18	335cde	35bc	276bcd	42b	***
Glyphosate + saflufenacil	450 + 50	127e	58bc	165de	45b	*
Glyphosate + carfentrazone	450 + 18	426bcd	146ab	1067abc	58b	***
Glyphosate + carfentrazone + sulfentrazone	450 + 9 + 53	137e	116abc	468abcd	34b	***
Glyphosate + carfentrazone + sulfentrazone	450 + 9 + 105	29f	17bc	36e	13b	NS
Glyphosate + MCPA/dichlorprop/mecoprop-p	450 + 395/765/320	278cde	40bc	353abcd	31b	***
Glyphosate + 2,4-D ester	450 + 560	1052ab	154ab	1337ab	121b	***

Note: Within columns, different letters indicate significant difference based on Tukey's honestly significant difference ($\alpha = 0.05$). *, **, and *** indicate significant difference between means at $P < 0.05$, 0.01, and 0.001, respectively, while NS indicates lack of significant difference ($P \geq 0.05$).

[a]Location main effect.

[b]Kochia accession main effect.

Fig. 1. Growing season monthly average temperature and precipitation at Coalhurst and Lethbridge during 2014 and 2015 compared with the 30 yr average (normal) monthly temperature and precipitation for this region. The Coalhurst site received 50 mm, and 25 mm of irrigation in June/July 2014 and May 2015, respectively. The Lethbridge site received 6 mm, 25 mm, and 25 mm in May, June, and July of 2015, respectively.



1999). While the 290 g a.e.·ha^{-1} rate of dicamba (plus glyphosate at 450 g a.e.·ha^{-1}) suppressed GR kochia (61% visual control in 2014 and 78% in 2015) at the Lethbridge location, this treatment resulted in excellent kochia control (94% visual control in 2014/2015) at Coalhurst (Table 2) and reduced shoot biomass (in 2014) by 88% (Table 3). The 2× label rate of dicamba at 580 g a.e.·ha^{-1} (plus glyphosate at 450 g a.e.·ha^{-1}) was excellent (91% visual control average among locations and years) at controlling GR kochia. Lower rates of dicamba have been shown to be ineffective at controlling kochia (Burton et al. 2014). In a greenhouse study, the chemical fallow rate of dicamba (140 g a.e.·ha^{-1}) suppressed GR kochia shoot biomass by 76% (Burton et al. 2014) and in a field study near Lethbridge, AB, dicamba at 139 g a.e.·ha^{-1} showed inadequate kochia control (Low 2016). Shoot and root biomass, glyphosate uptake into the leaves, and glyphosate translocation to roots can be reduced in johnsongrass [*Sorghum halepense* (L.) Pers.] when applying a mixture of glyphosate + dicamba versus glyphosate alone (Flint and Barrett 1989*a*). In field and greenhouse studies on kochia control, glyphosate + dicamba had an antagonistic effect due to reduced translocation of each active ingredient when applied in combination, where significantly better control was observed with glyphosate alone than with glyphosate + dicamba mixtures (Ou et al. 2018). In the current study, glyphosate and dicamba antagonism was not observed visually or quantitatively (in biomass estimates); however, our experiment was not designed to test this hypothesis directly (Tables 2 and 3).

Dicamba/diflufenzopyr have the combined activity of a synthetic auxin (group 4) and an auxin transport inhibitor (group 19) that focuses dicamba to the meristematic sinks, thereby achieving greater control efficacy with a lower rate of active ingredient (Shaner 2014). Greenhouse studies have shown 82% control (biomass reduction of GR kochia) with dicamba/diflufenzopyr applied at 100 g a.i.·ha^{-1} (Burton et al. 2014), but in our field studies this rate was inadequate for control in 2014 causing a biomass reduction of 65% only (Table 3). Field studies often exhibit lower herbicide efficacy compared with greenhouse studies using similar herbicide rates because of the impact of environmental stressors (competition, weather, etc.) on herbicide availability, uptake, and translocation. In the current study, glyphosate + dicamba/diflufenzopyr at 450 + 150/50 g a.i./a.e.·ha^{-1} (2× label rate of dicamba/diflufenzopyr) showed excellent control (90% visual control average among environments) causing a 90% reduction of GR kochia biomass in 2014.

Saflufenacil is a protoporphyrinogen oxidase (PPO) inhibitor (group 14) that is absorbed rapidly by leaves and roots and has moderate residual activity in soil (Shaner 2014). The label rate of saflufenacil (18 g a.i.·ha^{-1}) (plus glyphosate at 450 g a.e.·ha^{-1}) showed acceptable (≥80%) visual control in three out of four environments and reduced GR kochia biomass by 84%. This concurs with a similar study from Montana, US, that showed 100% visual control and 91% biomass reduction of GR kochia in response to saflufenacil (Kumar et al. 2014). The high rate of saflufenacil (50 g a.i.·ha^{-1}) (plus glyphosate 450 g a.e.·ha^{-1}) showed excellent GR kochia control (91% control among environments and a 90% reduction in biomass in 2014), and is an excellent, effective option for control of GR kochia in chemical fallow.

Table 4. Analysis of variance table showing the significance of main and interaction effects of herbicide treatment (H), glyphosate-resistant vs. glyphosate-susceptible kochia accession (A), and experimental location (L) on kochia visual control, plant density, and aboveground biomass at Lethbridge and Coalhurst, AB, in 2014 and 2015.

	2014			2015		
Fixed effect	Visual control (%)	Plant density (plants·m^{-2})	Aboveground biomass (kg·ha^{-1})	Visual control (%)	Plant density[a] (plants·m^{-2})	Aboveground biomass (kg·ha^{-1})
H	**<0.001**	0.363	**<0.001**	**<0.001**	0.595	0.192
A	**<0.001**	**0.001**	**<0.001**	**<0.001**	**<0.001**	0.054
H × A	**<0.001**	0.293	**0.009**	**<0.001**	0.895	0.418
L	**<0.001**	**<0.001**	**<0.001**	**<0.001**	N/A[b]	**0.044**
H × L	**<0.001**	0.347	**0.001**	**<0.001**	N/A	0.348
A × L	**<0.001**	0.097	**0.024**	**<0.001**	N/A	0.177
H × A × L	**<0.001**	0.188	0.186	**<0.001**	N/A	0.588

Note: Bolded values indicate significant main or interaction effects at $P < 0.05$. N/A, not applicable.

[a]P values for kochia density in 2015 are for the Lethbridge location only.

[b]Visual differences in kochia density were absent at Coalhurst in 2015, and thus density was measured in the untreated control plots only. Coalhurst 2015 kochia density data were absent from the analysis of variance.

Glyphosate + carfentrazone + sulfentrazone at the label rate (450 + 9 + 53 g a.i./a.e.·ha^{-1}) resulted in 90% visual control (average among environments) with only a 72% reduction in biomass in 2014. Increasing the rate of sulfentrazone in this mixture to 105 g a.i.·ha^{-1} resulted in excellent visual control of GR kochia (96% control) and a 98% reduction in kochia biomass (in 2014). Carfentrazone and sulfentrazone are both PPO inhibitors (group 14), but carfentrazone is a contact herbicide with little-to-no residual activity in soil, while sulfentrazone is systemic with moderate residual activity (half-life of 121–302 d) (Shaner 2014). This combination was among the best mixture options for controlling GR kochia, in part, because it included a quick (hours to days) contact herbicide resulting in rapid necrosis and plant cell death, in addition to extended residual activity to help control subsequent emergence of kochia seedlings.

GS kochia

In general, GS kochia visual control was excellent among treatments (≥90%), in part because all herbicide treatments were mixed with glyphosate; however, some herbicide treatments resulted in visual control that was considered acceptable only (≥80% but <90%) (Table 2). All treatments at both Lethbridge and Coalhurst achieved ≥80% control of GS kochia, with the exception of the glyphosate plus 2,4-D ester mixture, which resulted in just below the 80% control threshold at Lethbridge in 2014 and 2015 (Table 2). Glyphosate mixed with 2,4-D can result in antagonism when applied to field bindweed (*Convolvulus arvensis* L.) or johnsongrass because 2,4-D can affect the uptake and translocation of glyphosate (Flint and Barrett 1989*a*, 1989*b*). Perhaps this antagonism resulted in lower kochia control by the glyphosate plus 2,4-D ester mixture in the current study.

Biomass of GS kochia in 2014 supported the visual efficacy data with all treatments resulting in a biomass reduction of at least 90% compared with the untreated control (Table 3). Glyphosate + dicamba (450 + 580 g a.e.·ha^{-1}), glyphosate + dicamba/diflufenzopyr (450 + 150/50 g a.i./a.e.·ha^{-1}), and glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g a.i./a.e.·ha^{-1}) resulted in the greatest biomass reduction (98%–99% biomass reduction compared with the untreated control) and almost eliminated the GS kochia present (Table 3). Even though the herbicide treatments did not result in different visual control of GS kochia at Coalhurst in either year (e.g., 98%–99% visual control in 2014), differences in kochia biomass were observed among the herbicide treatments in 2014 (ranging from 7 to 154 kg·ha^{-1} among herbicide treatments) (Tables 2 and 3).

Differences between kochia accessions

Many of the herbicide mixtures resulted in greater control of GS kochia compared with GR kochia accessions. Visual control ratings showed greater control of GS kochia compared with GR kochia among environments ($P < 0.05$ in all environments) when treated with glyphosate alone, glyphosate + 2,4-D ester (450 + 560 g a.e.·ha^{-1}), and glyphosate + carfentrazone (450 + 18 g a.i./a.e.·ha^{-1}) (Table 2). Glyphosate + dicamba (450 + 290 g a.e.·ha^{-1}), glyphosate + dicamba/diflufenzopyr (450 + 75/25 g a.e./a.i.·ha^{-1}), and glyphosate + saflufenacil (both rates) resulted in greater control of GS compared with GR kochia in three out of four environments. The only treatment with no difference between kochia accessions in either location or year was glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g a.i./a.e.·ha^{-1}), as this was among the most effective treatments on GR kochia visual control (96%) and biomass reduction (98%). The remaining treatments did not show a clear trend of differences between kochia accessions based on visual control ratings.

Among herbicide treatments, the GR kochia accession had greater aboveground biomass (by about 7×; data not shown) than the GS kochia accession in 2014 (the herbicide treatments resulted in about 3× to 40× greater GR kochia biomass than the same treatments on GS kochia) (Tables 3 and 4). This was due, in part, to the greater density of GR than GS kochia present in 2014 (112 ± 4.5 GR vs. 83 ± 4.5 GS kochia plants·m^{-2}) and 2015 (223 ± 10.5 GR vs. 171 ± 10.5 GS kochia plants·m^{-2} at Lethbridge; not measured in Coalhurst); but could be due also to the lower efficacy of herbicide mixtures for GR kochia management (Tables 2 and 4). At Lethbridge in 2014, the glyphosate + carfentrazone (450 + 18 g a.i./a.e.·ha^{-1}), glyphosate + dicamba (450 + 290 and 580 g a.e.·ha^{-1}), glyphosate + saflufenacil (450 + 18 and 50 g a.i./a.e.·ha^{-1} rate), glyphosate + carfentrazone + sulfentrazone (450 + 9 + 53 and 105 g a.i./a.e.·ha^{-1}), and glyphosate + MCPA/dichlorprop/mecoprop-p (450 + 395/765/320 g a.i./a.e.·ha^{-1}) treatments all resulted in ≥80% reduction in kochia biomass among kochia accessions, while all treatments showed ≥80% biomass reduction at Coalhurst (Table 3). Glyphosate applied alone reduced GS kochia biomass in 2014 by about 97%, while the biomass of GR kochia was reduced by 7% only. This confirms that the GR kochia accession used was rather homogeneous for the glyphosate resistance trait.

Kochia accession differences in density, visual control, and biomass among locations and years could be attributed to differences in soil, weather conditions during or after application, and weather throughout the growing season. The two experimental locations had different soil parameters including soil texture (loam vs. clay loam), organic matter (2.5% vs. 3.6% OM), and pH (8.3 vs. 7.8 pH). Weather at the time of application may have influenced herbicide efficacy because heat, cold or drought stress can impact herbicide uptake and translocation. The total accumulated precipitation at Lethbridge and Coalhurst for the 2014 growing season (April to October) was above average (421 mm in 2014 vs. 313 mm 30 yr average), while the precipitation in 2015 was below average (197 mm in 2015 vs. 313 mm 30 yr average) (Fig. 1).

In conclusion, the best treatments (≥80% visual control in all environments and ≥80% biomass reduction in 2014 compared with the untreated control) for controlling GR and GS kochia in chemical fallow fields in southern Alberta were glyphosate + dicamba (450 + 580 g a.e.·ha^{-1}), glyphosate + dicamba/diflufenzopyr (450 + 150/50 g a.i./a.e.·ha^{-1}), glyphosate + saflufenacil (450 + 50 g a.i./a.e.·ha^{-1}), and glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g a.i./a.e.·ha^{-1}); and somewhat less consistently (≥80% visual control three out of four environments with ≥80% biomass reduction in 2014) glyphosate + saflufenacil (450 + 18 g a.i./a.e.·ha^{-1}). Glyphosate + carfentrazone + sulfentrazone (450 + 9 + 105 g a.i./a.e.·ha^{-1}) was consistently one of the best treatments for kochia control among environments and kochia accessions. Due to the recent discovery of triple-resistant kochia in Alberta, resistant to ALS inhibitors, glyphosate, and dicamba (Beckie et al. 2019), glyphosate mixtures with multiple effective modes of action are warranted for successful and sustainable kochia management. Rotating these herbicide mixtures with several effective modes of action (Beckie and Reboud 2009) on chemical fallow and subsequent crops could help mitigate the accumulation of multiple herbicide resistance traits by reducing recurrent selection pressure.

Resistance management is necessary due to the quick evolution of herbicide resistance in kochia. The first report of GR kochia in Canada was identified in 2011 in chemical fallow fields in Warner County, AB, and at the time (2012) only 4% of kochia populations surveyed were confirmed GR (Beckie et al. 2013; Hall et al. 2014). After only 5 yr, the incidence of glyphosate resistance in kochia populations increased from 4% (in 2012) to 50% (in 2017) (all kochia surveyed were ALS inhibitor–resistant and 18% were dicamba-resistant) (Beckie et al. 2019). The current study revealed several effective options for control of GS kochia in chemical fallow and that the efficacy of many herbicide mixtures can be reduced following the assimilation of the glyphosate resistance trait. It is clear that mixing and rotating multiple effective modes of action can be a valuable tool for mitigating herbicide resistance, but the effective options (and thus efficacy of control) can diminish quickly following the selection for new types of resistance. For this reason, farmers are urged to adopt a proactive approach to integrated weed management in which herbicides should comprise an important role supported by several other non-chemical tools. The use of cover crops, strategic spot tillage, mowing, and patch management are all tools that could help prolong the efficacy of these herbicide mixtures by mitigating seed production and limiting the number of kochia seeds returned to the soil seedbank.

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