Management of glyphosate-resistant kochia in western Canadian cropping systems

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Introduction

Repeated use of the broad-spectrum herbicide active ingredient glyphosate [group 9; a 5 enolpyruvylshikimate-3-phosphate (EPSP) synthase-inhibitor] for PRE-emergence, PRE-harvest and/or POST-harvest weed management, chemical fallow, or POST-emergence weed management in glyphosate-resistant (GR) crops contributes to the selection for GR weed species. Kochia [Bassia scoparia (L.) A.J. Scott] is the first known weed species to develop resistance to glyphosate in western Canada. Poorly managed, kochia can reduce crop yields and may be detrimental especially in relatively new GR crops such as corn or soybean.

Kochia populations resistant to acetolactate synthase (ALS)-inhibiting herbicides (group 2) were first discovered in western Canada in 1988 (Heap 2019). The frequency of ALS inhibitor resistance grew to greater than 90% of kochia populations over the course of two decades (Beckie et al. 2011). Today, all kochia populations screened in western Canada are resistant to ALS-inhibiting herbicides (Beckie et al. 2019). ALS inhibitor resistance in kochia has demonstrated the ability for herbicide resistance in kochia to spread rapidly in the contemporary cropping systems of western Canada.

In 2011, the first suspected cases of GR kochia in western Canada were confirmed in southern Alberta (Beckie et al. 2013). Subsequent surveys in Alberta (AB), Saskatchewan (SK) and Manitoba (MB) found GR kochia populations in chemical fallow (AB & SK), wheat, canola, lentil (SK), GR corn and GR soybean (MB) (Beckie et al. 2013, 2015; Hall et al. 2014). Although the original cases were believed to have been selected by repeated use of glyphosate in chemical fallow (Beckie et al. 2013), later cases were selected in GR row-crops (Gulden RH, pers comm). The baseline post-harvest kochia survey of Alberta in 2012 showed that about 4% of kochia populations in Alberta were resistant to glyphosate. A subsequent 2017 survey of Alberta showed that the incidence of glyphosate resistance in kochia had grown from 4% to 50% of kochia populations over the course of five years (Beckie et al. 2019). In addition, this survey also confirmed that 18% of kochia populations in Alberta were resistant to dicamba (group 4; a synthetic auxin herbicide). Our recent survey of Manitoba showed a similar increase in glyphosate-resistant kochia from 1% to 58% of kochia populations between 2013 and 2018 (Geddes et al. 2022).

Triple-resistant kochia populations (about 10% of kochia populations in Alberta in 2017) will be difficult to manage in western Canadian crop rotations, leave limited herbicide modes-of-action for chemical management and likely have substantial impact on crop yields (Geddes and Sharpe 2022). There is high risk of spread of multiple resistance in kochia due to protogynous flowering resulting in efficient outcrossing and pollen-mediated gene flow, and the tumbleweed seed dispersal mechanism resulting in efficient seed-mediated gene flow (Beckie et al. 2016). For this reason, immediate action is warranted to help reduce the spread of herbicide resistance in kochia populations, mitigate selection pressure for new herbicide-resistant kochia biotypes, and manage herbicide-resistant kochia populations effectively. Such action requires investment in research aimed at developing integrated kochia management strategies based on “weak points” in the biology and ecology of this weed species.

Kochia is a C4 weed species that thrives in warm-season environments. Unlike many other C4 species, however, kochia can germinate at low temperatures and commonly is one of the first weeds to emerge in spring (after about 50 growing degree-days) (Friesen et al. 2009; Schwinghamer and Van Acker 2008). Following the initial spring flush of kochia seedling emergence, kochia seedling recruitment may continue to occur throughout the growing season (Schwinghamer and Van Acker 2008). Due to prolonged emergence periodicity, kochia may emerge following in-crop herbicide application (Friesen et al. 2009; Schwinghamer and Van Acker 2008). Kochia seedlings that emerge as late as mid-August can produce viable seed prior to the first killing frost (Geddes and Davis 2021). Typically, kochia plants produce between 14,000 and 30,000 seeds per plant (Friesen et al. 2009; Beckie 2016). These seeds form a transient seedbank with short-lived seed persistence (< 2 years) (Beckie et al. 2018; Zorner et al. 1984). For this reason, competitive crops may reduce fecundity (seed production) of kochia plants that escape in-crop herbicide management and thereby limit the number of kochia seedlings that emerge in subsequent years.

Following harvest in the United States, kochia plants can regrow rapidly and produce viable seed before the first killing frost (Mickelson et al. 2004). Preliminary research has shown that kochia may regrow more slowly following harvest in northern Canadian climates; even to the point that postharvest herbicide application may not be warranted (Low 2016). This, of course, would be influenced by harvest timing. The time of harvest following which kochia regrowth can set seed prior to winter is unknown and requires investigation to determine when preharvest and postharvest weed management is warranted under Canadian conditions.
Despite widespread multiple-resistant kochia in the United States, information on using cropping systems to manage herbicide-resistant kochia is lacking. This research project will use a multi-experimental approach to determine how growers can adapt cropping systems to increase competition with weeds and mitigate the selection for – and/or manage existing populations of – GR kochia. Crop diversity, crop life cycle diversity, and crop harvest date in combination with preharvest and postharvest herbicide application will be evaluated in field experiments based on management of GR kochia populations. Cultural methods used to increase the competitive ability of diverse crop rotations will be evaluated also throughout a four-year crop rotation.

Test 1 – Impact of crop diversity and crop life cycle on management of glyphosate-resistant kochia

Objective 1. Determine the impact of crop diversity and crop life cycle on management of glyphosate-resistant kochia in western Canadian crop production by comparing two-year and four-year crop rotations.

Will the inclusion or exclusion of certain crops in crop rotations impact management of GR kochia?

- Can including winter-cereals in crop rotations increase management of GR kochia?
- Can growing perennial forage (alfalfa/grass mixture) limit GR kochia seed production and deplete kochia populations over 4 years?

Methodology/Experimental design

Crop rotation experiment: One fully-phased 4-year crop rotation experiment conducted at 2 locations.
Duration: 2019-2022
Locations:

- Lethbridge, AB (Geddes site-lead)
- Scott, SK (Mulenga site-lead, later transferred to Lokuruge)
    - Crops = spring wheat (SW), winter wheat (WW), canola (C), lentil (L) and alfalfa/grass mixture

Note: all canola was glufosinate-resistant (Liberty link) and all lentil was imidazolinone-resistant (Clearfield)

A randomized complete block design with a fully-phased treatment structure and four experimental replications per location was used to evaluate the effect of crop diversity and crop life cycle diversity on management of GR kochia in western Canadian crop rotations. Due to the limited availability of GR kochia seed and the use of fall-seeded crops in this experiment, GR kochia was planted and harvested at each experimental location in 2018 to increase seed supply, and winter wheat was seeded in fall 2018. The same rotation experiment was implemented in AB (led by Geddes) and SK (led by Mulenga; later Lokuruge) and was focussed on cool-season dryland crops including winter wheat, spring wheat, canola, lentil and an alfalfa/grass mixture. The experiment hosted seven different crop rotations and 17 treatments per replication. The effect of including multiple crop life cycles in crop rotations was tested using either summer- or winter-annual small grain cereals in similar crop rotations. A factorial treatment substructure is represented where rotations are implemented once using spring wheat as the rotational cereal crop and again by replacing spring wheat with winter wheat.

To avoid potential confounding effects of divergent environmental conditions among years (e.g., below average precipitation), the experiment was fully-phased and included each crop-phase of each rotation in each year. This treatment structure allows for increased internal replication of crop rotations, and a reduced number of sites across western Canada. This is important as we are limited on the availability of sites for work on GR kochia (i.e., sites require established GR kochia populations).

The experiments were conducted in fields with a previous populations of GR kochia to limit weed population dispersal. GR kochia seed was collected in fall 2018 and winter-annual crops were seeded. GR kochia populations were established in the experimental replications in fall 2018 and summer-annual crops were seeded in spring 2019. The experiment consists of two-year crop rotations with reduced crop diversity (cereal-oilseed or cereal-pulse) and four-year crop rotations with greater crop diversity (cereal-oilseed-cereal-pulse). The experiment spanned four years from 2019 to 2022. Due to the recent discovery of triple-herbicide-resistant (groups 2, 4 and 9) kochia populations in western Canada in 2017, herbicide regimes were constructed to limit the use of effective group 4 herbicides to once in four years. PRE-emergence herbicide management consisted of either a fall applied group 3 herbicide (Edge) prior to canola or strategic use of group 9 (RoundUp) plus either groups 14 or 15 herbicides (e.g., Aim, Heat Complete, Goldwing) applied prior to seeding the other crops. POST-emergence herbicide management consisted of alternating between applying groups 1, 6 and 27 (Achieve and Infinity), groups 1 and 4 (Horizon and Prestige XL or Horizon and OcTTain) or groups 1, 4 and 6 (e.g., Achieve and Buctril M) applied in spring or winter wheat based on recropping restrictions. Groups 1 and 10 (Centurion and Liberty) were applied in canola and group 2 (Solo) applied in lentil. The alfalfa/grass mixture remained absent of herbicide application and was cut twice per year.

Main measurements

- Crop densities
- Kochia densities (a) before post-emergence herbicide application, (b) after post-emergence herbicide application, and (c) prior to harvest
- Crop canopy % ground cover
- Crop canopy light interception
- Crop/kochia plant heights
- Crop/kochia/other weed plant biomass
- Kochia plant fecundity (seed production)
- Crop yield
- Kochia seed in dockage samples
- Kochia seedbank at the end of the 4-year study

Statistical analysis

Each response variable from the 2021 growing season was subject to ANOVA using proc MIXED in SAS Studio. Each location comprised a separate analysis. Crop rotation treatment, year, and their interaction were considered a fixed factors, while experimental replication was considered a random factor. Data were analyzed as a repeated measures where measurements were repeated in the same experimental unit (plot) each year. Data transformation were used meet the assumptions of ANOVA and significant main and interaction effects were determined based on the F-test using a significance level of $\alpha = 0.05$. Multiple comparisons were made using letter display based on Tukey's HSD $\alpha =$ (0.05). Least squares means estimates (lsmestimates) were used to draw conclusions across treatment groups such as "life cycle".

Results and discussion

Test 1 – Lethbridge, AB

Midseason kochia biomass responded to the crops grown in each rotation treatment resulting in treatment differences that varied across years and that were dependent on the phase of each crop rotation. However, high level observations and trends among the treatments in the Lethbridge, AB, location were parsed using lsmestimates. One clear trend was the difference between crop rotations comprised solely of summer-annual (SA) crops, compared with those alternating SA and winter-annual (SA-WA) crops. For example, when averaged across all years and all crop rotations categorized with SA and SA-WA life cycles respectively, crop rotations including winter wheat instead of spring wheat had 72% lower kochia biomass. The perennial (P) alfalfa/meadow brome treatment resulted in similar kochia biomass as the SA rotations when averages over all years. However, the perennial treatment completely controlled kochia in the latter two years of the 4-year study. This was because the first year of alfalfa/meadow brome establishment had the highest kochia biomass, which rapidly declined in subsequent years once the perennial treatment was established.

Kochia plant density was measured at three time points each year: (1) Early (before the in-crop herbicide treatment), mid (after the in-crop herbicide treatment), and late (before harvest). In general, kochia densities were greatest in the early measurement and declined over the course of each growing season due to herbicidal control and crop competition (Figure 1). The crop rotations that included winter wheat instead of spring wheat tended to have lower kochia biomass overall, and almost a complete decline in the kochia population in some treatments and years. When averaged across assessment timings, years, and crop rotation life cycles, rotations that included winter wheat had 60% lower kochia densities those including spring wheat. The perennial treatment had very high kochia densities at the start of the second year of establishment, but those densities declined rapidly in years 3 and 4. By the final year of the study, kochia densities in the SA-WA rotations and the P treatment were 82% and 97% lower, respectively, than the SA rotations.

Aboveground plant densities in the final year of the study (2022) were reflective of kochia seed densities in the soil seedbank for the SA and SA-WA rotations, but not the P treatment. After the four-year crop rotation study, the rotations that included winter wheat (SA-WA life cycle) resulted in half of the kochia seed in the soil seedbank overall compared with the same rotations that instead included spring wheat (SA life cycle). Interestingly, kochia seed persisted in the soil seedbank of the perennial treatment, resulting in a greater seedbank density overall, which was 170% that of the SA crop rotations on average. Therefore, integrating winter wheat into the crop rotations substantially reduced the kochia seedbank compared with spring wheat. However, the perennial treatment had a greater kochia seedbank than the summer-annual rotations despite having lower plant densities and biomass.

Test 1 – Scott, SK

The same crop rotation experiment conducted near Lethbridge, AB, was also conducted near Scott, SK. The experiment at Scott, SK was conducted according the protocol with no deviations to report. However, the kochia densities in the crop rotation at Scott were low overall despite multiple attempts to establish a greater kochia population by broadcasting more seed. This resulted in kochia density and biomass measurements that included many 0 values (i.e., no kochia plants present), which did not conform to the assumptions of ANOVA during statistical analyses. Therefore, data presented for the Scott, SK site are simple means ± standard errors (SE). Thus, these data can be interpreted as general trends, but should not be considered statistically significant.

Interestingly, an opposite trend was observed at the Scott site of the study than observed at Lethbridge. The plots that had winter wheat tended to have greater kochia densities. However, this was likely due to better establishment of the kochia in plots that were seeded to winter wheat in year 1 rather than the impact of winter wheat for kochia management.

On average, kochia biomass was 63% greater (numerically) in the SA-WA crop rotations compared with the SA crop rotations. However, similar to the density data, kochia biomass estimates did not conform to the assumption of ANOVA. Therefore, these data should not be used to draw overall conclusions regarding the treatment effects. Likewise, simple means for the kochia seedbank at the end of the study ranged among crop rotation treatments from 0 to 38 seeds m-2. Therefore, poor kochia establishment in the Scott experiment resulted in low kochia densities overall and made it difficult to parse treatment effects.

Test 2 – Impact of crop seeding density and row spacing on glyphosate-resistant kochia

Objective 2. Assess integrated cultural methods used to increase the competitive ability of diverse crop rotations based on management of glyphosate-resistant kochia in western Canada.

- Can increasing crop seeding densities increase the competitive ability of diverse crop rotations with GR kochia?
- Can reducing row spacing increase the competitive ability of diverse crop rotations with GR kochia?
- Can the integration of increased crop seeding densities and narrow row spacing have additive or synergistic effects on the competitive ability of diverse crop rotations and management of GR kochia?

Methodology/Experimental Design

Crop rotation experiment: One fully-phased 4-year crop rotation experiment conducted at 2 locations.

Duration: 2018-2021

Locations:

- Lethbridge, AB (Geddes site-lead)
    - Crops = spring wheat (SW), canola (C) and lentil (L)
- Winnipeg, MB (Gulden site-lead)
    - Crops = spring wheat (SW), canola (C), soybean (Soy) and grain corn (Crn)

Note: all canola was glufosinate-resistant (Liberty link), all lentil was imidazolinone-resistant (Clearfield) and all corn and soybean will be glyphosate-resistant (Roundup ready)

A randomized complete block design with a fully-phased treatment structure and four replications per location was used to evaluate the effect of integrating cultural tools to increase the competitive ability of crop rotations based on management of GR kochia. The crop rotations implemented in AB (led by Geddes) focused on cool-season dryland crops including spring wheat, canola and lentil. In AB, the wide-row 1X seeding density rotation A (less competitive rotation) follows a SW-C-SW-L sequence using recommended seeding densities with 46 cm (18″) row spacing. Competitive crop rotations consist of the same crops using either double the recommended seeding densities, narrow [23 cm (9″)] row spacing or integrating double the recommended seeding densities with narrow row spacing. The experiment implemented in AB hosted four crop rotations and 16 treatments per replication. The rotations implemented in MB (led by Gulden) are different from the rotations implemented in AB. In the MB experiment, soybean and corn are included in the rotations, while lentil is excluded. The MB rotations consist of a Crn-C-SW-Soy rotation sequence and followed the same treatment structure as the AB experiment. The inclusion of corn and soybean in the MB rotations provided the opportunity to evaluate relatively new, GR crops and how we could increase their competitive ability to facilitate their integration in MB crop rotations, while still achieving adequate management of GR weeds. In MB, the uncompetitive crop rotation (rotation A) was seeded using recommended seeding densities and wide row spacing [38 cm (15″) row spacing in spring wheat and canola, and 76 cm (30″) row spacing in corn and soybean]. The competitive crop rotations include the same crops using either double the recommended seeding densities, narrow row spacing [19 cm (7.5″) row spacing for spring wheat, canola and soybean, and 38 cm (15″) row spacing for corn], or integrating double the recommended seeding densities with narrow row spacing. The experiment implemented in MB hosted four different crop rotations and 16 treatments per replication.

The narrow row spacing used in MB (7.5″) is tighter than the narrow row spacing used in AB (9″). The experiment in MB was located in the Red River Valley where conventional tillage remains a standard practice. This tillage system often allows for narrower row spacing than zero- or minimum-tillage systems. The tighter row spacing in MB was chosen to reflect this, and also the availability of plot-sized equipment in this area.

The experiments were established in fields with populations of GR kochia in an attempt to limit kochia dispersal. GR kochia seed was collected from each site in fall 2017. In spring 2018, GR kochia seed was distributed over the entire experimental area to even out population densities and summer-annual crops were established. Due to the recent discovery of triple-resistant (groups 2, 4 and 9) kochia populations in western Canada in 2017, herbicide regimes were constructed to limit the use of group 4 herbicides to once in four years. PRE-emergence herbicide management consists of either a fall applied group 3 herbicide (Edge) prior to canola or strategic use of the group 14+15 herbicides Heat Complete prior to lentil or Focus prior to soybean and a group 14 herbicide (Aim) prior to wheat and corn. All PRE-emergence herbicides were applied in addition to glyphosate (RoundUp WeatherMax). POST-emergence herbicide management consisted of alternating between applying groups 1, 6 and 27 (Axial and Infinity) or groups 1 and 4 (e.g., Horizon and Prestige) applied in wheat, groups 1 and 10 (Centurion and Liberty) applied in canola, group 2 (Solo) applied in lentil, groups 2 and 6 (Viper ADV) applied in soybean (with Roundup) and groups 9 and 27 (Roundup and Armezon) applied in corn.

Measurements

- Crop densities
- Kochia densities (a) before post-emergence herbicide application, (b) after post-emergence herbicide application, and (c) prior to harvest
- Crop canopy % ground cover
- Crop canopy light interception
- Crop/kochia plant heights

- Crop/kochia/other weed biomass
- Kochia plant fecundity (seed production)
- Crop yield
- Kochia seed in dockage samples (in Lethbridge only)
- Kochia seedbank at the end of the four-year crop rotation

Statistical analysis

The response variables were subjected to ANOVA using proc MIXED in SAS Studio. Data were analyzed by site due to the presence of different crop rotations in Lethbridge and Winnipeg. Crop rotation phase, row spacing, and seeding rate were considered fixed effects, while experimental replication was considered a random effect. Data transformation and altered residual structures were used meet the assumptions of ANOVA and significant main and interaction effects were determined based on the F-test using a significance level of $\alpha = 0.05$. Multiple comparisons were made using letter display based on Tukey's HSD $\alpha = (0.05)$. The highest order significant main and interaction effects are presented.

Test 2 – Lethbridge, AB

All three factors (i.e., crop row spacing, seeding rate, and crop rotation phase) influenced kochia dynamics throughout the four-year crop rotation at Lethbridge, AB. In general, kochia plant densities were greatest in the wheat phase of the crop rotation that followed lentil (with the exception of the first year of the study) (Table 6). This was expected because no effective post-emergence herbicide options exist to manage group 2-resistant kochia in lentil (all kochia is group 2-resistant), resulting in a larger number of plants going to seed in the lentil phase of the crop rotation. Across years and assessment timings, the narrow (23 cm) row spacing resulted in 43% lower kochia densities than the wide (46 cm) row spacing. Double crop seeding rates resulted in 37% lower kochia densities compared with recommended seeding rates on average. Similar effects were observed for midseason kochia biomass, where both narrow row spacing and double seeding rates reduced kochia biomass by 55% and 53%, respectively. When used in combination, however, narrow row spacing and double crop seeding rates throughout the crop rotation reduced kochia biomass by 80% on average compared with wide row spacing and recommended seeding rates (data not shown). This corresponded with reduced kochia seed production resulting in less kochia seed collected as dockage with the grain yield samples. Both narrow row spacing and double crop seeding rates effectively reduced the kochia seedbank by the end of the four-year study by 44% and 34% on average, respectively.

Test 2 – Winnipeg, MB

The Winnipeg study was located on a dense patch of kochia on heavy clay soils. Unfortunately, this site had persistent issues with access to the study location, and herbicide residues terminating the canola crop in three out of four years. These factors led to several missed data points over the four years of the study. Missing data and the lack of crop establishment in some years precluded our ability to statistically analyze these data in a way that would address our hypotheses. While trends overall support the observations of the Lethbridge crop rotation experiment (data not shown), the Winnipeg data are largely unusable to address our hypotheses. Therefore, data from the Winnipeg site are not presented in this high-level summary.

Tests 3a and 3b – Impact of harvest timing and presence or absence of PRE- or POST-harvest herbicide on kochia seed production and viability.

Objective 3. Measure the seed production potential of glyphosate-resistant kochia before and after a range of harvest dates with and without application of PRE- and POST-harvest herbicide.

- When are PRE- or POST-harvest herbicides warranted to limit seed production of GR kochia?
- How does harvest date impact seed production potential and seedbank inputs of GR kochia prior to and following harvest?

Methodology/Experimental design

Single-year experiment: 7 field trials total for each kochia biotype (glyphosate-resistant and glyphosate-susceptible). The number of field trials to be conducted at each location are listed below.

Duration: 2018-2022

Locations: (14 site-years)

- Test 3a: Glyphosate-resistant (GR) kochia
  - Lethbridge, AB (Geddes site-lead) – 3 trials (2018, 2019 & 2020)
  - Scott, SK (Mulenga site-lead) – 2 trials (2020 & 2021)
  - Winnipeg, MB (Gulden site-lead) – 2 trials (2019 & 2021)
- Test 3b: Glyphosate-susceptible (GS) kochia
  - Lethbridge, AB (Geddes site-lead) – 3 trials (2018, 2019 & 2020)
  - Saskatoon, SK (Willenborg site-lead) – 2 trials (2020-2021)
  - Carman, MB (Gulden site-lead) – 2 trials (2021 & 2022)

Treatments: (18 treatments = 3 herbicide regimes x 6 harvest dates)

- Factor 1: Herbicide regime (3 regimes, including: untreated vs. preharvest vs. postharvest glyphosate + sa flufenacil)
  - Glyphosate (RoundUp WeatherMax) applied at 900 g a.e. ha-1 plus saflufenacil (Heat LQ) applied at 50 g a.i. ha-1 with Merge adjuvant (0.5% v/v) and with 200 L ha-1 water volume.
  - Preharvest herbicide applied 10 days prior to harvest.
  - Postharvest herbicide applied 10 days following harvest
- Factor 2: Harvest date (6 dates ranging from the late July to the beginning of October)

Populations of GR and/or glyphosate susceptible (GS) kochia were established in the spring, and maintained throughout the growing season. Beginning in late-July, kochia plots were cut (swathed @ 15-18 cm height) and biomass was removed from each plot. The early cutting simulated an early crop harvest date (e.g., silage or early harvest of winter-cereals). Cuttings took place in different plots every two weeks until early-October. The late cuttings simulated harvest of long-season crops (e.g., corn, soybean or sunflower). All six harvest dates included three different herbicide management regimes in a full factorial treatment structure: (a) without herbicide management (control, simulating swathing for kochia dry-down prior to harvest or swathing kochia patches), (b) with glyphosate plus saflufenacil applied PRE-harvest (to facilitate kochia dry-down for direct harvest or to help prevent regrowth after harvest), or (c) with glyphosate plus saflufenacil applied POST-harvest (to manage kochia regrowth prior to winter). Kochia seed production prior to harvest was evaluated by hand harvesting kochia plants prior to cutting and immediately after cutting (seed on lateral branches below the cutting height). The seed production potential of kochia regrowth following harvest was evaluated also. Measurements of kochia regrowth following harvest dates were used to assess the timing of harvest where PRE- or POST-harvest herbicide application may be warranted to prevent additional kochia seedbank inputs. Seed collected prior to harvest and after the first killing frost was tested for viability to measure the number of viable seeds produced based on harvest timing and herbicide management regime.

Glyphosate plus saflufenacil (RoundUp plus Heat LQ) was chosen as the herbicide combination used in this study because it is registered as a PRE-harvest herbicide in a wide range of crops that span early to late harvest dates in western Canada. Saflufenacil also has a wide range of crops that can be seeded in the spring subsequent to fall application. Preliminary research from the University of Saskatchewan (E. Bertholet, M.Sc. Research) has shown that saflufenacil can be effective for PRE-harvest dry-down of glyphosate-susceptible kochia in lentil.

Measurements

- Kochia emergence date
- Kochia plant density
- Kochia plant height and BBCH stage @ preharvest herbicide application and @ cutting for each of six harvest dates.
- Kochia biomass (a) before cutting, (b) after cutting, and (c) after the first killing frost for each of six harvest dates.
- Kochia seed production (a) before cutting, (b) after cutting, and (c) after the first killing frost for each of six harvest dates.

Statistical analysis

Kochia viable seed at harvest, seed on lateral branches below the cutting height, seed on regrowth following harvest, and total seed production across all assessment timings were subjected to ANOVA using proc MIXED in SAS Studio. Each model included 14 site-years of data from experiments across western Canada. Kochia biotype (glyphosate-resistant vs. glyphosate-susceptible), harvest date (1-6), herbicide regime (untreated vs. preharvest vs. postharvest), and their interactions were considered fixed effects, while experimental replication nested within site-year and site-year were considered random effects. Data transformation and altered residual structures were used meet the assumptions of ANOVA and significant main and interaction effects were determined based on the F-test using a significance level of α = 0.05. Multiple comparisons were made using letter display based on Tukey's HSD (α = 0.05). The highest order significant main and interaction effects are presented.

Results and discussion

Cumulative growing degree days (GDD) ranged between harvest dates and experimental locations from 1206 to 2822 GDD. Kochia plants began to produce seed between the third and fourth harvest dates which took place on average around 2083 to 2300 cumulative GDD, respectively. Therefore, kochia is a long-season plant and typically starts to produce seed in the third or fourth weeks of August. However kochia plants produced seed rapidly, and reached maximum seed production by the fifth harvest date (around 2483 GDD; mid-September) (Figure 1a). This suggests that early harvest dates associated with winter-annual crops or silage could be used as a tool to target kochia plants before they begin to produce seed.

Pre-harvest herbicide treatment reduced viable kochia seed consistently among all harvest dates by 28% on average compared with the untreated control (Figure 1b). This is a marginal, yet significant, reduction in seed kochia production.

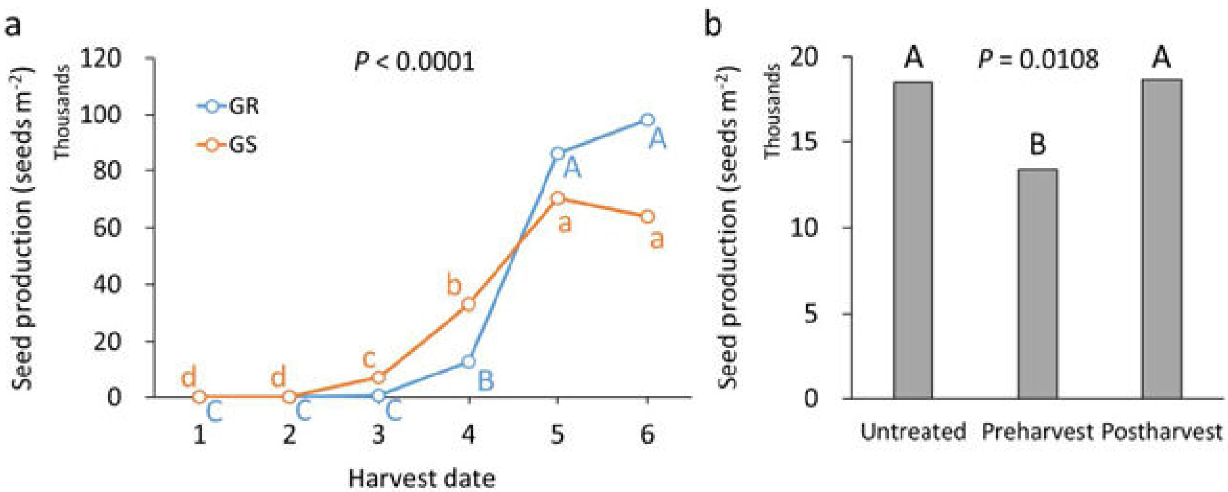

Figure 1. Kochia viable seed production at six harvest dates among 14 site-years of research across western Canada separated by (a) kochia biotype (GR, glyphosate-resistant vs. GS, glyphosate-susceptible), and (b) the effect of herbicide regime across all harvest dates. In subfigure "a", different letters indicate significant difference among harvest dates within each biotype based on Tukey's HSD (α = 0.05). Despite a significant interaction effect, no differences (P > 0.05) were observed among biotypes within any of the harvest dates. In subfigure "b", different letters indicate significant difference based on Tukey's HSD (α = 0.05).

On average, about 9% of the kochia seed present on plants at harvest remained on the lateral branches below the cutter bar height of 15-18 cm. This seed would be lost underneath combine and swather headers. Slightly more seed remained beneath this height for the sites with glyphosate-resistant kochia compared with glyphosate susceptible, but only for the sixth harvest date.

Cutting kochia plants early, while the plants remained vegetative, resulted in regrowth of these plants and the production of viable seeds after harvest (Figure 2). This occurred primarily after the first two harvest dates, where it represents a significant contribution to the soil seedbank. For example, the untreated kochia regrew after the first harvest date and produced about 45,000 seeds m-2 on average (Figure 2a). Postharvest herbicide treatment reduced the viable seed on kochia regrowth after these early harvest dates by 73% on average compared with the untreated control. GR kochia postharvest regrowth was greater than GS kochia after harvest date 1 (Figure 2b), presumably due to poorer efficacy of the pre-and post-harvest herbicide (glyphosate + saflufenacil) treatments on GR kochia.

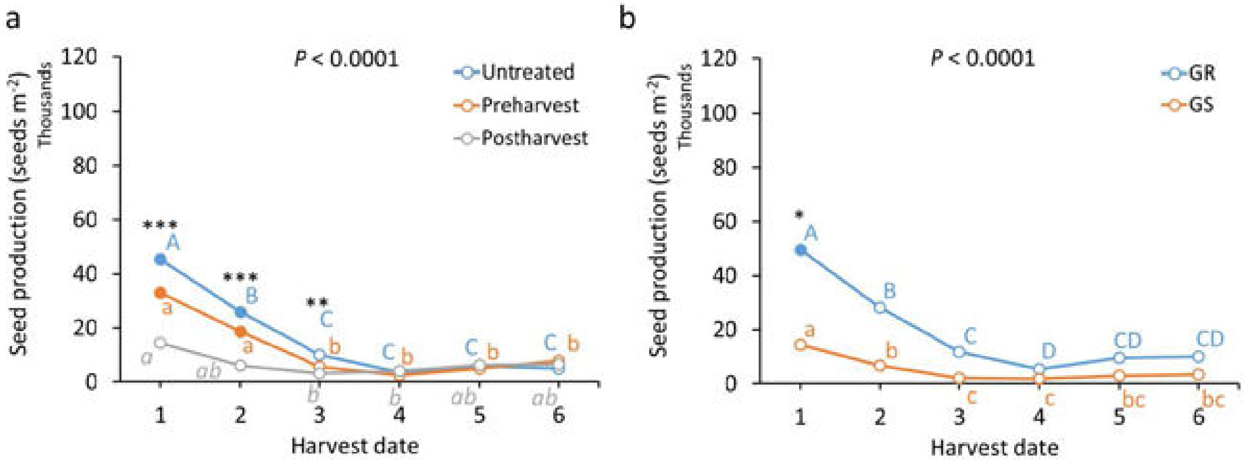

Figure 2. Kochia viable seed on regrowth following six harvest dates among 14 site-years of research across western Canada separated by (a) herbicide regime (untreated vs. preharvest vs. postharvest glyphosate + saflufenacil), and (b) glyphosate-resistant (GR) and -susceptible (GS) biotypes. Different letters indicate significant difference among harvest dates within each herbicide regime or biotype based on Tukey's HSD (α = 0.05), while solid vs. hollow circles indicate significant differences (P < 0.05) within each harvest date.

Total kochia seed production across assessment timings resulted in an "S-shaped" curve that outlines the optimum harvest date for kochia taking place on harvest date 3 (around 2083 GDD) (Figure 3). This is because harvest date 3 targeted kochia plants before they produced viable seed, but late enough that postharvest regrowth was negligible. Postharvest herbicide treatment extended the optimal harvest date window to harvest dates 1-3 (Figure 3). Taken together, these data suggest that early harvest dates can improve kochia management and mitigate seed return to the soil seedbank, especially when followed by a postharvest herbicide treatment to mitigate fall regrowth.

In conclusion, this research project resulted in a substantial advancement of knowledge leading to new methods to manage herbicide-resistant kochia in western Canada.

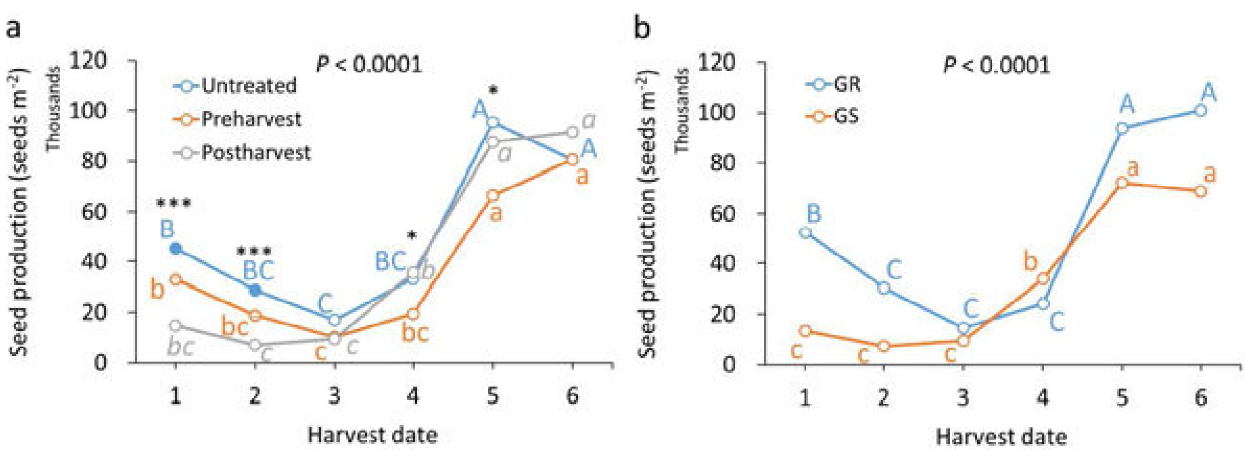

Figure 3. Total kochia viable seed production including the combined effects of seed production before harvest and regrowth following harvest for six harvest dates among 14 site-years of research across western Canada separated by (a) herbicide regime (untreated vs. preharvest vs. postharvest glyphosate + saflufenacil), and (b) kochia biotype (GR, glyphosate-resistant vs. GS, glyphosate-susceptible). Within subfigures, different letters indicate significant difference among harvest dates within (a) each herbicide regime, and (b) each kochia biotype based on Tukey's HSD (α = 0.05). Solid vs. hollow circles indicate significant differences (P < 0.05) between herbicide regime within each harvest date, while hatched circles indicate similarity to the other herbicide regimes. While the biotype by harvest date interaction was significant based on the F-test, differences among biotypes within each harvest date were absent using effect slicing at α = 0.05.

Growing winter wheat in place of spring wheat halved the kochia seedbank present at the end of the four-year crop rotation study in Lethbridge, AB. Integrating narrow (23 cm) rows with double the recommended crop seeding rates throughout a wheat-canola-wheat-lentil rotation decreased kochia biomass by 80% overall, which also reduced the kochia seedbank by the end of the crop rotation. Early harvest dates effectively cut kochia plants before they produced viable seed, and a post-harvest herbicide treatment mitigated kochia regrowth following the early harvest dates.

In brief, the recommended beneficial management practices for herbicide-resistant kochia based on this research project include:
Integrating alternative crop life cycles (winter-annuals) into crop rotations

- Reducing crop row spacing
- Increasing crop seeding rates
- Growing crops with harvest time that coincides with mid-late August (i.e., winter-annuals or silage)
- Cutting dense kochia patches in mid-August
- Earlier kochia cutting dates combined with postharvest herbicide to mitigate regrowth
- Preharvest herbicide application had a marginal, yet significant, effect (28% reduction) on kochia viable seed production

While each of these practices were effective for managing kochia when used alone, it is important that they are implemented in combination as part of a comprehensive integrated weed management program to provide additive efficacy for management of kochia populations and to reduce further selection for herbicide resistance in this species.

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