Optimization of residual herbicide applications

by

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B.S., Oklahoma Panhandle State University, 2018
M.S., Kansas State University, 2020

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

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Abstract

Optimization of residual herbicide applications is critical to control of herbicide-resistant Palmer amaranth (*Amaranthus palmeri S. Watson*) and waterhemp (*Amaranthus tuberculatus [Moq.] Sauer*). In this dissertation, one greenhouse study and three field studies were established to optimize residual herbicide applications. The objective of greenhouse trial was to evaluate the response of multiple-resistant Palmer amaranth to combinations of PS II- and HPPD-inhibitor herbicides. The first field experiment was established to quantify the effect of application timing and spray volume on residual herbicide efficacy in corn. The second field experiment was established to compare Palmer amaranth control with residual herbicides applied preemergence (PRE) or postemergence (POST) in Enlist (2,4-D-resistant) and XtendFlex (dicamba-resistant) cotton systems in Kansas. The final field trial was established to compare the impact of environmental conditions on the efficacy of VLCFA-inhibiting herbicides when applied at various times throughout the growing season.

In the greenhouse trial, PRE applications of metribuzin alone, metribuzin combinations, and atrazine + mesotrione resulted in 61 to 87 % control of a Palmer amaranth population resistant to TIR1-, EPSPS-, HPPD-, ALS-, PS II-, and PPO-inhibiting herbicides. POST treatments of atrazine alone and combinations with metribuzin resulted in 40 to 60% control of the same Palmer amaranth population. These results indicate herbicide combinations can be useful to manage multiple-resistant Palmer amaranth, even if resistance to those herbicides has been confirmed.

In the corn trial, Resicore (clopyralid + acetochlor + mesotroine) and TriVolt (isoxaflutole + thiencarbazone-methyl + flufenacet) were applied at 56, 122, and 187 L ha^{-1} in PRE-only or PRE followed by (fb) POST systems in 2021 (Colby and Ottawa, KS) and 2022

(Manhattan, Ottawa, and Scandia, KS). Palmer amaranth control was 94% or greater in Colby throughout the growing season. Resicore provided greater *Amaranthus* control than TriVolt in no-till systems. *Amaranthus* control was greater in PRE fb POST systems as compared to PRE-only systems. Spray volume did not effect weed control apart from waterhemp control in Ottawa 2021, where Resicore applied at 56 L ha^{-1} provided less control than TriVolt applied at 56 L ha^{-1} and Resicore applied at 187 L ha^{-1}. Data suggests that improper herbicide selection may be of greater consequence than spray volume for residual weed control.

Applications in the cotton trial included PRE fb early POST (EPOST) fb late POST (LPOST) in 2021 and PRE fb EPOST in 2022. In 2021, pendimethalin was applied as a blanket PRE. The EPOST application in 2021 included acetochlor, dimethenamid-P, or *S*-metolachlor + 2,4-D or dicamba or the trait premix, which was glyphosate + 2,4-D or dicamba + *S*-metolachlor, applied alone. In 2021, the LPOST included glyphosate + 2,4-D or dicamba. In 2021, the LPOST included glyphosate + trait herbicide. In 2022, PRE herbicides were fluometuron or fluometuron + acetochlor, dimethenamid-P, *S*-metolachlor, or pendimethalin fb EPOST including glyphosate + trait herbicide or in combination with residual herbicides. In 2021, there were no differences in end of season Palmer amaranth control (48 to 71%) observed among residual herbicides as long as more than one herbicide application was utilized. In 2022, Enlist systems provided less control than XtendFlex systems. The greatest control was observed when two applications of residual herbicides were utilized as compared to no over lapping residual apart from two applications of pendimethalin. Results indicate cotton herbicide trait system influences Palmer amaranth control; but, residual herbicide selection, multiple applications, and layered residual herbicides may be of greater importance.

To fulfill the objective of the final field trial, a bare-ground field experiment was established in Manhattan, KS in 2021 and 2022 where acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor were applied at various dates throughout the growing season to capture variations in rainfall and temperature. The effects of rainfall and accumulated soil growing degree days (SGDD) on the probability of successful weed control were tested by subjecting binary responses (greater or less than 80%) of each herbicide to logistic regression. Excessive rainfall and/or elevated temperatures decreased the probability of successful control of Palmer amaranth with acetochlor, dimethenamid-P, pyroxasulfone, and S-metolachlor, but pyroxasulfone and *S*-metolachlor may have an advantage at high temperatures and high rainfall. In a scenario, where the rainfall forecast is predicting little rainfall within 3 WAT, pyroxasulfone and *S*-metolachlor may not be the most effective options. However, acetochlor may be the best fit for hot and dry conditions, as less accumulated rainfall was required to achieve high probability of successful weed control. Dimethenamid-P had a disadvantage in hot and dry conditions but was more likely to have >80% control in cool and wet conditions, indicating dimethenamid-P may be a better fit at plating or prior to planting of corn and soybeans when conditions are cooler.

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Major Professor
Dr. Sarah Lancaster

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Chapter 1 - Literature Review

1.1 Corn and cotton in Kansas

The United States is one of the largest exporters of corn in the world. Approximately 10 to 20% of the US corn crop is exported to other countries and the remainder of the corn crop is utilized domestically for livestock feed, biofuels, human food, seed, and alcohols (USDA 2022). Approximately 36 million ha of corn are planted in the United States each year. Corn is the largest crop in Kansas in terms of yield and economic contribution and approximately 2.2 million ha of corn were planted in Kansas in 2022 (KDA 2019; NASS 2022). In Kansas and the Ogalala aquifer region, corn is the most irrigated crop (Norwood 2000). In 2017, approximately 611,000 ha of corn were irrigated in Kansas with the largest percentage grown in the region of Kansas where irrigation wells withdraw from the Ogalala aquifer (KDA 2017). Without irrigation, corn is less adapted for semi-arid climates, so producers may need to adopt crops that require minimal supplemental irrigation, like cotton (Ackerson and Krieg 1977).

Cotton has been grown in Kansas for over 100 years, but it did not gain popularity until cotton benefits were included in the 1995 farm bill (Thompson 2007). Cotton production has increased drastically in Kansas as an alternative crop that can aid in water conservation efforts and give producers an alternative income option (Bertone 2020; Baumhardt et al. 2021). In 2022, approximately 53,000 ha of cotton were planted in Kansas, which was an 18.2% increase from 2021 (NASS 2022). Historically, cotton production in Kansas was limited due to insufficient heat units for previously available cotton varieties, but with the commercialization of early maturing and cool-temperature tolerant varieties, cotton production in Kansas has increased (Duncan et al. 1993; Tolk and Howell 2010; Byrd and Wilson 2021). Heat units are the "amount of heat energy accumulated by plants in the growing season" and can be used as a predictive tool to define cotton development (Esparza et al. 2007). Heat units are calculated by subtracting the base temperature, 15.5 C, from the sum of the daily maximum temperature and the daily minimum temperature and then dividing by two. Other factors also influence cotton development, such as heat and moisture stress, sunlight, or quicker development of early maturing varieties (Byrd and Wilson 2021). In the Ogalala aquifer region, at least 1,000 C heat units are recommended to grow cotton (Esparza et al. 2007). Increased heat unit accumulation can result in greater lint yields. Peng et al. (1989) observed a 1.12 kg ha^{-1} lint yield increase for every heat unit increase. Cotton is more tolerant to changes in soil moisture content than corn, so it may be better for the semi-arid regions of Kansas (Ackerson and Krieg 1977). Cotton is a viable crop option for portions of southern Kansas where supplemental irrigation can be utilized, as cotton is a water-efficient crop and requires much less water than corn and may allow for reduced withdrawals from the Ogalala aquifer (Esparza et al. 2007). However, cotton is unsuitable for northern portions of Kansas due to limited heat unit accumulation (Baumhardt et al. 2021). Integrating cotton into Kansas cropping system can help diversify herbicide programs in Kansas which may aid in the prevention of further development of herbicide-resistant weed populations.

1.2 Palmer amaranth biology

Palmer amaranth (*Amaranthus palmeri* S. Watts) was considered the most troublesome and hard-to-control weed in corn systems in 2021 and cotton systems in 2022 by weed scientists across the United States (Van Wychen 2021, 2022). Of the *Amaranthus* species, Palmer amaranth is the most difficult to control (Mayo et al. 1995). Palmer amaranth is native to the southwestern United States (Ehleringer 1983). It is a summer annual weed species that can germinate from April to July in Kansas and can be extremely detrimental to summer annual crop yields due to the synchronous emergence of Palmer amaranth with the crop (Keeley et al. 1987; Berger et al. 2015; Liu et al. 2022). Palmer amaranth employs the C4 photosynthetic pathway, which gives this species an advantage over many crops due to its ability to withstand droughty conditions (Ehleringer 1983). Palmer amaranth has a rapid growth rate and can rapidly accumulate biomass, which often enables the species to intercept light and compete for space with agronomic crops (Morgan et al. 2001; Massinga et al. 2001, 2003).

Palmer amaranth is a dioecious weed species that is an obligate outcrosser. The primary mechanism of pollination is wind dispersion, which results in a forced-outcrossing and tremendous genetic variability (Franssen et al. 2001; Ward et al. 2013). Palmer amaranth is also a prolific seed producer. Keely et al. (1987) reported female plants producing up to 600,000 seeds $plant^{-1}$ when emergence occurred in March in southern California, but Palmer amaranth emerging in late summer produced as few as 115 seeds $plant^{-1}$. Massinga et al. (2001) reported Palmer amaranth seed production increased from 1,800 to 91,000 seeds m^{-2} as Palmer amaranth densities increased from 0.5 to 8 plants m^{-2}. Norsworthy et al. (2016) reported significant reductions in Palmer amaranth biomass and seed production in the presence of a cotton crop but recommended Palmer amaranth removal within 10 weeks of cotton emergence to prevent the dispersal of Palmer amaranth seed. Although late emergence, interspecific competition, and intraspecific competition can result in Palmer amaranth reduced in size and fecundity, seeds are still produced at levels adequate to replenish the weed seed bank (Keely et al. 1987; Norsworthy et al. 2016). When Palmer amaranth is left uncontrolled for three years, an initial planting of 20,000 seeds m^{-2} was shown to completely infest 0.77 ha (Norsworthy et al. 2014). Efforts should be made to prevent Palmer amaranth seed production. Depletion of the weed seed bank reduces the number of individuals that are exposed to weed control tactics and reduces the number of escapes that could contribute to the weed seed bank (Korres et al. 2018; Hare et al. 2020). Weed seed bank replenishment can be greatly reduced by utilizing residual herbicides, a multi-pass herbicide program, and crop rotation (Norsworthy et al. 2012; Shaner and Beckie 2014). Preventing weed seed bank replenishment is advantageous for crop production and conserving the remaining effective herbicides, as small weed populations play a large role in the sustainability of weed management practices (Walsh et al. 2013).

A Palmer amaranth population confirmed to be resistant to six mode of action groups: TIR1-, EPSPS-, HPPD-, ALS-, PS II-, and PPO-inhibiting herbicides was identified in Kansas (Shyam et al. 2021). Palmer amaranth populations with metabolic resistance are more likely to have multiple resistance or cross-resistance, especially for populations resistant to ALS-, PS II-, HPPD-, and PPO-inhibiting herbicides (Shyam et al. 2021). Kumar et al. (2020) observed reduced sensitivity to atrazine, chlorsulfuron, glyphosate, mesotrione, and 2,4-D in 75, 36, 47, 32, and 7%, respectively, of Palmer amaranth populations collected from south-central and western Kansas. The incidence of herbicide resistance is generally greater in fields where fewer herbicide mode of action groups are utilized each growing season (Evans et al. 2015). While not in Kansas, there are confirmed populations resistant to *S*-metolachlor, a common VLCFA-inhibiting herbicide, in Arkansas and Mississippi (Kouame et al. 2022). Brabham et al. (2019) confirmed reduced sensitivity in Arkansas to other VLCFA-inhibiting herbicides, which include acetochlor, dimethenamid-P, and pyroxasulfone. Resistance to VLCFA- and PS II-inhibiting herbicides is a challenge for growers to navigate, as atrazine, acetochlor, and metolachlor were reported to comprise 29, 15, and 12%, respectively, of the total kg of herbicide applied in corn (ERS USDA 2008).

Palmer amaranth is highly competitive with agronomic crops and when left uncontrolled, Palmer amaranth can be extremely detrimental to crop yields. When allowed to emerge with corn and left uncontrolled, Palmer amaranth at densities of 0.5 to 8 plants m^{-1} resulted in 11 to 91% yield loss which was attributed to a decline in water use efficiency (Massinga et al 2001, 2003). Corn seedlings reallocated resources to growing taller as soon as three days after emergence when weeds were allowed to emerge with the corn crop (Parker et al. 2006). Weeds removed at or before reaching 10-cm of height had minimal to no impact on corn yields, but it is generally recommended to control weeds, like Palmer amaranth, before reaching 5-cm of height (Cox et al. 2006; Crow et al. 2016). Crow et al. (2016) determined that corn yield loss due to Palmer amaranth competition was greatest when Palmer amaranth was allowed to compete from emergence to corn reaching V5 or V6. Massinga et al. (2003) reported a general decrease in corn water use as the Palmer amaranth density increased but emphasized that the rate of decrease of water use declined significantly once the Palmer amaranth density was greater than 2 plants m^{-1}. This was attributed to more shading between plants as Palmer amaranth density increased (Massinga et al. 2003). Photosynthetically active radiation reaching the lower corn leaves decreased as Palmer amaranth densities increased due to the height advantage Palmer amaranth often has over agronomic crops (Massinga et al. 2003).

In cotton, Palmer amaranth has been reported to cause 54 to 92% lint yield loss at densities of 0.8 to 1.1 plants m^{-1} (Rowland et al. 1999; Morgan et al. 2001; MacRae et al. 2013). Rowland et al. (1999) reported a 71 kg ha^{-1} decrease in cotton lint yield for each Palmer amaranth increase m^{-1}. Cotton lint yields can be maximized when cotton remains weed free six to eight weeks following cotton emergence, but the need for weed control generally decreases six to seven weeks after cotton emergence (Buchanan and Burns 1970). When a lint yield loss threshold of 2.7% was utilized, Fast et al. (2009) determined weed control was needed for approximately three weeks after cotton emergence. MacRae et al. (2013) determined yield loss could be minimized if Palmer amaranth was controlled before cotton reached 12-leaf. Buchanan and Burns (1970) observed decreased cotton height and stem diameter when cotton remained weed free for less than six weeks after emergence. Berger et al. (2015) observed decreased rates of photosynthesis, stomatal conductance, and total daily water use in cotton when Palmer amaranth plants were within 1 m of cotton plants, and cotton seed yield was not influenced by Palmer amaranth plants located at least 2.4 m away. However, for every 0.3 m closer, a Palmer amaranth plant was located to the cotton plant, seed yield was decreased by 14% (Berger et al. 2015). Morgan et al. (2001) reported no influence of Palmer amaranth proximity on total cotton fruit, fruiting position, or internode length but attributed the lack of influence to extreme growth variability in both plant species. Berger et al. (2015) observed the driving factors for lint yield loss due to Palmer amaranth competition are likely attributed to competition for light, rather than competition for water when grown under adequate rainfall.

1.3 Chemical weed control for Palmer amaranth management

Multi-pass programs paired with residual herbicides are a viable option for the control of many weed species. Multiple herbicide-resistant Palmer amaranth is consistently controlled by programs utilizing residual herbicides, multiple effective sites of action, and multiple herbicide applications (Parker et al. 2006; Evans et al. 2014; Crow et al. 2016; Kohrt and Sprague 2017; Chahal et al. 2018; Chahal and Jhala 2018; Inman et al. 2020). Residual herbicide applications are a critical component of weed management programs. These applications can reduce the abundance and size of weeds that need to be controlled with postemergence (POST) applications which increases the probability of achieving successful season-long weed control (Gower et al.

2002; Lindsey et al. 2012; Janak and Grichar 2016; Norsworthy et al. 2016; Kohrt and Sprauge, 2017). In general, following preemergence (PRE) applications with POST applications can result in increased Palmer amaranth control and reduced density and biomass (Chahal et al. 2018; Buol et al. 2021). Palmer amaranth that escaped PRE applications cause less yield loss than those that were never treated (Liphadzi and Dille 2006). However, in the absence of PRE applications, at least two timely POST applications should be utilized, as a delay in POST application or only one POST application can lead to increased numbers of emerged weeds and increased crop yield loss (Gower et al. 2003). Additionally, Palmer amaranth allowed to compete season long with the crop will accumulate more biomass and produce more seed, but Palmer amaranth that emerge later in the season will produce less seed (Norsworthy et al. 2016). Previous literature has also reported greater levels of Palmer amaranth control at the end of the season when PRE fb POST systems were utilized rather than PRE- or POST-only systems (Norsworthy et al. 2016; Kohrt and Sprague 2017; Chahal and Jhala 2018). Multi-pass systems have been shown to maximize crop yields as compared to PRE-only and POST-only systems (Buol et al. 2021). Including a PRE application allows for reduced early-season weed interference and allows for more time between planting and the POST application (Parker et al. 2006).

Generally, corn herbicide programs include residual herbicides from the PS II-, HPPD-, and VLCFA-inhibiting herbicide groups (Evans et al. 2014; Crow et al. 2016; Kohrt and Sprague 2017; Chahal et al. 2018; Chahal and Jhala 2018a). Atrazine applied alone delayed the need for weed control until V5, but tank mixes containing salfufenacil, dimethenamid-P, or pyroxasulfone delayed the need for weed control until V8 or V10 (Ulusoy et al. 2021). This indicates that PRE or EPOST applications with multiple residual herbicides can reduce or delay the need for a POST application (Ulusoy et al. 2021). Atrazine combined with VLCFA-inhibiting herbicides (acetochlor, pyroxasulfone, or *S*-metolachlor) and a HPPD-inhibiting herbicide (mesotrione) generally resulted in 80% or better Palmer amaranth control (Geier et al. 2006, Janak and Grichar 2016; Kohrt and Sprague 2017; Chalal and Jhala 2018a). Kohrt and Sprague (2017) reported up to 24, 64, 87, 49, and 97% control of atrazine-resistant Palmer amaranth with PRE applications of atrazine, isoxaflutole, mesotrione, atrazine + isoxaflutole, and atrazine + mesotrione 45 days after corn planting, respectively. Chahal and Jhala (2018) reported 39 to 55% Palmer amaranth control 93 days after PRE application of atrazine + *S*-metolachlor + mesotrione. In the same study, authors reported a 76 to 86% reduction of Palmer amaranth biomass and 48 to 76% reduction in Palmer amaranth density 21 days after PRE applications of atrazine + *S*-metolachlor + mesotrione (Chahal and Jhala 2018). Janak and Grichar (2016) reported 92 to 99% Palmer amaranth control up to 109 days after PRE applications of thiencarbazone-methyl + isoxaflutole and mesotrione + atrazine + *S*-metolachlor. But PRE applications of isoxaflutole or mesotrione alone resulted in variable Palmer amaranth control, specifically when rainfall did not promptly follow the PRE application (Janak and Grichar 2016). Previous literature has shown 91 to 100% Palmer amaranth control 8 weeks after treatment with atrazine + flufenacet + isoxaflutole and 95 to 100% control with *S*-metolachlor + flumetsulam + atrazine + clopyralid when applied PRE (Johnson et al. 2012). Poor redroot pigweed (*Amaranthus retroflexus* L). control was observed with PRE applications containing atrazine, atrazine + isoxaflutole, or *S*-metolachlor when little to no rainfall was received seven days before or after application (Stewart et al. 2010, 2012).

Historically, cotton herbicide programs included a PRE application followed by several POST or late-season POST-directed (LAYBY) applications. Cotton lint yields can be maximized when multiple herbicide applications are utilized (Buol et al. 2021). Duzy et al. (2015) reported net return increases when PRE and POST applications were utilized rather than LAYBY-only applications. Commercialization of herbicide-resistant cotton varieties, mainly glyphosate-resistant cotton, made POST-only programs a viable option for cotton growers, but POST-only programs have been linked to more rapid development of herbicide-resistant weeds as large weeds are often left uncontrolled (Inman et al. 2020; Crow et al. 2016). Residual herbicide groups commonly utilized in cotton include PPO-, PS II-, Microtubule-, and VLCFA-inhibiting herbicides (Price et al. 2008; Cahoon et al. 2015; Manuchehri et al. 2017; Inman et al. 2020; Buol et al. 2021). Palmer amaranth control greater than 98% has been observed when at least three POST applications of glufosinate, glyphosate, dicamba, or combinations were made in dicamba-resistant cotton (Inman et al. 2020). In 2,4-D-resistant cotton, Palmer amaranth control was 75% or greater when 2,4-D choline was applied on 10-cm tall Palmer amaranth alone or in combination with glufosinate, glyphosate, acetochlor, or *S*-metolachlor (Manuchehri et al. 2017). Applying VLCFA-inhibiting herbicides at any time, except for PRE alone, resulted in greater late-season Palmer amaranth control than when VLCFA-inhibiting herbicides were not utilized (Buol et al. 2021). Tank mixes of pendimethalin or acetochlor with diuron + fomesafen, fomesafen alone, diuron alone, or fluometuron alone applied PRE resulted in 86% or greater Palmer amaranth control 46 days after planting when followed by a POST application of glufosinate 27 days after planting (Cahoon et al. 2015). The addition of *S*-metolachlor to early postemergence (EPOST) and LAYBY applications of glyphosate increased cotton lint yield when compared to glyphosate alone (Cahoon et al. 2015). Manuchehri et al. (2017) also observed glufosinate- and glyphosate-only programs provided variable Palmer amaranth control and reduced seed cotton yield. Price et al. (2008) reported that including a residual herbicide increased weed control over half of the time when compared to systems without residual herbicides in programs with three or more passes. Season-long Palmer amaranth control can be achieved when two or more effective sites of action are utilized and a residual herbicide is included in the POST application, which can help eliminate weed seed bank replenishment (Kohrt and Spraque 2017).

1.4 Factors to consider with residual herbicide applications

Herbicides and the environment

The length of residual herbicide activity and persistence is determined by complex interactions between the herbicide and the environment. Intrinsic soil parameters (texture, organic matter, and pH) can alter the availability of herbicides for plant uptake which is determined by the chemical properties of the herbicide (adsorption, water solubility, and half-life), and extrinsic soil parameters (soil temperature, soil moisture, rainfall; Blumhorst et al. 1990, Pusino et al.1992; Salzmen and Renner 1992; Helling 2005; Janaki et al. 2019).

As weather patterns change and herbicide-resistant weeds continue to challenge growers, it is important to characterize the effect of the environment on the control of herbicide-resistant weeds and the efficacy of residual herbicides (Landau et al. 2021). Residual herbicides are an important tool in preventing the spread of herbicide-resistant Palmer amaranth, as they reduce the total number of weeds that the POST herbicide applications are required to control (Gower et al., 2002; Lindsey et al. 2012; Janak and Grichar 2016; Norsworthy et al. 2016; Kohrt and Sprauge, 2017).

Slower degradation of residual herbicide in soil may equate to longer periods of weed control (Mueller et al. 1999). Previous research has characterized the dissipation of acetochlor, *S*-metolachlor, dimethenamid-P, and pyroxasulfone, where pyroxasulfone had a longer duration of weed control than acetochlor, dimethenamid-P, and *S*-metolachlor, but control was less in years with less precipitation (Mueller and Steckel 2011). The anticipated increase in hot and dry conditions throughout crop-growing regions coupled with poor weed control due to the increased presence of herbicide-resistant weeds will likely result in decreased crop productivity (Landau et al. 2021). Weed control with residual herbicides is maximized when 10-cm or more rainfall is received within 15 days after application (DAA), which allows for adequate incorporation of herbicides into the soil-water solution and contact with the weed seeds (Landau et al. 2021a). Combinations of VLCFA-inhibiting herbicides and atrazine, HPPD herbicides + atrazine, and pendimethalin + atrazine had reduced efficacy when 0 to 1.7-mm of rainfall were received within seven DAA (Stewart et al. 2012). In general, weed control increased as rainfall received within 15 DAA and soil temperature increased (Landau et al. 2021a).

The rate of herbicide disappearance may increase following increases in soil water content and soil temperature, which may be attributed to changes in soil microflora (Zimdahl and Clark 1982; Baer and Calvet 1999; Stewart et al. 2012). Previous research has illustrated more rapid dissipation in tropical or southern climates than in temperate or northern climates mainly due to greater temperatures and precipitation (Helling 2005). Helling (2005) reported for every 10 C temperature increase there was a 2.2-fold increase in the rate of herbicide degradation. In dry and cool conditions or in areas with low soil organic matter, microbial degradation may be slower and result in a longer period of residual herbicide efficacy, making such areas more at risk of herbicide carryover (Helling 2005). However, when 67.8-mm was received within 4 days of PRE applications in Ontario, Canada on coarse textured soils weed control was poor, likely due to the leaching of herbicides out of the weed seed zone (Stewart et al. 2010, 2012). Zimdahl and Clark (1982) reported increased degradation rates of alachlor, propachlor, and *S*-metolachlor when soil water contents exceeded 50% of field capacity at 20 C. Alachlor, propachlor, and *S*-

metolachlor degradation increased as temperature increased from 10 to 30 C with soil water content at 50% field capacity, indicating increases in temperature and soil moisture will result in a shorter length of residual herbicide activity (Zimdahl and Clark 1982). Landau et al. (2021) reported the effect of soil temperature on residual herbicide efficacy was variable when less than 10-cm of rainfall was received within 15 DAA and dependent on herbicide and weed species. Decreased weed control at greater soil temperatures may be attributed to increased rates of herbicide degradation by microbes and certain weed species may be impacted more than others depending on the amount of herbicide required for uptake from the soil-water solution (Landau et al. 2021). Preemergence application may need to be followed by a POST application in years when little to no rainfall follows the application, regardless of the herbicide tank mixes utilized for PRE applications.

Herbicides and soil

Herbicide availability and persistence is greatly influenced by soil composition (i.e., organic matter content and soil texture), soil chemistry (i.e., soil pH), and soil microbial activity (Shaner and Henry 2007). Herbicide adsorption is significantly correlated to soil organic matter and clay content (Haymaker and Thompson 1972; Helling 2005; Bedmar et al. 2011; Wu et al. 2011; Westra et al. 2015; Sharipov et al. 2021). Herbicide adsorption is how tightly the herbicide molecule binds to a soil particle, which directly influences the amount of herbicide that is available for weeds to absorb from the soil water solution (Pusino et al.1992). However, herbicide adsorption can be described by either the soil adsorption coefficient (K_d) or the organic carbon-water partition coefficient (K_{oc}). The K_d is determined by dividing the herbicide concentration adsorbed to soil by the herbicide concentration in the solution. The K_{oc} value allows for the correlation of K_d and the soil organic carbon content, which allows for determination of an herbicide's adsorption characteristics apart from other soil characteristics (Mendes et al. 2014). Herbicide adsorption is often a good indicator of the degradation of residual herbicides (Wu et al. 2011; Sharipov et al. 2021). Soil texture (% sand, % silt, % clay) influences the rate at which residual herbicides degrade due to differences in the water holding capacities, net charge of the soil, and microbial activity (Schoenau et al. 2005). Fine-textured soils with high organic matter content have the greatest ability to adsorb herbicides (Helling 2005). Herbicide mobility in soil increases as the percentage of sand increases (Westra et al. 2014). Greater herbicide adsorption can lead to reduced weed control as less herbicide is available for plant uptake from the soil solution (Djurovic et al. 2009). Djurovic et al. (2009) observed greater acetochlor adsorption in soil with high clay content (23.6% clay) and low organic matter (3.4% OM) compared to soil with both high clay content (23.4% clay) and high organic matter (8.7% OM). While adsorption of pendimethalin and oxyfluorfen was shown to be greater in the soil with 8.7% organic matter (Djurovic et al. 2009). Westra et al. (2015) observed increased adsorption for *S*-metolachlor, dimethenamid-P, and pyroxasulfone in soils with high organic matter or medium- to fine-textured soils. Reinhardt and Nel (1988) reported that alachlor and *S*-metolachlor activity was negatively correlated to organic matter content indicating that organic matter can adsorb the herbicide and result in less effective weed control. Reduced control can be overcome by increasing the rate of herbicide applied if it is within the range allowed by the herbicide label. However, Graber et al. (2012) observed increased rates of *S*-metolachlor could not provide adequate weed control in soils amended with biochar containing 73 to 76% carbon.

Although herbicide adsorption is largely influenced by organic matter, the water solubility of herbicides can play a role in the degradation of residual herbicides (Wauchope et al.

2002). Water solubility is how much of the herbicide will dissolve in water and is generally measured as ppm (parts $million^{-1}$) or mg L^{-1}. It is related to the amount of herbicide readily available for plants to take up from the soil water solution. Water solubility is critical to consider when utilizing soil applied herbicides like pendimethalin, sulfentrazone, and all VLCFA-inhibiting herbicides as all these herbicides must be absorbed by the root or shoot of the weed to have herbicidal activity (Shaner et al. 2014). Helling (2005) stated that herbicides with water solubility greater than 30 mg L^{-1} are more at risk of leaching and have less risk of carryover to the following crop. Herbicide adsorption and water solubility have an inverse relationship. Westra et al. (2015) observed pyroxasulfone to be more readily available for plant uptake in the soil water solution and thus can be applied at lower rates than *S*-metolachlor and dimethenamid-P and provide comparable weed control, despite the fact that pyroxasulfone has less water solubility (3.49 mg L^{-1}) and greater adsorption coefficients (K_{oc} = 223) than dimethenamid-P and *S*-metolachlor (Table 1.1).

Microbial degradation is a critical process responsible for the breakdown of herbicides in the soil. Several factors can influence the activity of herbicide degrading microbes, including soil moisture, oxygen, organic matter, soil texture, and pH. Soil microbes are most active in well aerated and fertile, moist, and warm soils with high organic matter and approximately neutral pH, which facilitates more favorable conditions for herbicide degradation (Curran 2001; Long et al. 2014; Singh and Singh 2014). Microbial activity is greater in soils with greater levels of clay and high levels of soil organic matter (Rice et al. 2002; Long et al. 2014). Coarse-textured (sandy) soils have less water-holding capacities than medium or fine-textured (clayey) soils (Bouyoucos 1939). Decreased soil moisture and temperature can result in prolonged herbicide persistence due to reduced microbial degradation (Long et al. 2014).

However, herbicide degradation and availability are determined by more than just sorption to clay and organic matter particles or microbial activity. The pKa of the herbicide and pH of the soil are also critical in determining the length of effective control and availability for absorption by plants. Soil pH is critical as certain herbicides may be less stable under certain pH conditions (Hall et al. 1999; Simmons 2006). Soil pH has limited effects on VLCFA-inhibiting herbicides, but does influence the fate of ALS-, HPPD-, and PS II-inhibiting herbicides (Haymaker and Thompson 1972; Hall et al. 1999; Helling 2005; Schoenau et al. 2005; Curran 2016; Glaspie et al. 2021). To understand the relationship between soil pH and herbicides, the herbicide pKa is an important characteristic to consider (Haymaker and Thompson 1972; Glaspie et al. 2021). A molecule's pKa is the pH at which 50% of the herbicide molecules are ionized (charged, hydrophilic) and the other 50% are non-ionized (uncharged, lipophilic; Haymaker and Thompson 1972; Hall et al. 1999; Glaspie et al. 2021). For example, atrazine has a pKa of 1.7 and can take on more hydrogen ions when soil pH is low (≤ 5.5) thus resulting in a more positively charged herbicide molecule, which results in increased herbicide adsorption and slowed degradation (Mueller et al. 2010). However, as soil pH increases above 5.5, atrazine adsorption decreases which results in more rapid atrazine degradation due to the loss of hydrogen ions and positively charged molecules. This can lead to greater plant availability and increased risk of atrazine carryover (Mueller et al. 2010).

Herbicides can be split into five groups that influence molecular interactions: weak acid, weak base, cationic, nonionic polar, and nonpolar (Reader et al. 2015). At neutral pH levels, weak acid herbcides will be negatively charged and base herbicides will be positively charged. In acidic soil, acidic herbicides will be negatively charged, and basic herbicides will be positively charged. Since soil particles are negatively charged that means the weak acid will repel from the soil particle, while the weak base herbicide will bind to the soil particle. Under alkaline soil conditions, weak base residual herbicides, like the triazines, will be more readily available in the soil solution due to decreased amount of adsorption to the soil molecules which may result in increased crop injury or carryover (Reader et al. 2015). However, under acidic soil conditions activity of the weak base herbicides will decrease due to increased adsorption to the soil particles (Reader et al. 2015). It is critical to understand the role that pH, organic matter, and soil texture play in herbicide use rates, the prevention of off-target movement, and the maximization of weed control.

Tank mix interactions

Multiple herbicide-resistant Palmer amaranth can be controlled with tank mixes containing two or more effective sites of action (Kohrt and Sprague 2017). In addition to multiple effective sites of action, combining herbicides that exhibit additive or synergistic relationships may be another option to consider when managing multiple herbicide-resistant weeds. Colby (1967) first described a mathematical function to describe the relationship exhibited by combining herbicides. Colby’s equation is calculated as follows:

$$E = (X+Y)-(XY/100)$$

Where E is the expected control with a tank mix of two herbicides and X and Y are the observed responses of the individual herbicides applied in a study (Colby 1967; Chahal and Jhala 2018b). These responses can be defined as additive, synergistic, or antagonistic. Additive, synergistic, or antagonistic responses occur when the response of the herbicide tank mixes in the study is equal to, greater than, or less than the expected response, respectively (Colby 1967; Bollman et al. 2006; Chahal and Jhala 2018b).

Additive and synergistic interactions occur when PS II- and HPPD- inhibitor herbicides are applied PRE and POST for control of Palmer amaranth resistant to both sites of action (Bollman et al. 2006; Chahal and Jhala 2018b). Armel et al. (2003) reported 71% control of redroot pigweed PRE when mesotrione was applied alone compared to 90% with atrazine + mesotrione. Chahal and Jhala (2018b) reported additive control of Palmer amaranth resistant to both PS II- and HPPD- inhibiting herbicides when atrazine was tank mixed with isoxaflutole or mesotrione compared to isoxaflutole or mesotrione applied alone (Chahal and Jhala 2018b). In the same trial, the combination of atrazine + mesotrione applied POST resulted in 82% control while mesotrione applied alone resulted in 69% control.

An explanation for synergism between PS II- and HPPD-inhibiting herbicides is the complementary nature of their sites of action. Herbicides that inhibit PS II compete with plastoquinone and bind to the D1 protein in the PS II complex in the chloroplast thylakoid membrane, which halts energy production in the plant due to the cessation of electron transport and CO_2 fixation (Hess 2000; Shaner et al. 2014). HPPD-inhibitors inhibit the HPPD enzyme which results in reduced production of α-tocopherols and plastoquinones. Plastoquinones are an important aspect of carotenoid synthesis and α-tocopherols reduce the photooxidation of lipids, cell walls, and D1 proteins from the reactive oxygen produced during photosynthesis (Shaner et al. 2014). When plastoquinones are inhibited, there is less competition for the PS II-inhibiting herbicides to bind to the D1 protein, which allows for the herbicide to work more effectively (Hess 2000; Shaner et al. 2014; Chahal and Jhala 2018b). Both herbicide groups result in some sort of disruption of electron transport which results in an excessive accumulation of reactive oxygen species which damages cell tissues.

Although an herbicide tank mix is considered antoganostic, the tank mix can still be useful. Antagonism is characterized by the type of herbicide interaction that occurs, which results in antagonism being characterized as biochemical, competitive, physiological, or chemical antagonism (Green 1989). Biochemical antagonism occurs when one herbicide decreases the amount of herbicide that binds to the siter of action by reduced penetration or by increased metabolism. Competitive antagonism occurs when one herbicide binds to the site of action and prevents the binding of another herbicide. Physiological anatagonsim when herbicides have counteractive biologicals effects on the plant. Lastly, chemical antagonism occurs when herbcides chemically interact.

Zhang et al. (1995) reported antagonism to occur more frequently in monocot as compared to dicot weeds species. Appleby and Somabhi (1978) reported chemical antagonism when glyphosate was tank mixed with wettable powder formulations of atrazine and simazine as the glyphosate molecules bound to the clay particles in the wettable powders. However, the antagonism was found to be overcome by increasing the glyphosate rate. Selleck and Baird (1981) also reported reduced control of quackgrass (*Elymus repens* (L.) Gould), common dandelion (*Taraxacum officinale* F. H. Wigg.), smooth brome (*Bromus inermis* Leyss), and Canada thistle (*Cirsium arvense* (L.) Scop.) when glyphosate was tank mixed with residual herbicides such as amitrole, bromacil, chlorbromuron, linuron, metribzin, simazine, and terbacil. Competitive antagonism is commonly reported when ACCase-inhibiting and auxin mimic herbicides are combined as these herbicides compete for the synthetic auxin-receptor binding site on the plasma membrane bound recptor (Barnwell and Cobb 1993). Antagonism can be overcome by increasing the rate of the antagonized herbicide (Green 1989).

Application parameters

Research regarding the effects of application parameters, such as spray volume, on PRE applications is limited, while the influence of spray volume on POST applications is well documented. Greater spray volumes have been found to increase the efficacy of POST herbicides (Kells and Wanamarta 1987; Shaw et al. 2000; Ramsdale and Messersmith 2001; Creech et al. 2015, Ferguson et al. 2016a). Ferguson et al. (2014) found similar levels of control with glyphosate when applied with spray volumes that ranged from 2.5 to 152 L ha^{-1}. Creech et al. (2015) reported that the optimum spray volumes for systemic herbicides ranged between 70 and 94 L ha^{-1} and the optimum spray volume for contact herbicides was 187 L ha^{-1} or greater.

The effect of spray volume on residual herbicide applications applied PRE is not as clear-cut as POST herbicides. Borger et al. (2013, 2015) observed increased rigid ryegrass (*Lolium multiflorum*) control with trifluralin and pyroxasulfone applied PRE as spray volumes increased from 50 L ha^{-1} to 150 L ha^{-1} in no-tillage systems. Greater than 90% control of blackgrass (*Alopecurus myosuroides*) was observed when PRE applications of flufenacet were made using 200 L ha^{-1}, as compared to less than 70% control that was observed with carrier volume at 50 L ha^{-1} (J Thomas, Personal Communication). However, Striegel et al. (2021) found that carrier volumes did not influence weed control rather residual herbicide selection influenced weed control in conventional tillage systems. In a turfgrass system, there were no differences in control when large crabgrass (*Digitaria sanguinalis* L.), common dandelion (*Taraxacum officinale*), or ground ivy (*Glechoma hederacea* L.) were treated with microtubule- and PPO-inhibitibing and synthetic auxin herbicides applied at 19 or 561 L ha^{-1} (Ferguson et al. 2016b). This limited literature appears to suggest the utilization of lower carrier volumes in conventional tillage settings may not compromise weed control, but larger carrier volumes may be required to achieve adequate control in no-tillage systems to penetrate increased residue levels and to control weeds present at the time of application.

The difference in control achieved between the tillage systems may be attributed to the increased residue in the no-tillage systems that may inhibit the residual herbicides from reaching the soil, depending on the herbicide (Ghadiri et al. 1984; Johnson et al. 1989; Chauhan et al. 2006; Borger et al. 2015). A review conducted by Chauhan et al. (2006) found that 15 to 80% of residual herbicides can bind to the crop residue before reaching the soil surface. Volatile residual herbicides with low solubility, such as trifluralin, that must move into the soil after application via tillage or water and may require greater carrier volumes to ensure efficacy in conservation tillage systems (Chauhan et al. 2006, Borger et al. 2013, 2015). Messelhäuser et al. (2022) observed no differences in weed control between no-tillage and tillage treatments when cinmethylin, a low water-soluble residual herbicide (63 mg L^{-1}), was applied PRE.

The literature has demonstrated that it is important to understand the effect environmental conditions have on residual herbicides, but there is limited research on the effect of environmental conditions on VLCFA herbicides in Kansas. The effect of application parameters on POST herbicide applications is well documented, but gaps in research exist regarding the effect of application parameters on residual herbicides. It has also been demonstrated by literature that there is limited research regarding sequential applications of residual herbicides in cotton, specifically VLCFA herbicides outside of acetochlor and *S*-metolachlor. Literature discussing synergistic tank mixes for weed control is not lacking, but there is minimal research discussing the effect of synergistic tank mixes on Palmer amaranth resistant to both herbicide groups in the tank mix.

Therefore, the objective of these trials was to optimize residual herbicide applications to achieve complete weed control by quantifying the effect carrier volume has on weed control, sequential application of VLCFA herbicides, characterizing the impact of environmental conditions on VLCFA herbicides, and quantifying the response of multiple herbicide-resistant Palmer amaranth to synergistic tank mixes. Weed control will be greater in systems with multiple applications rather than single applications specifically when residual herbicides are utilized in multiple applications. Weed control will greater under well-watered and moderate temperatures with VLCFA-inhibiting herbicides, but control will vary with the different VLCFA-inhibiting herbicides under environmental extremes. Additionally, synergistic herbicide combinations will result in greater control of multiple herbicide-resistant Palmer amaranth than herbicide applied individually.

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Table 1.1. Chemical properties of herbicides commonly utilized in corn and cotton cropping systems in Kansas.

Mode of Action	Herbicide family	Common name	K_{oc}	Water solubility (mg L)	half-life (days)
EPSP Synthase Inhibitor	Glycine	glyphosate[a]	24000	15700	47
Glutamine synthetase inhibitor	Phosphinic acid	glufosinate ammonium[a]	100	1370000	7
HPPD Inhibitors	Isoxazole	isoxaflutole[a]	93-131[c]	6.8	0.5-2.4[c]
	Triketone	mesotrione[a]	14-390[c]	15000	15-21[c]
		tembotrione[a]	66	28.3	14.5
Photosystem II Inhibitors (Serine 2364 binders)	Triazine	atrazine[a]	100	33	146
	Urea	diuron[a]	480	42	90
		fluometuron[a]	100	110	85
PPO Inhibitors	Diphenylether	fomesafen[a]	60	50	100
Synthetic Auxins	Benzoic acid	dicamba[a]	2	4500	14
	Phenoxy	2,4-D[a]	61.7	569	6.2
VLCFA Inhibitors	Chlorocetamides	acetochlor[b]	156	223[a]	14
		dimethenamid-P[a]	55-125[c]	1174	20
		S-metolachlor[a]	200	488	15-50[c]
	Isoxazoline	pyroxasulfone[a]	57-114[c]	3.49	16-26[c]
	α-oxyacetamides	flufenacet[a]	113-742[c]	56	29-62[c]
ALS inhibitors	Sulfonyurea	nicosulfuron[a]	30	7500[b]	21

[a] K_{oc}, water solubility, and half-life sourced from Shaner et al. (2014)

[b] K_{oc}, water solubility, and half-life sourced from University of Hertfordshire (2022)

[c]Shaner et al. (2014) reported a range of values that varied with soil organic matter content, soil textural class, or pH.

Chapter 2 - Response of Herbicide-Resistant Palmer amaranth (*Amaranthus palmeri*) to Combinations of Herbicide Groups 5 and 27 Applied Preemergence and Postemergence

2.1 Abstract

Multiple-resistant Palmer amaranth (*Amaranthus palmeri* S. Watson) limits the number of effective herbicides available in corn. Combining herbicides that exhibit additive or synergistic relationships may improve weed control, even when resistance is present. The objective of this trial is to evaluate the response of multiple-resistant Palmer amaranth to combinations of PS II- and HPPD-inhibitor herbicides. Susceptible (MSS) and multiple-resistant (KCTR) Palmer amaranth populations were treated with atrazine, metribuzin, isoxaflutole, mesotrione, two-way combinations of these herbicides, or fomesafen applied PRE or POST (4- to 6-leaf). All treatments resulted in 87% or greater control of MSS, except for isoxaflutole and fomesafen applied PRE and metribuzin and fomesafen applied POST. Three weeks after PRE applications, 61 to 87 % control of KCTR was observed following applications of metribuzin alone, metribuzin combinations, and atrazine + mesotrione. Control was 40 to 60% following the POST applications of atrazine alone and combinations with metribuzin in KCTR. Three weeks after PRE, all PS II- and HPPD-inhibiting herbicides applied alone or in combination resulted in 2 plants pot^{-1} or less for MSS, while the non-treated check had 15 plants pot^{-1}. For KCTR, metribuzin, metribuzin combination, and atrazine + mesotrione resulted in 2 plants pot^{-1} or less 3 weeks after treatment, while the non-treated check had 10 plants pot^{-1}. Although, density observations corroborate control observations, control takes weed size, injury, and density into

consideration. These results indicate herbicide combinations can be useful to manage multiple-resistant Palmer amaranth, even if resistance to those herbicides has been confirmed.

2.2 Introduction

Of the *Amaranthus* species, Palmer amaranth (*Amaranthus palmeri* S. Watts) is considered the most difficult to control and the most troublesome weed in many broadleaf- and grass-cropping systems by weed scientists across the United States (Mayo et al. 1995; Van Wychen 2020, 2022). Palmer amaranth is summer annual weed species native to the southwestern United States, which has an extended germination window from April to July in Kansas and can be extremely detrimental to summer annual crop yields due to the synchronous emergence of Palmer amaranth with the crop (Ehleringer 1983; Keeley et al. 1987; Berger et al. 2015; Liu et al. 2021). Palmer amaranth interference has been observed to cause yield losses up to 91% in corn, 92% in cotton, 68% in grain sorghum, and 79% in soybean (Rowland et al. 1999; Massinga et al. 2001; Morgan et al. 2001; Bensch et al. 2003; MacRae et al. 2013). Palmer amaranth can effectively compete for light and space with agronomic crops as it has a rapid growth rate, rapidly accumulates biomass, and uses the C4 photosynthetic pathway, which gives this species an advantage over many crops due to its ability to withstand droughty conditions (Ehleringer 1983; Massinga et al. 2001, 2003; Morgan et al. 2001).

A Palmer amaranth population with confirmed resistance to six mode of action groups: TIR1-, EPSPS-, HPPD-, ALS-, PS II-, and PPO-inhibiting herbicides was identified in Kansas (Shyam et al. 2021). This Palmer amaranth population has metabolic resistance and is more likely to have multiple resistance or cross-resistance, especially for populations resistant to ALS-, PS II-, HPPD-, and PPO-inhibiting herbicides (Shyam et al. 2021). Kumar et al. (2020) observed reduced sensitivity to atrazine, chlorsulfuron, glyphosate, mesotrione, and 2,4-D in 75, 36, 47, 32, and 7%, respectively, of Palmer amaranth populations collected from south central and western Kansas. The incidence of herbicide resistance is generally greater in fields where fewer herbicide mode of action groups are utilized each growing season (Evans et al. 2016). While not in Kansas, there are confirmed populations resistant to *S*-metolachlor, a common VLCFA-inhibiting herbicide, in Arkansas and Mississippi (Kouame et al. 2022). Brabham et al. (2019) confirmed reduced sensitivity in Arkansas to other VLCFA-inhibiting herbicides, which include acetochlor, dimethenamid-P, and pyroxasulfone. Resistance to VLCFA- and PS II-inhibiting herbicides is an immense challenge for growers to navigate, as atrazine, acetochlor, and metolachlor were reported to comprise 29, 15, and 12% of the total kg of herbicide applied in corn, respectively (Fernandez-Cornejo et al. 2014).

Multiple herbicide-resistant Palmer amaranth can be controlled with combinations containing two or more effective sites of action (Kohrt and Sprague 2017a, 2017b). In addition to multiple effective sites of action, combining herbicides that exhibit additive or synergistic relationships may be another option to consider when managing multiple herbicide-resistant weeds. Colby (1967) first described a mathematical function to describe the relationship exhibited by combining herbicides, which yields the expected response when combining more than one herbicide. These responses can be defined as additive, synergistic, or antagonistic. Additive, synergistic, or antagonistic responses occur when the response of the herbicide combinations in the study is equal to, greater than, or less than the expected response, respectively (Colby 1967; Bollman et al. 2006; Chahal and Jhala 2018).

Additive and synergistic interactions have been observed when PS II- and HPPD-inhibitor herbicides have been applied PRE and POST for control of Palmer amaranth resistant to both sites of action (Bollman et al. 2006; Chahal and Jhala 2018). Combinations of metribuzin and 2-4,D amine often result in synergistic responses in annual grass species (Han et al. 2020). Johnson et al. (2012) reported up to 100% control of susceptible Palmer amaranth when isoxaflutole was applied alone and in combination with atrazine when applied PRE. Armel et al. (2003) reported 90% control of redroot pigweed (*Amaranthus retroflexus*) with atrazine + mesotrione and 71% control with mesotrione alone when applied PRE. Chahal and Jhala (2018) reported additive interactions for control of Palmer amaranth resistant to both PS II and HPPD-inhibiting herbicides with PRE applications when atrazine was combined with isoxaflutole or mesotrione compared to isoxaflutole or mesotrione applied alone (Chahal and Jhala 2018). However, in the same trial, the combination of atrazine + mesotrione applied POST resulted in 82% control while mesotrione applied alone resulted in 69% control.

An explanation for the synergistic effect that is often seen when combining PS II- and HPPD-inhibiting herbicides is the complementary nature of their sites of action (Chahal and Jhala 2018). Herbicides that inhibit PS II, such as atrazine, compete with plastoquinone and bind to the D1 protein in the PS II complex in the chloroplast thylakoid membrane, which halts energy production in the plant due to the cessation of electron transport and CO_2 fixation (Hess 2000; Shaner 2014). Herbicides like mesotrione which are HPPD-inhibitors inhibit the HPPD enzyme which results in reduced production of α-tocopherols and plastoquinones. Plastoquinones are an important aspect of carotenoid synthesis and α-tocopherols reduce the photooxidation of lipids, cell walls, and D1 proteins from the reactive oxygen produced during photosynthesis (Shaner 2014). When the plastoquinones are inhibited, there is less competition for the PS II-inhibiting herbicides to bind to the D1 protein, which allows for the herbicide to work more effectively (Hess 2000; Shaner 2014; Chahal and Jhala 2018). Both herbicide groups result in some sort of disruption of electron transport which results in an excessive accumulation of reactive oxygen species that damages cell tissues. Literature discussing synergistic combinations for weed control is not lacking, but there is minimal research discussing the effect of synergistic combinations on Palmer amaranth resistant to both herbicide groups in the combination. Therefore, the objective of this trial is to evaluate the response of PS II- and HPPD-inhibitor-resistant Palmer amaranth to known synergistic combinations of PS II- and HPPD-inhibitor herbicides. Additionally, susceptible Palmer amaranth will be effectively controlled by all PS II- and HPPD-inhibitor herbicides applied individually and in combination. However, multiple herbicide-resistant Palmer amaranth will not be controlled by individual applications of PS II- and HPPD-inhibitor herbicides, but combinations of these herbicides will increase Palmer amaranth control.

2.3 Materials and Methods

To fulfill the objective, a greenhouse study was conducted in 2022 in the Kansas State University Weed Science greenhouse in Manhattan, Kansas. Greenhouse conditions for the study were 30/18 C day/night temperature and a 15-h photoperiod was supplemented with a metal-halide lighting system. Seeds from a Palmer amaranth field population resistant to 2,4-D, ALS-, EPSPS-, HPPD-, PPO-, and PS II-inhibitor herbicides (KCTR) and a susceptible population from Mississippi were soaked in 1:1 solution of distilled water and 6% sodium hypochlorite for 10 minutes. Seeds were rinsed three times with 15 ml of distilled water each time. Approximately 150 ml of Miracle-Gro Moisture Control® potting mix (The Scotts Company LLC, Marysville, OH) was placed in the bottom half of 6 x 6 x 6.5-cm pots and an additional 150 ml of field soil was placed on top of the potting mix. The field soil was collected from a produce farm near Manhattan, KS and was a silty clay loam (16% sand, 54% silt, 30% clay) with a pH of 7.8 and 2.2% organic matter. Before sowing seeds and herbicide application, soil filled pots were sub-irrigated with municipal water to field capacity and allowed to drain overnight to obtain uniform, water-holding soil moisture. Twenty seeds were spread on the surface of the soil and a thin layer of field soil was used to cover the seeds. The preemergence (PRE) treatments were applied immediately after planting. Palmer amaranth were thinned down to 1 plant pot^{-1} when plants reached cotyledon to two-leaf stage. The postemergence (POST) treatments were applied when Palmer amaranth reached four- to six-leaf.

The study was conducted in a split-plot design with eight replications. The main plot was application timing (PRE or POST), sub-plots were Palmer amaranth population (KCTR or MSS), and herbicide treatment was randomly assigned to the sub-plots. A non-treated check was included in each application timing and Palmer amaranth population subplot with in each replication. Herbicides and application rates can be found in Table 2.1. Herbicide rates were based on a ½ X rate of a maximum labeled field use rate. Treatments were applied using a bench-track sprayer (Generation III, DeVries Manufacturing, RR1 Box 184, Hollandale, MN) equipped with an even flat spray nozzle tip (8002 EVS, Teejet Spraying Systems Co., Wheaton, IL) calibrated to deliver a spray volume of 94 L ha^{-1} at 2.96 km hr^{-1} and 186 kPa. Before spraying PRE herbicide applications, all pots were treated with 700 g ai ha^{-1} mefenoxam (Subdue Maxx® Fungicide, Syngenta, Greensboro, NC) to prevent *Pythium* damping-off. Immediately after spraying, PRE and POST treatments were covered with plastic wrap to prevent volatilization/movement within in the greenhouse bay. All pots were kept covered until the non-treated checks and the POST treatment Palmer amaranth began to emerge. All pots were sub-irrigated every two days and drained within 24 hours. Each pot was sub-irrigated in its own container to prevent cross-contamination among pots. Pots were misted daily to keep the soil surface moist to prevent crusting until Palmer amaranth had emerged.

Palmer amaranth control was visually assessed three weeks after treatment (WAT) using a 0 to 100% scale, where 0% equals no injury relative to the non-treated check and 100% equals complete plant death. Plant height and biomass was recorded three weeks after each application timing and Palmer amaranth density in PRE treatments was recorded three weeks after the PRE application. Biomass was dried in a forced air dryer at 50 C for 7 days and weighed. The response (control, height, density, and biomass) of susceptible (MSS) and multiple herbicide-resistant (KCTR) Palmer amaranth to combinations of PS II- and HPPD-inhibiting herbicides applied PRE and POST were analyzed using Colby's equation (Equation 2.1; Colby 1967).

Equation 2.1 $$E = (X+Y)-(XY/100)$$

Where E is the expected response variable as calculated by the observed control, height reduction, density reduction, and biomass reduction achieved with individual applications of PS II- and HPPD-inhibiting herbicide (X and Y) used in this study (Chahal and Jhala 2018).

Statistical analysis

Palmer amaranth control, height, density, and above ground biomass were tested for normality and homogeneity with the Shapiro-Wilks goodness-of-fit and Levene's test in R. Normality and variance assumptions were not met for control, height, density, and biomass. Data transformation methods did not result in the data meeting normality and variance assumptions, so models were fit using the aligned rank transformation model art() in R package ARTool (Kay 2019a). This specific general linear mixed model was developed for data that does not have a normal distribution and allows for the use of an ANOVA. The model was then subjected to ANOVA using anova() in R packaged stats ($p \geq 0.05$; R CORE TEAM 2022). Contrasts were made using art.con in ARTool and means were then separated using Tukey's honest significant difference test in R package emmeans, multcomp, and multcompView (Hothorn et al. 2008;

Graves et al. 2019; Kay 2019 a, b; Lenth 2022). Orthogonal contrasts were used to compare one and two herbicides, PRE and POST applications, applications with and without atrazine, applications with and without metribuzin, and atrazine and metribuzin. The p-values to determine the significance for the orthogonal contrasts were obtained using the pairwise p-value matrix in R package emmeans ($p \geq 0.05$; Lenth 2022). Expected and observed values of the combinations were then compared using Wilcoxon signed-rank test using R package stats ($p \geq 0.05$; R CORE Team 2021). If the expected response is similar to the observed response, the combination is considered additive; if the expected response is less than the observed response, the combination is considered synergistic; and if the expected response is greater than the observed response the combination is considered antagonistic.

2.4 Results and Discussion

Palmer amaranth control

Palmer amaranth population × application timing × herbicide interaction for Palmer amaranth control was significant (Table 2.2). Three WAT, all combinations of PS II- and HPPD-inhibiting herbicides applied PRE or POST resulted in 100% control of the MSS population (Figure 2.1). PRE applications of fomesafen resulted in 63% control and POST applications of metribuzin alone resulted in 60% control of the MSS population (Figure 2.1). Control of the KCTR population was variable and ranged from 9% to 86%. Combinations of metribuzin with isoxaflutole or mesotrione, atrazine + mesotrione applied PRE or POST and metribuzin applied PRE resulted in 48 to 86% control of the KCTR population (Figure 2.1). PRE applications of isoxaflutole alone resulted in only 9% control of the KCTR population.

No differences were observed between expected and observed control values calculated using Colby's equation (Colby 1967) and observed values, signifying additive interactions occurred for susceptible and multiple herbicide-resistant Palmer amaranth control regardless of application timing, except for combinations of metribuzin with mesotrione applied POST in the MSS population and combinations of metribuzin with isoxaflutole applied PRE in the KCTR population (Table 2.3). A combination of metribuzin and mesotrione applied POST in the MSS population resulted in a synergistic interaction where the observed control (100%) was greater than the expected control (95%) calculated by Colby's equation (Colby 1967). Metribuzin and isoxaflutole applied PRE in the KCTR population resulted in a synergistic interaction where the observed control (86%) was greater than the expected control (64%) calculated by Colby's equation (Colby 1967).

Orthogonal contrasts demonstrated no differences in PRE and POST applications, with and without atrazine, with and without metribuzin, and atrazine and metribuzin (Table 2.4). However, greater control was observed with combinations of herbicides as compared to herbicides applied individually (Table 2.4).

Control of the MSS population was similar to findings of Shyam et al. (2021) who observed 95% or greater control of the same susceptible population with atrazine, fomesafen, mesotrione, metribuzin, and atrazine + mesotrione. However, in the present study applications of fomesafen PRE and POST resulted 73% or less control. Control of the KCTR population was variable in the present study, which has been illustrated in previous literature. Shyam et al. (2021) reported 100, 36, 29, 90 and 42% control of the KCTR population with atrazine, metribuzin, fomesafen, mesotrione, and atrazine + mesotrione, respectively. Kumar et al. (2020) also reported variable control of herbicide-resistant Palmer amaranth field collections. Faleco et al. (2022a) reported almost 100% control of atrazine-resistant Palmer amaranth with PRE applications of metribuzin, while in the present study PRE applications of metribuzin alone resulted in 83% control of the KCTR population. However, PRE applications containing combinations of metribuzin with HPPD- inhibiting herbicides may provide greater control of multiple herbicide-resistant Palmer amaranth than PS II- and HPPD- inhibiting herbicides applied alone, which would be helpful when rotating to soybeans in a field with multiple herbicide-resistant Palmer amaranth. Herbicide programs utilizing combinations of metribuzin with isoxaflutole or mesotrione would fit well with GT27 soybeans (isoxaflutole-tolerant; BASF Corportation, Research Triangle Park, NC) or HT4 soybeans (mesotrione-tolerant; Bayer CropScience, St. Louis, MO; Rennberger, Personal Communication).

Previous research reported a synergistic control response when combinations of PS-II and HPPD-inhibiting herbicides were applied POST on Palmer amaranth and redroot pigweed (Abendroth et al. 2006; Hugie et al. 2008; Woodyard et al. 2009; Jhala et al. 2014; Kohrt and Sprague 2017b). Although there were limited synergistic responses in this trial, control of both MSS and KCTR was generally increased when more than one herbicide was used. Previously reported results by Johnson et al. (2012) previously reported a synergistic response of atrazine + isoxaflutole on control of susceptible Palmer amaranth when applied PRE. However, results were similar to Chahal and Jhala (2018) who reported no synergistic interactions in PRE applications of atrazine + mesotrione or isoxaflutole.

Palmer amaranth height

Palmer amaranth population × application timing × herbicide interaction was significant for Palmer amaranth height 3 WAT (Table 2.2). For the MSS population, all treatments resulted in Palmer amaranth height less than the non-treated check (PRE = 9.7 cm; POST = 31.7 cm), except for metribuzin alone applied POST (10.8 cm; Table 2.5). For the KCTR population, all treatments resulted in Palmer amaranth similar in height to the non-treated check (PRE=8.4 cm;

POST = 15.6 cm), with the exception of atrazine applied with mesotrione (5.9 cm) and metribuzin applied with isoxaflutole (7.1 cm) applied POST (Table 2.5). Orthogonal contrasts demonstrated that herbicide combinations and PRE vs. POST applications resulted in greater height reductions than herbicides applied individually.

In general, combinations of herbicides resulted in Palmer amaranth smaller in height for the MSS and KCTR populations than herbicides applied individually (Table. 2.4). All combinations of PS II- and HPPD-inhibiting herbicides resulted in Palmer amaranth that were 0.6-cm or less in height in the MSS population for both PRE and POST applications (Table 2.5). Additionally, POST applications of metribuzin combinations resulted in smaller Palmer amaranth than metribuzin applied alone. For the KCTR population, POST applications of mesotrione alone resulted in Palmer greater in height than combinations of atrazine and mesotrione (Table 2.5). All combinations resulted in additive interactions, regardless of application timing or Palmer amaranth population. All combinations were found to be synergistic, indicating that individual applications of PS II- and HPPD-inhibiting herbicides resulted in Palmer amaranth greater in height than Palmer amaranth following combinations of PS II- and HPPD-inhibiting herbicides (Table 2.5).

Heights observed in the present trial were generally correlated with levels of control observed. Heights were greater with individual applications of PS II- and HPPD-inhibiting herbicides compared to combination of PS II- and HPPD-inhibiting herbicides and fomesafen, which resulted in less control and larger plants, regardless of application timing. Chandi et al. (2013) observed greater heights in susceptible Palmer amaranth populations as compared to glyphosate-resistant populations. Liphadzi and Dille (2006) reported 40 to 71% reduction in Palmer amaranth height reduction at corn tasseling when PRE applications of 25 g ai ha^{-1} of isoxaflutole alone were made. Barnes et al. (2019) also observed significant reductions in Palmer amaranth height with PRE applications of atrazine combined with *S*-metolachlor, while de Sanctis et al. (2021) reported no differences in Palmer amaranth height between PRE application of flumioxazin and flumioxazin combined with metribuzin or pyroxasulfone. Woodyard et al. (2009) reported synergistic interactions for waterhemp with combinations of bromoxynil and mesotrione but reported limited synergistic interactions for common lambsquarters, which the authors attributed to greater weed heights at the time of application. Kohrt and Sprague (2017b) reported greater control when atrazine, mesotrione, and combinations thereof were applied to 8-cm as compared to 15-cm tall multiple herbicide-resistant Palmer amaranth. This indicates that greater control may be observed when smaller weeds are treated with combinations of PS II- and HPPD-inhibiting herbicides. It is generally recommended that Palmer amaranth be controlled prior to reaching 10 cm (Berger et al. 2014; Crow et al. 2016; Cuvaca et al. 2019).

Palmer amaranth biomass

Palmer amaranth population × application timing × herbicide interaction for Palmer amaranth biomass 3 WAT was significant (Table 2.2). For the MSS population, all herbicide applications resulted in less biomass than the non-treated check except for fomesafen applied PRE (Table 2.6). For the KCTR population, all individually applied herbicides resulted in biomass levels similar to the non-treated checks, except for metribuzin applied PRE and atrazine applied POST. Combinations of PS II- and HPPD- inhibitor herbicides applied PRE generally resulted in a less biomass than herbicides applied alone for the KCTR population, apart from metribuzin applied alone. However, for the POST applications there were no differences between herbicides applied alone or in combination. Orthogonal contrasts showed greater biomass reduction when a tank mix was utilized as compared to an individual herbicide (Table 2.4). All herbicide combinations resulted in a synergistic biomass response across both application timings and Palmer amarnanth populations (Table 2.6).

In the present trial, PRE applications of combinations of metribuzin and HPPD-inhibiting herbicides suppressed multiple-herbicide-resistant Palmer amaranth, which is similar to findings reported by Faleco et al. (2022 a, 2022b) who observed complete suppression of multiple herbicide-resistant Palmer amaranth (resistant to imazethapyr, atrazine, and glyphosate) and waterhemp (resistant to imazethapyr, atrazine, glyphosate, and 2,4-D) with PRE applications of only metribuzin. Chahal et al. (2019) observed 95 to 100% reduction of biomass when various rates of atrazine and mesotrione were applied in combination POST on atrazine- and HPPD-inhibitor-resistant Palmer amaranth. Kohrt and Sprague (2017b) reported 77, 92, and 100% biomass reduction when atrazine, mesotrione, and atrazine mixed with mesotrione, respectively, were applied to 8-cm tall atrazine- and HPPD-inhibitor-resistant Palmer amaranth. However, when Palmer amaranth reached 15-cm, biomass reduction decreased to 47, 68, and 88% when atrazine, mesotrione, and atrazine + mesotrione were applied, respectively (Kohrt and Sprague 2017b).

Palmer amaranth density

The interaction of Palmer amaranth population × herbicide was significant for Palmer amaranth density 3 WAT of the PRE application timing (Table 2.2). All PS II- and HPPD-inhibiting herbicides applied alone or in combination resulted in fewer plants pot^{-1} than the non-treated check for the MSS population 3WAT (Table 2.7). When HPPD-inhibiting herbicides were applied alone, density was greater than when HPPD-inhibiting herbicides were applied in combination with PS II-inhibiting herbicides, but when there were no differences between the PS II-inhibiting herbicides applied alone the respective combinations (Table 2.7). For KCTR, Metribuzin, metribuzin with isoxaflutole, metribuzin with mesotrione, and atrazine with mesotrione resulted in 1, 1, 2, and 2 plants pot^{-1}, respectively, which was significantly less than the non-treated check (10 plants pot^{-1}; Table 2.7). Orthogonal contrasts demonstrated that combinations of PS II- and HPPD-inhibitors resulted in fewer plant pot^{-1} than herbicides applied alone, apart from metribuzin applied alone in KCTR (Table 2.4). This indicates that metribuzin is effective in suppressing Palmer amaranth density alone and in combination with HPPD-inhibiting herbicides for the management of multiple herbicide-resistant Palmer amaranth. The orthogonal contrasts demonstrated that applications including metribuzin resulted in fewer plants pot^{-1} than applications including atrazine. Additionally, orthogonal contrasts demonstrated fewer plants pot^{-1} with atrazine as compared to without atrazine and with metribuzin as compared to without metribuzin. All herbicide combinations resulted in a synergistic response for density demonstrating that utilizing PS II- and HPPD-inhibiting herbicide in combination can be effective in managing both susceptible and multiple herbicide-resistant Palmer amaranth (Table 2.4).

Atrazine, metribuzin, mesotrione, and combinations of PS II- and HPPD- inhibiting herbicides resulted in fewer plant pot^{-1} for the MSS population. Density levels were variable for the KCTR population, but combinations of PS II- and HPPD-inhibiting herbicides generally resulted in fewer plants pot^{-1} than individually applied herbicides, except for metribuzin. PRE applications of metribuzin and metribuzin combinations resulted in up to 2 plants pot^{-1}, while Faleco et al. (2022a) who reported 100% reduction in density of atrazine resistant Palmer amaranth with PRE applications of metribuzin. Chahal and Jhala (2018) also reported variable density reduction (6 to 86%) of herbicide-resistant Palmer amaranth due to PRE applications of atrazine + mesotrione or isoxaflutole compared to the herbicides applied individually. For POST applications, Chahal and Jhala (2018) reported 82 to 85% density reduction of PS II- and HPPD-inhibiting herbicide-resistant Palmer amaranth with combinations of atrazine and mesotrione, but when applied individually, density was only reduced 15 to 40%. Crow et al. (2016) reported fewer herbicide-resistant Palmer amaranth m^{-1} when POST applications of more than one herbicide were utilized.

2.5 Conclusion

Variability in responses of the KCTR population was previously reported by Shyam et al. (2021) and may be partially explained by the genetic variability that is often observed in field populations of Palmer amaranth (Franssen et al. 2001; Ward et al. 2013). Few synergistic interactions were observed for control for both populations, but all combinations of PS II- and HPPD-inhibiting herbicides resulted in synergistic interactions for height, biomass, and density for the KCTR population. This indicates that these combinations can be effective in suppressing multiple herbicide-resistant Palmer amaranth. Complete suppression may not be achieved, but this combination may result in Palmer amaranth that are less competitive with crops and produce less viable seed (Norsworthy et al. 2016).

Variable suppression observed in this trial may reflect the challenges faced by producers when endeavoring to control field populations of multiple herbicide-resistant Palmer amaranth (Van Wychen 2021, 2022). In the present trial, PRE applications containing metribuzin consistently resulted in greater suppression of multiple herbicide-resistant Palmer amaranth than PS II- and HPPD- inhibiting herbicides applied alone. Previous research has also demonstrated consistent control of multiple herbicide-resistant Palmer amaranth with combinations of two or more effective sites of action (Kohrt and Sprague 2017a, 2017b).

Although increased levels of suppression may be obtained by using herbicide combinations with multiple sites of action that are additive in nature, producers should still implement integrated weed management practices to mitigate the development of multiple herbicide-resistant Palmer amaranth. These practices include combinations of multiple effective sites of action, multi-pass herbicide programs, overlapping residual herbicides, crop rotation, rotation of crop herbicide-resistance traits, tillage when necessary, and the adoption of a zero-tolerance mentality when it comes to prolific seed producers, like Palmer amaranth.

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Table 2.1. PRE and POST herbicide treatments applied on susceptible (MSS) and multiple herbicide-resistant (KCTR) Palmer amaranth populations.[a]

Herbicide group	Herbicide treatments	Rate	Trade names	Manufacturer information[b]
		g ai ha^{-1}		
5	Atrazine	897	Aatrex® 4L	Syngenta Crop Protection
5	Metribuzin	213	Tricor® DF	UPL NA
27	Mesotrione	53	Callisto®	Syngenta Crop Protection
27	Isoxaflutole	26	Balance Flexx®	Bayer CropScience
5 + 27	Atrazine + mesotrione	897 + 53	Aatrex® 4L + Callisto®	Syngenta Crop Protection
5 + 27	Atrazine + isoxaflutole	897 + 26	Aatrex® 4L + Balance Flexx®	Syngenta + Bayer CropScience
5 + 27	Metribuzin + mesotrione	213 + 53	Tricor® DF + Callisto®	UPL NA +_Syngenta
5 + 27	Metribuzin + isoxaflutole	213 + 26	Tricor® DF + Balance Flexx®	UPL NA + Bayer CropScience
5 + 27	Fomesafen	13	Reflex®	Syngenta Crop Protection

[a] PRE = preemergence; POST = postemergence (4-6 L Palmer amaranth); POST application was applied with 1% v/v crop oil concentrate (Prime Oil®, Winfield Solutions, LLC, St. Paul, MN); MSS = Mississippi Susceptible Palmer amaranth population; KCTR = Kansas multiple herbicide-resistant Palmer amaranth population

[b]Manufacturer information: Syngenta Crop Protection, Greensboro, NC; UPL NA Inc., King of Prussia, PA; Bayer CropScience, St. Louis, MO

Table 2.2. Analysis of variance of fixed effects and all interactions 3 weeks after treatment for Palmer amaranth control, expected control, height reduction, expected height reduction, density reduction, expected density reduction, biomass reduction, and expected biomass reduction as result of herbicide applications on susceptible and multiple herbicide-resistant Palmer amaranth at PRE and POST.[a]

	Response			
Effect	Control	Height[a]	Density	Biomass
	p-value			
Population	<0.0001	<0.0001	<0.0001	<0.0001
Application timing	<0.0001	<0.0001	–	<0.0001
Herbicide	<0.0001	<0.0001	<0.0001	<0.0001
Population x Application timing	<0.0001	0.0145	–	0.0175
Population x Herbicide	<0.0001	<0.0001	<0.0001	<0.0001
Application timing x Herbicide	<0.0001	<0.0001	–	<0.0001
Population x Application timing x Herbicide	<0.0001	<0.0001	–	<0.0001

[a] PRE = preemergence; POST = postemergence (4-6 leaf Palmer amaranth)

Table 2.3. Expected control 3 weeks after treatment of susceptible (MSS) and resistant (KCTR) Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied in combination preemergence (PRE) and postemergence (POST).

		Palmer amaranth popution[b]					
Application timing[a]	Herbicide	MSS			KCTR		
		Observed	Expected[c]	p-value[d]	Observed	Expected[c]	p-value
			%			%	
PRE	Atrazine + Isoxaflutole	100	100	0.7001[e]	24	18	0.5923
	Atrazine + Mesotrione	100	100	1.000	79	28	0.0645
	Metribuzin + Isoxaflutole	100	100	0.3816	87	64	0.0071
	Metribuzin + Mesotrione	100	100	1.000	85	65	0.4877
POST	Atrazine + Isoxaflutole	100	100	0.4881	28	55	0.666
	Atrazine + Mesotrione	100	100	0.1709	37	56	1.000
	Metribuzin + Isoxaflutole	100	96	0.5897	40	29	0.7897
	Metribuzin + Mesotrione	100	95	0.0323	60	35	0.8329

[a] PRE = preemergence; POST = postemergence (4-6 leaf Palmer amaranth); POST application was applied with 1% v/v crop oil concentrate

[b] MSS = Mississippi susceptible Palmer amaranth; KCTR = Kansas multiple herbicide-resistant Palmer amaranth

[c] Expected values were calculated using Colby's equation (Colby 1967) as follows: $E = (X + Y) - (XY/100)$, where E is the expected control as calculated by the observed control (X and Y) achieved with individual applications of PS II- and HPPD-inhibiting herbicide used in this study.

[d] Expected and observed values of the combinations were then compared using Wilcoxon signed-rank test using R package stats. If the expected response is similar to the observed response ($p \geq 0.05$), the combination is considered additive; if the expected response is less than the observed response ($p \leq 0.05$), the combination is considered synergistic; and if the expected response is greater than the observed response the combination is considered antagonistic ($p \leq 0.05$).

[e] Significance level $\alpha = 0.05$ used to determine significant comparisons.

Table 2.4. Orthogonal contrast means for Palmer amaranth control, height, biomass, and density 3 weeks after treatment of susceptible (MSS) and resistant (KCTR) Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied alone and in combination preemergence (PRE) and postemergence (POST).

Contrasts	Control	Height	Biomass	Density
	%	cm	g pot^{-1}	plants pot^{-1}
PRE vs. POST	55 vs. 61	8.4 vs. 4.3**	0.4 vs. 0.3	-
1 vs. 2 herbicides	53 vs. 78**	7.2 vs. 2.8**	0.4 vs. 0.1**	3 vs. 2*
Atrazine vs. Metribuzin	69 vs. 77	3.6 vs. 3.7	0.2 vs. 0.2	3 vs. 2*
Isoxaflutole vs. Mesotrione	64 vs. 72	4.6 vs. 4.5	0.3 vs 0.2	3 vs. 2

* Significant at $\alpha \leq 0.001$

** Significant at $\alpha \leq 0.0001$

Table 2.5. Observed and expected Palmer amaranth height when PS II- and HPPD- inhibiting herbicides were applied alone and in combination preemergence (PRE) and postemergence (POST) 3 weeks after treatment.

		Palmer amaranth popution[b]					
Application timing[a]	Herbicide	MSS			KCTR		
		Observed	Expected[c]	p-value[d,e]	Observed	Expected	p-value
		cm			cm		
PRE	Atrazine	0.6 hi[f]			9.2 a-f		
	Metribuzin	0.6 ghi			3.3 f-i		
	Isoxaflutole	5.1 d-i			8.3 a-f		
	Mesotrione	2.8 f-i			7.6 a-f		
	Atrazine + Isoxaflutole	0.6 ghi	5.6	0.0043	6.4 b-h	16.7	0.0002
	Atrazine + Mesotrione	0 i	3.4	0.0325	3.5 e-i	16.1	0.0009
	Metribuzin + Isoxaflutole	0.3 hi	5.6	0.0045	2.7 f-i	11.2	0.0009
	Metribuzin + Mesotrione	0.1 i	3.3	0.0128	2.6 f-i	10.7	0.0009
	Fomesafen	7.5 b-f			7.5 b-f		
	Non-treated check	9.7 a-e			8.4 a-f		
POST	Atrazine	0 i			8.5 a-f		

Metribuzin	10.8 a-f			10.6 a-f		
Isoxaflutole	3.6 f-i			12.9 a-d		
Mesotrione	6.6 c-i			16.2 ab		
Atrazine + Isoxaflutole	0 i	3.6	0.0007	8.4 a-f	20.7	0.0027
Atrazine + Mesotrione	0 i	6.6	0.0004	5.9 c-i	24.2	0.0173
Metribuzin + Isoxaflutole	0 i	14.1	0.0092	7.5 c-i	22.1	0.0009
Metribuzin + Mesotrione	0 i	16.8	0.0015	7.1 b-h	25.8	0.0009
Fomesafen	8.6 b-g			14.1 abc		
Non-treated check	31.7 a			15.6 ab		

[a] PRE = preemergence; POST = postemergence (4-6 L Palmer amaranth); POST application was applied with 1% v/v crop oil concentrate

[b] MSS = Mississippi susceptible Palmer amaranth; KCTR = Kansas multiple herbicide-resistant Palmer amaranth

[c] Expected values were calculated using Colby's equation (Colby 1967) as follows: E = (X + Y) – (XY/100), where E is the expected control as calculated by the observed control (X and Y) achieved with individual applications of PS II- and HPPD-inhibiting herbicide used in this study.

[d] Expected and observed values of the combinations were then compared using Wilcoxon signed-rank test using R package stats. If the expected response is similar to the observed response ($p \geq 0.05$), the combination is considered additive; if the expected response is

less than the observed response ($p \leq 0.05$), the combination is considered synergistic; and if the expected response is greater than the observed response the combination is considered antagonistic ($p \leq 0.05$).

[e] Significance level $\alpha = 0.05$ used to determine significant comparisons.

[f]Means followed by the same letter are not significantly different (α=0.05). Means were separated with the Tukey's honest significant difference test.

Table 2.6. Observed and expected Biomass 3 weeks after treatment of susceptible (MSS) and resistant (KCTR) Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied alone and in combination preemergence (PRE) and postemergence (POST).

Application timing[a]	Herbicide	Palmer amaranth popution[b]					
		MSS			KCTR		
		Observed	Expected[c]	p-value[d,e]	Observed	Expected	p-value
		g pot^{-1}			g pot^{-1}		
PRE	Atrazine	0.01 hi[f]			0.87 abc		
	Metribuzin	0.01 hi			0.20 ghi		
	Isoxaflutole	0.26 e-h			0.84 a-d		
	Mesotrione	0.05 ghi			0.64 a-f		
	Atrazine + Isoxaflutole	0.00 hi	0.30	0.0036	0.42 b-g	1.70	0.0002
	Atrazine + Mesotrione	0.00 i	0.10	0.0325	0.12 ghi	1.50	0.0006
	Metribuzin + Isoxaflutole	0.00 hi	0.30	0.0046	0.09 ghi	1.00	0.0009
	Metribuzin + Mesotrione	0.00 hi	0.10	0.0128	0.08 ghi	0.80	0.0019
	Fomesafen	0.40 b-g			0.64 a-f		
	Non-treated check	0.83 a-d			0.70 a-f		

	Atrazine	0.00 i			0.40 c-g		
	Metribuzin	0.39 d-g			0.31 b-g		
	Isoxaflutole	0.06 ghi			0.77 a-e		
	Mesotrione	0.09 ghi			0.66 a-f		
POST	Atrazine + Isoxaflutole	0.00 i	0.10	0.0068	0.43 b-g	1.20	0.0013
	Atrazine + Mesotrione	0.00 i	0.10	0.0004	0.32 f-i	1.10	0.0095
	Metribuzin + Isoxaflutole	0.00 i	0.40	0.0092	0.40 fgh	1.10	0.0009
	Metribuzin + Mesotrione	0.00 i	0.50	0.0015	0.35 e-h	1.00	0.0072
	Fomesafen	0.34 fgh			0.88 ab		
	Non-treated check	1.04 a			0.93 ab		

[a] PRE = preemergence; POST = postemergence (4-6 L Palmer amaranth); POST application was applied with 1% v/v crop oil concentrate

[b] MSS = Mississippi susceptible Palmer amaranth; KCTR = Kansas multiple herbicide-resistant Palmer amaranth

[c] Expected values were calculated using Colby's equation (Colby 1967) as follows: E = (X + Y) – (XY/100), where E is the expected control as calculated by the observed control (X and Y) achieved with individual applications of PS II- and HPPD-inhibiting herbicide used in this study.

[d] Expected and observed values of the combinations were then compared using Wilcoxon signed-rank test using R package stats. If the expected response is similar to the observed response ($p \geq 0.05$), the combination is considered additive; if the expected response is

less than the observed response ($p \leq 0.05$), the combination is considered synergistic; and if the expected response is greater than the observed response the combination is considered antagonistic ($p \leq 0.05$).

[e] Significance level $\alpha = 0.05$ used to determine significant comparisons.

[f] Means followed by the same letter are not significantly different (α=0.05). Means were separated with the Tukey's honest significant difference test.

Table 2.7. Observed and expected density of susceptible and resistant Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied alone and in combination preemergence (PRE) 3 weeks after treatment.

Herbicide	Palmer amaranth popution[a]					
	MSS			KCTR		
	Observed	Expected[b]	p-value[c,d]	Observed	Expected	p-value
	plants pot^{-1}			plants pot^{-1}		
Atrazine	0 fg[e]			8 ab		
Metribuzin	0 efg			1 d-g		
Isoxaflutole	2 cd			6 ab		
Mesotrione	2 c-f			4 bc		
Atrazine + Isoxaflutole	0 efg	2	0.0088	7 ab	13	0.0053
Atrazine + Mesotrione	0 g	2	0.0044	2 cde	12	0.0009
Metribuzin + Isoxaflutole	0 efg	2	0.0023	1 d-g	7	0.0009
Metribuzin + Mesotrione	0 bc	2	0.0142	2 cde	6	0.0045
Fomesafen	4 fg			6 ab		
Non-treated check	15 a			10 ab		

[a] MSS = Mississippi susceptible Palmer amaranth; KCTR = Kansas multiple herbicide-resistant Palmer amaranth

[b] Expected values were calculated using Colby's equation (Colby 1967) as follows: E = (X + Y) – (XY/100), where E is the expected control as calculated by the observed control (X and Y) achieved with individual applications of PS II- and HPPD-inhibiting herbicide used in this study

[c] Expected and observed values of the combinations were then compared using Wilcoxon signed-rank test using R package stats. If the expected response is similar to the observed response ($p \geq$

0.05), the combination is considered additive; if the expected response is less than the observed response ($p \leq 0.05$), the combination is considered synergistic; and if the expected response is greater than the observed response the combination is considered antagonistic ($p \leq 0.05$).

[d] Significance level $\alpha = 0.05$ used to determine significant comparisons.

[e] Means followed by the same letter are not significantly different (α=0.05). Means were separated with the Tukey's honest significant difference test.

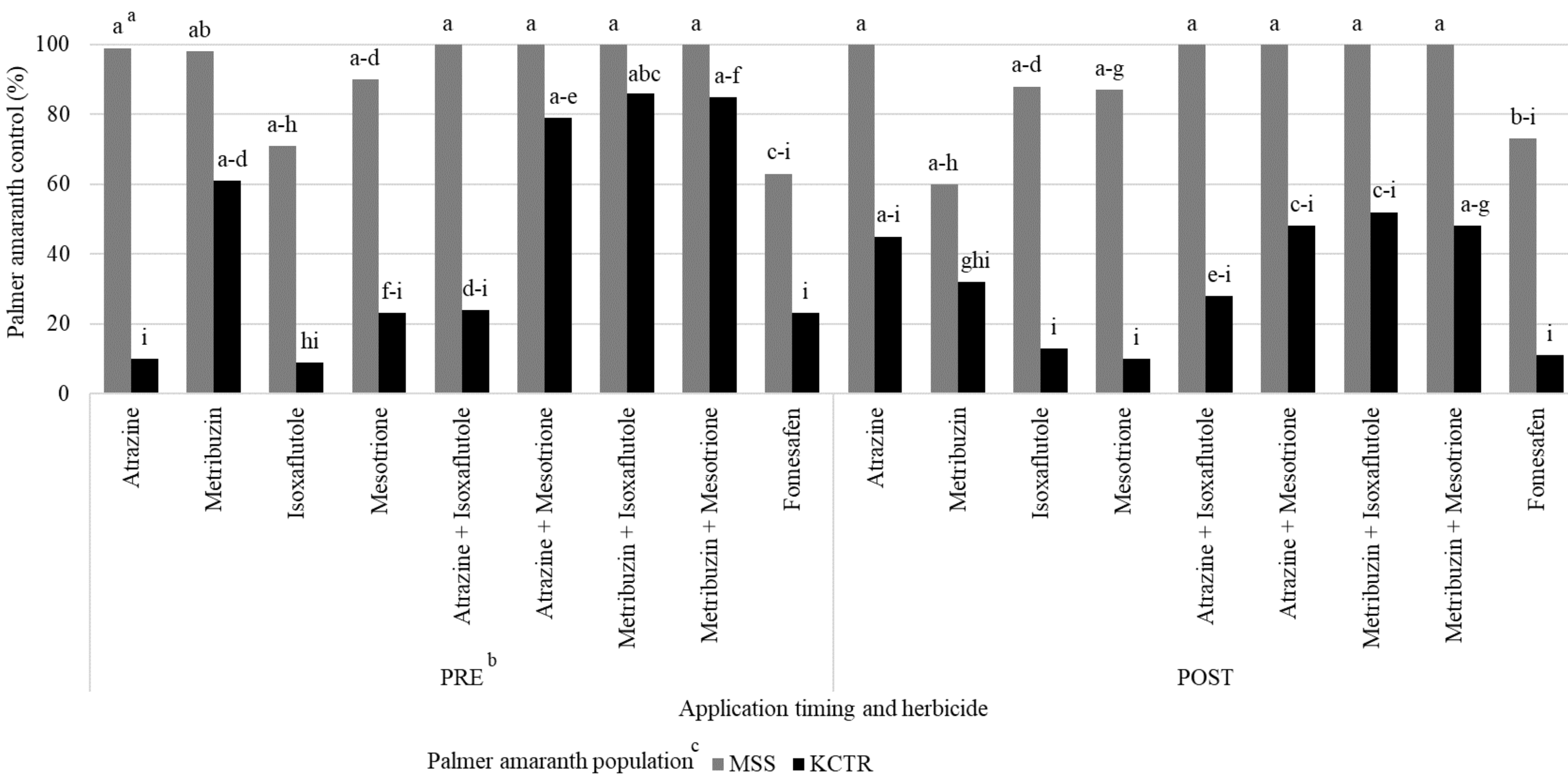

Figure 2.1. Control of susceptible and resistant Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied alone and in combination preemergence (PRE) and postemergence (POST) 3 weeks after treatment.

[a] Means followed by the same letter are not significantly different (α=0.05). Means were separated with the Tukey's honest significant difference test.

[b] MSS = Mississippi susceptible Palmer amaranth; KCTR = Kansas multiple herbicide-resistant Palmer amaranth

[c] PRE = preemergence; POST = postemergence (4-6 leaf Palmer amaranth); POST application was applied with 1% v/v crop oil concentrate

Chapter 3 - Effect of Spray Volume on Residual Herbicide Efficacy in Corn

3.1 Abstract

Optimization of residual herbicide applications is critical to control Palmer amaranth (*Amaranthus palmeri S. Watson*) and waterhemp (*Amaranthus tuberculatus [Moq.] Sauer*). Experiments were established to quantify the effect of application timing and spray volume on residual herbicide efficacy in corn in 2021 (Colby and Ottawa (no-till), KS) and 2022 (Manhattan, Ottawa (no-till), and Scandia (no-till), KS). Resicore (clopyralid + acetochlor + mesotroine) and TriVolt (isoxaflutole + thiencarbazone-methyl + flufenacet) were applied at 56, 122, and 187 L ha^{-1} in preemergence (PRE)-only or preemergence followed by (fb) postemergence (POST) systems. In 2021, POST herbicides included dicamba+diflufenzopyr and glyphosate and in 2022 mesotrione and atrazine were also included. Dominant weed species were Palmer amaranth (Colby, Manhattan, and Scandia) and waterhemp (Ottawa). Palmer amaranth control was 94% or greater in Colby throughout the growing season. Resicore provided greater *Amaranthus* control than TriVolt in no-till systems. *Amaranthus* control was greater in PRE fb POST than PRE-only systems. Spray volume did not impact weed control apart from waterhemp control in Ottawa 2021, where Resicore applied at 56 L ha^{-1} provided the least control when compared to TriVolt applied at 56 L ha^{-1} and Resicore applied at 187 L ha^{-1}. No yield differences were observed among treatments, apart from Manhattan and Ottawa 2022 where the nontreated check resulted in less yield than all treatments. These experiments suggest that herbicide selection is of greater importance than spray volume for residual weed control.

3.2 Introduction

Palmer amaranth (*Amaranthus palmeri* S. Watts) and waterhemp (*Amaranthus tuberculatus* [Moq.] Sauer) were considered the most troublesome weeds in corn cropping systems by weed scientists across the United States in 2020 (Van Wychen 2020). Population of these species with confirmed multiple herbicide-resistance occur across the United States (Bell et al; 2013; Shyam et al. 2021; Faleco et al. 2022; Heap 2022). A wide variety of physiological and morphological adaptations make the *Amaranthus spp.* extremely competitive with corn (Ehleringer 1983; Ward et al. 2013; Massinga et al. 2001,2003; Steckel and Sprague 2004). Palmer amaranth interference have been observed to cause up to 91% corn yield loss and waterhemp interference has been observed to cause corn yield losses up to 74% (Massinga et al. 2001; Steckel and Sprague 2004; Cordes et al. 2004). The timing of *Amaranthus spp.* emergence in relation to corn emergence is critical, as early season germination is more detrimental to corn yields than weeds that emerge later in the season (Massinga et al. 2001,2003; Steckel and Sprague 2004).

One way to address herbicide-resistant (HR) weed management is to implement residual herbicides into the weed management program in a way that eliminates or minimizes weed seed dispersal (Shaner and Beckie 2014). *Amaranthus spp.* are prolific seed producers and when combined with genetic variability can result in drastic differences in plants within a given field (Steckel et al. 2003; Ward et al. 2013). Keely et al. (1987) reported that female plants produce up to 600,000 seeds plant^{-1} when they emerge in March, but Palmer amaranth emerging in September produced as few as 115 seeds plant^{-1}. Steckel et al. (2003) reported that waterhemp plants emerging in late May produce as many as one million seeds plant^{-1} when grown in full sunlight, but as sunlight decreased and emergence was delayed, seed production decreased.

Although late emergence, interspecific competition, and intraspecific competition can lead to plants reduced in size and seed yield, seeds are still produced at levels adequate to replenish the weed seed bank (Keely et al. 1987; Massinga et al. 2003; Steckel et al. 2003; Norsworthy et al. 2016b). When Palmer amaranth is left uncontrolled for three years, an initial planting of 20,000 seeds m^{-2} completely infested 0.77 ha (Norsworthy et al. 2014). Efforts should be made to prevent *Amaranthus spp*. seed production. Depletion of the weed seed bank reduces the number of individuals that are exposed to weed control tactics and reduces the number of plants that could contribute to the weed seed bank (Korres et al. 2018; Hare et al. 2020). Weed seed bank replenishment can be greatly reduced by utilizing residual herbicides in combination with a multi-pass herbicide program and crop rotation (Norsworthy et al. 2012; Shaner and Beckie 2014). Preventing weed seed bank replenishment is advantageous for crop production and conserving the remaining effective herbicide programs, as low weed populations play a large role in the sustainability of weed management practices (Walsh et al. 2013).

An effective technique to control multiple herbicide-resistant *Amaranthus spp.* is utilizing residual herbicides, multiple effective sites of action, and multiple passes (Parker et al. 2006; Evans et al. 2014; Crow et al. 2016; Kohrt and Sprague 2017; Chahal et al. 2018; Chahal and Jhala 2018; Inman et al. 2020). The combination of multi-pass programs with residual herbicides is a viable option for control of many weed species. For annual grass species, postemergence (POST) only systems were shown to have decreased control regardless of herbicide used in the POST application when compared to a preemergence (PRE) application of glyphosate followed by a POST application (Parker et al. 2006). It is not recommended to utilize only glyphosate in a PRE application, but this does highlight the importance of early season weed control. In general, following PRE applications with POST applications can increase *Amaranthus spp.* control and reduce density and biomass (Chahal et al. 2018; Buol et al. 2021). Palmer amaranth that escapes PRE applications cause less yield loss than those that were never treated (Liphadzi and Dille 2006). However, in the absence of PRE applications at least two timely POST applications should be utilized, as a delay in POST application or only one POST application can lead to increased numbers of emerged weeds and increased yield loss (Gower et al. 2003). Including a PRE application allows for reduced early-season weed interference and allows for more time between planting and the POST application (Parker et al. 2006). Multi-pass systems have been shown to maximize crop yields as compared to PRE-only and POST-only systems (Buol et al. 2021, Parker et al. 2006). Preemergence applications followed by POST applications can provide greater economic returns than PRE-only and POST-only systems partially due to the season-long *Amaranthus spp.* control that can be achieved with PRE fb POST systems (Chahal and Jhala 2018a).

The incidence of herbicide resistance is generally greater in fields where few herbicide groups are utilized each growing season (Evans et al. 2014). Residual herbicide applications are an important component of weed management programs because they reduce the abundance and size of weeds that must be controlled with POST applications and increase the probability of achieving season-long weed control (Gower et al., 2002; Lindsey et al. 2012; Janak and Grichar 2016; Norsworthy et al. 2016a; Oliveira et al. 2017; Kohrt and Sprauge, 2017). Season-long *Amaranthus spp.* control can be achieved when two or more effective herbicide groups are utilized and a residual herbicide is included in the POST application (Kohrt and Spraque 2017; Oliveira et al. 2017). Utilizing multiple effective herbicides is critical to consider due to the identification of Palmer amaranth and waterhemp population resistant to critical residual herbicide groups 2, 5, 15, 14, and 27 (Heap 2022). Introducing novel herbicides and reintroducing older herbicides will not solve the issue of herbicide resistance but can aid growers in controlling herbicide-resistant weeds. An example of the reintroduction of an older herbicide, is flufenacet. Flufenacet is a soil-applied oxyacetamide that has excellent activity against annual grasses and small-seeded broadleaf weeds similar to other herbicides in herbicide group 15 (Steckel et al. 2003). Flufenacet was initially synthesized in 1988 by Bayer Crop Science and commercialized in 1998 as a component of Axiom DF (Bayer Crop Science, St. Louis, MO), a premix of flufenacet and metribuzin used in soybeans. In 2005, Radius herbicide (Bayer Crop Science, St. Louis, MO), a premix of flufenacet and isoxaflutole used in corn, was commercialized. More recently in 2021, TriVolt (Bayer Crop Science, St. Louis, MO), a premix of flufenacet, isoxaflutole, and thiencarbazone-methyl, was commercialized for use in corn.

Other techniques that may be explored to optimize residual herbicide applications include alteration of application parameters, such as spray volume. There is a plethora of research regarding application parameters surrounding POST application but very little peer-reviewed research regarding PRE applications. There is a need to understand application parameters surrounding residual herbicide applications because there is little research regarding the effect that spray volume has on the efficacy of residual herbicides. Understanding these parameters could help producers be more effective in managing herbicide-resistant weeds and preventing weed seed bank replenishment. Most research has focused on POST applied herbicide rather than residual herbicides. Borger et al. (2013, 2015) observed increased rigid ryegrass control by trifluralin and pyroxasulfone as spray volumes increased from 50 L ha^{-1} to 150 L ha^{-1} in no-tillage systems. Greater than 90% control of black grass (*Alopecurus myosuroides Huds)* was observed when PRE applications of flufenacet were made using 200 L ha^{-1}, compared to less than 70% control with carrier volume at 50 L ha^{-1} (J Thomas, Personal Communication).

However, Striegel et al. (2021) found that carrier volumes did not influence weed control, rather residual herbicide selection influenced weed control in conventional tillage systems. In a turfgrass system, there were no differences in control when large crabgrass was treated with pendimethalin applied at 561 or 19 L ha^{-1} (Ferguson et al. 2016). This limited literature appears to suggest the utilization of lower carrier volumes in conventional tillage systems may not compromise weed control, but larger carrier volumes may be required to achieve adequate control in no-tillage systems.

The difference in control achieved between the tillage systems may be attributed to the increased residue in the no-tillage systems that may prevent the residual herbicides from reaching the soil, depending on the herbicide (Ghadiri et al. 1984, Johnson et al. 1989, Chauhan et al. 2006, Borger et al. 2015). A review by Chauhan et al. (2006) found that 15 to 80% of residual herbicides can be tied up in crop residue. Residual herbicides may bind to the residue before reaching the soil surface. Volatile residual herbicides with low solubility, such as trifluralin, that are required to be moved into the soil after application via tillage or water may require high carrier volumes to ensure efficacy in conservation tillage systems (Chauhan et al. 2006, Borger et al. 2015). Messelhäuser et al. (2022) observed no differences in weed control between no-tillage and tillage treatments when cinmethylin, a residual herbicide with low solubility, was applied. Martin et al. (1978) observed less than 10% of spray solution penetrated heavy corn residue when applied with carrier volumes as high as 2400 L ha^{-1}. There is a need to optimize application parameters surrounding residual herbicide applications because there is little research regarding the effect of carrier volume on weed control. Steps towards understanding this could help producers be more effective in managing HR weeds and preventing weed seed bank replenishment.

Therefore, the objectives of this trial were to quantify the influence of application timing and spray volume on weed control, economic returns, and sprayer productivity of residual herbicide applications in corn in Kansas corn production systems. It is hypothesized that spray volume will have minimal impact on residual herbicide efficacy, but application timing will be of greater importance for maintaining season long weed control. Specifically, PRE followed by POST systems will result in greater control than PRE-only systems.

3.3 Materials and Methods

Site years

Field experiments were conducted in 2021 at Colby, KS at the Northwest Research-Extension Center (Latitude: 39.38, Longitude: -101.07) and at Ottawa, KS at the East Central Kansas Experiment Field (Latitude: 38.54, Longitude: -95.24); and in 2022 at Manhattan, KS at the Ashland Bottom Research Station (Latitude: 39.13, Longitude: 96.61), Scandia, KS at the North Central Kansas Irrigation Field (Latitude: 39.83, Longitude: -97.84), and Ottawa, KS at the East Central Kansas Experiment Field (Latitude: 38.54, Longitude: -95.24).

Land preparation and planting

Corn planting dates, seeding rates, tillage practices, rainfall amounts, irrigation amounts, and soil properties for each location can be found in Table 3.1. The same corn hybrid, DKC 59-82 RIB (glyphosate tolerant; *Bt* trait = VT Double Pro; Bayer Crop Science, St. Louis, MO), was planted in all locations and was selected due to drought tolerance, standability, and high yield potential. Corn at Colby 2021 was planted into a conventionally tilled seed bed that was under irrigation where the previous crop was soybean. Ahead of planting in Colby 2021, the field was fertilized with 263 kg nitrogen ha^{-1} using anhydrous ammonia (82-0-0). Corn at Ottawa in 2021 and 2022 was planted into rainfed, strip-tilled soybean residue, which was fertilized with 136 kg nitrogen ha^{-1}, 53 kg phosphorus ha^{-1}, 35 kg potassium ha^{-1}, and 11 kg sulfur ha^{-1} on November 19, 2020 and December 14, 2021 utilizing UAN (28-0-0), liquid starter (7-21-7), potassium thiosulfate (0-0-25-17). Six days prior to planting in Ottawa 2021 and one day prior to planting in Ottawa 2022 a pre-plant burndown application was applied to control early season weeds (Table 3.2). Corn stands in Ottawa 2021 were poor due to excessive rainfall immediately following planting (Table 3.1). There was opportunity to replant, but due to impending rainfall and no guarantee of better stands the authors decided not to replant. Corn in Scandia 2022 was planted into no-till soybean residue that was under irrigation (Table 3.1). In Scandia 2022, 179 kg ha^{-1} of nitrogen was applied on April 21, 2022 using anhydrous ammonia and 13 kg ha^{-1} of nitrogen and 44 kg ha^{-1} of phosphorus was applied at the time of planting using ammonium phosphate (10-34-0). Corn in Manhattan 2022 was planted into a conventionally tilled seed bed that was under rainfed conditions where the previous crop was soybean. One hundred sixty-eight kg ha^{-1} of nitrogen was applied on April 12, 2022 using urea ammonium nitrate (28-0-0).

Herbicide applications

The experimental design was a randomized complete block with four replications. In Ottawa 2021, only three replications were used as one replication was abandoned due to poor corn stands. Individual plots were 3 m by 9 m in size.

Herbicide were applied early postemergence (EPOST) in 2021 or PRE in 2022, which will both be referred to as PRE henceforth (Table 3.2). PRE applications were either applied alone or were followed by (*fb*) a late postemergence (LPOST) in 2021 and EPOST in 2022, which will be referred to as POST henceforth (Table 3.2). The EPOST in 2021 applications occurred when the corn was at the V2 (28-cm) growth stage and LPOST 2021 applications occurred when corn was V8 (91-cm) growth stage. At the time of the EPOST application in

2021, weeds were four to six leaf and less than 10 cm tall in Colby. In Ottawa 2021, there were no weeds present at the time of the EPOST application due to the oversaturated conditions experienced following corn planting. In 2021, the LPOST application only occurred in Ottawa and not in Colby because the corn was greater than V8 and 91-cm and the authors did not want to risk crop injury from an off-label herbicide application. In 2022, the PRE application occurred on the day of planting and the EPOST occurred prior to the corn reaching 30-cm in height. Treatments also included a non-treated check and weed-free check, which was kept weed free with hand weeding.

Spray solution for the PRE application was applied directly to plots at 56, 122, 187 L ha^{-1} spray volume using a CO_2 powered backpack sprayer and a 4-tip, 2.04 m hand-held boom equipped with various nozzle and pressures to achieve the spray volumes (Table 3.3). The resulting droplet size was coarse, medium, and medium for spray volumes 56, 122, and 187 L ha^{-1}, respectively. Previous research has indicated that spray volume has minimal effect on droplet size, rather nozzle type, operating pressure, and nozzle size were of greatest importance (Creech et al. 2015). Spray solution for the POST application was applied directly to plots at 140 L ha^{-1} spray volume using a CO_2 powered backpack sprayer and a 4-tip, 2.04 m hand-held boom equipped with TT110015 at 276 kPa.

Data collection

Control of individual weed species was visually assessed prior to POST applications, 8 WAT, and at corn harvest. Weed control evaluations occurred prior to POST application at 8 weeks after planting (WAP) in Ottawa 2021, 2 WAP in Manhattan 2022, and 4 WAP in Ottawa 2022 and Scandia 2022. In Colby 2021, weed control was visually assessed at 4, 8, and 12 WAT and at corn harvest. Weed control was evaluated on a 0 to 100% weed control scale with 0%

indicating no control and 100% indicating complete weed control (Canadian Weed Science Society 2018). Palmer amaranth was the dominant weed species in Colby 2021 and Manhattan 2022. Waterhemp and fall panicum (*Panicum dichotomiflorum* Michx.) were the dominant weed species in Ottawa 2021 and 2022. The dominant weed species in Scandia were Palmer amaranth and large crabgrass (*Digitaria sanguinalis* L. Scop.).

To further evaluate weed control, weed biomass, and weed densities were collected at 8 WAT and at harvest within a 0.25 m^{-2} quadrant at two representative locations within each plot. Weed biomass and densities were recorded for individual weed species. Weed biomass samples were dried for ~10 days at 50 C and then weighed to obtain the dry weight. Weed biomass and density data were calculated by taking the average of the plot and multiplying by 4 to get the biomass and density m^{-2}. Corn grain was harvested from the center two rows of each plot with a small plot combine. Grain yields were adjusted to 15.5% moisture content.

Economic analysis

A partial budget analysis was conducted to estimate profitability of the different spray volumes and residual herbicides. Comparisons were made among spray volumes, residual herbicides, and PRE-only and PRE fb POST treatments at Colby 2021, Ottawa 2021, Manhattan 2022, Ottawa 2022, and Scandia 2022. Resicore applied at 56 L ha^{-1} in a PRE-only system was used as a base line. This was selected as the baseline due to the lower application costs and efficiency associated with a PRE-only system and utilization of low spray volumes. Additionally, Resicore was a more widely utilized product at the time of analysis as compared to TriVolt. Resicore was commercialized in 2016 and TriVolt was commercialized 2022 (Corteva Agrisciences, Indianapolis, IN; Bayer Crop Science, St. Louis, MO). Factors such as the tillage cost, planting cost, taxes, and insurance were not considered in the partial budget analysis because these expenses are fixed. Spraying costs were estimated using the K-State Machinery cost calculator (Ibendahl and Griffin 2020).

A self-propelled sprayer with a 36-m boom and 1136-L tank, requiring a 300 hp tractor using $1.25/L diesel and at speed of 19.3 km hr^{-1} was used in the calculator. Estimated machinery costs for PRE applications utilizing 56, 122, and 186 L ha^{-1} spray volumes were $5.68, $6.59, and $7.68 ha^{-1}, respectively. For the POST application the estimated machinery cost was $6.97 ha^{-1} when applied using 140 L ha^{-1}. These costs do not include labor. Sprayer efficiency used in the machine calculator was calculated by dividing the net productivity by gross productivity and multiplying by 100. Net productivity and gross productivity were calculated using Sprayers101 Productivity Calculator (Wolf 2019). Herbicide prices for Callisto, Resicore, Status, AMS, and COC were based on the approximate cost published in the K-State Research and Extension 2022 chemical weed control guide with prices from November 1, 2021 (Lancaster et al. 2022). Prices for Aatrex 4L, Roundup Powermax, Roundup Powermax III, and TriVolt were obtained from Nutrien Ag Solutions in Clay Center, KS on November 10, 2022. Prices for Aatrex 4L, Callisto, Roundup Powermax, Roundup Powermax III, Resicore, TriVolt, Status, COC, and AMS were $5.81 L^{-1}, $82.84 L^{-1}, $11.37 L^{-1}, $12.71 L^{-1}, $19.43 L^{-1}, $69.88 L^{-1}, $144.62 kg^{-1}, $7.93 L^{-1}, and $3.05 L^{-1}, respectively.

Effective field capacity

Effective field capacity (EFC) was calculated using the Sprayers101 Productivity Calculator (Wolf 2019). Theoretical field capacity of a sprayer is the theoretical number of hectares a sprayer can cover within an hour without turns, loading, transport, or cleaning (Hancock et al. 1991; ASABE 2005,2006; Wolf Personal Communication). While EFC is the number of hectares a sprayer can cover within an hour while accounting for time lost due turning, transport, and cleaning (Hancock et al. 1991; ASABE 2005,2006; Wolf 2019). When calculating EFC more factors are considered, including spray volume, tank size, travel speed, field length, number of headlands, turning speed, and fill time (Wolf 2019). Nomenclature related to the calculation of EFC is in Table 3.4 and the formulas utilized to calculate EFC are in Table 3.5.

Data analysis

Weed control, weed biomass, and yield data were visually assessed for normality and heteroskedasticity using Shapiro-Wilk test in R package stats (R Core Team 2022) and Levene's test in R package car (Fox and Weisberg 2019). Data that did not fit ANOVA assumptions were transformed with a logarithmic transformation ($\log(x + 1)$). Data that did not fit the ANOVA assumptions are as follows: waterhemp biomass 8 WAT in Ottawa 2021; Palmer amaranth biomass and density at 8 WAT and at corn harvest in Manhattan 2022; waterhemp control 8 weeks after POST (WAPOST), waterhemp biomass at 8 WAT and at corn harvest, and fall panicum biomass and density at 8 WAT and corn harvest in Ottawa 2022; Palmer amaranth control 8 WAPOST, Palmer amaranth biomass at corn harvest, large crabgrass control prior to EPOST applications and 8 WAPRE, and large crabgrass biomass 8 WAT in Scandia 2022.

Data were subjected to analysis of variance (ANOVA) using base R (R Core Team, 2021). Replication was considered a random effect; application timing, residual herbicide tank mix, and spray volume were considered fixed effects. Site years were not compared or combined due to differences in herbicide treatments and weed species. Transformed data were back transformed after analysis ($e^x - 1$). Means were separated using Tukey's HSD Test ($\alpha = 0.05$) in R package agricolae version 1.3-5 (de Mendiburu, 2021).

3.4 Results and Discussion

Environmental conditions

In Ottawa 2021, 287 mm of rainfall was received after planting (Table 3.1). Total received rainfall in Ottawa 2021 (703 mm) was greater than the 30-year average (605 mm). In Colby (690 mm), Manhattan (622 mm), and Scandia (614 m) total rainfall or rainfall + irrigation was greater than the 30-year average (Colby = 391 mm; Manhattan = 608 mm; Scandia = 606 mm). Precipitation in Colby and Scandia was below the 30-year average. In Ottawa 2022, the total rainfall was 228 mm below the 30-year average (535 mm).

Palmer amaranth control

At Colby, no significant interactions or main effects were detected (Table 3.6). High levels of Palmer amaranth control were maintained throughout the corn growing season. Palmer amaranth control was 93, 94, 95, and 95% 4 WAT, 8 WAT, 12 WAT, and at harvest, respectively. Palmer amaranth biomass was 104 and 15 g m^{-2} 8 WAT and at harvest. Palmer amaranth density was 1.3 and 0.2 plants m^{-2} 8 WAT and at harvest. Bleaching of corn leaves ccurred at V2 due to TriVolt applications, but injury was not evaluated. Previous literature has reported corn injury as result of tank mixes of atrazine, flufenacet, and isoxaflutole and was increased under high pH and low organic matter soil conditions (Steckel et al. 2003). The soil pH was 7.1 and organic matter was 2.8% in Colby (Table 3.1). The high soil pH may explain the injury. However, injury did not cause yield loss.

In Manhattan, no significant interactions or main effects were detected prior to POST applications, but the main effects of herbicide and application timing were significant for Palmer amaranth control 8 WAPRE, 8 WAPOST, and at harvest (Table 3.7). In Manhattan, Palmer amaranth control was 100% prior to POST applications. In general, high levels of Palmer amaranth control were maintained throughout the growing season (CWSS 2018; Table 3.8). Applications of TriVolt resulted in 88% or greater Palmer amaranth control, regardless of the evaluation time and two-pass systems provided 89% or greater Palmer amaranth control, regardless of the evaluation time (Table 3.8). Although Resicore and PRE-only systems resulted in significantly less control, the differences were no more than 8% at any given evaluation timing. The differences observed in Palmer amaranth control, were confirmed by the differences observed in densities 8 WAT and biomass and densities at harvest. No significant interactions or main effect were detected for Palmer amaranth biomass 8 WAT, but the main effects of application timing, herbicide, and both application timing and herbicide were significant for density 8 WAT, biomass at harvest, and density at harvest, respectively (Table 3.7). Palmer amaranth biomass 8 WAT was 94 g m^{-2}. Eight WAT, PRE fb POST systems resulted in fewer Palmer amaranth than PRE-only treatments (Table 3.9). At harvest, TriVolt applications resulted in similar biomass to the weed-free check at harvest (Table 3.9). At harvest, PRE-only systems resulted in 9 plants m^{-2} and PRE fb POST systems resulted 4 plants m^{-2} (Table. 3.9). Applications of Resicore resulted in more Palmer amaranth plants m^{-2} at harvest than applications of TriVolt (Table 3.9). In general, the differences observed between treatments was minimal, especially regarding biomass. Biomass is critical to consider due to direct correlation between biomass and Palmer amaranth seed production (Norsworthy et al. 2016b). Keeley et al. (1987) reported cessation of Palmer amaranth seed production when individual Palmer amaranth plants weighed 1 g or less. Results in Manhattan indicate that these treatments maybe effective in reducing the replenishment of the weed seed bank, which is critical for the prevention of further development of herbicide-resistant weeds, as low weed populations play a significant role in the sustainability of weed management practices (Walsh et al. 2013).

In Scandia, no significant interactions or main effects were detected for Palmer amaranth control prior to POST applications, but the main effects of herbicide and application timing were significant 8 WAPRE, application timing was significant 8 WAPOST, and all main effects were significant at harvest (Table 3.10). Prior to POST applications, Palmer amaranth control was 86%. TriVolt applied in PRE-only systems resulted in 51% Palmer amaranth control 8 WAPRE as compared to PRE-only systems including Resicore and PRE fb POST systems including Resicore or TriVolt, which resulted in 77% or greater Palmer amaranth control (Table 3.11). At 8 WAPOST, PRE-only systems resulted in 59% Palmer amaranth control and PRE fb POST systems resulted in 95% Palmer amaranth control. Palmer amaranth control at harvest was 88% or greater in PRE-only systems including Resicore and PRE fb POST systems including Resicore or Trivolt, while PRE-only systems including TriVolt resulted in 74% Palmer amaranth control (Table 3.11). No significant effects were dected for biomass 8 WAT, but the main effect of application timing was significant for density 8 WAT and at harvest and the interaction of of herbicide and application timing was significant for biomass at harvest (Table 3.12). In general, Palmer amaranth biomass and density confirmed visual control estimates observed in PRE-only and PRE fb POST systems. Biomass and density were greater in PRE-only systems than PRE fb POST systems at 8 WAT and harvest (Table 3.13). However, different from the visual control estimates, applications of Resicore and TriVolt resulted in similar densities 8 WAT (Table 3.13).

In Colby and Manhattan, greater levels of Palmer amaranth control were maintained throughout the season, which may be attributed to the lack of weeds present at the time of application and adequate levels of rainfall and/or irrigation received prior to and following the residual herbicide applications. Greater differences in Palmer amaranth control were observed among treatments in Scandia, a no-till location with supplemental irrigation. These differences may be attributed to the presence of weeds at the time of application and the lower levels of rainfall received before and after application. In Scandia, only 42 mm of rainfall was received 14 days prior to application, no rainfall was received within 7 days after application, and 89 mm was received 7 to 28 days after application. Janak and Grichar (2016) reported high levels of Palmer amaranth control up to 109 days after planting with PRE applications of thiencarbazone-methyl + isoxaflutole or mesotrione + atrazine + *S*-metolachlor. However, PRE applications of isoxaflutole or mesotrione applied alone resulted in variable Palmer amaranth control, specifically when rainfall did not follow the PRE application in a timely manner. Previous literature has shown 91 to 100% Palmer amaranth control 8 WAT with PRE tank mixes of atrazine + flufenacet + isoxaflutole and 95 to 100% control with PRE tank mixes of *S*-metolachlor + flumetsulam + atrazine + clopyralid (Johnson et al. 2012). Poor redroot pigweed (*Amaranthus retroflexus* L.) control was observed with PRE applications containing atrazine, atrazine + isoxaflutole, or *S*-metolachlor when little to no rainfall was received 7 days before or after application (Stewart et al. 2010, 2012). Andr et al. (2014) observed less suppression of redroot pigweed seed production in years when rainfall was greater than average but observed the greatest seed suppression and greatest control with PRE applications of thiencarbazone-methyl + isoxaflutole.

In general, Palmer amaranth suppression in Manhattan and Scandia was greater in PRE fb POST systems than PRE-only systems at the time of corn harvest. Previous literature has also reported high levels of Palmer amaranth control at the end of the season when PRE fb POST systems were utilized (Norsworthy et al. 2016a; Kohrt and Sprague 2017; Chahal and Jhala 2018). Kohrt and Sprague (2017) reported season-long Palmer amaranth control in corn when using PRE fb POST systems, especially when using tank mixes with two or more effective herbicide groups. Chahal and Jhala (2018) reported 39 to 55% Palmer amaranth control 93 days after PRE application with PRE-only applications of atrazine + *S*-metolachlor + mesotrione, but Janak and Grichar (2016) reported 92 to 99% Palmer amaranth control up to 109 days after PRE-only applications of thiencarbazone-methyl + isoxaflutole and mesotrione + atrazine + *S*-metolachlor.

In Manhattan and Scandia, PRE-only systems generally resulted in greater weed biomass and density. At 8 WAT in Manhattan, PRE fb POST systems resulted in density levels similar to the weed-free check and low-density levels were maintained until corn harvest. In Scandia at 8 WAT, PRE fb POST systems resulted in density levels similar to the weed free check. At harvest, there were no differences among PRE-only systems, PRE fb POST systems, and the weed free check for both Palmer amaranth biomass and density. Previous research has also reported elevated and variable Palmer amaranth biomass and density levels in PRE-only systems (Norsworthy et al. 2016a; Kohrt and Sprague 2017; Chahal and Jhala 2018; Buol et al. 2021). In Manhattan, PRE applications of TriVolt resulted in minimal Palmer amaranth biomass and density at harvest. Chahal and Jhala (2018) reported 76 to 86% reduction of Palmer amaranth biomass and 48 to 76% Palmer amaranth density reduction with PRE applications of atrazine + *S*-metolachlor + mesotrione 21 DAT in a PRE fb POST system. Although treatments utilized in this trial resulted in low biomass and density levels, mature Palmer amaranth present at corn harvest will contribute to the weed seed bank. Depletion of the weed seed bank reduces the number of individuals that are exposed to weed control tactics and reduces the number of escapes that could contribute to the weed seed bank (Korres et al. 2018; Hare et al. 2020).

Waterhemp control

In Ottawa 2021, no significant interactions or main effects were detected for Palmer amaranth control prior to POST applications (Table 3.14). The ineraction of spray volume and herbicide was significant for Palmer amaranth control 8 WAPRE and at harvest, while the main effect of herbicide and application timing was significant 8 WAPOST (Table 3.14). Waterhemp control was 87% prior to POST. At 8 WAPRE Resicore applied at 56 L ha^{-1} resulted in 61% waterhemp control, while Resicore applied at 187 L ha^{-1} resulted in 93% waterhemp control and TriVolt applied at 56 L ha^{-1} resulted in 91% waterhemp control (Table 3.15). At 8 WAPOST, PRE-only applications of Resicore resulted in 65% waterhemp control and TriVolt resulted in 79% waterhemp control (Table 3.16). Preemergence only systems resulted in 64% waterhemp control and PRE fb POST systems resulted in 79% waterhemp control 8 WAPOST. At harvest, Resicore applied at 56 L ha^{-1} resulted in 48% waterhemp control, while Resicore applied at 187 L ha^{-1} resulted in 85% waterhemp control and TriVolt applied at 56 L ha^{-1} resulted in 84% waterhemp control (Table 3.15). The analysis of interactions of main effects revealed no significant effects for waterhemp biomass and density at 8 WAT and harvest (Table 3.17). Waterhemp biomass was 58 g m^{-2} at 8 WAT and 36 g m^{-2} at harvest. Waterhemp density was 15 plants m^{-2} at 8 WATand 6 plants m^{-2} at harvest.

In Ottawa 2022, No significant interactions were detected for Palmer amaranth control, but the main effect of herbicide was significant for Palmer amaranth controil prior to POST, 8 WAPRE and at harvest and application timing was significant for Palmer amaranth control 8 WAPRE, 8 WAPOST, and at harvest (Table 3.18). Prior to POST applications in Ottawa 2022, applications of Resicore resulted in greater waterhemp control than TriVolt (Table 3.19). Following the POST applications, Resicore continued to provide greater control 8 WAPRE and at harvest a compared to TriVolt (Table 3.19). Waterhemp control ranged from 87 to 90% in

PRE fb POST systems 8 WAPRE and at harvest, as compared to PRE-only systems which provided up to 73% control at harvest (Table 3.19). Two-pass systems and Resicore treatments were more likely to provide season-long waterhemp control. No significant interactions were detected for Palmer amaranth biomass and density at 8 WAT and at harvest, but application timing was significant for density 8 WAT, biomass at harvest, and density at harvest and herbicide for biomass and density at harvest (Table 3.20). Biomass and density levels were expected given increased levels of control with applications of Resicore and PRE fb POST systems. At 8 WAT, waterhemp biomass was 88 g m^{-2}. Waterhemp densities 8 WAT in the PRE fb POST systems were similar to the weed-free check and less than PRE-only systems (Table 3.21). At harvest, the least biomass was associated with applications of Resicore and in PRE fb POST systems (Table 3.24). In general, weed density confirmed visual weed control estimates apart from waterhemp density at harvest, which showed that as long as weed control measures were taken there were no differences among Resicore, TriVolt, and the weed-free check. The PRE fb POST systems resulted in fewer plants m^{-2} than PRE-only systems, which is reflected by the high levels of visual waterhemp control observed at harvest (Table 3.21).

Early season waterhemp control is critical to maximize corn yields, as season long waterhemp competition can decrease corn yields by up to 74% (Steckel and Sprague 2004). The present treatments provided up to 87% waterhemp control. Johnson et al. (2012) reported 99 to 100% waterhemp control 8 WAT with PRE tank mixes of atrazine + flufenacet + isoxaflutole and *S*-metolachlor + flumetsulam + atrazine + clopyralid. Benoit et al. (2019) reported 90% waterhemp control and biomass and density levels similar to the weed free check 8 WAT when atrazine + isoxaflutole was applied in PRE-only systems. When allowed to compete throughout the season, waterhemp biomass ranged from 430 to 1310 g m^{-2} and produced 3,000 to 16,000 seeds plant^{-1} (Steckel and Sprague 2004). Later emerging waterhemp were smaller and produced fewer seed and in some cases, when the corn canopy closed, waterhemp seed production was suppressed completely.

Ottawa in 2021 was the only location where spray volume was a significant treatment effect. All other locations confirmed findings of Striegel et al. (2021), who observed no effect of spray volume on residual herbicide efficacy and differences between herbicide treatments demonstrated that herbicide selection was of greater importance. The effect of spray volume in Ottawa 2021 may be attributed to the presence of weeds at planting due to the location being in a no-till system, in which case low spray volumes may negatively impact the efficacy of certain active ingredients in the premixes utilized in this trial. Changes in spray volumes were accompanied with changes in nozzles, pressure, and droplet size. In the case of Ottawa 2021, Resicore applied at 56 L ha^{-1} resulted in lower levels of waterhemp control. In 2021, this tank mix contained acetochlor, atrazine, clopyralid, glyphosate, mesotrione, AMS, and COC. Creech et al. (2015) reported the optimum spray volume for systemic herbicides to range between 70 and 94 L ha^{-1} and the optimum spray volume for contact herbicides to be 187 L ha^{-1} or greater, which may be a partial explanation for the differences in control. However, one would expect the same to be true for TriVolt as well. Another point of consideration could be the excessive levels of rainfall prior to the first application. Decreased residual activity of the acetochlor component of Resicore due to excessive rainfall paired with poor coverage as a result of decreased spray volume may explain the decreased control observed with applications of Resicore with 56 L ha^{-1}.

Fall panicum control

In Ottawa 2021, no significant interactions or main effects were detected for fall panicum control prior to the POST application, however, a significant interaction between spray volume and application timing was detected for fall panicum control 8 WAPRE and at harvest and the main effects of application time and herbicide were signciant 8 WAPOST (Table 3.14). Fall panicum control was 93% prior to POST applications. Preemergence only systems resulted in 77% fall panicum control and PRE fb POST systems resulted in 92% control 8 WAPRE (Table 3.22). Resicore applied in a PRE-only system resulted in 43% fall panicum control at 8 WAPOST and 31% control at harvest, while TriVolt applied in a PRE-only system and PRE fb POST systems resulted in 79% or greater control 8 WAPOST and at harvest (Table 3.22). No significant effects were detected for fall panicum biomass 8 WAT or density at harvest, while herbicide was significant for density 8 WAT and application timing was signficnat for biomass at harvest (Table 3.17). There were no treatment effects for fall panicum biomass 8 WAT (71 g m^{-2})or density at harvest (17 plants m^{-2}). Greater suppression of fall panicum was observed with applications of TriVolt and in PRE fb POST systems at 8 WAT and harvest, which corresponds to the visual control estimates observed. Resicore applied PRE resulted in 62 plants m^{-2} 8 WAT, while TriVolt applications resulted in 18 plants m^{-2} 8 WAT (Table 3.23). Densities reported for TriVolt applications, the weed free check, and the non-treated check were not different. For fall panicum density at harvest there were no significant treatment effects. Biomass at was 159 g m^{-2} harvest in PRE-only systems and 29 g m^{-2} in PRE fb POST systems, which was similar to the weed-free check (Table 3.23).

In Ottawa 2022, no significant interactiosn were detected for fall panicum control across all evaluation times, but the main effect of herbicide was significant for control prior to POST applications, 8 WAPRE, and at harvest and application timing was significant for 8 WAPRE, 8 WAPOST, and at harvest (Table 3.18). Fall panicum control was 90% prior to POST applications. In general, PRE-only systems resulted in significantly less fall panicum control than

PRE fb POST systems (Table 3.24). In PRE fb POST systems fall panicum control ranged from 96 to 97% and PRE-only systems resulted in 70 to 73% fall panicum control at 8 WAPRE , 8 WAPOST, and at harvest (Table 3.24). The visual control estimates coincide with the decreased biomass and density levels observed in PRE fb POST systems as compared PRE-only systems at 8 WAT and harvest, regardless of the residual herbicide applied PRE (Table 3.21). However, in PRE-only systems residual herbicide selection was more critical, as TriVolt provided the greatest fall panicum suppression when applied in a PRE-only system as compared to Resicore at 8 WAT and harvest (Table 3.21).

Previous research has reported variable control of Panicum spp. with tank mixes of flufenacet and isoxaflutole at similar rates to this study. Grichar et al. (2005) observed 64 to 99% Texas panicum (*Panicum texanum* Buckl.) control approximately 11 weeks after PRE applications of flufenacet + isoxaflutole applied at 350 + 70 g ai ha^{-1}. But the addition of 1,112 g ai ha^{-1} atrazine resulted in more consistent Texas panicum control with a range of 94 to 98%. Preemergence and POST applications of mesotrione have been shown not to adequately control fall panicum (Armel et al. 2003). Johnson et al. (1997) reported 51% fall panicum control 7 weeks after planting with PRE applications of glyphosate, atrazine, and metolachlor. However, the present trial demonstrated that more consistent control and suppression of fall panicum can be achieved with use of TriVolt in PRE-only systems and utilizing more than one herbicide application. Greater control with TriVolt may be attributed to the addition of thiencarbazone-methyl, which offers good control of annual grasses like fall panicum (Santel 2012; Lancaster and Norsworthy 2020).

Large crabgrass control

In Scandia, there was a significant effect of herbicide detected for large crabgrass control prior to POST applications, a significant interaction between herbicide and application timing was detected at 8 WAPRE, and the main effect of application timing was significant at 8 WAPOST and harvest. Prior to POST applications, TriVolt and Resicore applied PRE resulted in 93% and 72% large crabgrass control (Table 3.25). At 8 WAPRE, applications of Resicore in PRE-only systems resulted in 51% large crabgrass control, while in PRE-only systems with TriVolt or in PRE fb POST systems large crabgrass control was 85% or greater (Table. 3.26). Similar to fall panicum, two-pass systems provided season-long control of large crabgrass control. In PRE-only systems large crabgrass control was 71 to 74% at 8 WAPOST and harvest, while PRE fb POST systems resulted in 98% control at both evaluation times (Table 3.25). For large crabgrass biomass and density, the main effects of herbicide and application timing were significant for biomass and density 8 WAT and biomass at harvest and the main effect of application timing was significant for desnty at harvest (Table 3.20). For large crabgrass, two-pass systems were more effective at reducing large crabgrass biomass and densities than PRE-only systems at 8 WAT (Table 3.13). Residual herbicide also had a significant effect on large crabgrass biomass and density. However, there were no differences among Resicore, TriVolt, and the weed-free check for both large crabgrass biomass and density (Table 3.13). At harvest, there were no differences among herbicide systems and the weed-free check, but all resulted in less biomass and fewer plant m^{-2} than the non-treated check, which indicates that treatments utilized in the present trial may be effective options for season-long large crabgrass suppression (Table 3.13).

Multi-pass systems have previously been found to effectively control large crabgrass, especially when combinations of atrazine and *S*-metolachlor applied PRE (Whaley et al. 2006).

Previous literature has shown 97% large crabgrass control 8 WAT with PRE tank mixes of atrazine + flufenacet + isoxaflutole applied at 1,168 + 290 + 50 g ai ha^{-1} (Johnson et al. 2012).

Use of TriVolt in PRE-only systems resulted in greater fall panicum and large crabgrass control than applications of Resicore in PRE-only systems, but when a POST application was included, there were no differences in control. The likely reason for TriVolt applied in PRE-only systems providing greater levels of grass control is the thiencarbazone-methyl component of the premix. Thiencarbazone-methyl provides excellent control of already emerged grass seedlings and provides some residual efficacy as well, especially when tank mixed with isoxaflutole (Santel 2012; Lancaster and Norsworthy 2020).

Yield

Analysis of the interaction of main effects of residual herbicide, application timing, and spray volume revealed a significant interaction for corn yield among residual herbicide, application timing, and spray volume in Manhattan 2022 and a significant main effect for corn yield of residual herbicide in Ottawa 2022 (Table 3.27). The ANOVA did not revail significant effects on corn yield for Colby 2021, Ottawa 2021, and Scandia 2022 (Table 3.27). Corn yield was 12995, 9910, and 9755 kg ha^{-1} for Colby 2021, Ottawa 2021, and Scandia 2022, respectively. In Manhattan 2022, as long a weed control measure was utilized corn yield was greater than the nontreated check (Table 3.28). In Ottawa 2022, yield was greater in treatments where a weed control measure was utilized (Table 3.29). In both locations, there was no differences between the treatments and the weed free check. In locations where there were no treatment effects, total rainfall or rainfall + irrigation was greater than the 30-year average. In Ottawa 2022, the total rainfall was 228 mm below the 30-year average and rainfall received following tasseling was below average, which may have contributed to the increased yield loss observed. Locations where there was minimal to no yield loss, control of Palmer amaranth or waterhemp was 86% or greater prior to POST applications that occurred between 4 and 8 WAP. In Ottawa 2022, waterhemp control was as low as 68%. The combination of decreased control with drier conditions may explain increased yield loss observed in Ottawa 2022. Early season weed control is critical to minimize the risk of corn yield loss, as the critical period of weed control in corn is between corn growth stages V1 to V6 (Massinga et al. 2001; Steckel and Sprague 2004; Page et al. 2012).

Partial budget analysis

Partial budget analyses are helpful in determining the change in profit from adopting an alternative management strategy and can help improve growers' decision making (Horton 1982; North Dakota State University 2009). Table 3.30 presents the results from the partial budget analysis Ottawa 2021, Manhattan 2022, and Ottawa 2022 (rainfed locations) and Colby 2021 and Scandia 2022 (irrigated locations) using Resicore applied at 56 L ha^{-1} in a PRE-only system as the base line. This was selected as the baseline due to the lower application costs and effieciency associated with a PRE-only system and utilization of low spray volumes. Additionally, Resicore was a more established product at the time of analysis and was available at lower cost as compared to TriVolt (Corteva Agrisciences, Indianapolis, IN; Bayer Crop Science, St. Louis, MO). The greatest return for the rainfed locations was observed when TriVolt was applied at 187 L ha^{-1} in PRE-only systems (\$107 ha^{-1}). The PRE-only systems may be more profitable because there was not the added expense of an additional sprayer pass for the POST application and additional costs of POST herbicides (Chahal and Jhala 2018). However, PRE-only systems had reduced weed control at the rainfed locations when compared to PRE fb POST systems in the present study and in previous research (Parker et al. 2006; Evans et al. 2014; Crow et al. 2016;

Kohrt and Sprague 2017; Chahal et al. 2018; Chahal and Jhala 2018; Inman et al. 2020). Although there were no treatment effects for yield loss, the presence of weeds at the end of the season can result in the replenishment of the weed seed bank, which may result in additional costs for weed control in the following year (Norsworthy et al. 2014, 2016a, 2016b; Peterson 1999). At Ottawa 2021, TriVolt applied at 56 L ha^{-1} in PRE-only systems resulted in the greatest returns, which corresponds to weed control at time of corn harvest where TriVolt applied at 56 L ha^{-1} resulted in greater levels of weed control than Resicore applied at 56 L ha^{-1} (\$559 ha^{-1}; Table 3.30). Resicore applied at 122 L ha^{-1} in a PRE fb POST system resulted in the least return at Manhattan 2022 (-\$508 ha^{-1}), despite having lower machinery costs than applications applied at 187 L ha^{-1}. At Ottawa 2022, Resicore applied at 122 L ha^{-1} in PRE fb POST systems resulted in the greatest added income (\$1 ha^{-1}) as well as the greatest return (\$59 ha^{-1}). When location and spray volume were averaged together, the most profitable to least profitable combinations of application timing and herbicide was TriVolt in a PRE-only system, Resicore in a PRE-only system, Resicore in a PRE fb POST system, and TriVolt in PRE fb POST systems.

Returns at the irrigated locations were less than the rainfed systems. The irrigated locations were not averaged because Colby did not have a second application. In Colby 2021, Resicore applied at 122 L ha^{-1} resulted in the greatest added income (\$309 ha^{-1}), while Resicore applied at 187 L ha^{-1} had the greatest return (\$2 ha^{-1}). In Scandia 2022, Resicore applied at 187 L ha^{-1} in a PRE-only system resulted in the greatest added income (\$12 ha^{-1}) as well as the greatest return (\$10 ha^{-1}). All PRE fb POST systems in Scandia 2022 resulted in losses. The greatest loss was observed when TriVolt was applied at 122 L ha^{-1} in a PRE fb POST system (\$-74).

Effective field capacity

When different combinations of boom width, speed, spray volume, and tank size are considered, there is a wide range in effective field capacity values. The effective field capacity values are presented in Table 3.31. The greatest effective field capacity (45.7 ha hr^{-1}) was observed with a sprayer equipped with a 36 m boom and 4542 L tank traveling at 29 km hr^{-1} and using 56 L ha^{-1} spray volume. The least effective field capacity (9.4 ha hr^{-1}) was observed with a sprayer equipped with a 24 m boom and 1514 L tank traveling at 19 km hr^{-1} and using 187 L ha^{-1} spray volume. Generally, effective field capacity decreased as spray volume increased and as tank size, boom width, and speed decreased. When considering the data collected in this trial, effective field capacity may be increased by altering spray volume when applying residual herbicides without compromising weed control. However, the greatest effective field capacity values were generally observed when the sprayer was traveling at greater forward speeds, which can negatively affect herbicide applications and can result in greater levels of herbicide off target movement. Meyer et al. (2016) observed minimal differences in Palmer amaranth control with dicamba when POST applications were made at 5 km hr^{-1} as compared to 20 km hr^{-1}. Previous non-peer reviewed research has shown increased black grass control with flufenacet when applied 12 km hr^{-1} as compared to 16 km hr^{-1} (de la Pasture 2018). Increased forward speeds can result in boom instability and increased turbulence behind the boom due to distortion of the vertical air jet which results in the smaller spray particles escaping from the solution and moving downwind (Nuyttens et al. 2007). Taylor et al. (1989) observed a 90% increase in off-target movement when sprayer speeds increased from 7 to 10 km hr^{-1}. Miller and Smith (1997) observed a 144% increase in off target movement when speeds increased from 4 to 16 km hr^{-1}. Although increased forward speeds may result in increased effective field capacity, applicators should consider the risks of decreased weed control and increased off-target movement. Rather than increasing forward speed, applicators should consider altering spray volumes to try to meet their goals of increased effective field capacity as the present trial has illustrated that spray volume has minimal impact on weed control.

3.5 Conclusion

Generally, PRE fb POST systems resulted in greater levels of Amaranthus spp. and annual grass spp. control regardless of the residual herbicide applied PRE. In PRE fb POST systems weed control was 88% or greater at harvest across all locations. When considering tillage systems, TriVolt generally performed better in conventional tillage systems then no-tillage systems. TriVolt provided greater levels of annual grass suppression in PRE-only systems, but when PRE applications were followed with a POST application there were no differences. In general, spray volume had no impact on residual herbicide efficacy, except for the case of waterhemp control in Ottawa 2021 where Resicore applied with 56 L ha^{-1} resulted in poor waterhemp control. Spray volume having minimal impact on residual herbicide efficacy is beneficial for growers and applicators, as low spray volumes generally resulted in lower costs and greater effective field capacity. Increasing effective field capacity for residual herbicide applications is critical for growers and applicators as it allows for more timely applications as applicators will be able to cover more acres during busy periods, like corn planting, when the bulk of residual herbicides are applied. Differences in weed control among herbicide treatments demonstrate that herbicide selection should be of greater importance when considering techniques to optimize residual herbicide applications. Although high levels of weed suppression were maintained at harvest with PRE fb POST systems with the treatments used in this trial, mature weeds were still present at corn harvest and will contribute to the weed seed bank. When managing troublesome weeds, like Palmer amaranth or waterhemp, it is critical to implement an integrated weed management program that has a goal of 100% control and takes application parameters, herbicide selection, and multi-pass systems into consideration.

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Table 3.1. Planting, soil chatactersistics, irrigation, and precipitation information for corn studies conducted in 2021 and 2022 in Kansas.

	2021		2022		
Factors	Colby	Ottawa	Manhattan	Ottawa	Scandia
Planting date	5/13/21	5/4/21	4/27/22	6/15/22	5/15/22
Planting rate (seeds ha^{-1})	74,130	69,190	59,280	69,190	74,130
Tillage practice	Conventional	No-tillage	Conventional	No-tillage	No-tillage
PP[a] applied	–	4/21/21	–	6/13/22	–
PRE[a] applied	6/3/21	6/1/21	4/27/22	6/15/22	5/15/22
POST[a] applied	–	6/28/21	5/16/22	7/17/22	6/16/22
Corn harvest[b]	10/14/21	9/24/21	9/30/21	10/6/21	11/11/22
Soil type	Silt loam	Silt loam	Silt loam	Silt loam	Silt loam
Organic matter (%)	2.8	2.9	2.9	3.7	2.8
pH	7.1	5.5	6.6	5.6	6.1
Sand (%)	16	10	14	13	16
Silt (%)	0	67	64	65	65
Clay (%)	24	23	22	22	19
Irrigation	Yes	No	No	No	Yes
Number events	13	–	–	–	7
Total applied (mm)	375	–	–	–	222
Precipitation (mm)[c]					
30-year average	391	605	608	535	606
Total season	690	703	622	307	614
14 days before PRE	79	156	0.76	42	47
Up to 7 days after PRE	86	0	48	21	0

7 to 28 days after PRE	122	134	93	61	89

[a] PRE = Preemergence application; POST = Postemergence application

[b] Corn grain yields were estimated by harvesting the center two rows of each plot with a small plot combine. Grain yields were adjusted to a standard 15.5% moisture content.

[c] Moisture amounts are from 14 days prior to PRE application to corn harvest and include irrigation. Season rainfall values were retrieved from the Kansas Mesonet (Kansas State University 2022). Weather stations were located within 2,300 M of each trial location. The 30-year average values were retrieved from National Oceanic and Atmospheric Administration (National Climatic Data Center 2022) from the time of corn planting to corn harvest.

Table 3.2. Herbicide treatments applied in 2021 and 2022 in corn systems in Kansas.

Application timing[a]	Herbicide tank mix	Active ingredient	Rate
PP 2021	2,4-D LV6[c] + Roundup PowerMax[d]	2,4-D + glyphosate	317 g ae ha^{-1} + 1262 g ae ha^{-1}
PP 2022	Roundup PowerMax	Glyphosate	1262 g ae ha^{-1}
PRE 2021[b]	Resicore[e] + Aatrex 4L[f]	(acetochlor + clopyralid + mesotrione) + atrazine	(1962 g ai ha^{-1} + 133 g ae ha^{-1} + 210 g ai ha) + 1634 g ai ha^{-1}
PRE 2022[b]	Resicore + Aatrex 4L	(acetochlor + clopyralid + mesotrione) + atrazine	(1177 g ai ha^{-1} + 80 g ae ha^{-1} + 126 g ai ha^{-1}) + 1634 g ai ha^{-1}
PRE 2021 & 2022	TriVolt[d] + Aatrex 4L	(flufenacet + isoxaflutole + thiencarbazone-methyl) + atrazine	(375 g ai ha^{-1} + 75 g ai ha^{-1} + 30 g ai ha^{-1}) + 1634 g ai ha^{-1}
POST 2021	Status[g] + Roundup PowerMax	(dicamba + diflufenzopyr) + glyphosate	(280 g ae ha^{-1} + 112 g ae ha^{-1}) + 1262 g ae ha^{-1}
POST 2022	Status + Aatrex + Roundup PowerMax + Callisto[f]	(dicamba + diflufenzopyr) + atrazine + glyphosate + mesotrione	(140 g ae ha^{-1} + 56 g ai ha^{-1}) + 546 g ai ha^{-1} + 1262 g ae ha^{-1} + 105 g ai ha^{-1}

[a] PP = preplant; PRE = preemergence; POST = postemergence

[b] In 2021, 1262 g ae ha^{-1} glyphosate + 946 ml COC + 2.5% v/v AMS included in tank mix. In 2022, 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS included in tank mix at Scandia, KS and 946 ml COC at Ottawa, KS.

[c] Winfield Solutions, LLC, St. Paul, MN

[d] Bayer Crop Science, St. Louis, MO

[e] Corteva Agrisciences, Indianapolis, IN

[f] Syngenta, Greensboro, NC

[g] BASF, Research Triangle Park, NC

Table 3.3.Nozzle characteristics and spray pressure utilized for preemergence application spray volumes.

		Nozzle		
Spray volume ($L\ ha^{-1}$)	Pressure (kPa)	Type	Orifice size ($L\ min^{-1}$)	Spray angle
56	121	TT[a]	0.37	110
122	231	TT	0.57	110
187	317	TT	0.76	110

[a] TT = Turbo TeeJet; TeeJet Technologies, Wheaton, IL

Table 3.4. Nomenclature and values related to the calculation of effective field capacity of a self-propelled sprayer with example values. Table adapted from ASABE (2005,2006) and Wolf (2019).

Symbol	Definition of the variable	Units	Value(s)
W	Boom width	m	36
S	Field speed	m hr^{-1}	19.3
$\mathbf{S_t}$	Turn speed	m hr^{-1}	12.9
TFC	Theoretical Field Capacity	ha hr^{-1}	–
V	Spray volume	L ha^{-1}	56; 122; 187
$\mathbf{V_h}$	Volume hr^{-1}	L hr^{-1}	–
$\mathbf{L_f}$	Field length	m	805
H	Number headlands	–	2
$\mathbf{L_s}$	Swath length	m	–
$\mathbf{t_{pass}}$	Time $pass^{-1}$	s	–
$\boldsymbol{\pi}$	Pi	–	3.14
$\mathbf{d_t}$	Turn distance	m	–
$\boldsymbol{\hat{p}_{st}}$	Spray to turn proportion	–	–
$\mathbf{t_{turn}}$	Turn time	s	–
$\mathbf{t_{st}}$	Time spent turning	s	–
$\mathbf{t_{slt}}$	Time spent loading and transporting	min	–
$\mathbf{T_{cap}}$	Tank capacity	L	1,135.6
$\mathbf{T_{rem}}$	Tank remainder (5% of tank capacity)	L	56.8
$\mathbf{t_{empty}}$	Time to empty	min	–
$\mathbf{t_{ne}}$	Net time to empty	min	–
FCT	Field capacity counting turns	ha hr^{-1}	–
$\mathbf{t_{clean}}$	Total clean time	min	60
$\boldsymbol{\hat{p}_{ct}}$	Spray to cleaning and loading proportion	–	–
$\mathbf{t_{load}}$	Total time spent loading	min	15
EFC	Effective Field Capacity	ha hr^{-1}	–
$\mathbf{t_{tps}}$	Total time transporting	min	30
g	Loss to turns, loading, and cleaning	–	–

$\mathbf{t_{cper}}$	Cleaning time tank^{-1}	min	–
$\mathbf{t_{tper}}$	Transport time tank^{-1}	min	–
$\mathbf{T_{clean}}$	Clean every ‘x’ tanks	–	4
$\mathbf{T_{tps}}$	Transport every ‘x’ tanks	–	4

Table 3.5. Formulas related to the calculation of effective field capacity of a self-propelled sprayer. Table adapted from ASABE (2005, 2006) and Wolf (2019).

Step	Description	Equation
1	Theoretical Field Capacity (ha hr^{-1})	$\frac{W * (S * 1000)}{10000} = TFC$
2	Volume sprayed hr^{-1}	$V * p_g = V_h$
3	Swath length (m)	$L_f - (H * W * 2) = L_s$
4	Time $pass^{-1}$ (s)	$\frac{L_s}{S/3.6} = t_{pass}$
5	Turn distance (m)	$2 * (H - 1) * W + 0.5\pi W = d_t$
6	Time to turn (s)	$\frac{d_t}{S_t/3.6} = t_{turn}$
7	Spraying to turning proportion	$\frac{t_{pass}}{t_{pass} + t_{turn}} = \hat{p}_{st}$
8	Productivity counting turns	$p_g * \hat{p}_{st} = FCT$
9	Time to empty (min)	$\frac{T_{cap} - T_{rem}}{V_h * 60} = t_{empty}$
10	Net time to empty (min)	$\frac{t_{empty}}{\hat{p}_{st}} = t_{ne}$
11	Cleaning time $tank^{-1}$ (min)	$\frac{t_{clean}}{T_{clean}} = t_{cper}$
12	Transport time $tank^{-1}$ (min)	$\frac{t_{tps}}{T_{tps}} = t_{tper}$
13	Spraying to loading and transporting proportion	$\frac{t_{ne}}{t_{ne} + t_{load} + t_{cper} + t_{tper}} = \hat{p}_{ct}$
14	Effective field capacity (ha hr^{-1})	$p_t * \hat{p}_{ct} = EFC$

Table 3.6. Analysis of variance for Palmer amaranth control, biomass, and density in corn at Colby, KS in 2021.

Fixed effects	4 WAT[a]	8 WAT	12 WAT	Control at harvest[b]	Biomass 8 WAT	Density 8 WAT	Biomass at harvest	Density at harvest
	p-value[c]							
Spray volume	0.1931	0.9841	0.9998	0.4891	0.6382	0.5621	0.9474	0.5250
Herbicide	0.2136	0.2122	0.1625	0.1975	0.6649	0.8168	0.9223	0.6880
Spray Volume x Herbicide	0.1967	0.3157	0.2787	0.3198	0.8761	0.7142	0.7038	0.8498

[a] WAT = weeks after treatment

[b] Measurements were taken at corn harvest.

Table 3.7. Analysis of variance for Palmer amaranth control in corn at Manhattan, KS in 2022 as influenced by spray volume, herbicide, and application timing and their interactions.

Fixed effects	Control prior to POST[a]	8 WAPRE[b]	8 WAPOST[b]	Control at harvest[c]	Biomass 8 WAT[d]	Density 8 WAT	Biomass at harvest	Density at harvest
				p-value[e]				
Spray volume	1.0000	0.3625	0.2794	0.5467	1.0000	0.8953	0.5083	0.1977
Herbicide	1.0000	0.0132	0.0035	0.0026	0.9811	0.0824	0.001	0.0002
Application timing	–	<0.0001	0.0007	0.0059	0.9985	0.0069	0.1331	0.0111
Spray Volume x Herbicide	1.0000	0.8568	0.4162	0.4876	0.9999	0.6252	0.4517	0.0509
Spray volume x Application timing	–	0.0888	0.3285	0.5598	1.0000	0.9782	0.5537	0.5048
Herbicide x Application timing	–	0.8813	0.8972	0.7274	0.9922	0.4301	0.1481	0.9993
Spray volume x Herbicide x Application timing	–	0.1872	0.6832	0.6063	0.999	0.6231	0.6416	0.1891

[a] Control prior to POST application = 2 weeks after planting

[b] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[c] Measurements were taken at corn harvest.

[d] WAT = weeks after treatment

Table 3.8. Palmer amaranth control as influenced by application timing in corn at Manhattan, KS in 2022 at 8 WAPRE, 8 WAPOST, and corn harvest.[a]

Treatment	8 WAPRE	8 WAPOST	Harvest[b]
	Palmer amaranth control (%)		
Residual herbicide[c]			
Resicore	85 b[d]	83 b	92 b
TriVolt	89 a	88 a	95 a
Application timing[e]			
PRE[a]	83 b	83 b	92 b
PRE fb POST[a]	91 b	89 a	95 a

[a] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[b] Measurements were taken at corn harvest.

[c]Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] Means within a column of a treatment and evaluation timing followed by the same letter are not significantly different and means were separated using Tukey’s HSD tests (α = 0.05).

[e] PRE = preemergence; fb followed by; POST = postemergence

Table 3.9. Palmer amaranth biomass and density 8 WAT and at corn harvest in corn at Manhattan, KS in 2022 as influenced by application timing and residual herbicide.

Treatment	8 WAT[a]		Harvest[c]	
	Biomass	Density	Biomass	Density
	g m^{-2}	plants m^{-2}	g m^{-2}	plants m^{-2}
Application timing[b]				
PRE	–	28 b[d]	–	9 b
PRE fb POST	–	8 c	–	4 c
Non-treated Check	–	238 a	–	74 a
Weed Free	–	0 c	–	0 d
Herbicide				
Resicore[e]	–	–	4 b	9 b
TriVolt[e]	–	–	2 c	4 c
Non-treated Check	–	–	469 a	74 a
Weed Free	–	–	0 c	0 d

[a] WAT = weeks after treatment

[b] PRE = preemergence; fb followed by; POST = postemergence

[c] Measurements were taken at corn harvest.

[d] Means within a column of a treatment and evaluation timing, followed by the same letter are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

[e] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

Table 3.10. Analysis of variance for Palmer amaranth and large crabgrass control in corn at Scandia, KS in 2022 as influenced by spray volume, herbicide, and application timing and their interactions.

	Palmer amaranth				Large crabgrass			
Fixed effects	Control prior to POST[a]	8 WAPRE[b]	8 WAPOST[b]	Harvest[c]	Control prior to POST	8 WAPRE	8 WAPOST	Harvest
	p-value[d]							
Spray volume	0.1514	0.0993	0.7895	0.0121	0.3465	0.1518	0.3218	0.2662
Herbicide	0.7824	0.03749	0.4585	0.0373	0.0471	0.0034	0.1321	0.0728
Application timing	–	<0.0001	0.0089	<0.0001	–	<0.0001	0.0003	0.0001
Spray Volume x Herbicide	0.6549	0.4492	0.3848	0.6764	0.2748	0.2329	0.8592	0.9639
Spray volume x Application timing	–	0.2281	0.9200	0.1016	–	0.1071	0.2555	0.3822
Herbicide x Application timing	–	0.0342	0.4035	0.0243	–	0.0069	0.1953	0.1359
Spray volume x Herbicide x Application timing	–	0.4254	0.3798	0.5144	–	0.5624	0.8935	0.9297

[a] Control prior to POST application = 4 weeks after planting

[b] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[c] Measurements were taken at corn harvest.

Table 3.11. Palmer amaranth control as influenced by residual herbicide applied PRE in PRE-only and PRE fb POST systems in corn at Scandia, KS in 2022 at 8 WAPRE, 8 WAPOST, and corn harvest.[a]

Application timing[b]	8 WAPRE Residual herbicide		8 WAPOST	Harvest[e] Residual herbicide	
	Resicore[c]	TriVolt[d]		Resicore	TriVolt
			Palmer amaranth control (%)		
PRE	77 a[d]	50 b	59 b	88 a	74 b
PRE fb POST	92 a	91 a	95 a	96 a	97 a

[a] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[b] PRE = preemergence; fb followed by; POST = postemergence

[c] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] Means within an evaluation time, followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

[e] Measurements were taken at corn harvest.

Table 3.12. Analysis of variance for Palmer amaranth and large crabgrass biomass and density in corn in Scandia, KS in 2022 as influenced by spray volume, herbicide, and application timing and their interactions.

	Palmer amaranth				Large crabgrass			
	8 WAT[a]		Harvest[b]		8 WAT		Harvest	
Fixed effects	Biomass	Density	Biomass	Density	Biomass	Density	Biomass	Density
	p-value[c]							
Spray volume	1.0000	0.8274	0.1847	0.4871	0.9809	0.8726	0.4301	0.2647
Herbicide	0.9982	0.071	0.1832	0.7337	0.0362	0.0471	0.0712	0.8336
Application timing	0.9840	<0.0001	0.0021	0.0281	0.0002	0.0006	0.0269	0.0047
Spray Volume x Herbicide	0.9947	0.3143	0.2294	0.3699	0.5304	0.3529	0.5326	0.8477
Spray volume x Application timing	0.9995	0.8583	0.409	0.8731	0.5934	0.8717	0.4355	0.5498
Herbicide x Application timing	0.9801	0.1726	0.0123	0.1269	0.5574	0.8248	0.7977	0.8719
Spray volume x Herbicide x Application timing	0.9999	0.2692	0.8275	0.6044	0.2931	0.6378	0.5609	0.8755

[a] WAT = weeks after treatment

[b] Measurements were taken at corn harvest.

Table 3.13. Palmer amaranth and large crabgrass biomass and density 8 WAT and at corn harvest in corn at Scandia, KS in 2022 as influenced by treatment.[a]

	Palmer amaranth				Large crabgrass			
	8 WAT[a]		Harvest[b]		8 WAT		Harvest	
Treatment	Biomass	Density	Biomass	Density	Biomass	Density	Biomass	Density
	g m^{-2}	plants m^{-2}	g m^{-2}	plants m^{-2}	g m^{-2}	plants m^{-2}	g m^{-2}	plants m^{-2}
Application timing[c]								
PRE	–	11 b[d]	37 b[†]	3 b	8 b[c]	6 b	37 b	3 b
PRE fb POST	–	1 c	1 c	1 b	1 c	1 c	1 b	1 b
Non-treated Check	–	20 a	252 a	7 a	102 a	64 a	252 a	7a
Weed Free	–	0 c	0 c	0 b	0 c	0 c	0 b	0 b
Herbicide[e]								
Resicore	–	7 b	–	–	5 b	4 b	–	–
TriVolt	–	4 b	–	–	1 b	1 b	–	–
Non-treated Check	–	20 a	–	–	102 a	64 a	–	–
Weed Free	–	0 b	–	–	0 b	0 b	–	–

[a] WAT = weeks after treatment

[b] Measurements were taken at corn harvest.

[c] PRE = preemergence; fb followed by; POST = postemergence

[d] Means within a column of a treatment within evaluation time, followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

[e] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

Table 3.14. Analysis of variance for waterhemp and fall panicum control in corn at Ottawa, KS in 2021.

	Waterhemp				Fall panicum			
Fixed effects	Control prior to POST[a]	8 WAPRE[b]	8 WAPOST[b]	Harvest[c]	Control prior to POST	8 WAPRE	8 WAPOST	Harvest
	p-value[c]							
Spray volume	0.4735	0.1147	0.2302	0.1537	0.5791	0.1904	0.0544	0.6273
Herbicide	0.2159	0.1663	0.0484	0.6843	0.1196	0.0530	0.0036	0.0007
Application timing	–	0.0059	0.0407	0.0020	–	0.0043	0.0019	0.0005
Spray Volume x Herbicide	0.1760	0.0103	0.0523	0.0015	0.6171	0.1979	0.4325	0.5798
Spray volume x Application timing	–	0.2969	0.6772	0.7879	–	0.2957	0.5875	0.7577
Herbicide x Application timing	–	0.1423	0.1701	0.6442	–	0.1466	0.0308	0.0086
Spray volume x Herbicide x Application timing	–	0.0859	0.2912	0.0613	–	0.3669	0.8111	0.8352

[a] Control prior to POST application = 8 weeks after planting

[b] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[c] Measurements were taken at corn harvest.

Table 3.15**. Waterhemp control 8 WAPRE and at corn harvest as influenced by residual herbicide applied tank mix applied PRE at various spray volumes in corn at Ottawa, KS in 2021.[a]**

	8 WAPRE[a]		Harvest[b]	
	Residual herbicide[c]			
Spray volume ($L\ ha^{-1}$)	Resicore	TriVolt	Resicore	TriVolt
	Waterhemp control (%)			
56	48 b[d]	85 a	61 b	91 a
122	74 ab	56 ab	83 ab	82 ab
187	84 a	73 ab	93 a	85 ab

[a] WAPRE = weeks after preemergence application; PRE = preemergence application

[b] Measurements were taken at corn harvest.

[c] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] Means within an evaluation time, followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 3.16. Waterhemp control 8 WAPOST as influenced by application timing or residual herbicide tank mix applied PRE in corn at Ottawa, KS in 2021.[a]

Treatment			
Application timing[b]		Residual herbicide[c]	
PRE	PRE fb POST[a]	Resicore	TriVolt
Waterhemp control (%)			
65 b[d]	79 a	65 b	79 a

[a] WAPOST = weeks after postemergence application

[b] PRE = preemergence; fb = followed by; POST = postemergence

[c] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] Means within treatment, followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 3.17. Analysis of variance for waterhemp and fall panicum biomass and density in corn at Ottawa, KS in 2021 as influenced by spray volume, herbicide, and application timing and their interactions.

	Waterhemp				Fall panicum			
	8 WAT[a]		Harvest[b]		8 WAT		Harvest	
Fixed effects	Biomass	Density	Biomass	Density	Biomass	Density	Biomass	Density
	p-value[c]							
Spray volume	0.5955	0.1969	0.8971	0.3638	0.7541	0.8914	0.8645	0.6565
Herbicide	0.6281	0.1557	0.4695	0.8453	0.5026	0.0158	0.1123	0.8330
Application timing	0.5671	0.1069	0.1832	0.5943	0.8092	0.1004	0.0135	0.1226
Spray Volume x Herbicide	0.1418	0.0532	0.6415	0.4266	0.9106	0.5876	0.6951	0.8769
Spray volume x Application timing	0.5648	0.1771	0.3741	0.6292	0.7558	0.2275	0.9822	0.5006
Herbicide x Application timing	0.7923	0.1246	0.5066	0.9909	0.8186	0.2173	0.3379	0.2926
Spray volume x Herbicide x Application timing	0.7997	0.1962	0.4692	0.7530	0.9780	0.3070	0.8886	0.5652

[a] WAT = weeks after treatment

[b] Measurements were taken at corn harvest.

Table 3.18. Analysis of variance for waterhemp and fall panicum control in corn at Ottawa, KS in 2022.

	Waterhemp				Fall panicum			
Fixed effects	Control prior to POST[a]	8 WAPRE[b]	8 WAPOST[b]	Harvest[c]	Control prior to POST	8 WAPRE	8 WAPOST	Harvest
	p-value[c]							
Spray volume	0.6067	0.4728	0.2079	0.9492	0.8423	0.5747	0.9475	0.6111
Herbicide	0.0006	0.0079	0.5291	0.0102	0.2303	0.1502	0.0545	0.2194
Application timing	–	0.0002	0.0078	0.0014	–	<0.0001	0.0023	0.0006
Spray Volume x Herbicide	0.7414	0.8922	0.6405	0.7062	0.6407	0.4593	0.9861	0.9166
Spray volume x Application timing	–	0.2699	0.1975	0.5723	–	0.7436	0.9491	0.5598
Herbicide x Application timing	–	0.2269	0.7964	0.1932	–	0.1948	0.0582	0.2358
Spray volume x Herbicide x Application timing	–	0.8549	0.5389	0.9568	–	0.5537	0.9618	0.9187

[a] Control prior to POST application = 4 weeks after planting

[b] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[c] Measurements were taken at corn harvest.

Table 3.19. Waterhemp control prior to POST applications, 8 WAPRE, 8 WAPOST, and at corn harvest as influenced by treatment in corn at Ottawa, KS in 2022.[a]

Treatment	Prior to POST	8 WAPRE	8 WAPOST	Harvest[b]
Residual herbicide[c]	Waterhemp control (%)			
Resicore	82 b[d]	83 a	–	88 a
TriVolt	93 a	66 b	–	74 b
Application timing[e]				
PRE	–	63 b	63 b	73 b
PRE fb POST	–	87 a	88 a	90 a

[a] Prior to POST = 4 weeks after planting; WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[b] Measurements taken at corn harvest.

[c] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] Means within a column of a treatment within evaluation timing followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

[e] PRE = preemergence; fb = followed by; POST = postemergence

Table 3.20. Analysis of variance for waterhemp and fall panicum biomass and density in corn at Ottawa, KS in 2022 as influenced by spray volume, herbicide, and application timing and their interactions.

Fixed effects	Waterhemp				Fall panicum			
	8 WAT[a]		Harvest[b]		8 WAT		Harvest	
	Biomass	Density	Biomass	Density	Biomass	Density	Biomass	Density
	p-value[c]							
Spray volume	0.4759	0.4007	0.4456	0.1441	0.686	0.0814	0.7092	0.2573
Herbicide	0.3066	0.2947	0.0012	0.0483	0.1712	0.0229	0.232	0.3727
Application timing	0.0338	0.0003	0.0006	0.0007	0.0053	<0.0001	<0.0001	<0.0001
Spray Volume x Herbicide	0.6614	0.8061	0.6216	0.0758	0.4385	0.0659	0.2758	0.2211
Spray volume x Application timing	0.5482	0.5357	0.7219	0.1217	0.6783	0.1109	0.7448	0.3805
Herbicide x Application timing	0.8498	0.7821	0.0716	0.3305	0.1685	0.0283	0.0458	0.4570
Spray volume x Herbicide x Application timing	0.6461	0.8583	0.0689	0.3586	0.5281	0.4149	0.3773	0.3923

[a] WAT = weeks after treatment

[b] Measurements were taken at corn harvest.

Table 3.21. Waterhemp and fall panicum biomass and density at 8 WAT and corn harvest in corn at Ottawa, KS in 2022 as influenced by treatment.[a]

	Waterhemp				Fall panicum			
	8 WAT[a]		Harvest[b]		8 WAT		Harvest	
Treatment	Biomass g m^{-2}	Density plants m^{-2}	Biomass g m^{-2}	Density plants m^{-2}	Biomass g m^{-2}	Density plants m^{-2}	Biomass g m^{-2}	Density plants m^{-2}
Application timing[c]								
PRE[a]	–	29 b[d]	20 b[†]	29 b	7 b[c]	–	–	42 a
PRE fb POST[a]	–	7 c	5 c	7 c	0 c	–	–	5 b
Non-treated Check	–	58 a	313 a	58 a	21 a	–	–	30 ab
Weed Free	–	0 c	0 c	0 c	0 c	–	–	0 b
Herbicide[e]								
Resicore	–	–	5 c[†]	4 b	–	–	–	–
TriVolt	–	–	21 b	8 b	–	–	–	–
Non-treated Check	–	–	313 a	26 a	–	–	–	–
Weed Free	–	–	0 c	0 b	–	–	–	–

[a]WAT = weeks after treatment

[b] Measurements taken at corn harvest.

[c]PRE = preemergence; fb followed by; POST = postemergence

[d]Means within a column of a treatment within evaluation timing, followed by the same letter are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

[e] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

Table 3.22. Fall panicum control 8 WAPRE as by application timing and 8 WAPOST and at corn harvest influenced by application timing and residual herbicide in corn at Ottawa, KS in 2021.[a]

Application timing[d]	8 WAPRE	8 WAPOST		Harvest[b]	
		Residual herbicide[c]			
		Resicore	TriVolt	Resicore	TriVolt
		Fall panicum control (%)			
PRE	70 b[e]	43 b	79 a	31 b	79 a
PRE fb POST	96 a	81 a	87 a	81 a	88 a

[a] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[b] Measurements were taken at corn harvest.

[c] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] PRE = preemergence; fb followed by; POST = postemergence

[e] Means within an evaluation timing followed by the same letter are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

Table 3.23. Fall panicum density at 8 WAT and corn harvest in corn at Ottawa, KS in 2021 as influenced by treatment.[a]

	8 WAT[a]	Harvest[b]
Treatment	Density	Biomass
	plants m^{-2}	g m^{-2}
Application timing[c]		
PRE[a]	–	159 b[c]
PRE fb POST[s]	–	29 c
Non-treated Check	–	462 a
Weed Free	–	0 c
Herbicide[d]		
Resicore	62 a	–
TriVolt	18 b	–
Non-treated Check	26 ab	–
Weed Free	0 b	–

[a] WAT = weeks after treatment

[b] Measurements taken at corn harvest.

[c] PRE = preemergence; fb followed by; POST = postemergence

[d] Means within a column of a treatment within evaluation timing followed by the same letter are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

[d]Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

Table 3.24. Fall panicum control 8 WAPRE, 8 WAPOST, and at corn harvest as influenced by application timing in corn at Ottawa, KS in 2022.[a]

Application timing[b]	8 WAPRE	8 WAPOST	Harvest[c]
	Fall panicum control (%)		
PRE	70 b[d]	72 a	73 b
PRE fb POST	96 a	96 a	93 a

[a] WAPRE = weeks after preemergence application; WAPOST = weeks after postemergence application

[b] PRE = preemergence; fb followed by; POST = postemergence

[c] Measurements were taken at corn harvest.

[d] Means within a column followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 3.25. Large crabgrass control at prior to post, 8 WAPOST, and at corn harvest as influenced by treatment in corn at Scandia, KS in 2022.[a]

Treatment	Prior to POST	8 WAPOST	Harvest[b]
Residual herbicide[c]	Large crabgrass control (%)		
Resicore	72 b[d]	–	–
TriVolt	92 a	–	–
Application timing[e]			
PRE	–	71 b	74 b
PRE fb POST	–	98 a	98 a

[a] Prior to POST = 4 weeks after planting; WAPOST = weeks after postemergence application

[b] Measurements were taken at corn harvest.

[c] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[d] Means within a column of a treatment within evaluation timing followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

[e] PRE = preemergence; fb followed by; POST = postemergence

Table 3.26. Large crabgrass control 8 WAPRE as influenced by residual herbicide tank mix applied PRE and by application timing in corn at Scandia, KS in 2022.[a]

Application timing[c]	Residual herbicide[b]	
	Resicore	TriVolt
	Large crabgrass control (%)	
PRE	51 b[d]	85 a
PRE fb POST	96 a	97 a

[a] WAPRE = weeks after preemergence application

[b] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[c] PRE = preemergence; fb followed by; POST = postemergence

[d] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 3.27. Analysis of variance for corn yield for Colby and Ottawa, KS in 2021 and in Manhattan, Scandia, and Ottawa, KS in 2022 as influenced by spray volume, herbicide, and application timing, and their interactions.

Fixed effects	Colby	Ottawa 2021	Manhattan 2022	Ottawa 2022	Scandia 2022
			p-value[a]		
Spray volume	0.9729	0.9729	0.1580	0.6822	0.8468
Herbicide	0.6041	0.8622	0.2380	0.0471	0.9026
Application timing		0.7837	0.6208	0.6609	0.7740
Spray Volume x Herbicide	0.5871	0.758	0.8682	0.5733	0.9358
Spray volume x Application timing		0.6146	0.0606	0.2636	0.5785
Herbicide x Application timing		0.3702	0.2420	0.7588	0.6251
Spray volume x Herbicide x Application timing		0.5305	0.0297	0.8215	0.389

Table 3.28. Corn yield as influenced by application timing, spray volume, and residual herbicide applied PRE in Manhattan, KS in 2022.

Application timing[a]	Residual herbicide[b]	Spray volume (L ha^{-1}) 56	122	187
			kg ha^{-1}	
PRE only	Resicore	9888.5 a[c]	11122.6 a	9167.4 a
	TriVolt	9636.3 a	9931.4 a	10622.0 a
PRE fb POST	Resicore	8993.5 a	8388.7 a	10977.2 a
	TriVolt	9621.0 a	10477.1 a	10834.7 a
Weed Free Check			9598.3 a	
Nontreated Check			1993.8 b	

[a] PRE = preemergence; fb followed by; POST = postemergence

[b] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[c] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 3.29. Corn yield as influenced by residual herbicide applied PRE in Ottawa, KS in 2022.[a]

Residual herbicide[b]	Yield
	kg ha^{-1}
Resicore	6343.2 a[c]
TriVolt	5578.2 a
Weed Free Check	6627.0 a
Nontreated Check	3542.9 b

[a] PRE = preemergence

[b] Resicore tank mix = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine + 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS

[c] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 3.30. Partial budget comparing spray volume, application timing, and residual herbicide in corn systems in Kansas.

System[a]	Spray volume (L ha^{-1})	Herbicide[b]	Ottawa 2021			Manahttan 2022			Ottawa 2022			Rainfed Average[d]	Colby 2021			Scandia 2022		
			Added income	Added expense	Net change[c]	Added income	Added expense	Net change	Added income	Added expense	Net change	Net change	Added income	Added expense	Net change	Added income	Added expense	Net change
			$ ha^{-1}															
PRE only	56	TriVolt	547	-12	559	-76	3	-79	-235	3	-238	80	119	104	-15	-10	3	-13
	122	Resicore	184	1	183	370	1	369	-315	1	-316	79	251	252	1	-6	1	-7
		TriVolt	112	-10	122	13	4	9	-563	5	-568	-146	-76	-89	-14	7	5	2
	187	Resicore	246	1	245	-216	2	-218	-179	2	-182	-52	122	124	2	12	2	10
		TriVolt	410	-9	419	220	5	215	-307	6	-312	107	95	82	-13	-7	6	-13
PRE fb POST	56	Resicore	459	59	400	-268	57	-325	-146	57	-203	-43	–	–	–	2	57	-55
		TriVolt	33	48	-15	-80	60	-140	-481	60	-541	-232	–	–	–	15	60	-46
	122	Resicore	592	60	533	-450	58	-508	59	58	1	9	–	–	–	0	58	-58

	TriVolt	350	49	302	177	61	115	-423	61	-485	-23	–	–	–	-13	61	-74
187	Resicore	77	60	17	327	59	268	-158	59	-217	22	–	–	–	-1	59	-60
	TriVolt	313	50	263	284	62	222	-169	63	-232	84	–	–	–	6	63	-56

[a] PRE = preemergence; fb followed by; POST = postemergence

[b] Resicore tank mix 2021 = 1962 g ai ha^{-1} acetochlor + 133 g ae ha^{-1} clopyralid + 210 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine Resicore tank mix 2022 = 1177 g ai ha^{-1} acetochlor + 80 g ae ha^{-1} clopyralid + 126 g ai ha^{-1} mesotrione + 1634 g ai ha^{-1} atrazine; TriVolt tank mix = 375 g ai ha^{-1} flufenacet + 75 g ai ha^{-1} isoxaflutole + 30 g ai ha^{-1} thiencarbazone-methyl + 1634 g ai ha^{-1} atrazine. In Ottawa 2021, Ottawa 2022, and Scandia 2022 the tank mix also included 1262 g ae ha^{-1} glyphosate + 2337 ml COC + 2.5% v/v AMS.

[c] Net change was calculated by subtracting the net income of Resicore applied at 56 L ha^{-1} in a PRE-only system from the net income of target treatment.

[d] The net change was averaged across the rain fed locations (Ottawa, KS in 2021 and 2022 and Manhattan, KS in 2022). The net change was not averaged across the irrigated locations (Colby, KS in 2021 and Scandia, KS in 2022) due to the absence of the POST application in Colby, KS in 2021.

Table 3.31. Effective field capacity comparing the spray volumes in this trial when utilized in combination with varying boom widths, tank sizes, and forward speeds.

		Spray volume (L ha^{-1})								
		56			122			187		
		Forward speed (km hr^{-1})								
Boom width (m)	Tank size (L)	19	24	29	19	24	29	19	24	29
		Effective field capacity (ha hr^{-1})								
24	1514	20.2	22.1	23.6	12.8	13.5	14.1	9.4	9.8	10.1
	2839	27.9	31.2	33.8	19.6	21.1	22.3	15.1	16	16.7
	3028	28.5	32	34.8	20.3	21.9	23.2	15.7	21.9	17.5
	3407	29.7	33.4	36.5	21.5	23.4	24.9	17	18.1	19
27	4542	32.3	36.8	40.5	24.7	27.2	29.2	20	21.7	22.9
	2839	31.5	34.8	37.4	21.2	22.7	23.8	16.1	16.9	17.5
	3028	32.3	35.8	38.5	22.1	23.7	24.8	16.8	17.7	18.4
	3407	33.7	37.6	40.7	23.6	25.4	26.8	18.2	19.3	20
36	4542	37.1	41.9	45.7	27.4	29.9	31.8	21.8	23.3	24.5

Chapter 4 - Palmer amaranth (*Amaranthus palmeri*) in Kansas Cotton (*Gossypium hirsutum)*

4.1 Abstract

Multiple applications of residual herbicides offer overlapping weed control, which is critical for control of weeds with extended windows of emergence, like Palmer amaranth (*Amaranthus palmeri* S. Watson). Field experiments were established in 2021 and 2022 to compare weed control with residual herbicides applied preemergence (PRE) or postemergence (POST) in Enlist (2,4-D-resistant) and XtendFlex (dicamba-resistant) cotton systems in Kansas. Applications included PRE followed by (fb) early POST (EPOST) fb late POST (LPOST) in 2021 and PRE fb EPOST in 2022. In 2021, pendimethalin was applied as a blanket PRE. The EPOST application in 2021 included acetochlor, dimethenamid-P, or *S*-metolachlor + 2,4-D or dicamba or the trait premix, which was glyphosate + 2,4-D or dicamba + *S*-metolachlor, applied alone. In 2021, the LPOST included glyphosate + 2,4-D or dicamba. In 2022, PRE herbicides were fluometuron or fluometuron + acetochlor, dimethenamid-P, *S*-metolachlor, or pendimethalin fb EPOST including glyphosate + trait herbicide or in combination with residual herbicides. The dominant weed species was Palmer amaranth. At LPOST in 2021, applications of dimethenamid-P provided greater control in XtendFlex than Enlist systems. At EPOST in 2022, fluometuron with dimethenamid-P or *S*-metolachlor provided the greatest control. In 2021, there were no differences in end of season Palmer amaranth control (48 to 71%) observed among residual herbicides as long more than one herbicide application was utilized. In 2022, Enlist systems provided less control than XtendFlex systems. Generally, the greatest control was observed when two applications of residual herbicides were utilizes as compared to no over lapping residual apart from two applications of pendimethalin. Results indicate cotton herbicide

trait system influences Palmer amaranth control; but, residual herbicide selection, multiple applications, and layered residual herbicides may be of greater importance.

4.2 Introduction

Cotton has been produced in Kansas for well over 100 years, but it did not gain popularity until cotton benefits were included in the 1995 farm bill (Thompson 2007). Cotton production has increased drastically in Kansas as an alternative crop that can aid in water conservation efforts and give producers an alternative income option (Bertone 2020; Baumhardt et al. 2021). In 2022, approximately 53,000 ha of cotton were planted, which was an 18.2% increase from 2021 (USDA National Agricultural Statistics Service 2022). Historically, cotton production in Kansas has been limited due to the inability to accumulate enough heat units for previously available cotton varieties, but with the commercialization of early maturing and cool temperature tolerant varieties, cotton production has increased dramatically (Duncan et al. 1993; Tolk and Howell 2010; Byrd and Wilson 2021). Cotton is more tolerant to changes in soil moisture content than corn, so it may be more adaptable to the arid regions of Kansas (Ackerson and Krieg 1977). Cotton is a viable crop option for portions of southern Kansas where supplemental irrigation can be applied due to its increased water use efficiency compared to corn, which may also allow for reduced withdrawals from the Ogalala aquifer (Esparza et al. 2007). Integrating cotton into Kansas cropping systems can help diversify herbicide programs in Kansas and aid in the prevention of further development of herbicide-resistant populations.

Palmer amaranth (*Amaranthus palmeri* S. Watts) was considered the most troublesome weed in cotton cropping systems by weed scientists across the United States in 2020 (Van Wychen 2022). Palmer amaranth is extremely competitive with cotton (Berger et al. 2015; Ehleringer 1983; Ward et al. 2013). In cotton, Palmer amaranth has been reported to cause 54 to 92% lint yield loss at densities of 0.8 to 1.1 plants m^{-1} (Rowland et al. 1999; Morgan et al. 2001; MacRae et al. 2013). Rowland et al. (1999) reported a 71 kg ha^{-1} decrease in cotton lint yield for each additional Palmer amaranth observed m of row^{-1}. The timing of Palmer amaranth emergence in relation to cotton emergence is critical, as season-long inference is more detrimental to cotton yields than weeds that emerge later in the season (Buchanan and Burns 1970; Fast et al. 2009; MacRae et al. 2013). Cotton lint yields can be maximized when cotton remains weed free six to eight weeks following cotton emergence, but the need for weed control generally falls six to seven weeks after cotton emergence (Buchanan and Burns 1970). When a lint yield loss threshold of 2.7% was utilized, Fast et al. (2009) determined the need for complete weed control approximately three weeks after cotton emergence. MacRae et al. (2013) determined yield loss could be minimized if Palmer amaranth was controlled before cotton reached 12-leaf. This indicates effective herbicide-programs need to be utilized during cotton emergence and early development to maintain cotton lint yields.

One way to address herbicide-resistant weed management is to implement herbicide programs that eliminates weed seed dispersal (Shaner and Beckie 2013). Palmer amaranth is a prolific seed producer (Ward et al. 2013). Female Palmer amaranth plants can produce up to 600,000 seeds plant^{-1} with emergence in March, but as few as 115 seeds plant^{-1} with a September emergence (Keeley et al. 1987). Regardless of the time of emergence, efforts should be made to prevent Palmer amaranth seed production. Depleting the weed seed bank reduces the number of individuals that are exposed to weed control tactics and reduces the potential number of escapes that could contribute to the weed seed bank (Korres et al. 2018; Hare et al. 2020). Preventing weed seed bank replenishment is important because low weed populations influence the sustainability of weed management practices (Walsh et al. 2013).

Commercialization of herbicide-resistant cotton varieties, mainly glyphosate-resistant cotton, has made POST-only programs a viable option for cotton growers. However, POST-only programs have been linked to more rapid development of herbicide-resistant weeds as there are often large weeds left uncontrolled (Inman et al. 2020; Crow et al. 2016). The incidence of herbicide resistance is generally greater in fields where few herbicide mode of action groups are utilized each growing season (Evans et al. 2015). More recently, XtendFlex (Bayer CropScience, St. Louis, MO) cotton varities were commercialized in 2015 and Enlist (Corteva Agriscience, Indianapolis, IN) cotton varieties were commercialized 2017. The Enlist technology allows for in-crop use of 2,4-D choline, glufosinate, and glyphosate. The insertion of the AAD-12 gene confers resistance to 2,4-D by coding for an aryloxyalkanoate dioxygenase enzyme, which transforms 2,4-D to a non-lethal form (Wright et al. 2010; Richberg et al. 2012). The XtendFlex technology allows for in-crop use of dicamba, glufosinate, and glyphosate. Resistance to dicamba is conferred through the insertion of the dicamba monoxygenase gene from *Stenotrophomonas maltophilia* which resulted in dicamba being demethylated into a non-toxic state (Behrens et al. 2007). However, there is limited peer reviewed research directly comparing these herbicide trait systems.

In addition to using residual herbicides to reduce weed seed dispersal, effective resistance management programs incorporate multiple sites of action and multiple passes (Evans et al. 2014; Norsworthy et al. 2012; Inman et al. 2020; Buol et al. 2021). Multi-pass programs paired with residual herbicides is a viable option for control of many weed species. Historically, cotton herbicide programs included a PRE application followed by several POST or late-season POST-directed (LAYBY) applications. Cotton lint yields can be maximized when multiple herbicide applications are made (Buol et al. 2021). Greater than 98% Palmer amaranth control has been observed when at least three POST applications of glufosinate, glyphosate, dicamba, and combinations thereof were made in dicamba-resistant cotton (Inman et al. 2020). In 2,4-D resistant cotton, Palmer amaranth control was 75% or greater when 2,4-D choline was applied alone or in combination with glufosinate, glyphosate, acetochlor, or *S*-metolachlor on 10-cm tall Palmer amaranth (Manuchehri et al. 2017). Applying VLCFA-inhibiting herbicides at any time, except for PRE alone, has been shown to result in greater late-season Palmer amaranth control than when VLCFA-inhibiting herbicides were not utilized (Buol et al. 2021). Tank mixes of pendimethalin or acetochlor with diuron + fomesafen, fomesafen alone, diuron alone, or fluometuron alone applied PRE resulted in 86% or greater Palmer amaranth control 46 days after planting when followed with a POST application of glufosinate 27 days after planting (Cahoon et al. 2015b). The addition of acetochlor to early postemergence (EPOST) and LAYBY applications of glyphosate have been observed to significantly increase cotton lint yield compared to glyphosate alone (Cahoon et al. 2015a). Manucheri et al. (2017) also observed glufosinate and glyphosate-only programs in 2,4-D resistant cotton provided variable Palmer amaranth control and reduced seed cotton yield, but combinations of glyphosate and 2,4-D choline were effective when Palmer amaranth ranged from 5- to 10-cm in size.

The availability of these transgenic varieties in early maturity groups makes these varieties a viable option for Kansas cotton growers and will provide them with an additional tool to manage herbicide-resistant weeds. Due to the limited availability of early maturing cotton varieties, there is limited research related to weed control and general cotton production in Kansas and it is critical to establish effective weed control programs for Kansas cotton growers. Therefore, the objectives of this trial were to compare weed control with currently available residual herbicides applied PRE or POST in Enlist and XtendFlex cotton systems in Kansas. Weed control will be similar between the cotton trait systems, but weed control will vary among the residual herbicides utilized and will increase as the number of herbicide applications increase, specifically when those applications include a residual herbicide.

4.3 Materials and Methods

Site years

To fulfill the objectives, field experiments were established on Kansas State University South Central Experiment Field near Hutchison, KS (Latitude: 37.94, Longitude: -98.10) in 2021 and 2022.

Planting details and soil data are in Table 4.1. Prior to planting, 112 kg ha^{-1} of nitrogen (Urea 46-0-0) was applied, and the field was cultivated. Two cotton varieties were planted, PHY 205W3FE (2,4-D-resistant; Corteva Agrisciences, Indianapolis, IN) and NG 2982B3XF (dicamba-resistant; Bayer CropScience, St. Louis, MO). Cotton was planted at 123,500 seeds ha^{-1} for a targeted plant population of 76,570 to 86,450 plants ha^{-1} and was planted with a 4-row planter at 5-cm deep to reach moisture. Cotton was grown under overhead irrigation. Monthly irrigation and precipitation total and monthly average temperature for both site years are presented in Table 4.2. Thirty-year monthly precipitation and temperature averages are also presented in Table 4.2.

Herbicide applications

Herbicides and herbicide programs utilized in this trial can be found in Tables 4.3, 4.4, and 4.5. A split-plot design with four replications was used. Cotton variety was the main plot, and the herbicide treatments were randomly assigned to subplots. Each main plot included a nontreated check and a weed free check. Individual plots were 3 m by 9 m in size. In 2021, application timings included preemergence (PRE) only or PRE followed by (*fb*) early POST (EPOST) *fb* late POST (LPOST). In 2021, PRE applications occurred immediately after planting, EPOST occurred when cotton was 2-leaf, and LPOST occurred when cotton was 6-leaf to 1st position match head square. Palmer amaranth plants were approximately 10-cm in height at EPOST. At the time of the LPOST, Palmer amaranth size was variable and ranged from 2- to 117-cm on height. In 2022, application timings included PRE fb EPOST. In 2022, PRE applications occurred immediately after planting and EPOST occurred when cotton was 6-leaf and Palmer amaranth were 10-cm in height. The authors want to clarify that all herbicide treatments were within label restrictions, apart from PRE applications of dimethenamid-P and combinations of 2,4-D choline and dimethenamid-P (Corteva Agriscience 2022). However, to accurately compare herbicide trait systems the authors believed it was necessary to include treatments of dimethenamid-P.

Spray solution was applied directly to plots with 140 L ha^{-1} spray volume using a CO2 powered backpack sprayer and a 4-tip, 1.9-m hand-held boom equipped with TT 110015 for the preemergence application (PRE; 2021 and 2022) and TTI110015 nozzles (TeeJet Technologies, 1801 Business Park Dr, Springfield, IL62703) for the early postemergence (EPOST; 2021 and 2022) and postemergence (LPOST; 2021) applications at 220 kPa. The center two rows of each plot received the full rate, whereas the two outer rows acted as a buffer between treatments. Following EPOST applications in 2022, it became apparent that the Enlist cotton was planted in part of the XtendFlex main plot, which resulted in severe injury in the Enlist cotton. Weed control was evaluated in the effected plots but were removed from the yield component analysis.

Data collection

Visual weed control was evaluated from 7 weeks after planting (WAP) in 2021 and 4 WAP in 2022 to the end of the season (October 28, 2021; October 13, 2022). Weed control was evaluated on a 0 to 100% weed control scale with 0% indicating no control and 100% indicating complete weed control (Canadian Weed Science Society 2018). Palmer amaranth was the dominant weed species in 2021 and 2022.

To further evaluate control, Palmer amaranth biomass and density were collected at the end of the season with 0.25 m^{-2} quadrant at two different representative locations within each plot. Weed biomass and densities were taken for individual weed species. Weed biomass samples were dried for ~10 days at 50 C and then weighed to obtain the dry weight. Data was then transformed by taking the average of the plot and multiplying by 4 to get the biomass and density m^{-2}.

Cotton plant populations were determined on June 28, 2021, and July 25, 2022. Cotton stand counts were taken in the middle two rows using 3 m of row^{-1} from each row in each plot. In 2021, plant populations were poor and variable across the experiment, which was attributed to seed being planted too deep to get to moisture and high temperatures after emergence. Due to the poor plant populations, plots were not to taken to yield.

In 2022, to further evaluate response to herbicide efficacy, cotton yield component data were collected at the end of the season by collecting 5 plants from each of the center 2 rows in each plot. Yield components measured included fruiting nodes $plant^{-1}$, total bolls $plant^{-1}$, and harvestable bolls $plant^{-1}$. Bolls were considered harvestable if the mature black layer was present on the seed and/or bolls were cracked (Ritchie et al. 2007).

Data analysis

Palmer amaranth control, Palmer amaranth biomass, Palmer amaranth density, cotton plant populations, and cotton yield component data were assessed for normality and heteroskedasticity using Shapiro-Wilk test in R package stats (R Core Team 2022) and Levene's test in R package car (Fox and Weisberg 2019). Data did not violate ANOVA assumptions, so data were not transformed. Data were subjected to ANOVA using base R (R Core Team 2022). Replication and replication within cotton variety were considered random effects. Herbicide treatment, and cotton variety were considered fixed effects. Site-years were not compared due to differences in treatments between years. Means were separated using Tukey's HSD Test (α = 0.05) in R package agricolae (de Mendiburu 2021).

Palmer amaranth biomass, Palmer amaranth density, and cotton yield component data were subjected to the correl function in R package agricolae (de Mendiburu 2021). Pearson coefficients were considered weak if less than 0.3, moderate if greater than 0.3 but less than 0.5, and strong if greater than 0.5 (Mukaka 2012). A general linear model for cotton yield components was selected with stepwise regression using Palmer amaranth biomass and density due to strong and significant (pearson coefficient = ≥ 0.5, p-value = ≤0.0001) correlation with cotton yield components. The model was developed with train() in R package caret version 6.0-90 (Kuhn 2021) and selected based on AIC value, McFadden's r-squared value, and residual plots.

4.4 Results and Discussion

Environmental conditions

Thirty-year precipitation and temperature normals from 1991 to 2020 were referenced from the National Oceanic Atmospheric Administration (Arquez et al. 2010). All months received less rainfall than the 30-year average except for September and October 2021, which were slightly wetter (Table 4.2). In general, conditions in 2021 and 2022 were drier and slightly warmer than the 30-year normal, especially in 2021 at planting and emergence which resulted in poor stand establishment (Table 4.2)

Palmer amaranth control in 2021

Prior to the LPOST application, there was a significant interaction of herbicide trait system and residual herbicide for Palmer amaranth control (Table 4.6). In general, Palmer amaranth control prior to LPOST applications did not differ between herbicide trait systems, regardless of residual herbicide utilized apart from dimethenamid-P, which resulted in 31% control in Enlist systems and 70% control in XtendFlex systems (Table 4.7). This indicates less control was observed when dimethenamid-P was combined with 2,4-D choline. No significant interactions were detected for Palmer amaranth control 8 WAEPOST, however, the main effect of residual herbicide and herbicide trait system were significant (Table 4.6). No significant interactions were detected for Palmer amaranth control 8 WALPOST, however, the main effect herbicide trait system was significant (Table 4.6). When POST applications were utilized, there were no differences in control among residual herbicides 8 WAEPOST and control ranged from 69 to 76% (Table 4.8). However, when no POST applications were utilized Palmer amaranth control was 0%. At 8 WAEPOST and 8 WALPOST, Palmer amaranth control was greater in XtendFlex trait systems than Enlist trait systems (Table 4.9). When pooled across herbicide treatments, Palmer amaranth control at 8 WAEPOST was 50% in Enlist systems and 71% in XtendFlex systems (Table 4.9). At 8 WALPOST, Palmer amaranth control was 67% in Enlist systems and 80% in XtendFlex systems, regardless of residual herbicide (Table 4.9). No significant interactions were detected for Palmer amaranth control at the end of the season, however, the main effect residual herbicide was significant (Table 4.6). Including a POST application resulted in control at the end of the season that ranged from 48 to 71% regardless of herbicide trait system (Table 4.8). When POST applications were utilized, Palmer amaranth biomass did not differ among residual herbicides or from the weed-free check (Table 4.10). The PRE-only treatment resulted in similar biomass levels to the non-treated check with 566 and 447 g m^{-2}. Additionally, utilization of POST applications resulted in no differences among residual herbicides in XtendFlex trait systems than Enlist trait systems for Palmer amaranth density (Table 4.10). The only difference that existed among trait systems were the elevated densities observed in the non-treated check in the XtendFlex trait system (220 plants m^{-2}) as compared to the Enlist system (117 plants m^{-2}; Table 4.10).

Palmer amaranth control in 2022

No significant interactions were detected for Palmer amaranth control prior to EPOST, however, the main effect of residual herbicide was significant (Table 4.11). Prior to EPOST applications in 2022, PRE applications of fluometuron resulted in 56% control while combinations of fluometuron with dimethenamid-P or *S*-metolachlor resulted in 83% or greater Palmer amaranth control (Table 4.12) No significant interactions were detected for Palmer amaranth control 8 WAPRE, however, the main effect of residual herbicide was significant (Table 4.11). At 8 WAPRE, treatments with two applications of acetochlor resulted in 81% control, while less Palmer amaranth control (57%) was observed in treatments with two applications of pendimethalin or treatments with no overlapping residual (Table 4.13). No significant interactions were detected for Palmer amaranth control 8 WAEPOST, however, the main effect of herbicide trait system was significant (Table 4.11). Palmer amaranth control was greater in XtendFlex trait systems than Enlist trait systems at 8 WAEPOST (Table 4.14). At 8 WAEPOST, Enlist and XtendFlex trait systems resulted in 61 and 72% control (Table 4.14). No significant interactions were detected for Palmer amaranth control 8 WAPRE, however, the main effect of residual herbicide was significant (Table 4.11). At the end of the season, XtendFlex trait systems resulted in 79% control and Enlist trait systems resulted in 68% control (Table 4.14) Treatments with two applications of acetochlor, dimethenamid-P, or *S*-metolachlor resulted in 74% or greater Palmer amaranth control at the end of the season (Table 4.13). There were no differences among residual herbicide treatments for Palmer amaranth biomass and density at the end of the season (Table 4.15). Two applications of pendimethalin was the only residual herbicide treatment with Palmer amaranth biomass greater than the weed-free check (Table 4.15).

Palmer amaranth control in 2021 was poor at the end of the season (≤71%) which may be attributed to the presence of large Palmer amaranth at the time of the LPOST application. Crow et al. (2016) reported poor control (≤63%) of large Palmer amaranth (>20-cm tall) when herbicide tank mixes did not contain dicamba + diflufenzopyr. While Meyer and Norsworthy (2019) illustrated 83% and 85% control of 30-cm Palmer amaranth with applications of 2,4-D choline or dicamba. Blythe (2021) reported acceptable Palmer amaranth control late in the season when Palmer amaranth that were less than 10-cm were sprayed with 2,4-D, dicamba, or glufosinate. To increase the likelihood of control, it is best practice to control Palmer amaranth prior to reaching 5-cm (Crow et al. 2016). Palmer amaranth is quick to outgrow the recommended height for control for POST herbicide tank mixes due to its rapid growth rate (Ehlinger 1983; Crow et al. 2016). In 2022, fluometuron-only treatments resulted in the least Palmer amaranth control which may be partially attributed to the high levels of sand present in the soil. Previous research has illustrated reduced efficacy of fluometuron when applied on soils with greater levels of sand (Patterson et al. 1982). Palmer amaranth control was greatest in treatments with sequential applications of residual herbicides as compared to treatments with no overlapping residual herbicides. This agrees with Buol et al. (2021) and Blythe (2021). Buol et al. (2021) reported greater late-season weed control with two applications of acetochlor or *S*-metolachlor. In Enlist, XtendFlex, and glyphosate-resistant cotton systems, Blythe (2021) observed greater control with PRE applications of acetochlor + fomesafen followed by two

POST applications, regardless of the herbicide trait system. However, Palmer amaranth control was greater in the absence of PRE applications when dicamba + glyphosate or glufosinate + glyphosate POST was made as compared to 2,4-D + glyphosate POST.

Findings in the present trial agree with previous research, which has illustrated the importance of multiple herbicide applications and utilization of residual herbicides to adequately provide season long weed control in cotton (Cahoon et al. 2014; Cahoon et al. 2015a, b; Manucheri et al. 2017; Hare et al. 2020; Inman et al. 2020; Blythe 2021). Inman et al. (2020) observed 91% or greater Palmer amaranth control when PRE applications were followed by at least one POST application of dicamba + glufosinate or two or more POST applications of dicamba + glufosinate without a PRE application. Cahoon et al. (2015a) reported increased Palmer amaranth control in XtendFlex cotton with PRE applications of acetochlor + dicamba and in programs with dicamba applied POST when compared to glyphosate- and glufosinate-only programs. While in Enlist systems, Manucheri et al. (2017) observed increased control in systems that included multiple POST applications of 2,4-D applied alone or in combination with glyphosate and glufosinate. However, when glyphosate or glufosinate were applied alone control was decreased. The authors attributed the decreased control with glufosinate-only treatments to low humidity levels at the time of application. Greater humidity levels are necessary to ensure the efficacy of contact herbicides, like glufosinate (Anderson et al. 1993; Coetzer et al. 2000; Manucheri et al. 2017). Combinations of glufosinate and dicamba or glyphosate and 2,4-D choline were reported to be antagonistic when applied POST for control of barnyardgrass (Echinochloa crus-gallo (L.)) and Palmer amaranth, especially when weeds were greater than 10-cm (Meyer and Norsworthy 2019; Lammers 2021). This indicates that use of glufosinate in

Enlist or XtendFlex cotton systems may be limited in south central or southwestern Kansas due to the often-low humidity levels in those regions.

Plant populations

No significant interactions were detected for cotton populations in 2021 and 2022, however, the main effect of herbicide trait system in 2021 and in 2022 herbicide trait system and residual herbcides was significant (Table 4.6, 4.11). In 2021, cotton population differed between herbicide trait systems. The greatest cotton populations were observed in Enlist systems (36,178 plants ha^{-1}) as compared to XtendFlex systems (20,846 plants ha^{-1}; Table 4.17). Cotton populations were highly variable and ranged between 2,151 and 86,074 plants ha^{-1} in 2021. The low plant populations observed in the XtendFlex system in 2021 may be a partial explanation for the greater Palmer amaranth densities observed in 2021 in the XtendFlex system, which may be explained by a lack of competition from an optimum cotton population. In 2022, cotton populations differed between herbicide trait systems. Greater cotton populations were observed in Enlist systems (113,718 plants ha^{-1}) as compared to XtendFlex systems (96,526 plants ha^{-1}; Table 4.17). In 2022, when POST applications were utilized, cotton populations ranged from 100,830 to 112,166 plant ha^{-1}, regardless of residual herbicide (Table 4.18). However, cotton populations observed with two applications of dimethenamid-P (100,830 plants ha^{-1}) were not different than the non-treated check (87,957 plants ha^{-1}; Table. 4.15). Previous research has observed decreased crop safety with POST applications of dimethenamid-P (Hayes et al. 2004). Results indicate that the Enlist cotton variety used in the present trial may be better suited for dry and hot conditions present in south central Kansas than the XtendFlex cotton variety used in the present trial. Previous research has reported variable responses of different cotton varieties to changes in air and soil temperatures (Reddy et al. 2017; Nabi and Mullins 2008). Nabi and

Mullins (2008) reported significant decreases in emergence when soil temperatures were 38 C or greater. In addition to temperature, adequate moisture and nutrients is critical for the uniform emergence of cotton (Reddy et al. 2017; Nabi and Mullins 2008). Soil temperatures from the day of planting to the day of EPOST application in 2021 were variable and ranged between 17 and 39 C. A combination of high temperatures, delayed irrigation, and poor water holding capacity of the location soil may explain poor Palmer amaranth control in PRE-only treatments and poor cotton emergence in 2021. Although considerably less rainfall was received in 2022 than 2021, supplemental irrigation was more timely following planting and PRE applications in 2022 which may explain the generally greater cotton populations in 2022 as compared to 2021.

Yield components

Yield and yield components were not measured in 2021 due to low and variable plant populations among experimental plots. In 2022, no significant interactions were detected for yield components, however, the main effect of residual herbicide was significant for all yield components (Table 4.11). In 2022, there were no differences among residual herbicides for all yield components measured, apart from *S*-metolachlor and the weed-free check (Table 4.19). Results agree with Hare et al. (2020) and Buol et al. (2021) who observed maximized cotton yields with sequential applications of herbicides. However, there was strong negative correlation between yield components collected and Palmer amaranth biomass and density measured at the end of the season (Table 4.20). This was supported by these data, which show that in addition to a strong correlation, a linear relationship existed between Palmer amaranth biomass and density and the measured yield components. As Palmer amaranth biomass and density decreased, the number of fruiting nodes, total bolls, and harvestable bolls decreased (Figure 4.1, 4. 2). Relationships between Palmer amaranth density and biomass have been established in previous literature (Norsworthy et al. 2016; MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). Morgan et al. (2001) observed decreased cotton lint yields and cotton biomass with increased densities of Palmer amaranth. Previous research has reported 54 to 92% lint yield loss at Palmer amaranth densities of 0.42 to 1.1 plants m^{-2} (Norsworthy et al. 2016; MacRae et al. 2013; Morgan et al. 2001; Rowland et al. 1999). Increased lint and seed yield is generally observed when boll retention, number of fruiting sites, and number of boll m^{-2} are increased (Worley et al. 1974; Rauf et al. 2004; Kilby et al. 2013; Huang 2016). Although the present trial did not demonstrate varietal differences for yield components, it is critical for growers to consider yield, disease tolerance, seed availability, and the availability of the herbicides associated with the trait system rather than selecting exclusively for the herbicide trait system (Blythe 2021).

4.5 Conclusion

Palmer amaranth control was greatest when PRE applications were followed by two POST applications or by one EPOST application including a residual herbicide. Palmer amaranth control was the least in PRE only systems and in PRE fb EPOST systems with no overlapping residual herbicide. In general, residual herbicides did not perform differently in Enlist and XtendFlex cotton systems, apart from dimethenamid-P in 2021. Dimethenamid-P combined with 2,4-D choline resulted in less Palmer amaranth control than when combined with dicamba. However, dimethenamid-P is not currently an approved tank mix partner for 2,4-D choline (Corteva Agriscience 2022). In the present trial, Palmer amaranth control was greater in XtendFlex systems than Enlist systems. Although XtendFlex systems provided greater control than Enlist systems, the results of the present trial noted reduced cotton population in XtendFlex systems as compared to Enlist systems, but there were no differences in cotton yield components observed. Growers need to take care to consider the differences that exist among varieties, whether that be differences in yield potential, disease and pest tolerance, maturity group, seed availability, and the availability of the herbicides associated with the trait system rather than selecting exclusively for the herbicide trait system (Blythe 2021). Additionally, growers may want to consider what herbicide trait system best fits their location. Both herbicides are susceptible to off-target movement and have potential to injure sensitive vegetation, which has led to the implementation of many counter measures to limit the potential negative impact of these herbicides (Johnson et al. 2012; Marple et al. 2008; Wax et al. 1969). However, these technologies play a critical role in weed management because they are another tool in the toolbox for growers to use in controlling herbicide- resistant weeds. The present trial has illustrated the importance of utilizing these technologies in conjunction with residual herbicides and multi-pass herbicide programs to adequately control Palmer amaranth.

4.6 References

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Table 4.1. Planting date and rate, tillage practice, herbicide application dates, and soil chatacterisitcs for cotton studies conducted in 2021 and 2022 in Hutchinson, KS.

Factors	2021	2022
Planting date	5/26/21	6/13/22
Planting rate (seeds ha^{-1})	123,500	123,500
Tillage practice	Conventional	
PRE[z] applied	5/26/21	6/13/22
EPOST applied[y]	6/16/21	7/14/22
LPOST applied[x]	7/12/21	–
Biomass and density measured[w]	10/28/21	10/13/22
Soil type	Nalim loam	
Organic matter (%)	1.4	2.6
pH	7.6	6.8
Sand (%)	78	50
Silt (%)	14	32
Clay (%)	8	18

[z] PRE = Preemergence application; EPOST = Early postemergence application; LPOST = Late post

[y] In 2021, cotton was at the 2-Leaf stage and in 2022 cotton was at the 6-Leaf stage at time of EPOST application.

[x] In 2021, cotton growth stage ranged between 6-Leaf to first position match head square stage.

[w] Palmer amaranth biomass and density measured with 0.25 m^{-2} quadrant at two representative locations in each plot.

Table 4.2. Monthly irrigation and precipitation total and monthly average temperature in 2021 and 2022 and 30-year monthly precipitation and temperature averages for Hutchinson, KS.

Factor		2021	2022	30-year average[z]
Irrigation (cm)				
	May	0	–	–
	June	3.8	3.8	–
	July	6.4	5.6	–
	August	9.5	7.2	–
	September	4.1	2.5	–
	October	0	0	–
Precipitation (cm)[y]				
	May	9.2	15.8	11.9
	June	4.8	7.3	11.6
	July	7.3	3.2	9.3
	August	7.2	1.2	9
	September	7.0	2.4	6.3
	October	7.4	1.1	6
	Total season (irrigation + precipitation)	66.6	50.1	54.1
Average temperature (C)				
	May	16.9	–	17.9
	June	25.6	0.4	23.9
	July	25.7	4.3	26.5
	August	26.7	0.7	25.4
	September	23.6	3.7	20.8
	October	16.3	0.3	13.6

[z] The 30-year normal values from 1991 to 2020 were retrieved from National Oceanic and Atmospheric Administration (Arquez et al. 2010).

[y] Monthly rainfall and temperature values were retrieved from the Kansas Mesonet (2022).

Table 4.3. Herbicide product, application rates and timings, and manufacturer information for herbicide treatments used for Palmer amaranth control in cotton in Hutchinson, KS in 2021 in cPRE only and PRE fb EPOST fb LPOST systems.[z]

Application timing	Trade name	Active ingredients	Rates	Manufacturer information[y]
			g ai ha^{-1} or g ae ha^{-1}	
PRE	Prowl H_2O	Pendimethalin	1065	BASF Corporation
EPOST	Dual II Magnum	*S*-metolachlor	1606	Syngenta Crop Protection
EPOST	Outlook	Dimethenamid-P	763	BASF Corporation
EPOST	Warrant	Acetochlor	788	Bayer Crop Science
EPOST, LPOST	RoundUp PowerMax	Glyphosate	867	Bayer Crop Science
EPOST	Enlist Duo	2,4-D choline + glyphosate	793 + 834	Bayer Crop Science
EPOST	Tavium	*S*-metolachlor + dicamba	1109 + 549	Syngenta Crop Protection
EPOST, LPOST	Enlist One	2,4-D choline	799	Corteva Agriscience
EPOST, LPOST	Xtendimax	Dicamba	559	Bayer Crop Science

[z] fb = followed by; PRE = preemergence (at planting); EPOST = early postemergence (2-Leaf cotton); LPOST = late postemergence (6-Leaf cotton to 1st position match head square)

[y] Manufacturer information: BASF Corporation, Research Triangle Park, NC; Bayer CropScience, St. Louis, MO; Corteva Agriscience, Indianapolis, IN; Syngenta Crop Protection, LLC, Greensboro, NC

Table 4.4. Herbicide product, application rates and timings, and manufacturer information for herbicide treatments used for Palmer amaranth control in cotton in Hutchinson, KS in 2022 in PRE only and PRE fb EPOST weed control systems.[z]

Application timing	Trade name	Active ingredients	Rates	Manufacturer information[y]
			g ai ha or g ae ha	
PRE	Cotoran 4L	Fluometuron	1122	Adama
PRE, EPOST	Dual II Magnum	*S*-metolachlor	1392, 1071	Syngenta Crop Protection
PRE, EPOST	Outlook	Dimethenamid-P	631, 473	BASF Corporation
PRE, EPOST	Prowl H_2O	Pendimethalin	1065, 1065	BASF Corporation
PRE, EPOST	Warrant	Acetochlor	1345, 1009	Bayer Crop Science
EPOST	RoundUp PowerMax 3	Glyphosate	1262	Bayer Crop Science
EPOST	Enlist One	2,4-D choline	799	Corteva Agriscience
EPOST	Xtendimax	Dicamba	559	Bayer Crop Science

[z] fb = followed by; PRE = preemergence (at planting); EPOST = early postemergence (6-Leaf cotton)

[y] Manufacturer information: Adama US, Raleigh, NC; BASF Corporation, Research Triangle Park, NC; Bayer CropScience, St. Louis, MO; Corteva Agriscience, Indianapolis, IN; Syngenta Crop Protection, LLC, Greensboro, NC

Table 4.5. Herbicide programs for the management Palmer amaranth in Enlist and XtendFlex cotton in 2021 in Hutchinson, KS.[z]

	Weed control system[y]		
Year	PRE	EPOST	LPOST[e]
2021	Pendimethalin	–	–
	Pendimethalin	Acetochlor + trait herbicide[x]	Glyphosate + trait herbicide
	Pendimethalin	Dimethenamid-P + trait herbicide	Glyphosate + trait herbicide
	Pendimethalin	*S*-metolachlor + trait herbicide	Glyphosate + trait herbicide
	Pendimethalin	Trait premix[w]	Glyphosate + trait herbicide
	Pendimethalin	Trait herbicide	Glyphosate + trait herbicide
2022	Fluometuron	Glyphosate + trait herbicide	–
	Fluometuron + acetochlor	Glyphosate + trait herbicide + acetochlor	–
	Fluometuron + dimethenamid-P	Glyphosate + trait herbicide + dimethenamid-P	–
	Fluometuron + pendimethalin	Glyphosate + trait herbicide + pendimethalin	–
	Fluometuron + *S*-metolachlor	Glyphosate + trait herbicide +*S*-metolachlor	–

[z] Enlist = 2,4-D-resistant cotton; XtendFlex = Dicamba-resistant cotton

[y] PRE = preemergence (at planting); EPOST = early postemergence (2-Leaf cotton in 2021; 6-Leaf cotton in 2022); LPOST = late postemergence (6-Leaf cotton to 1st position match head square)

[x] Trait herbicide: Enlist = 2,4-D choline = 799 g ae ha^{-1}; XtendFlex = dicamba = 559 g ae ha^{-1}; Applications with dicamba included 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra

Agent, Bayer Crop Science, St. Loius, MO); 2,4-D choline + glyphosate tank mixes were tank mixed with 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN)

[w] Trait premix: Enlist = 834 g ae ha^{-1} glyphosate + 793 g ae ha^{-1} 2,4-D choline; XtendFlex = 549 g ae ha^{-1} dicamba + 1109 g ai ha^{-1} *S*-metolachlor

Table 4.6. Analysis of variance for Palmer amaranth control, Palmer amaranth biomass and density at the end of the season, and cotton plant populations in Hutchinson, KS in 2021 as influenced by herbicide-resistant cotton systems and residual herbicide and their interactions.

Fixed effects	Prior to EPOST	8 WAPRE	8 WALP	End of season	Biomass	Density	Cotton population
	p-value						
Herbicide trait system	0.0019	0.0011	0.0019	0.3483	0.6609	0.2507	0.0134
Residual herbicide	<0.0001	<0.0001	0.2512	<0.0001	<0.0001	<0.0001	0.7759
Herbicide trait system x Residual herbicide	0.0233	0.2179	0.3289	0.7876	0.6099	0.0467	0.9501

Table 4.7. Palmer amaranth control prior to LPOST herbicide applications as influenced by residual herbicides applied EPOST in Enlist and XtendFlex cotton systems in Hutchinson, KS in 2021.[z]

Residual herbicide	Herbicide trait system[y]	
	Enlist	XtendFlex
	Palmer amaranth control (%)	
Acetochlor[w]	36 bcd[s]	65 ab
Dimethenamid-P[w]	31 cde	70 a
S-metolachlor[w]	58 abc	73 a
Trait premix[v]	46 abc	62 abc
Trait herbicide[u]	44 abc	69 a
PRE only[t]	5 de	3 e

[z] EPOST = early postemergence (2-Leaf cotton); LPOST = late postemergence (6-Leaf cotton to 1st position match head square)

[y] Enlist = 2,4-D-resistant cotton; XtendFlex = Dicamba-resistant cotton

[w] In Enlist cotton applied with 2,4-D choline + 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN); In XtendFlex cotton applied with dicamba + 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra Agent, Bayer Crop Science, St. Loius, MO)

[v] Trait premix: Enlist = 834 g ae ha^{-1} glyphosate + 793 g ae ha^{-1} 2,4-D choline; XtendFlex = 549 g ae ha^{-1} dicamba + 1109 g ai ha^{-1} *S*-metolachlor

[u] Trait herbicide: Enlist = 2,4-D choline = 799 g ae ha^{-1}; XtendFlex = dicamba = 559 g ae ha^{-1}

[t] PRE = Preemergence application; PRE only = 1065 g ai ha^{-1} pendimethalin applied at planting

[s] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

Table 4.8. Palmer amaranth control 8 WAEPOST and at the end of the season in herbicide-resistant cotton systems as influenced by residual herbicide applied EPOST in 2021.[z]

Residual herbicide[y]	8 WAEPOST	End of season
	Palmer amaranth control (%)	
Acetochlor[x]	74 a[t]	68 a
Dimethenamid-P[x]	76 a	69 a
S-metolachlor[x]	75 a	71 a
Trait premix[w]	73 a	69 a
Trait herbicide[v]	69 a	48 a
PRE only[u]	0 b	0 b

[z] WAEPOST = weeks after early postemergence application; EPOST = early postemergence (2-Leaf cotton); End of Season = October 28, 2021

[y] All EPOST applications were followed by a late postemergence (LPOST) application when cotton was 6-Leaf to 1st position match head square. In Enlist cotton LPOST = 2,4-D choline + glyphosate + 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN); In XtendFlex cotton LPOST = dicamba + glyphosate + 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra Agent, Bayer Crop Science, St. Loius, MO)

[x] In Enlist cotton applied with 2,4-D choline + 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN); In XtendFlex cotton applied with dicamba + 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra Agent, Bayer Crop Science, St. Loius, MO)

[w] Trait premix: Enlist = 834 g ae ha^{-1} glyphosate + 793 g ae ha^{-1} 2,4-D choline; XtendFlex = 549 g ae ha^{-1} dicamba + 1109 g ai ha^{-1} *S*-metolachlor

[v] Trait herbicide: Enlist = 2,4-D choline = 799 g ae ha^{-1}; XtendFlex = dicamba = 559 g ae ha^{-1}

[u] PRE = Preemergence application; PRE only = 1065 g ai ha^{-1} pendimethalin applied at planting

[t] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

Table 4.9. Palmer amaranth control 8 WAEPOST and 8 WALPOST as influenced by herbicide trait systems in Hutchinson, KS in 2021.[z]

Herbicide trait system[y]	8 WAEPOST	8 WALPOST
	Palmer amaranth control (%)	
Enlist	50 b[x]	67 b
XtendFlex	71 a	80 a

[z] WAEPOST = weeks after early postemergence application; WALPOST = weeks after late postemergence application

[y] Enlist = 2,4-D-resistant cotton; Xtendflex = dicamba-resistant cotton

[x] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

Table 4.10. Palmer amaranth biomass and density at the end of the season in herbicide-resistant cotton systems as influenced by residual herbicide applied EPOST in 2021.[z]

Residual herbicide[x]		Herbicide trait system[y] Enlist	XtendFlex
	Biomass	Density	
	g m^{-2}	—— plants m^{-2} ——	
Acetochlor[w]	161 b[s]	13 c[r]	8 c
Dimethenamid-P[w]	150 b	12 c	5 c
S-metolachlor[w]	163 b	11 c	11 c
Trait premix[v]	183 b	8 c	8 c
Trait herbicide[u]	185 b	11 c	8 c
PRE only[t]	566 a	62 bc	57 bc
Non-treated	437 a	117 b	220 a
Weed-free	0 b	0 c	0 c

[z] EPOST = early postemergence (2-Leaf cotton); End of Season = October 28, 2021

[y] Enlist = 2,4-D-resistant cotton; XtendFlex = dicamba-resistant cotton

[x] All EPOST applications were followed by a late postemergence (LPOST) application when cotton was 6-Leaf to 1st position match head square. In Enlist cotton LPOST = 2,4-D choline + glyphosate + 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN); In XtendFlex cotton LPOST = dicamba + glyphosate + 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra Agent, Bayer CropScience, St. Loius, MO)

[w] In Enlist cotton applied with 2,4-D choline + 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN); In XtendFlex cotton applied with dicamba + 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra Agent, Bayer Crop Science, St. Loius, MO)

[v] Trait premix: Enlist = 834 g ae ha^{-1} glyphosate + 793 g ae ha^{-1} 2,4-D choline; XtendFlex = 549 g ae ha^{-1} dicamba + 1109 g ai ha^{-1} *S*-metolachlor

[u] Trait herbicide: Enlist = 2,4-D choline = 799 g ae ha^{-1}; XtendFlex = dicamba = 559 g ae ha^{-1}

[t] PRE = Preemergence application; PRE only = 1065 g ai ha^{-1} pendimethalin applied at planting

[s] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).
[r] Means followed by the same letter of a response are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

Table 4.11. Analysis of variance for Palmer amaranth control, Palmer amaranth biomass, and Palmer amaranth density at the end of the season in Hutchinson, KS in 2022 as influenced by herbicide-resistant cotton systems and residual herbicide and their interactions.

Fixed effects	Prior to EPOST	8 WAPRE	8 WAEPOST	End of the season	Palmer amaranth biomass	Palmer amaranth density
	p-value					
Herbicide trait system	0.5351	0.0845	0.0339	0.0019	0.4234	0.1826
Residual herbicide	0.0324	0.0066	0.0619	<0.0001	<0.0001	<0.0001
Herbicide trait system x Residual herbicide	0.2326	0.9426	0.8021	0.2819	0.1313	0.2551

Table 4.12. Palmer amaranth control prior to EPOST applications in herbicide-resistant cotton systems as influenced by residual herbicide tank mixes with fluometuron applied PRE in 2022.[z]

Residual herbicide[y]	Palmer amaranth control
	——— % ———
Acetochlor	77 ab[x]
Dimethenamid-P	83 a
Pendimethalin	78 ab
S-metolachlor	85 a
Fluometuron only	56 b

[z] EPOST = early postemergence application (6-Leaf cotton)

[y] All EPOST applications were followed by a late postemergence (LPOST) application when cotton was 6-Leaf to 1st position match head square. In Enlist cotton LPOST = 2,4-D choline + glyphosate + 2.5% v/v ammonium sulfate (N-Pak, WinField Solutions, LLC, St. Paul, MN); In XtendFlex cotton LPOST = dicamba + glyphosate + 1% v/v drift reduction agent (Intact, Precision Laboratories, LLC, Waukegan, IL) + 1% v/v volatility reducing agent (VaporGrip Xtra Agent, Bayer CropScience, St. Loius, MO)

[x] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

Table 4.13. Palmer amaranth control 8 WAPRE and at the end of the season in herbicide-resistant cotton systems as influenced by split applications of residual herbicides applied in PRE fb EPOST systems in 2022.[z]

Residual herbicide[y]	8 WAPRE	End of season
	Palmer amaranth control (%)	
Acetochlor	81 a[x]	84 a
Dimethenamid-P	76 ab	85 a
Pendimethalin	57 b	68 bc
S-metolachlor	65 ab	74 ab
No over-lapping residual[w]	57 b	60 c

[z] WAPRE = weeks after preemergence application; end of season = October 13, 2022; PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

[y] PRE residual herbicides were combined with fluometuron *fb* the same residual herbicide combined with glyphosate + trait herbicide EPOST (Trait herbicide in Enlist system = 2,4-D choline; XtendFlex system = dicamba).

[x] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD (α = 0.05).

[w] No over-lapping residual = fluometuron fb glyphosate + trait herbicide

Table 4.14. Palmer amaranth control at 8 WAEPOST and at the end of the season as influenced by Enlist and XtendFlex cotton systems in 2022.[z]

Herbicide trait system[y]	8 WAEPOST	End of season
	Palmer amaranth control (%)	
Enlist	61 b[x]	68 b
XtendFlex	72 a	79 a

[z] WAEPOST = weeks after early postemergence application; End of season = October 13, 2022

[y] Enlist = 2,4-D-resistant cotton; Xtendflex = dicamba-resistant cotton

[x] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD (α = 0.05).

Table 4.15. Palmer amaranth biomass and density at the end of the season in herbicide-resistant cotton systems as influenced by split applications of residual herbicides applied in PRE fb EPOST systems in 2022.[z]

Residual herbicide[y]	Biomass	Density
	g m^{-2}	plants m^{-2}
Acetochlor	76 bc[x]	10 b
Dimethenamid-P	76 bc	3 b
Pendimethalin	108 b	10 b
S-metolachlor	67 bc	6 b
No over-lapping residual[w]	90 bc	14 b
Non-treated	310 a	53 a
Weed-free	0 c	0 b

[z] End of season = October 13, 2022; PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

[y] PRE residual herbicides were combined with fluometuron *fb* the same residual herbicide combined with glyphosate + trait herbicide EPOST (Trait herbicide in Enlist system = 2,4-D choline; XtendFlex system = dicamba).

[x] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD (α = 0.05).

[w] No over-lapping residual = fluometuron *fb* glyphosate + trait herbicide.

Table 4.16. Analysis of variance for cotton plant populations and cotton yield components in Hutchinson, KS in 2022 as influenced by herbicide-resistant cotton systems and residual herbicide and their interactions.

Fixed effects	Cotton plants ha^{-1}	Fruiting nodes $plant^{-1}$	Total bolls $plant^{-1}$	Harvestable bolls $plant^{-1}$
	p-value			
Herbicide trait system	<0.0001	0.8989	0.9044	0.2845
Residual herbicide	0.0023	<0.0001	0.0003	<0.0001
Herbicide trait system x Residual herbicide	0.6341	0.5794	0.6797	0.2628

Table 4.17. Cotton plant populations as influenced by Enlist and XtendFlex cotton systems in 2021 and 2022.[z]

Herbicide trait	2021	2022
	plants ha^{-1}	
Enlist	36,178 a[y]	113,718 a
XtendFlex	20,846 b	96,526 b

[z] Enlist = 2,4-D-resistant cotton; XtendFlex = dicamba-resistant cotton

[y] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD (α = 0.05).

Table 4.18. Cotton plant populations in herbicide-resistant cotton systems as influenced by split applications of residual herbicides applied in PRE fb EPOST systems in 2022.[z]

Residual herbicide[y]	Plant population
	Plants ha^{-1}
Acetochlor	112,166 a[x]
Dimethenamid-P	100, 830 ab
Pendimethalin	109, 207 a
S-metolachlor	107, 593 a
No over-lapping residual[w]	107, 324 a
Non-treated	87, 957 b
Weed-free	108, 400 a

[z] PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

[y] PRE residual herbicides were combined with fluometuron *fb* the same residual herbicide combined with glyphosate + trait herbicide EPOST (Trait herbicide in Enlist system = 2,4-D choline; XtendFlex system = dicamba).

[x] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

[w] No over-lapping residual = fluometuron *fb* glyphosate + trait herbicide.

Table 4.19. Cotton yield components in herbicide-resistant cotton systems as influenced by residual herbicide applied in PRE fb EPOST systems in 2022.[z]

Residual herbicide[y]	Fruiting node	Total bolls	Harvestable bolls
		plant^{-1}	
Acetochlor	3.5 a[x]	3.6 ab	3.4 ab
Dimethenamid-P	3.9 a	4.2 ab	3.9 ab
Pendimethalin	3.4 a	3.8 ab	3.6 ab
S-metolachlor	3.4 a	2.8 b	2.7 b
No over-lapping residual[w]	3.3 a	3.2 b	2.9 b
Non-treated	0.7 b	0.6 c	0.5 c
Weed-free	4.0 a	4.6 a	4.5 a

[z] PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

[y] PRE residual herbicides were combined with fluometuron *fb* the same residual herbicide combined with glyphosate + trait herbicide EPOST (Trait herbicide in Enlist system = 2,4-D choline; XtendFlex system = dicamba).

[x] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

[w] No over-lapping residual = fluometuron *fb* glyphosate + trait herbicide.

Table 4.20. Pearson correlation coefficients and corresponding P-values for cotton yield component response to Palmer amaranth biomass and density at the end of the season.[z]

	Fruiting node plant^{-1}	Retained total bolls plant^{-1}	Retained harvestable bolls plant^{-1}
Palmer amaranth biomass	-0.5956163***[y,x]	-0.6265573***	-0.6256839***
Palmer amaranth density	-0.6385192***	-0.687577***	-0.6850928***

[z] End of season = October 13, 2022

[y]Correlation coefficients were nonsignificant or significant at *P ≤ 0.05, **P ≤ 0.01 or ***P ≤ 0.001.

[x]Pearson coefficient: <0.3 = weak correlation, >0.3 but <0.5 = moderate correlation, >0.5 = strong correlation.

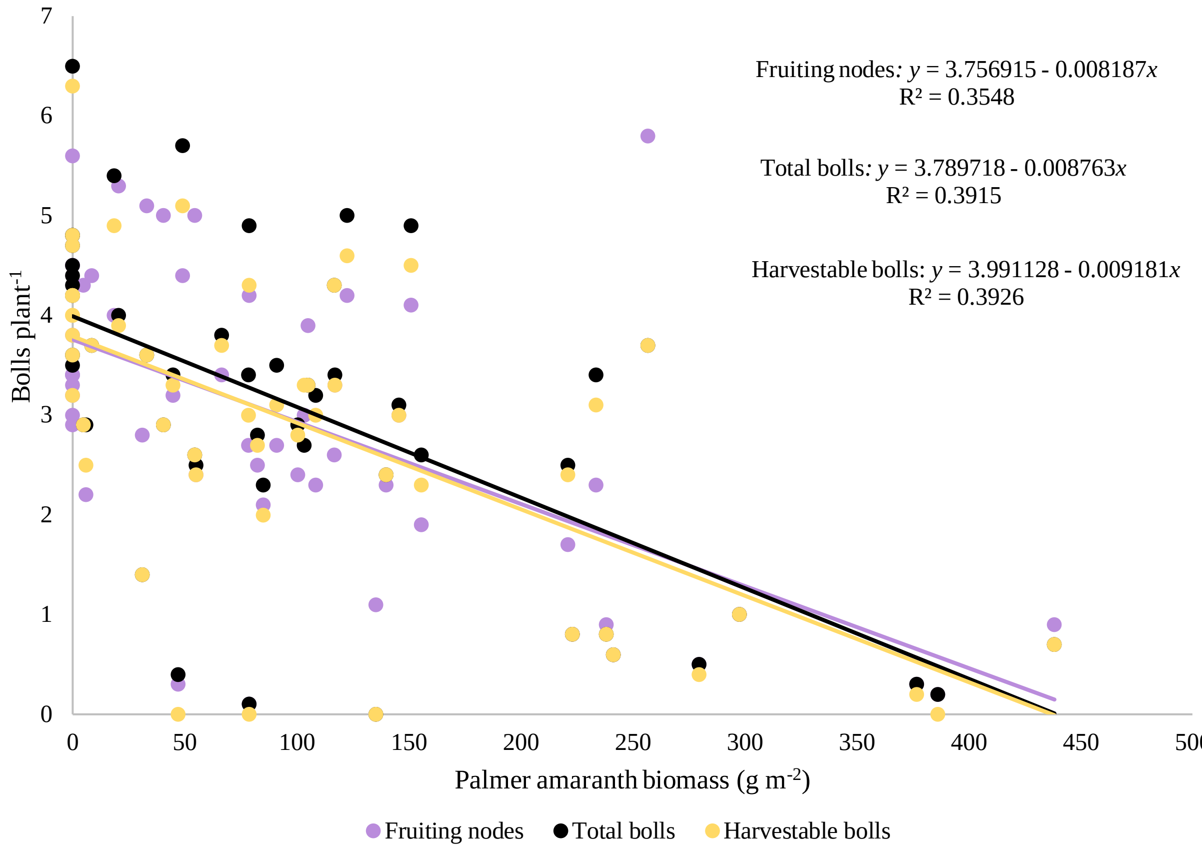

Figure 4.1. Linear regression of Palmer amaranth biomass, fruiting nodes plant^{-1}, harvestable bolls plant^{-1}, and total bolls plant^{-1} herbicide-resistant cotton systems as influenced by residual herbicide applied in PRE fb EPOST systems in Hutchinson, KS in 2022.[z]

[z] PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

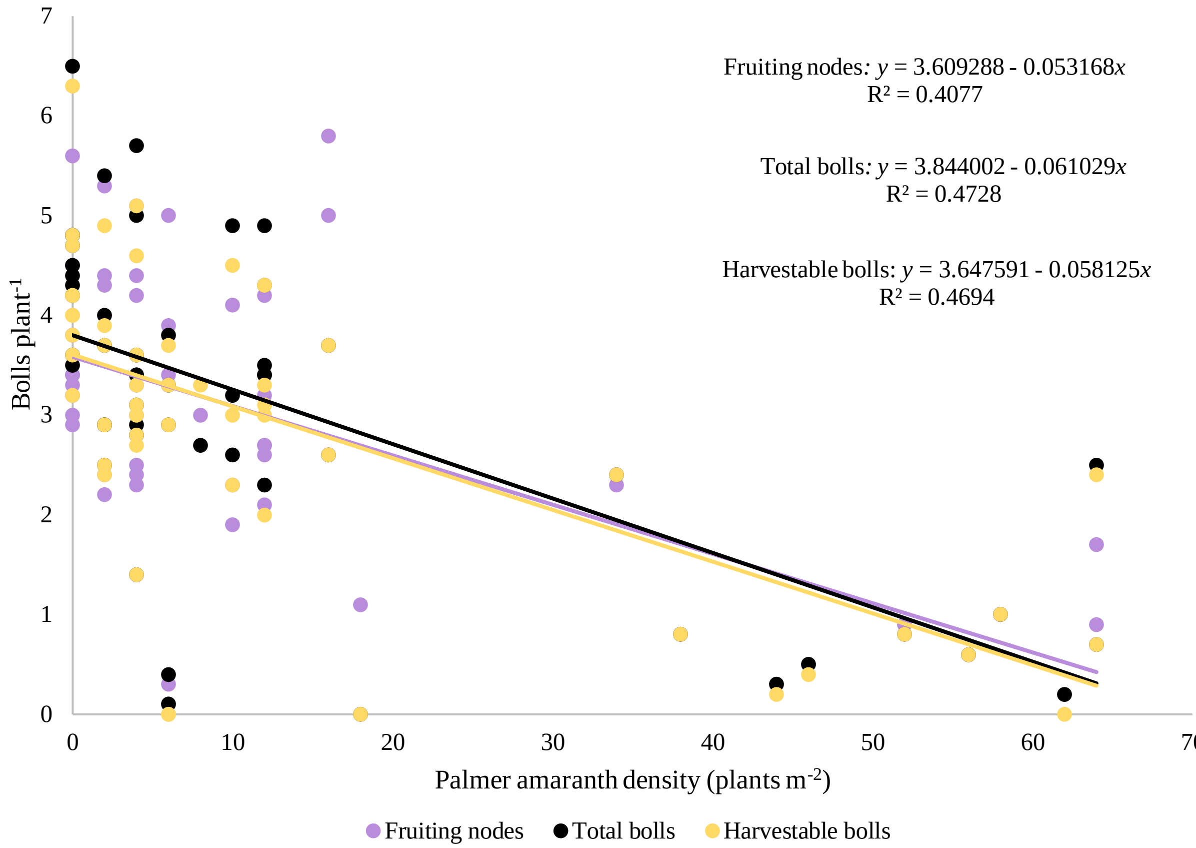

Figure 4.2. Linear regression of Palmer amaranth density, fruiting nodes plant^{-1}, harvestable bolls plant^{-1}, and total bolls plant^{-1} herbicide-resistant cotton systems as influenced by residual herbicide applied in PRE fb EPOST systems in Hutchinson, KS in 2022.[z]

[z] PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

Chapter 5 - Precipitation and Temperature Effects on VLCFA-Inhibiting Herbicides

5.1 Abstract

As weather extremes and herbicide-resistant weeds continue to challenge growers, it is important to characterize the effect of the environment on the efficacy of residual herbicides. The objective of this trial was to compare the impact of environmental conditions on the efficacy of VLCFA-inhibiting herbicides when applied at various times throughout the growing season. To fulfill this objective, a bare-ground field experiment was conducted in Manhattan, KS in 2021 and 2022. The experiment included four herbicides, acetochlor (1682 g ai ha^{-1}), *S*-metolachlor (2142 g ai ha^{-1}), dimethenamid-P (1104 g ai ha^{-1}), and pyroxasulfone (219 g ai ha^{-1}). Herbicides were applied on April 14, April 29, May 14, June 4, and June 18, 2021, and April 18, May 23, June 21, and July 12, 2022. Visible weed control and weed height were recorded 1 to 8 weeks after treatment (WAT) on a weekly basis and were subject to logistic and linear regression. Weed density and biomass were collected 8 WAT. The dominant weed species was Palmer amaranth (*Amaranthus palmeri* S. Watson). Accumulated rainfall and accumulated soil growing degree days (SGDD) from application to evaluation were collected. Accumulated rainfall received from application to 8 WAT ranged from 0.3- to 34.9-cm and SGDD accumulated from application to 8 WAT ranged from 30.9 to 2031.0 SGDD. To test the effects of rainfall and SGDD on the probability of successful weed control, binary responses (greater or less than 80%) of each herbicide were subjected to logistic regression. The probability of successful weed control following applications acetochlor decreased as accumulated rainfall increased. The probability of successful weed control was 80% with acetochlor when as little as 3-cm of rainfall was received in warm conditions (1750 SGDD). The probability of successful weed control by dimethenamid-

P decreased as both rainfall and SGDD increased. The probability of successful weed control by dimethenamid-P was 90% or greater when rainfall was less than 14-cm and SGDD was less than 1050 SGDD. However, the proability of successful weed control was less than 90% once accumulated SGDD exceeded 1050 regardless of the amount of accumulated rainfall. Applications of pyroxasulfone resulted in 90% or greater probability of successful weed control when 20 to 22-cm accumulated rainfall was received when SGDD ranged from 450 to 2050. For *S*-metolachlor, the propability of successful weed control was 90% or greater when accumulated rainfall increased from 4- to 22-cm and when SGDD decreased from 2050 to 150, but the proabability of successful weed control decreased as accumulated rainfall decreased and SGDD increased.

5.2 Introduction

Climatic conditions can significantly impact herbicide efficacy. Precipitation amounts and timing relative to residual herbicide application are critical to ensure the efficacy of residual herbicides (Myers and Harvey 1993; Stewart et al. 2012; Jhala et al. 2015; Janak and Grichar 2016; Hay et al. 2018; Landau et al. 2021; Mobli et al. 2023; Silva et al. 2023). Few studies exist that directly quantify the relationship between residual herbicide and precipitation, rather most authors' attribute their results to wet or dry conditions following application. Landau et al. (2021) and Stewart et al. (2010, 2012) quantify the relationship between environmental conditions and residual herbicide efficacy. Landau et al. (2021) reported weed control is maximized with residual herbicides when 10-cm or more rainfall is received within 15 days after application (DAA), which allows for adequate incorporation of herbicides into the soil-water solution and contact with the weed seeds. When a minimum of 10 cm of rainfall was received within 15 days after treatment, soil temperature had less effect on weed control, while less than 10 cm of rainfall resulted in decreased weed control with increased soil temperatures (Landau et al. 2021). Stewart et al. (2010, 2012) reported reduced weed control in environments where ≤1.7-cm of rainfall followed residual herbicide applications within 7 days. Alternatively, in environments where rainfall surpassed the monthly average by 60 to 64% resulted in poor weed control (Stewart et al. 2010, 2012). The anticipated increase in hot and dry conditions throughout crop-growing regions coupled with poor weed control due to the increased presence of herbicide-resistant weeds will likely result in decreased crop productivity (Landau et al. 2021).

Residual herbicides are a critical component of weed management programs across many crops, as residual herbicides often improve the efficacy of postemergence (POST) herbicide applications due to reduced number and size of weeds exposed to the POST herbicide (Shaner and Beckie 2014; Walsh et al. 2013; Norsworthy et al. 2012; Liphadzi and Dille 2006). Increased weed control was observed over half of the time when residual herbicides were utilized as compared to systems without residual herbicides in programs with three or more passes (Price et al. 2008). Season-long Palmer amaranth control can be achieved when two or more effective sites of action are utilized and a residual herbicide is included in the POST application, which can help eliminate weed seed bank replenishment (Kohrt and Spraque 2017). The prevention of weed seed bank replenishment is critical for crop production and the conservation of the remaining effective herbicides, as small weed populations play a large role in delaying the development of herbicide-resistant weeds (Walsh et al. 2013).

Palmer amaranth (*Amaranthus palmeri* S Watson) is a summer annual weed species that can germinate as early as March and can be extremely detrimental to summer annual crop yields (Keeley et al. 987; Berger et al. 2015; Liu et al. 2021). Palmer amaranth interference has been observed to cause yield losses up to 91% in corn, 92% in cotton, 68% in grain sorghum, and 79% in soybean (Rowland et al. 1999; Massinga et al. 2001; Morgan et al. 2001; Bensch et al. 2003; MacRae et al. 2013). Palmer amaranth uses the C4 photosynthetic pathway, which gives this species an advantage over many crops due to its ability to withstand droughty conditions (Ehleringer 1983). Palmer amaranth has a rapid growth rate and biomass accumulation, which often enables the species to compete for light and space with agronomic crops (Massinga et al. 2001; Morgan et al. 2001). In 2000, very long chain fatty acid (VLCFA) inhibiting herbicides were applied on 3 and 66% of soybean and corn acres (NASS 2000a, b). However, the increased presence of herbicide-resistant weeds may be the explanation of the resurgence of use of residual herbicides like the VLCFA-inhibiting herbicides, particularly herbicide-resistant Palmer amaranth. In 2021, 41% of corn acres were treated with glyphosate and 61% of corn acres were treated VLCFA-inhibiting herbicides (NASS 2022). In 2020, 78% of soybean acres were treated with glyphosate and 19% of soybean acres were treated with VLCFA-inhibiting herbicides (NASS 2021).

The VLCFA-inhibiting herbicides have been a part of herbicide programs in many crops for the control of grassy and small-seeded broadleaf weeds since their discovery in 1953 (Hamm 1974; Shaner et al. 2014). Specifically, chlorocetamide and pyrazole herbicides compose most VLCFA-inhibiting herbicides applied in cropping systems in the U.S. (Shaner et al. 2014). The first chloroacetamide herbicide, α-Chloro-N,N-diallylacetamide (CDAA), was made commercially available in 1956 by Monsanto company for control of grassy weeds in several major crops, which was the first case of a herbicides being applied preemergence (PRE) to a crop (Hamm 1974). The VLCFA-inhibiting herbicides are absorbed by plants after germination but prior to emergence (Fuerst 1987; Matthes et al.1998). The VLCFA-inhibiting herbicides are absorbed by the coleoptile in broadleaf weeds and radicle in grass weeds, which inhibits root and shoot development due to the inhibition of the biosynthesis of very long chain fatty acids which comprise epicuticular wax, plant membranes, and seed storage lipids (Fuerst 1987; Matthes et al. 1998).

Slower degradation of residual herbicide in soil may equate to longer periods of weed control (Mueller et al. 1999). Previous research has characterized the dissipation of acetochlor, *S*-metolachlor, dimethenamid-P and pyroxasulfone, where pyroxasulfone had a longer duration of weed control than acetochlor, dimethenamid-P, and *S*-metolachlor, but control was less in years with less precipitation (Mueller and Steckel 2011). The rate of herbicide degradation may increase following increases in soil water content and temperature, which may be attributed to changes in microbial activity in the soil (Zimdahl and Clark 1982; Baer and Calvet 1999; Stewart et al. 2012). The primary pathway of degradation for VLCFA-inhibiting herbicides is microbial degradation (Zimdahl and Clark 1982). More rapid dissipation of herbicides was observed in tropical or southern climates than in temperate or northern climates which was attributed to greater temperatures and precipitation in the tropical climates (Helling 2005). microbial degradation may be slower and result in a longer period of residual herbicide efficacy in dry and cool conditions or areas with low soil organic matter which makes such areas more at risk of herbicide carryover (Helling 2005). Helling (2005) reported for every 10 C temperature increase there was a 2.2-fold increase in the rate of herbicide degradation. Zimdahl and Clark (1982) reported increased degradation rates of alachlor, propachlor, and *S*-metolachlor when soil water contents exceeded 50% of field capacity at 20 C as compared to when soil water content was 20% of field capacity. Alachlor, propachlor, and *S*-metolachlor degradation increased as temperature increased from 10 to 30 C with soil water content at 50% field capacity as compared to when soil water contents was 20% of field capacity, indicating increases in temperature and soil moisture will result in a shorter length of residual herbicide activity (Zimdahl and Clark 1982). Decreased soil moisture and temperature can result in prolonged herbicide persistence due to reduced microbial degradation (Long et al. 2014). Preemergence application may need to be followed by a POST application in years when little to no rainfall follows the application, regardless of herbicide tank mixes utilized for PRE applications.

Understanding the effect of environment on VLCFA-inhibiting herbicides will help growers make management decisions on how to use these herbicides to maximize weed control. Therefore, the objective of this research is to determine the effect of precipitation and temperature on the efficacy of the acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor. It is hypothesized that the selected VLCFA-inhibiting herbicides will vary in response to different levels of rainfall and temperatures. Specifically, pyroxasulfone will be able to withstand the greater levels of rainfall due to low water solubility values, while dimethenamid-P may result in greater control under less rainfall. All VLCFA-inhibiting herbicides will likely have reduced levels of control when greater levels of rainfall are combined with high temperatures due to increased microbial degradation.

5.3 Materials and Methods

Site years

Field experiments were conducted in 2021 and 2022 at the Ashland Bottoms Research Station near Manhattan, Kansas (MHK; Latitude: 39.13, Longitude: 96.61) in a fallow field, previously planted to grain sorghum (2021) or soybean (2022). Site information is in table 5.1.

A split-plot design with four replications was used. Application date was the main plot, and the residual herbicide was randomly assigned to subplots. Each main plot included a nontreated check. Individual plots were 3 m by 9 m in size. Herbicides were applied on April 14, April 29, May 14, June 4, and June 18, 2021, and April 18, May 23, June 21, and July 12, 2022. Residual herbicide treatments included acetochlor (1,682.1 g ai ha^{-1}; Warrant®, Bayer CropScience, St. Louis, MO), dimethenamid-P (1,103.7 g ai ha^{-1}; Outlook®, BASF Corp., Research Triangle Park, NC), pyroxasulfone (219.2 g ai ha^{-1}; Zidua SC®, BASF Corp., Research Triangle Park, NC), and *S*-metolachlor (2,141.8 g ai ha^{-1}; Dual II Magnum®, Syngenta Corp., Greensboro, NC). Herbicide rates were selected based on current recommendations (2022 Chemical Weed Control Guide). Prior to each application, the ground was cultivated to ensure it was weed free. Spray solution was applied directly to plots with 140 L ha^{-1} spray volume using a CO_2 powered backpack sprayer and a 4-tip, 1.9-m hand-held boom equipped with TT 11001 nozzles (TeeJet Technologies, Springfield, IL 62703) at 220 kPa.

Data collection

Weed control evaluations were taken on a weekly basis from 1 to 8 weeks after treatment (WAT). However, only data from 4 and 8 WAT were subjected to an ANOVA. Weekly control and height data were subjected to logistic and linear regression to capture the effect environment and days. Additionally, data from 4 and 8 WAT was presented separately to reflect control at a time when POST herbicide application are commonly made. Weed biomass and density was collected 8 WAT for all application dates. At the start of trial, four Onset MX2201 HOBO Pendant MX Soil and Water Temperature Data Loggers® (Onset Computer Corporation, Bourne, MA) were placed 5-cm under the soil surface to measure soil temperature. Soil temperature sensors were programmed to take hourly readings. Soil temperature data were used to calculate accumulated soil growing degree days (SGDD) with the base temperature of 10 C and maximum temperature of 30 C from day of application to 8 weeks after treatment (WAT).

Statistical analysis

Palmer amaranth control and height at 4 and 8 WAT and Palmer amaranth biomass and density at 8 WAT were assessed for normality and heteroskedasticity using Shapiro-Wilk test in R package stats (R Core Team 2022) and Levene's test in R package car (Fox and Weisberg 2019). Palmer amaranth biomass in 2021 and density in 2022 did not fit analysis of variance (ANOVA) assumptions and thus were transformed with a logarithmic transformation (log(x+1)). Data were subjected to ANOVA using base R (R Core Team 2022; α =0.10). Replication was considered a random effect, and application date and residual herbicide were considered fixed effects. Site years were not compared due to differences in application dates, application intervals, and rainfall (Landau et al. 2021; Silva et al. 2023). Results of the ANOVA are presented in the appendix. Transformed data were back transformed after analysis (e^x-1). Means were separated using Tukey's HSD Test ($\alpha = 0.05$) in R package emmeans version 1.8.3 (Lenth 2022).

To test the effect of SGDD and rainfall on weed control and days for Palmer amaranth to reach 10-cm in height data were subjected to logistic regression using glm() in R package stats (R Core Team 2022). Prior to analysis, responses were transformed to binary variables. Weed control ratings ≥80% were considered successful (response =1) and <80% control was considered unsuccessful (response = 0; CWSS 2018; Landau et al. 2021). Weed height ≥ 10-cm (response = 1) and weed height < 10-cm (response = 0) were used as previous research has reported greater POST herbicide efficacy when Palmer amaranth less than 10-cm were targeted (Crow et al. 2016; Meyer and Norsworthy 2019). Hosmer–Lemeshow P-value was used to test lack-of-fit with hoslem.test() in R package ResourceSelection (Lele et al. 2019) where $p > 0.10$ is an acceptable fit. All graphs were built in R package ggplot2 (Wickham 2016).

5.4 Results and Discussion

Environmental conditions and weeds

In 2021, the accumulated rainfall for the season (April 1st to September 30th) was 9.1-cm less than the 30-year normal (61.2 cm) for the same time frame (Table 5.2). However, rainfall in May 2021 (15.2 cm) and July 2021 (15 cm) was greater than the 30-year normal. Applications made on May 14, 2021, were followed by 13.7 cm of rainfall within 2 WAT. Applications made on April 14, June 4, and June 18, 2021, did not accumulate greater than 5 cm of rainfall until 5, 6, and 4 WAT, respectively (Table 5.3). Rainfall accumulation is important point of consideration as adequate levels precipitation are recommended within 1 to 2 weeks of making applications of soil applied herbicides to ensure herbicide efficacy (Myers and Harvey 1993; Stewart et al. 2010, 2012; Landau et al. 2021). The amount of precipitation required for the activation of VLCFA-inhibiting herbicides can vary with soil type and individual VLCFA-inhibiting herbicides (Anonymous 2019, 2020, 2021, 2022). The Dual II Magnum® (*S*-metolachlor) label recommends 1 cm of precipitation on coarse textured soils and 2.5 cm of precipitation fine textured soils within 2 days of application (Anonymous 2022). The Outlook® (dimethenamid-P) herbicide label does not a specify a precipitation amount or interval. The Warrant® (acetochlor) herbicide label deems 1 to 2 cm to be adequate levels of precipitation to move the herbicide into the weed seed germination zone but does not specify a time interval in which it is required (Anonymous 2020). The Zidua® SC (pyroxasulfone) herbicide label recommends 1 cm of precipitation prior to weed germination and emergence (Anonymous 2021). Dry conditions following residual herbicide applications has frequently been associated with poor weed control as precipitation is required to incorporate herbicides into the soil solution where it can be absorbed by emerging weeds (Landau et al. 2021; Mobli et al. 2023; Silva et al. 2023).

In 2022, the total in-season rainfall was only 1 cm greater than the 30-year normal. The months of May, June, and July received 9.8, 3.6, and 10.2 cm more rainfall than the 30-year normal for those same months, respectively. The only application date that did not received 5-cm or greater rainfall within 2 WAT was April 18, 2022, but was followed by 7.6 cm of rainfall within 4 WAT. The maximum accumulated SGDD in 2022 was greater than 2021 (Table 5.4). The differences may be accounted for by the later application dates in 2022 as compared to 2021 (Table 5.5). Additionally, average temperatures in May and July in 2022 were greater than May and July in 2021 (Table 5.5). However, average temperatures in June, August, and September in 2021 were greater than those recorded in 2022.

The dominant weed species in 2021 and 2022 was Palmer amaranth. Palmer amaranth has been ranked the one of the most troublesome weeds in U.S. cropping systems (Vanwychen 2021, 2022). In 2021, common waterhemp (*Amaranthus tuberculatus* (Moq.) Sauer) and large crabgrass (*Digitaria sanquinalis* (L.) Scop.) were observed. In 2022, common waterhemp and Nuttall's alkaligrass (*Puccinellia nuttalliana* (Schult.) Hitchc.) were observed. These weeds were not included in the analysis due variable distribution within trial locations in 2021 and 2022. The trial location in 2022 was unintentionally placed in a low-lying area, which resulted in wetter soil conditions following rainfall. This maybe a partial explanation for the presence of Nuttall's alkaligrass, which prefers damp soil conditions.

Palmer amaranth control

In 2021, there were no significant effects at 4 WAT (Table 5.6). There were no differences among treatments and Palmer amaranth control was 95%. No weeds were present for the first 4 weeks following applications on April 14, 2021, which may be a partial explanation for the lack of significant effects.

At 8 WAT, there was a significant interaction between application date and residual herbicide for Palmer amaranth control (Table 5.6). Similar to results reported 4 WAT, there were no differences observed among application dates for dimethenamid-P, pyroxasulfone, and *S*-metolachlor (Table 5.7). Acetochlor applied on April 29th, June 4th, and June 18th resulted in Palmer amaranth control greater than levels observed following applications made on May 14th (43%). The low levels of Palmer amaranth control following acetochlor applications on May 14th may largely be attributed to the 11.9-cm rainfall that were accumulated within 2 WAT. Alternatively, herbicide application made on April 29th and June 18th were followed by 1.8- and 2.4-cm of rainfall within 2 WAT. June 4th applications were followed by 0.1 cm of rainfall 1

WAT, but within 3 WAT 2-cm of rainfall were accumulated. This indicates a minimum of 2 cm of rainfall may be an adequate level of rainfall to dissolve VLCFA-inhibiting herbicides into the soil-water solution.

In 2022, there were no interactions for Palmer amaranth control 4 WAT, however, the main effect of residual herbicide was significant (Table 5.6); therefore, data were pooled across application dates. Applications of acetochlor resulted in 71% Palmer amaranth control, while dimethenamid-P, pyroxasulfone, and *S*-metolachlor resulted in 90 to 91% control (Table 5.8). All application dates were followed by 3.7 to 21.2 cm or greater of rainfall within 2 WAT (Table 5.3).

At 8 WAT, there were no interactions for Palmer amaranth control, however, the main effects of residual herbicide and application date were significant (Table 5.6); therefore, data were pooled across application dates and residual herbicide. Pyroxasulfone resulted in greater Palmer amaranth control than dimethenamid-P and acetochlor (Table 5.8). By 8 WAT, applications made on April 18th, May 23rd, June 21st, and July 12th had accumulated 30.1, 38.6, 31.8, and 18.9 cm of rainfall, respectively (Table 5.3). This indicates that pyroxasulfone may be able to provide a longer length of residual than acetochlor and dimethenamid-P despite high levels of accumulated rainfall. Westra et al. (2015) reported a lower adsorption coefficient for pyroxasulfrone than *S*-metoalchlor and dimethenamid-P. This would allow pyroxasulfone to be more available for plant absorption in soil water solution, which may be a partial explanation for the increased levels of Palmer amaranth control observed following pyroxasulfone applications in the present study. Applications made on May 23rd resulted in less Palmer amaranth control than applications made on April 18th, June 21st, and July 12th (Table 5.9). Applications made on

May 23rd were followed by the greatest amount of accumulated rainfall by 8 WAT, which may be a partial explanation for the poor weed control observed (Table 5.3).

Logistic regression models were built to illustrate the roll environment plays in the efficacy of the residual herbicides tested in this trial. The contour plots illustrate the effect of the accumulated rainfall and SGDD from day of application to 4 WAT and from 5 WAT to 8 WAT (Figure 5.1, 5.2). Directionality of the contours indicates if the environmental factors interacted or were additive. More diagonal contours indicate an interaction, while more horizontal or vertical contours indicate an additive effect. Individual models were built for each residual herbicide (Table 5.10). The probability of successful weed control following acetochlor applications decreased as accumulated rainfall increased, but the probability of successful weed control was greater than 90% when less than 15 cm of accumulated rainfall was received with 4 WAT and 1600 or less SGDD were accumulated. Additionally, the lowest probability of successful weed control was 13% and was associated with 18.9 cm of accumulated rainfall. However, the probability of successful weed control with acetochlor was 95% or greater when conditions were dry (<7.4 cm) regardless of SGDD (Figure 5.1). The Warrant® (acetochlor) herbicide label deems 1 to 2 cm to be adequate levels of precipitation to move the herbicide into the weed seed germination zone (Anonymous 2020). While for dimethenamid-P the probability of successful weed control was less than 1% when 18.9 cm of rainfall were received and combined with cooler temperatures (Figure 5.1). The probability of successful weed control with dimethenamid-P was 90% or greater when 16 cm or less rainfall was accumulated when 700 SGDD or less was accumulated. Additionally, probability of successful weed control was 90% or greater when 800 to 1200 SGDD was accumulated regardless of accumulated rainfall and when accumulated SGDD was 1300 or greater a minimum of 7 cm of rainfall was required (Figure

5.1). Unfortunately, the Outlook® herbicide label makes no mention of precipitation requirements following application (Anonymous 2019). Up to 4 WAT, pyroxasulfone and *S*-metolachlor resulted in 90% or greater probability of successful weed control across all SGDD and rainfall values observed in the present trial (100 to 1650 SGDD; 0 to 19 cm rainfall). The Zidua® herbicide label states that following applications with 1-cm of precipitation can improve weed control, but greater than 2.5 cm can result in reduced weed control (Anonymous 2021). Dual II Magnum® label provides a range of precipitation values based on soil textural classes. For the silt clay loam soils observed at the trial locations, 2.5 cm of precipitation is recommended within 2 days of applications. The short time interval may be recommended as photodegradation can become an important pathway of degradation when herbicide molecules remain unincorporated for prolonged periods of time (Oliveira et al. 2013; Westra 2012). Excessive rainfall decreased the probability of successful control with acetochlor and Dimethenamid-P. Both acetochlor and dimethenamid-P were negatively impacted by cool and hot conditions, but the interactions with rainfall differed between the herbicides. Pyroxasulfone and *S*-metolachlor appeared to provide high probabilities of weed control despite variations in rainfall and SGDD from day of application to 4 WAT.

From 5 to 8 WAT, the probability of successful weed control following applications acetochlor and dimethenamid-P decreased as accumulated rainfall increased (Figure 5.2). Additionally, the probability of successful weed control was 80% when as little as 3-cm of rainfall was received in warm conditions (1750 SGDD). Dimethenamid-P generally resulted in a greater probability of successful weed control under cool and dry conditions, while acetochlor was able to withstand high temperatures (Figure 5.2). The probability of successful weed control by dimethenamid-P decreased as both rainfall and SGDD increased. The probability of successful weed control by dimethenamid-P was 90% when less rainfall was received in warmer conditions and when greater rainfall was received in cooler conditions, when rainfall was less than 14 cm and SGDD was less than 1050 SGDD. However, the proability of successful weed control was less than 90% once accumulated SGDD exceeded 1050 regardless of the amount of accumulated rainfall. From 5 to 8 WAT, applications of pyroxasulfone resulted in 90% or greater probability of successful weed control when 20 to 22 cm accumulated rainfall was received when SGDD ranged from 450 to 2050. For *S*-metolachlor, the propability of successful weed control was 90% or greater when accumulated rainfall increased from 4 to 22 cm and when SGDD decreased from 2050 to 150, but the proabability of successful weed control decreased as accumulated rainfall decreased and SGDD increased (Figure 5.2).

Previous research has reported variable amounts of rainfall required for herbicide activation, but the common consensus is that rainfall is required within 10 to 15 days after treatment to optimize efficacy of residual herbicides (Myers and Harvey 1993; Stewart et al. 2010, 2012; Whitaker et al. 2011; Westra et al. 2014; Cahoon et al. 2015; Janak and Grichar 2016; Jhala et al. 2015; Hay et al. 2018; Landau et al. 2021; Mobli et al. 2023; Silva et al. 2023). Previous research demonstrated a minimum of 5 cm of rainfall for acetochlor and 10 to 15 cm of rainfall for *S*-metolachlor are required to be accumulated within 15 days after treatment to obtain a minimum of 80% waterhemp control (Landau et al. 2021). Hay et al. (2018) reported 64, 54, 69, and 78% waterhemp control 8 WAT with encapsulated acetochlor, dimethenamid-P, *S*-metolachlor, and pyroxasulfone, respectively, when conditions were dry following a 2-week delay in herbicide activation. Alternativley, Westra et al. (2014) reported potential for decreased weed control following applications of pyroxasulfone and *S*-metolachlor when significant rainfall events (7 cm) occur within 10 days after treatment due to the movement of herbicides deeper into the soil profile (>7.5 cm). Myers and Harvey (1993) observed poor control of common lambsquarters when preemergence applications of atrazine tank mixed with metolachlor or acetochlor (≤51%) were followed by 1.5 cm of rainfall within 54 days after treatment. Alternatively, Jhala et al. (2015) reported poor levels of Palmer amaranth control with encapsulated acetochlor under adequate moisture conditions but recommended its use in PRE fb POST systems. Cahoon et al. (2015) observed 84% or greater Palmer amaranth control when applications of encapsulated acetochlor + dicamba were followed by a minimum of 1.3 cm rainfall within 10 days after treatment, while Hay et al. (2018) observed 68% or less Palmer amaranth control when 1.8 cm of rainfall was received within 7 days of treatment. Silva et al. (2023) reported more reliable control of waterhemp with herbicide pre-mixes rather than individual herbicides, specifically when inadequate levels of rainfall. Whitaker et al. (2011) observed a wide range in Palmer amaranth control at 20 (57 to 96%) and 40 (4 to 86%) days after treatment with *S*-metolachlor when adequate levels of rainfall (3.5-cm) were received within 2 WAT, where lower levels of Palmer amaranth control were associated with low organic matter soils (Whitaker et al. 2011). This may be attributed to the reduced water holding capacity of soils with low levels of soil organic matter.

Palmer amaranth height, biomass, and density

In 2021, there was a significant interaction between application date and residual herbicide for Palmer amaranth height at 4 WAT and 8 WAT (Table 5.6). No weeds were present for the first 4 WAT on April 14, 2021, so height data was not taken. There were no differences in Palmer amaranth height among residual herbicides and the non-treated check following applications made on April 29th and June 18th (Table 5.11). Following applications made on May 14th, there were no differences between the non-treated check and applications of acetochlor, while there were no Palmer amaranth present 4 WAT with pyroxasulfone and *S*-metolachlor. Four WAT on June 4th there were no weeds present following applications of all residual herbicides, but the non-treated check resulted in Palmer amaranth that were 6.7 cm in height.

At 8 WAT, there were no differences in Palmer amaranth height among residual herbicides and the non-treated check following applications made on April 14th and April 29th (Table 5.12). All residual herbicides applied on May 14th, June 4th, and June 18th reduced Palmer amaranth height relative to non-treated plots. There were no Palmer amaranth present following pyroxasulfone applications on May 14th, dimethenamid-P, *S*-metolachlor applications on June 4th and *S*-metolachlor applications on June 18th. There were few differences in Palmer amaranth height among residual herbicides applied May 14th, June 4th, and June 18th. Pyroxasulfone resulted in shorter Palmer amaranth than acetochlor when applied on May 14th and *S*-metolachlor resulted in shorter Palmer amaranth than dimethenamid-P when applied on June 18th.

At 4WAT in 2022, there were no interactions for Palmer amaranth height, however, the main effects of residual herbicide and application date were significant (Table 5.6); therefore, data were pooled across application dates and residual herbicide. There were no differences in Palmer amaranth height among acetochlor, dimethenamid-P, *S*-metolachlor, and the non-treated check 4 WAT (Table. 5.13). Applications of pyroxasulfone resulted in smaller plants than the non-treated check but was not different than other herbicides. Applications made on April 18th (2.8 cm) resulted in Palmer amaranth smaller in size than Palmer amaranth following applications made on June 21st (13.8 cm) and July 12th (7.5 cm). No Palmer amaranth height data was reported 4 weeks after applications made on May 23rd due to flooded field conditions.

At 8 WAT, there was a significant interaction between application date and residual herbicide for Palmer amaranth height (Table 5.6). There were no differences in Palmer amaranth height among residual herbicides and the non-treated check following applications made on April 18th and May 23rd (Table 5.14). Pyroxasulfone resulted in the smallest Palmer amaranth following applications made on June 21st, but all other treatments were similar to the non-treated check. Pyroxasulfone also resulted in the smallest Palmer amaranth following applications on July 12th. Acetochlor and *S*-metolachlor resulted in Palmer amaranth similar in size to the non-treated check following applications made on July 12th.

In 2021 and 2022, Palmer amaranth were 10-cm or less in height 4 WAT regardless of application date or residual herbicide. Palmer amaranth were larger 8 WAT in 2022 as compared to 2021. The largest amount of accumulated rainfall was observed following the May 23, 2022, application date, which may be the partial explanation for the overall larger Palmer amaranth observed 8 WAT in 2022 as compared to 2021. Greater Palmer amaranth height is anticipated following later application dates due to greater SGDD accumulation (Horak and Loughlin 2000). Horak and Loughlin (2000) reported 231-, 174-, and 207-cm tall Palmer amaranth when thermal time reached 789, 970, and 1162 GDD, respectively.

Linear regression models were built to test the number of days for Palmer amaranth to reach 10-cm in height as influenced by residual herbicide. Palmer amaranth reached 10 cm in height at 23, 26, 30, 28, and 21 days after treatment for acetochlor, dimethenamid-P, pyroxasulfone, *S*-metolachlor, and the nontreated check, respectively (Figure 5.3). This indicates that pyroxasulfone may be able to suppress Palmer amaranth growth for a longer time than other VLCFA-inhibiting herbicides used in the present trial despite large amount of accumulated rainfall, which reflects control observations. Although pyroxasulfone was shown to have the smallest Palmer amaranth following the May 23rd application date, POST control would be unlikely although previous research has reported successful control of large Palmer amaranth late in the growing season (Crow et al. 2016; Meyer and Norsworthy 2019). Although pyroxasulfone resulted in Palmer amaranth reaching 10 cm after a longer period, all herbicides apart from acetochlor resulted in similar length of Palmer amaranth suppression. This indicates that in a herbicide program utilizing acetochlor, a postemergence application may need to be deployed earlier than dimethanmid-P, pyroxasulfone, and *S*-metolachlor.

Data in the current trial indicate that a POST applied within 4 weeks of a single application of VLCFA-inhibiting may be more effective in targeting Palmer amaranth of ideal size, which is 10 cm or less in height. Cuvaca et al. (2019) reported a 2-times and 27-times rate increase of dicamba to control 15- and 30-cm Palmer amaranth as compared to plants that were 10-cm or less in height (Crow et al. 2016; Meyer and Norsworthy 2019). The probability of Palmer amaranth reaching 10-cm was less with applications VLCFA-inhibiting herbicides as compared to the non-treated check (Figure 5.2). Liphadzi and Dille (2006) reported smaller Palmer amaranth in corn as a PRE application of isoxaflutole alone was utilized as compared to no residual herbicide. Beyond herbicide efficacy, Palmer amaranth height is important to consider due to the negative effect Palmer amaranth has on light distribution within the crop canopy. Massinga et al. (2003) reported 60 to 80% light interception 1 m above the ground by Palmer amaranth within a corn canopy. Light interference can result in decreased photosynthesis rates which results in decreased dry matter accumulation and yield (Rajcan and Swanton 2001).

In 2021, there was a significant interaction between herbicide and application date for Palmer amaranth biomass and the main effect of herbicide was significant for density 8 WAT (Table 5.6). For Palmer amaranth biomass, there were no differences among residual herbicides following applications made on April 14th (Table 5.15). Herbicides applied on April 29th resulted in less Palmer amaranth biomass than the non-treated check except for dimethenamid-P and *S*-

metolachlor. On May 14th, biomass was greater following applications of acetochlor than dimethenamid-P, pyroxasulfone, and *S*-metolachlor. Applications of acetochlor following the May 14th application resulted in the greatest biomass, which indicates that a PRE only application of acetochlor may not be effective in maintaining less vigorous weeds, specifically following large rain events. This can decrease the effectiveness of herbicides utilized in postemergent herbicide applications. Herbicides applied on June 4th resulted in less Palmer amaranth biomass than the non-treated check except for dimethenamid-P and *S*-metolachlor. The largest amount of biomass was observed in the non-treated check following the June 18th application date with 521.2 g m^{-2}. Additionally, dimethenamid-P applied on June 18th resulted in biomass greater than *S*-metolachlor, which had no biomass present 8 WAT. Although detected by the ANOVA, there were no differences in Palmer amaranth densities among residual herbicides. Applications of acetochlor, dimethenamid-P, pyroxasulfone, *S*-metolachlor, and the non-treated check resulted in 5.0, 2.0, 0.8, 0.6, and 6.6 plants m^{-2}, respectively.

In 2022, there were no interactions for Palmer amaranth biomass and density 8 WAT, however, the main effect of application date was significant for biomass and density; therefore, data were pooled across herbicides (Table 5.6). In general, there were no differences among application dates for Palmer amaranth biomass except for applications made on April 18th (35.9 g m^{-2}) and June 21st (404.8 g m^{-2}; Table 5.16). Density following April 18th applications was greater than density following applications on June 21st or July 12th.

Apart from acetochlor applied on May 14, 2021 and acetochlor and dimethenamid-P applied on June 18, 2021, biomass and density levels were low if a herbicide was utilized. This indicates that acetochlor may be less effective in suppression of Palmer amaranth when applications were followed by 11.9-cm of rainfall within 2 WAT or 2.4-cm of rainfall within 2

WAT in combination with high levels of accumulated SGDD (Table 5.4, 5.15). This reflects control observed at 4 and 8 WAT as well. This poor suppression may be attributed to movement of acetochlor out of the seed zone and more microbial degradation due to warm and wet soil conditions (Zimdahl and Clark 1982). An explanation for lower levels of biomass and density observed following April 14th and April 29th applications may be the cooler temperatures often experience in April (Table 5.5). In 2022, Palmer amaranth were smaller, but were present at greater quantities following early applications while Palmer amaranth were larger and present at smaller densities following late applications. Greater levels of biomass accumulation should be expected following later application dates due to greater SGDD accumulation (Horak and Loughlin 2000). In the present trial, biomass levels were 35.9, 62.4, 404.8, and 314.8 g m^{-2} following applications made on April 18, May 23, June 21, and July 12, 2022, respectively (Table 5.15). The accumulated SGDD at time of biomass collection following applications made on April 18, May 23, June 21, and July 12 when biomass was collected was 603.9, 1188.4, 1714.6, and 2031.0, respectively (Table 5.4). This agrees with Keeley et al. (1987) and Horak and Loughlin (2000) who reported increases in Palmer amaranth biomass as temperatures increased. Additionally, lower densities observed following later application dates may be attributed to increased soil temperatures at the time of cultivation of the application date block and drier conditions experienced following applications made on June 21st and July 12th. Buol et al. (2021) reported reduction in biomass following applications of acetochlor and *S*-metolachlor following applications made in late May and June, while applications made in early May resulted higher levels of Palmer amaranth biomass. Additionally, the authors did not observe any differences in density levels among application timings following applications of acetochlor and *S*-metolachlor (Buol et al. 2021). Palmer amaranth density is important to consider as density has been observed to effect crop yields and crop water use and accumulated biomass has been shown to directly effect the amount of seed procuded by Palmer amaranth. Palmer amaranth densities of 8.0, 1.1, and 8.0 plants m^{-1} resulted in up to 91, 92, and 79% yield loss in corn, cotton, and soybeans, respectively (Rowland et al. 1999; Massinga et al. 2001; Bensch et al. 2003). Massinga et al. (2001) reported Palmer amaranth seed production increased from 1,800 to 91,000 seeds m^{-2} as Palmer amaranth densities increased from 0.5 to 8 plants m^{-2}. Keeley et al. (1987) and Norsworthy et al. (2016) reported that greater levels of Palmer amaranth seed production were associated with greater Palmer amaranth biomass. Although fewer and smaller Palmer amaranth plants would be associated with redeuced fecundity, seeds are still produced at levels adequate to replenish the weed seed bank (Keely et al. 1987; Norsworthy et al. 2016). Preventing weed seed bank replenishment is critical for conserving the remaining effective herbicides, as small weed populations play a large role in the delaying the development of herbicide resistant weeds (Walsh et al. 2013).

5.5 Conclusion

The effect of rainfall and temperature on the tested VLCFA-inhibiting herbicides varied. Generally, excessive rainfall and/or high temperatures decreased the probability of successful control for all herbicides evaluated, but pyroxasulfone had an advantage at high temperatures and high rainfall. This advantage maybe largely attributed to the molecule's low water solubility and decreased adsorption as compared to acetochlor, dimethenamid-P, and *S*-metolachlor (Westra et al. 2015). *S*-metolachlor may also be an effective option for Palmer amaranth control under high rainfall conditions. However, when at least 34.5 cm of rainfall was received within 8 WAT Palmer amaranth control was 18% regardless of residual herbicide. In the present trial all applications received an activating rainfall withing 3 WAT. In a scenario where the rainfall forecast is predicting little rainfall within 3 WAT, pyroxasulfone and *S*-metolachlor may not be the most effective options. Acetochlor may be the best fit for hot and dry conditions, as less accumulated rainfall was required to achieve high probability of successful weed control, which aligns with current recommendation (Jhala et al. 2015). Dimethenamid-P had a disadvantage in hot and dry conditions but was more likely to have ≥80% control in cool and wet conditions. If POST applications are made at or prior to 4 WAT, the VLCFA-inhibiting herbicide selected is less important as Palmer amaranth control remained high and Palmer amaranth remained less than 10-cm in height, which allows for greater efficacy of POST herbicides. However, once 4 WAT is surpassed, pyroxasulfone and *S*-metolachlor resulted in the lowest probabilities of Palmer amaranth reaching 10 cm and the greatest control, which indicates that these herbicides may provide growers and applicators with the greatest flexibility for POST applications. Further testing needs to be conducted over multiple site-years to gather more weather data and control data to further assess the impact of climatic conditions on the efficacy of VLCFA-inhibiting herbicides to develop robust models.

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Table 5.1. Soil characteristics of trial locations in 2021 and 2022 in Manhattan, KS.

Year	Replication	pH	Organic matter	Sand	Silt	Clay
			%			
2021	–	5.8	2.6	13	59	28
2022	1	7.5	2.2	18	64	18
	2	7.5	1.7	14	68	18
	3	7.4	2.3	15	66	19
	4	7.4	2.5	15	65	20

Table 5.2. Monthly precipitation levels for the duration of the trial in 2021 and 2022 in Manhattan, KS.

Month	2021[a]	2022[a]	30-year normals[b]
	cm		
April	6.2	2.4	9.1
May	15.2	20.7	10.9
June	2.5	15.8	12.2
July	15.0	15.0	10.2
August	4.1	3.9	11.5
September	8.9	4.4	7.3
Season total	51.9	62.2	61.2

[a] Monthly precipitation values were retrieved from the Kansas Mesonet (Kansas State University 2023). Weather stations were located within 2,300 M of each trial location.

[b] The 30-year normal values were retrieved from National Oceanic and Atmospheric Administration (National Climatic Data Center 2023) from the time of the initial herbicide application to 8 weeks after the last application date.

Table 5.3. Accumulated precipitation amounts received from the date of application to 8 weeks after treatment in 2021 and 2022 in Manhattan, KS.[a]

		Weeks after treatment							
Year	Application date	1	2	3	4	5	6	7	8
		cm							
2021	April 14	1.6	2.0	2.1	3.8	13.5	14.2	17.2	17.2
	April 29	0.1	1.8	11.88	13.7	15.2	15.2	15.3	15.5
	May 14	10.1	11.9	13.4	13.5	13.5	15.4	15.9	16.2
	June 4	0.1	0.1	2.0	2.5	2.7	16.6	16.6	17.16
	June 18	1.9	2.4	2.7	16.5	16.5	17.1	17.5	20.1
2022	April 18	0.1	3.3	7.6	8.6	11.4	21.3	24.7	29.7
	May 23	9.9	13.3	18.3	18.3	27.1	34.4	34.5	34.5
	June 21	8.8	16.1	16.2	16.2	23.5	23.8	23.9	24.6
	July 12	0	7.3	7.5	7.6	8.4	10.6	11.5	11.

[a] Precipitation values were retrieved from the Kansas Mesonet (Kansas State University 2023). Weather stations were located within 2,300 M of each trial location.

Table 5.4. Accumulated soil growing degree days (SGDD) measured from the date of application to 8 weeks after treatment in 2021 and 2022 in Manhattan, KS.[a]

Year	Application date	Weeks after treatment							
		1	2	3	4	5	6	7	8
		SGDD (C)[b] –							
	April 14	31.0	104.8	180.1	233.1	305.1	400.2	486.3	582.2
	April 29	180.1	233.1	305.1	400.2	486.3	582.2	698.0	800.5
2021	May 14	305.1	400.2	486.3	582.2	698.0	800.5	912.4	1025.3
	June 4	582.2	698.0	800.5	912.4	1025.3	1118.2	1295.1	1383.6
	June 18	800.5	912.4	1025.3	1118.2	1295.1	1383.6	1496.5	1628.6
	April 18	51.1	102.2	149.1	293.4	332.8	393.3	514.0	603.9
	May 23	393.3	514.0	603.9	689.2	773.6	893.3	1028.4	1188.4
2022	June 21	878.2	977.7	1028.4	1188.4	1371.8	1456.8	1616.2	1714.6
	July 12	1188.4	1371.8	1456.8	1616.2	1714.6	1839.2	1952.1	2031.0
	July 12	1188.4	1371.8	1456.8	1616.2	1714.6	1839.2	1952.1	2031.0

[a] Onset MX2201 HOBO Pendant MX Soil and Water Temperature Data Loggers® (Onset Computer Corporation, Bourne, MA) were placed 5 cm under the soil surface to measure soil temperature. Soil temperature sensors were programmed to take hourly readings.

[b] Accumulated SGDD were calculated using the following equation: $SGDD = \frac{T_{\max} + T_{min}}{2} - T_{base}$. The minimum temperature utilized was 10 C and the maximum temperature utilized was 30 C.

Table 5.5. Monthly temperature values for the duration of the trial in 2021 and 2022 in Manhattan, KS.

Month	2021[a]	2022[a]	30-year normals[b]
	C		
April	12	12	13
May	17	19	18
June	25	24	24
July	25	26	27
August	26	25	25
September	23	22	20
Season total	12	12	13

[a] Monthly temperature values were retrieved from the Kansas Mesonet (Kansas State University 2023). Weather stations were located within 2,300 M of each trial location.

[b] The 30-year normal values were retrieved from National Oceanic and Atmospheric Administration (National Climatic Data Center 2023) from the time of the initial herbicide application to 8 weeks after the last application date.

Table 5.6. Analysis of variance for Palmer amaranth control, height, biomass, and density as influenced by VLCFA-inhibiting herbicides in in Manhattan, KS in 2021 and 2022.

Year	Effect	Palmer amaranth control		Palmer amaranth height		Palmer amaranth biomass[b]	Palmer amaranth density[b]
		4 WAT[a]	8 WAT	4 WAT	8 WAT		
		p-value[c]					
2021	Herbicide	0.0634	0.0021	<0.0001	<0.0001	<0.0001	0.0560
	Application date	0.3242	0.2537	0.0109	<0.0001	<0.0001	0.3519
	Herbicide x Application date	0.0613	0.0079	0.0552	<0.0001	<0.0001	0.1257
2022	Herbicide	<0.0001	<0.0001	0.0042	<0.0001	0.3431	0.1227
	Application date	0.2913	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Herbicide x Application date	0.1917	0.4678	0.7719	0.0022	0.9981	0.3129

[a] WAT = weeks after treatment

[b] Measurements were taken at 8 WAT.

[c] Significance level used $p \leq 0.10$.

Table 5.7. Palmer amaranth control 8 weeks after treatment in Manhattan, KS in 2021 as influenced by application date and residual herbicide.

Application date	Residual herbicide			
	Acetochlor	Dimethenamid-P	Pyroxasulfone	*S*-metolachlor
	———Palmer amaranth control (%)———			
April 14	76 ab[a]	100 a	93 a	91 a
April 29	96 a	63 ab	100 a	98 a
May 14	43 b	81 ab	100 a	91 a
June 4	91 a	100 a	95 a	100 a
June 18	88 ab	69 ab	96 a	100 a

[a] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

Table 5.8. Palmer amaranth control 4 and 8 weeks after treatment in Manhattan, KS in 2022 as influenced by residual herbicide.

Residual herbicide	4 WAT[a]	8 WAT
	Palmer amaranth control (%)	
Acetochlor	71 b[b]	37 b
Dimethenamid-P	90 a	49 b
Pyroxasulfone	90 a	74 a
S-metolachlor	91 a	54 ab

[a] WAT = weeks after treatment

[b] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

Table 5.9. Palmer amaranth control 8 weeks after treatment in Manhattan, KS in 2022 as influenced by application date.

Application date	Palmer amaranth control (%)
April 18	64 a[a]
May 23	20 b
June 21	62 a
July 12	70 a

[a] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 5.10. Parameter estimates for the logistic regression models discriminating probability of successful control of Palmer amaranth using acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor.

WAT[a]	Residual herbicide	Intercept[b]	Accumulated rainfall (R)	Accumulated SGDD (T)	R×T	AIC	Hosmer–Lemeshow P-value[c]	Obs.
4	Acetochlor	6.0472***	-0.4226*	-0.0001	0.0001	85.7710	0.6067	140
	Dimethenamid-P	19.2810**	-1.4249*	-0.0161*	0.0015	48.2080	0.9978	142
	Pyroxasulfone	26.5700	0.0000	0.0000	-0.0000	8.0000	1.0000	76
	S-metolachlor	26.5700	-0.0000	-0.0000	-0.0000	8.0000	1.0000	80
8	Acetochlor	6.5490***	-0.2966**	-0.0020	0.0001	143.8500	0.1129	125
	Dimethenamid-P	5.7880***	-0.2214**	-0.2979*	0.0001	163.1200	0.1288	136
	Pyroxasulfone	-0.3536	0.1100	0.0078**	-0.0003**	86.9090	0.5002	168
	S-metolachlor	7.1310***	-0.2241*	-0.0021	0.0000	133.7800	0.4530	171

[a] WAT = Weeks after treatment

[b] *** = significant at α = 0.05, * = significant at α = 0.10

[c] Hosmer–Lemeshow P-value was used to test lack-of-fit ($p > 0.10$ = acceptable fit)

Table 5.11. Palmer amaranth height 4 weeks after treatment in Manhattan, KS in 2021 and 2022 as influenced by residual herbicide.

Residual herbicide	2021	2022
	Palmer amaranth height (cm)	
Acetochlor	1.7 b[a]	10.5 ab
Dimethenamid-P	0.7 b	9.6 abc
Pyroxasulfone	0.1 b	3.5 c
S-metolachlor	0.0 b	4.9 bc
Non-treated	5.0 a	15.6 a

[a] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

Table 5.12. Palmer amaranth height 4 weeks after treatment in Manhattan, KS in 2021 and 2022 as influenced by application date.

Year	Application date	Palmer amaranth height (cm)
2021	April 14	0.0 b[ab]
	April 29	0.4 b
	May 14	3.9 a
	June 4	1.5 ab
	June 18	1.8 ab
2022	April 18	2.8 c
	May 23	11.3 ab
	June 21	13.8 a
	July 12	7.5 bc

[a] No weeds were present on date of evaluation time.

[b] Means followed by the same letter within a year are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 5.13. Palmer amaranth height 8 weeks after treatment in Manhattan, KS in 2021 as influenced by application date and residual herbicide.

	Application date				
Residual herbicide	April 14	April 29	May 14	June 4	June 18
	Palmer amaranth height (cm)				
Acetochlor	4.3 e[a]	7.2 de	65.5 bcd	18.5 cde	33.7 cde
Dimethenamid-P	0.0 e	16.0 de	20.4 cde	0.0 e	43.2 b-e
Pyroxasulfone	2.5 e	0.2 e	0.0 e	14 de	13.4 de
S-metolachlor	4.5 e	2.5 e	20.1 cde	0.0 e	0.0 e
Non-treated	11.4 de	37 cde	89.6 ab	69.9 bc	133.4 a

[a] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 5.14. Palmer amaranth height 8 weeks after treatment in Manhattan, KS in 2022 as influenced by application date and residual herbicide.

Residual herbicide	Application date			
	April 18	May 23	June 21	July 12
	Palmer amaranth height (cm)			
Acetochlor	37.0 fgh[a]	154.0 a-d	179.5 ab	134.5 a-d
Dimethenamid-P	32.8 gh	142.5 a-e	145 abc	109.2 a-g
Pyroxasulfone	27.3 h	134 a-f	129.5 a-d	56.8 d-h
S-metolachlor	29.6 fgh	83 b-h	143.0 abc	140.2 abc
Non-treated	44.8 e-h	70.2 c-h	182.5 a	159.2 ab

[a] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

Table 5.15. Palmer amaranth biomass 8 weeks after treatment in Manhattan, KS in 2021 as influenced by VLCFA-inhibiting herbicide and application date.

Residual herbicide	Application date				
	April 14	April 29	May 14	June 4	June 18
	Palmer amaranth biomass (g m^{-2})				
Acetochlor	0.0 c	0.0 c	99.7 ab	1.0 c	6.8 bc
Dimethenamid-P	0.0 c	0.9 c	1.8 c	0.4 c	21.5 abc
Pyroxasulfone	0.1 c	0.0 c	0.1 c	0.5 c	1.8 c
S-metolachlor	0.1 c	0.0 c	4.6 bc	1.1 c	0.0 c
Non-treated	1.3 c	12.2 bc	18.5 bc	15.9 bc	521.7 a

[a] Means followed by the same letter are not significantly different and means were separated using Tukey's HSD tests ($\alpha = 0.05$).

Table 5.16. Palmer amaranth biomass and density 8 weeks after treatment in Manhattan, KS in 2022 as influenced by application date.

Application date	Biomass	Density
	g m^{-2}	Plants m^{-2}
April 18	35.9 c	42 a
May 23	115.2 bc	9 b
June 21	505.9 a	7 b
July 12	393.4 ab	9 b

[a] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD tests (α = 0.05).

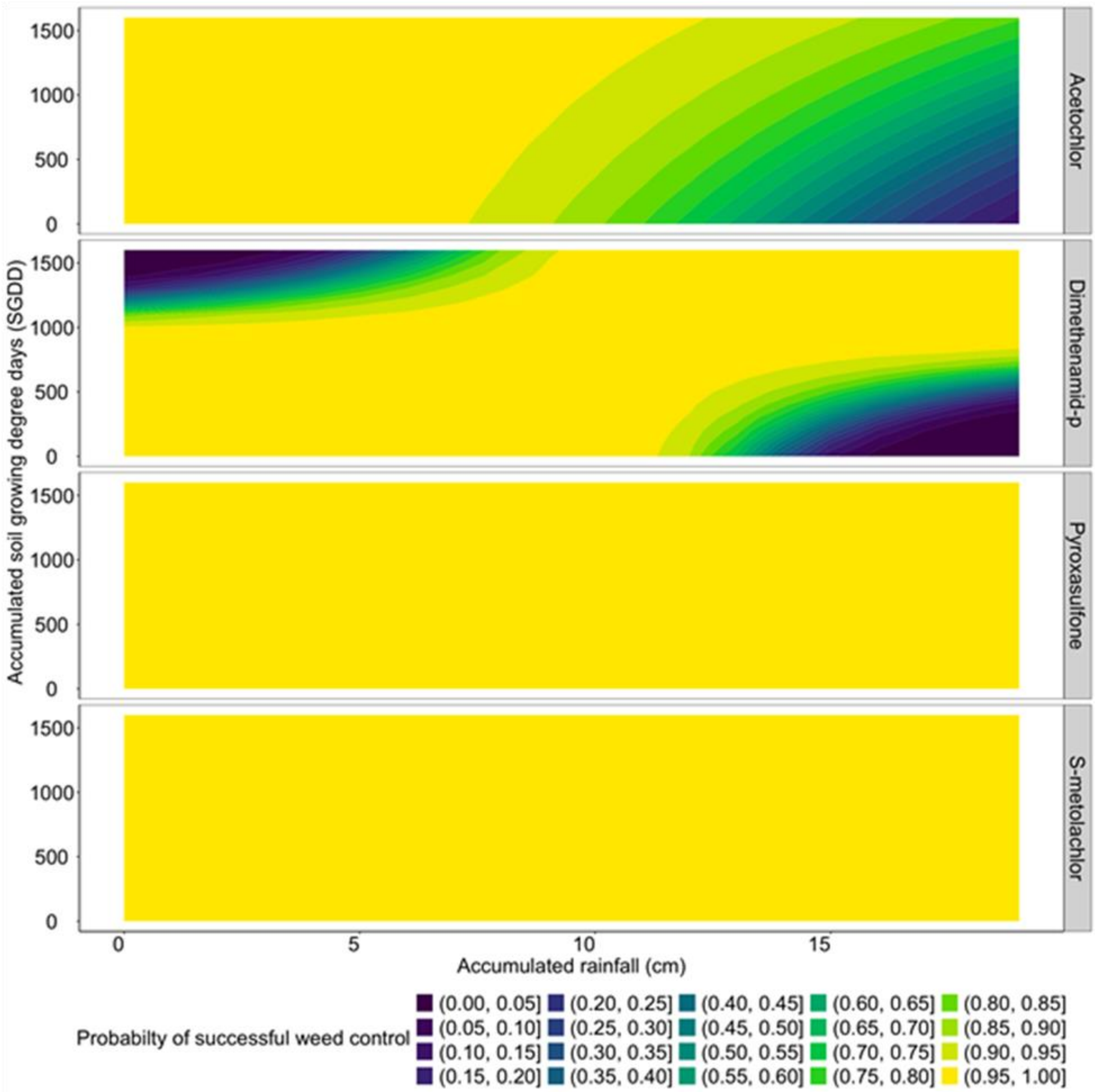

Figure 5.1. Contour plots of probability of successful control of Palmer amaranth as a function of accumulated rainfall and soil growing degree days from application to 4 weeks after treatment.

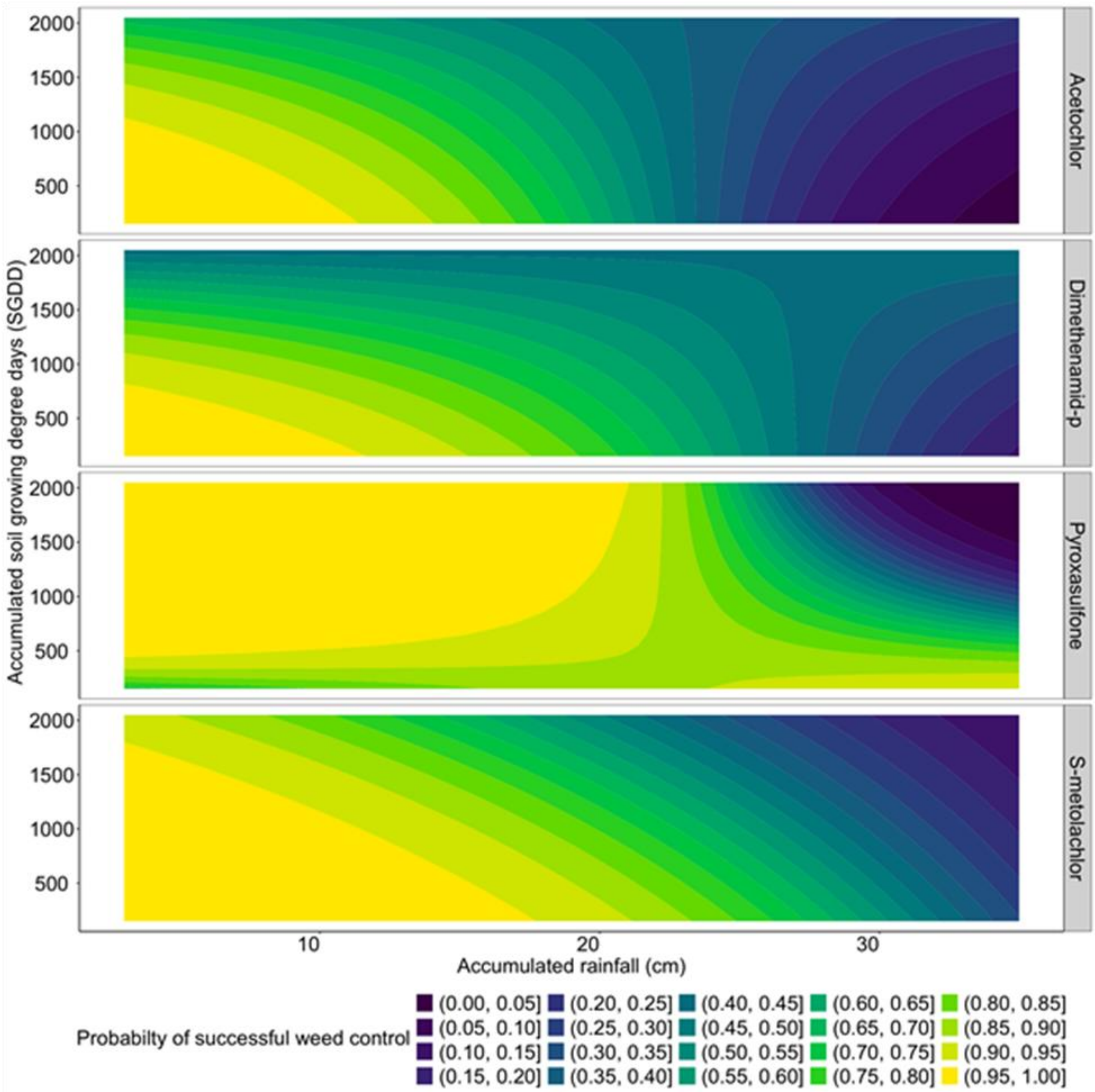

Figure 5.2. Contour plots of probability of successful control of Palmer amaranth as a function of accumulated rainfall and soil growing degree days from application to 8 weeks after treatment.

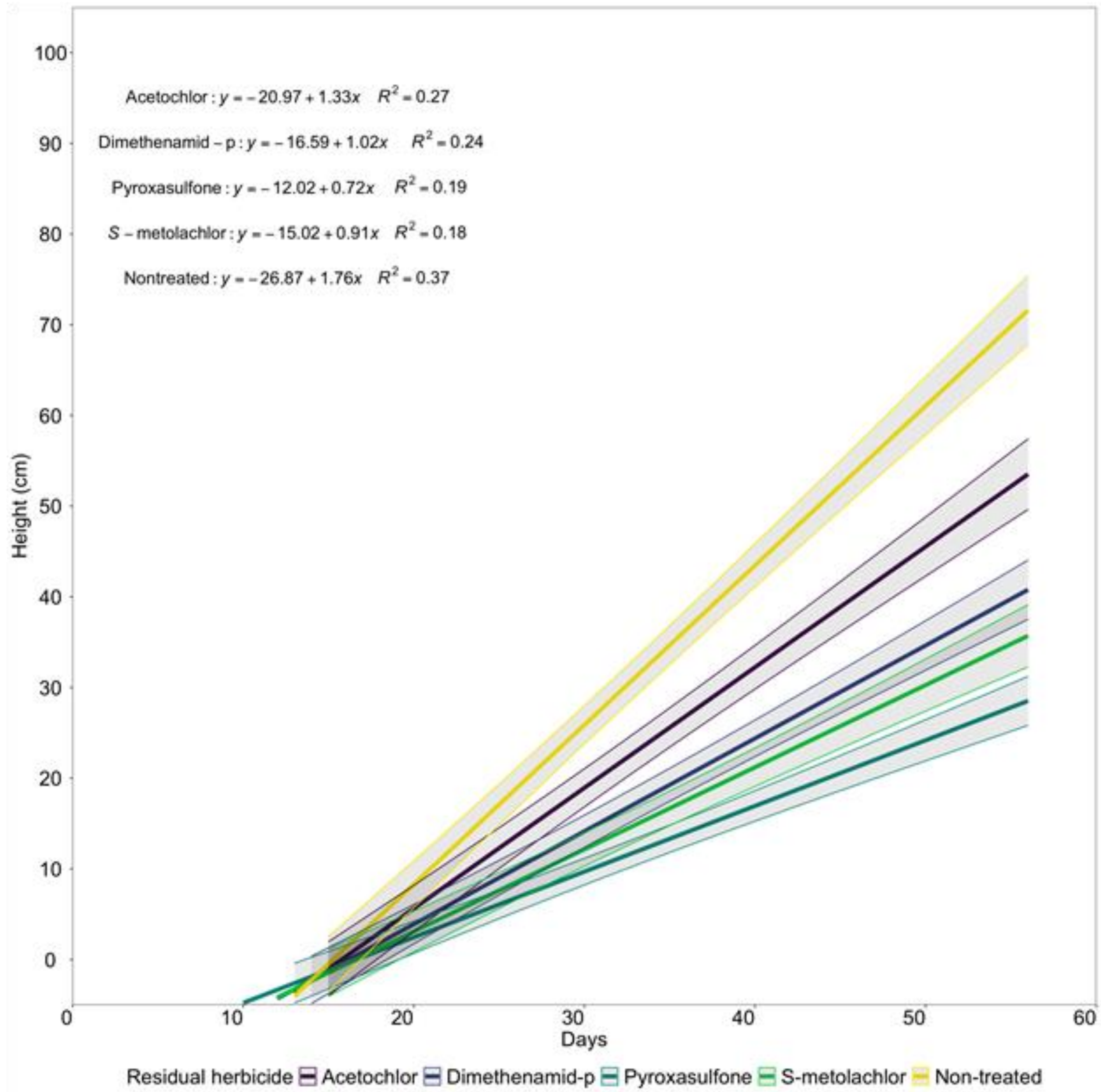

Figure 5.3. Palmer amaranth height as function of days and residual herbicide. Shaded region = predicted response +/- standard error of fit.

Chapter 6 Degradation of VLCFA-inhibiting herbicides

6.1 Introduction

Postemergence only programs became increasingly common and the use of many herbicides declined following the commercialization of glyphosate-resistant crops (Shaner 2000). Very long chain fatty acid (VLCFA) inhibiting herbicides comprised 15% of total active ingredient applied in 2008 (Fernandez-Cornejo et al. 2014). In 2020, VLCFA-inhibiting herbicides were applied on 19% of soybean acres (NASS 2021). In 2021, VLCFA-inhibiting herbicides were applied on 61% of corn acres (NASS 2022). The increased use of residual herbicides like the VLCFA-inhibiting herbicides may be attributed to the increased presence of herbicide-resistant weeds, as the use of residual herbicides is critical in the management of herbicide-resistant weeds, specifically troublesome weeds like Palmer amaranth (*Amaranthus palmeri* S. Watson) and waterhemp (*Amaranthus tuberculatus* Moq. Sauer; Norsworthy et al. 2012).

The first VLCFA-inhibiting herbicide, α-Chloro-N,N-diallylacetamide (CDAA), was discovered in 1953 and commercialized in 1956 and was used for the control of grassy weeds in several major crops and was the first case herbicides being applied preemergence (PRE) to a crop (Hamm 1974; Shaner et al. 2014). The VLCFA-inhibiting herbicides, specifically chloroacetamide and pyrazole herbicides, are used across many crops for the control of grassy and small-seeded broadleaf weeds (Hamm 1974; Shaner et al. 2014). These herbicides inhibit emergence not germination as VLCFA-inhibiting herbicides are absorbed by plants prior to emergence but after germination (Fuerst 1987; Matthes et al.1998; Shaner et al. 2014). The VLCFA-inhibiting herbicides are absorbed by the coleoptile in broadlead weeds and the radicle in grass weeds, which inhibits root and shoot development due to the inhibition of the biosynthesis of very long chain fatty acids which comprise epicuticular wax, plant membranes, and seed storage lipids (Fuerst 1987; Matthes et al.1998).

6.2 Fate of VLCFA-inhibiting herbicides

To maximize the efficacy of VLCFA-inhibiting herbicides it is important to understand the movement and fate of these herbicides in soil. There are several factors to consider including: adsorption, absorption, volatilization, photodegradation, chemical degradation, and microbial degradation (Blasioli et al. 2011). However, the primary factors impacting VLCFA-inhibiting herbicides are adsorption and microbial degradation (Zimdahl and Clark 1982).

6.2.1 Degradation pathways

Microbial degradation is a critical process responsible for the breakdown of herbicides in the soil. Several factors can influence the activity of herbicide degrading microbes, including soil moisture, oxygen, organic matter, and soil texture. Soil microbes are most active in well aerated and fertilized, moist, warm, and fine-textured soils with high organic matter and approximately neutral pH, which facilitates more favorable conditions for herbicide degradation (Rice et al. 2002; Long et al. 2014; Singh and Singh 2014). The VLCFA-inhibiting herbicides degrade more rapidly under warm and wet conditions, as compared to drier and/or cooler conditions (Zimdahl and Clark 1982; Mueller et al. 1999; Mueller and Steckel 2011; Long et al. 2014; Westra et al. 2014). Bouchard et al. (1982) also observed increased rates of metolachlor degradation at depths of 10- to 40-cm in a silt loam soil as temperatures increased from 7 to 37 C. Mueller et al. (1999) observed that acetochlor and dimethenamid had similar rates of degradation but dissipated more rapidly than metolachlor under well-watered field conditions when applied on silt loam soils with low organic matter. Oliveira et al. (2013) reported soil properties to have less impact on the degradation of acetochlor when 4.3- to 5.3-cm of rainfall were received within 14 days of application, which indicates that soil properties may be of greater importance when less rainfall is received within 14 days of application. Kočárek et al. (2018) observed more rapid dissipation of dimethenamid-P when a 3-cm irrigation event immediately followed as compared to rainfed treatments that did not receive more than 2.9-cm of rainfall until 45 days after treatment.

Oliveira et al. (2013) reported approximately 2 times slower acetochlor degradation in soil at 60- to 90-cm in depth as compared to soil at 0- to 15-cm in depth. The author attributed this to reduction in the presence of herbicide degrading microbial communities. Previous research has also reported 3.3 times slower degradation of *S*-metolachlor in sterilized soil as compared to unsterilized soil with various physiochemical characteristics, which indicates microbial is the main mechanism of degradation for *S*-metolachlor (Long et al. 2014).

Under certain conditions photodegradation and hydrolysis can degrade VLCFA-inhibiting herbicides (Zimdahl and Clark 1982). Photodegradation can become an important pathway of degradation when herbicide molecules remain unincorporated for prolonged periods of time (Oliveira et al. 2013, Westra 2012). However, once incorporated whether through rainfall or tillage, photodegradation becomes less important as photodegradation only occurs in the top 4-mm of soil (Ye 2003; Oliveira et al. 2013; Westra 2012). Khalil et al. (2018a) reported no effects of crop residue amount, crop residue moisture at time of application, residue type, or age of residue on the interception of pyroxasulfone from reaching the soil surface. The VLCFA-inhibiting herbicides are resistant to chemical degradation (hydrolysis) as this class of herbicides is non-ionizable (Chamberlin et al. 2012; Kennedy 2014). Chamberlin et al. (2012) reported slightly elevated levels of hydrolysis for acetochlor, dimethenamid, and metolachlor when under pH 12 conditions, which indicates that the VLCFA-inhibiting herbicides can withstand a broad range of soil pH levels. Szmigielski et al. (2014) reported decreased availability of pyroxasulfone in soils with low pH (pH 4.2) or high organic matter.

6.2.2 Soil composition

Herbicide availability is greatly influenced by soil composition (i.e., organic matter content and soil texture) and herbicide adsorption. Herbicide adsorption (K_{oc}) is significantly correlated to soil organic matter and clay content (Haymaker and Thompson 1972; Helling 2005; Bedmar et al. 2011; Westra et al. 2015; Yamaji et al. 2016; Bedmar et al. 2017; Sharipov et al. 2021). Herbicide adsorption is how tightly the herbicide molecule binds to a soil particle, which directly influences the amount of herbicide that is available for weeds to absorb from the soil water solution (Pusino et al.1992). Herbicide adsorption is often a good indicator of the degradation of residual herbicides (Sharipov et al. 2021). Soil texture (% sand, % silt, % clay) influences the rate at which residual herbicides degrade due to differences in the water holding capacities, net charge, and microbial activity (Schoenau et al. 2005). Fine-textured soils with high organic matter content have the greatest ability to adsorb herbicides (Helling 2005). While coarse-textured (sandy) soils have less water-holding capacities than fine-textured (clayey) soils, but the water-holding capacities of coarse soils can improve with greater levels of soil organic matter (Bouyoucos 1939). Herbicide mobility in soil increases as the percentage of sand increases (Westra et al. 2014).

For VLCFA herbicides, herbicide binding is closely correlated to the amount of organic matter present in the soil, except for triallate, which is not impacted by organic matter content (Eberlein et al. 1984; Westra et al. 2015). Greater herbicide adsorption can lead to reduced weed control as less herbicide is available for plant uptake from the soil water solution (Djurovic et al. 2009). However, reduced control can be overcome by increasing the rate of herbicide applied if it is within the range allowed by the herbicide label (Reinhardt and Nel 1988). VLCFA-inhibiting herbicides have both a lower and upper limit for organic matter content. Below certain levels of organic matter, VLCFA herbicides are more susceptible to off target movement through leaching or runoff and are more likely to cause crop injury, as the herbicides are more available in the soil water when low levels of organic matter are present (Bogdan 2021). Slower degradation and increased adsorption acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor has been observed in fine textured soils with high organic matter (Reinhardt and Nel 1988; Candia et al. 2014; Kucharski et al. 2014; Westra et al. 2015; Sharipov et al. 2021). However, Djurovic et al. (2009) observed greater acetochlor adsorption in soil with high clay content and low organic matter as compared to soil with both high clay content and high organic matter. Similarly, Sharipov et al. (2021) reported greater adsorption of dimethenamid-P and *S*-metolachlor in soils with greater organic matter, but less clay content than soils with less organic matter but greater clay content which further indicates that soil organic matter may be more indicative degradation than clay content. Additionally, Szmigielski et al. (2014) reported that clay content was not a significant predictor of pyroxasulfone adsorption. Landry (2022) reported that pyroxasulfone degraded more rapidly in clay loam soils with >2.5% organic matter than sandy loam soils with 0.9% organic matter and silty clay loam soils with 6.6% organic matter. The slower degradation in sandy soil types was attributed to poor water holding capacity and low organic levels, which would not facilitate conditions for microbial degradation. Slower degradation in high clay content and high organic matter is attributed to increased adsorption, which makes the herbicide less available for uptake by microbes and plants.

Water solubility of herbicides can also play a role in the degradation of residual herbicides (Wauchope et al. 2002). Water solubility is how much of the herbicide will dissolve in water and is generally measured as ppm (parts million^{-1}) or mg L^{-1}. It is related to the amount of herbicide readily available for plants to take up from the soil water solution. Helling (2005) stated that herbicides with water solubility greater than 30 mg L^{-1} are more at risk of leaching and have less risk of carryover to the following crop. Herbicide adsorption and water solubility have an inverse relationship. Westra et al. (2015) observed pyroxasulfone to be more readily available for plant uptake in the soil water solution and thus can be applied at lower rates than *S*-metolachlor and dimethenamid-P and provide comparable weed control, even though pyroxasulfone has less water solubility (3.49 mg L^{-1}) and greater adsorption coefficients (K_{oc} = 223) than dimethenamid-P and *S*-metolachlor (Table 6.1). Pyroxasulfone was also found to be more mobile in the soil profile than *S*-metolachlor (Westra et al. 2014). This would allow pyroxasulfone to be more available for plant absorption in soil water solution, which may be a partial explanation for the increased levels of Palmer amaranth control observed following pyroxasulfone (Westra et al. 2015).

6.2.3 Loss in the environment

Volatilization of common VLCFA-inhibiting herbicides, like acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor, is generally uncommon unless under specific conditions. The vapor pressure and Henry's Law of Constants value of acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor are low, especially in comparison to highly volatile compounds like dicamba acid (Table 6.1). Herbicides with higher vapor pressure values are more likely to volatilize. Prueger et al. (2005) observed increased levels of metolachlor volatilization within 24 h of application when applied under warm and moist conditions, which was attributed the displacement of the metolachlor molecules adsorbed to the soil particle with water molecules. However, Yamaji et al. (2016) reported no loss of pyroxasulfone to volatilization under warm and moist conditions. Oliveira et al. (2013) attributed dissipation of acetochlor to microbial degradation and adsorption and not to volatilization. Jonas (1994) also reported low levels of dimethenamid-P volatilization (6.6%) from soil within 24 h of application when tested under controlled conditions with 40% relative humidity and 20 C.

Leaching is the movement of herbicides downward in the soil profile in water and runoff is the movement of herbicides across the soil surface in water (Bessin 2015). Acetochlor, dimethenamid-P, *S*-metolachlor, and flufenacet are labeled with a ground water advisory statement which may be attributed to these herbicides being they are characterized to be moderately mobile in the soil and are more easily dissolved in water (Table 6.1; Loux et al. 2015). Caution should be taken when these herbicides are applied on course soil textures, low organic matter soil; or on soils with high water tables (Minnesota Department of Agriculture 2018). Bedmar et al. (2017) reported increased persistence of *S*-metolachlor in topsoil (A horizon), subsoil (B horizon), and parent material (C horizon) than acetochlor, which is critical as herbicides that leach deeper than the A horizon are much more likely to contaminate groundwater. Kočárek et al. (2018) concluded dimethenamid-P posed little risk to ground water as 0.4% of the of dimethenamid-P was found in soil samples taken from 5- to 15-cm deep, while a much higher proportion was observed in the topsoil (0- to 5-cm). Oliveira et al. (2013) reported no acetochlor was detected at soil depths deeper than 40-cm across 136 different locations with a wide range of soil characteristics. Zhang et al. (2021) reported the greatest potential for leaching of acetochlor to occur in soils with 0.54% organic matter as compared to soils with 2.13% organic matter. Jursík et al. (2013) observed greater leaching of metolachlor than acetochlor in silt loam soil with soil sorption capacity of 209 mmol kg^{-1}.

6.3 Methods of residue analysis

Historically, herbicide residue analysis methods generally included a bioassay to detect the concentration of herbicides in soil by utilizing a bioassay species such as annual ryegrass (*Lolium multiflorum* Lam.), canola (*Brassica napus* L.), cucumber (*Cucumis sativus* L.), giant foxtail (*Setaria faberi* Herrm.), oriental mustard (*Brassica juncea* L.), sorghum (*Sorhgum bicolor* L. Moench), sugar beet (*Beta vulgaris* L.), and winter wheat (*Triticum aestivum* L.) by recording emergence, plant biomass, shoot length, shoot biomass, root biomass, and reduction in top growth (Burnside and Schultz 1978; O'Sullivan 2005; Watson and Checkel 2005; Parker et al. 2005; Szmigielski et al. 2014; Mueller and Senseman 2015; Khalil et al. 2018 a,b). Bioassays can be advantageous as this method directly measure the activity of the herbicide and does not require expensive analytical equipment or the use of solvents (Mueller and Senseman 2015). However, bioassays can be time consuming, results are obtained slowly, and results may not be reproducible due to variability in patterns of plant growth (Mueller and Senseman 2015).

Modern methods to determine herbicide concentration utilize mass spectrometry (MS) technology in conjunction with gas chromatography (GC) or liquid chromatography (LC; Sanchez-Brunete et al. 1994; Gallaher and Mueller 1996; Mueller et al. 1999; Lehotay et al. 2007; Shaner and Henry 2007; Xu et al. 2008; Mueller and Steckel 2011; Jursík et al. 2013; Oliveira et al. 2013; Candia et al. 2014; Kucharski et al. 2014; Long et al. 2014; Westra et al. 2014,2015; Mueller and Senseman 2015; Kočárek et al. 2018; Sharipov et al. 2021; Zhang et al. 2021). The goal of GC/MS and LC/MS is to identify by separating the target substance from the chemical extractant (Alder et al. 2006; Raina 2011; Brinco et al 2023). The GC/MS separates the target substance from the chemical extract by adding the extract to a chromatogram with a gas carrier and heating gasses, which separates the target substance from the chemical extract (Raina

2011; Brinco et al 2023). The resulting separated substance is identified in the MS by measuring the mass-to-charge ratio (m/z) of the separated compound. The LC uses the process of ionization instead of heat to separate the target substance ions according to their m/z (Raina 2011). The ions are then identified and quantified in the MS. Unlike GC, LC does not use gas to separate target substances from the chemical extract. LC uses high-performance liquid chromatography (HPLC) to separate the target compound, which utilizes a liquid mobile phase instead of a gas mobile phase to move extractants between columns (Raina 2011; Brinco et al 2023).

There are several advantages and disadvantages that exist for both GC/MS and LC/MS analytical techniques (Andre and Pico 2004; Alder et al. 2006; Brinco et al. 2023). One advantage of GC/MS over LC/MS is age of the GC/MS technique has allowed for the development of extensive mass spectrum libraries for the screening of unknow compounds while access to such libraries for LC/MS is more limited (Andre and Pico 2004; Alder et al. 2006). The LC/MS technology can be utilized across a broad spectrum of compounds, while GC/MS is not suitable for low-volatile and polar compounds or compounds prone to degradation by heat (Andre and Pico 2004; Brinco et al. 2023). The gas phase of the GC/MS consumes high amounts of high purity, expensive gases, while the liquid and stationary phase of LC/MS can be variable, which makes the LC/MS technique more flexible. However, GC instrumentation is less expensive than LC instrumentation (Brinco et al. 2023). Both techniques are sensitive, but LC/MS less sensitive than GC-MS and is more impacted by matrix effects which can impact ionization (Andre and Pico 2004; Alder et al. 2006). However, this can be resolved with proper sample clean-up procedures (Andre and Pico 2004; Alder et al. 2006).

The AOAC official method 2007.01 for pesticide residue extraction from plants and other solid media is the QuEChERS (quick, easy, cheap, effective, rugged, and safe) method (Lehotay et al. 2007). There are three main steps included in the QuEChERS method. Step 1 includes the combination of 15 g of a homogenized sample (plant or soil material) with 15 ml of acidified acetonitrile (MeCN + 1% v/v HOAc) and 6 g of QuEChERS salts (4 g $MgSO_4$ + 1.5 g NaOAc) and is then shaken and centrifuged. The extracted liquid is then decanted and combined with another $MgSO_4$/PSA (primary secondary amine) sorbent at a rate of 3/1 w/w and 200 mg 1 ml extractant^{-1} and then centrifuged. The extractant was then moved in to autosampler vials to be analyzed by gas chromatography/mass spectrometry (GC/MS) or liquid chromatography/tandem mass spectrometry (LC/MS/MS). The QuEChERS method has been found to be an effective soil extraction across multiple herbicide families, including chloroacetamides (Đurović-Pejčev et al. 2019). The QuEChERS method was observed to have greater recovery rates than traditional methanol-acetone and acetone-hexane extraction methods for chloroacetamide herbicides (Đurović-Pejčev et al. 2019). Recovery rates are an important point of consideration when evaluating various extraction and analytical methods. Mueller and Senseman (2015) stated that recovery rate values between 80 and 120% are acceptable. The recovery rates for the extraction methods discussed are located in Table 6.2.

Bourchard et al. (1982) and Harvey (1987) used less common methods and reagents, as these trials were less modern. Bouchard et al. (1982) determined concentration of metolachlor by spiking herbicide solutions with 14C analogs prepared in 0.01 M CaCI2 and a 5 ml aliquot of the solution was added to 0.5 g soil to create concentrations that ranged from 0.12 to 4 µg herbicide g soil^{-1}. The soil was then placed on a rotary shaker for 24 h, centrifuged, and decanted. A 1-ml aliquot was counted with a liquid scintillation spectrometer and differences observed from the initial concentrations were attributed to adsorption to soil particles. Harvey (1987) extracted metolachlor by refluxing 100 g of soil with 250 ml of dichloromethane for 2 h and then evaporating the dichloromethane. The remaining residues were resuspended with 20 ml of ethyl acetate and 5-µl aliquots were analyzed by GC.

Extraction methods used by Gallaher and Mueller (1996), Mueller et al. (1999), Mueller and Steckel (2011), Oliveria et al. (2013), and Landry (2022) were similar. Extraction began by adding methanol to the soil samples at the rate of 2 ml g of soil^{-1}. Samples were placed on a reciprocating shaker or shaken by a robot system. Gallaher and Mueller (1996), Mueller et al. (1999), Mueller and Steckel (2011), and Landry (2022) decanted, filtered, placed a small aliquot in autosampler vials. Gallaher and Mueller (1996) extracted atrazine, metribuzin, and clomazone from soil. Mueller et al. (1999) extracted acetochlor, alachlor, metolachlor, and dimethenamid-P from soil. Mueller and Steckel (2011) extracted acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor and Landry (2022) extracted pyroxasulfone from soil. Oliveria et al. (2013) extracted acetochlor from soil. Sharipov et al. (2021) also utilized methanol to extract *S*-metolachlor and dimethenamid-P from soil by combining 50 ml of methanol with soil samples and shaking for 24 h. The samples were then centrifuged and filtered using 0.7-µm glass syringe filter and 1.5-ml aliquots were analyzed by HPLC.

Methods utilized by Shaner and Henry (2007) and Westra et al. (2015) were similar. Shaner and Henry (2007) combined 10 g of soil with 10 ml of water and 10 ml of water saturated toluene to extract metolachlor. Subsequently, samples were shaken, centrifuged, and decanted. A 2-ml aliquot was spiked with 0.1 mg mL^{-1} of butylate and analyzed. Westra et al. (2015) extracted dimethenamid-P, *S*-metolachlor, pyroxasulfone from 10 g of soil with 10 ml of 1 mg mL^{-1} herbicide stock solution and samples were centrifuged to separate soil and herbicide solution. Samples were decanted and a 3-mL aliquot with 3 mL of toluene. Samples were shaken, decanted, and a 2- ml aliquot was spiked with 0.5 ng mL^{-1} of butylate, which serves as an internal standard. Samples were then analyzed with a GCMS.

Sánchez-Brunete et al (1994) and Parker et al. (2005) utilized ethyl acetate as the solvent for herbicide extraction from soil. Sánchez-Brunete et al (1994) extracted alachlor and metolachlor by shaking 20 g of soil with ethyl acetate for 30 min, which was then filtered through filter paper and celite. The filter cake was rinsed with ethyl acetate and removed under suction. The collected solvent was then concentrated, and an aliquot was analyzed by gas chromatography. Parker et al. (2005) extracted metolachlor, *S*-metolachlor, acetochlor, and microencapsulated acetochlor by combining 50 g of soil with 100 ml of ethyl acetate and samples were shaken for 24 h, centrifuged, and decanted. A 20-ml aliquot was evaporated and residues were resuspended in 2 ml of ethyl acetate and analyzed by GCMS.

Long et al. (2014) and Zhang et al. (2021) utilized acetone as the extraction solvent. Long et al. (2014) extracted *S*-metolachlor from soil with 25 ml of acetone and 5 ml of water, shaken, and filtered. Samples were evaporated after filtration and a 2 ml aliquot was filtered through a 0.45-µm filter prior to analysis with HPLC. Zhang et al. (2021) extracted acetochlor from 5-g soil samples with 15 ml of acetone and 5 ml of water and was placed in an ultrasonical bath for 30 min and subsequently centrifuged and extracted. The acetone was then evaporated from the filtrate. The remaining water was purified with C-18 solid phase extraction (SPE) column and the subsequent elute was discarded. The column was rinsed with methanol and the rinsate was collected. The methanol was evaporated and the remaining residues were resuspended in n-hexane for detection.

Đurović-Pejčev et al (2019) utilized compared three different extraction methods: QuEChERS, solid liquid extraction (SLE), and Soxhlet. For the QuEChERS method, spiked soil was combined with acetonitrile, water, and QuEChERS packets (4 g magnesium sulphate, 1 g sodium chloride, 1 g sodium citrate tribasic dihydrate,0.5 g sodium citrate dibasic sesquihydrate) and placed in an ultrasonic bath. An aliquot of extractant was added to the QuEChERS d-SPE kit (150 mg primary-secondary amine, 150 mg C 18 sorbent, 900 mg magnesium sulphate) and placed in an ultrasonic bath and centrifuged. The samples were then evaporated using nitrogen gas and the resulting residues were reconstituted with 2 mL of acetone and analyzed with GC-MS. For the SLE method, Na_2SO_4 was added to spiked soil samples and combined with a methanol-acetone solution. The samples were stirred and centrifuged. Samples were subsequently filtered, evaporated, and residues were reconstituted with 5 mL of an ethyl acetate-acetone solution. An aliquot of extractant was filtered through a glass column that was filled with Na_2SO_4 and florisil. The column was rinsed with an ethyl acetate-acetone solution and the rinsate was evaporated and reconstituted with acetone and analyzed. The final method utilized was the Soxhlet method. Spiked soil was added to an extraction thimble, left for 24 hrs, and extracted with 150 mL of an acetone–*n*-hexane solution using a Soxhlet extractor for another 24 hrs. The sample was then evaporated and the residues were reconstituted with *n*-hexane and placed in columns with silica gel. The columns were then rinsed with *n*-hexane and diethyl ether– *n*-hexane. The rinsate was evaporated, reconstituted with acetone, and analyzed.

6.3.4 Avoidance of contamination

Avoidance of contamination is critical as contamination of samples can lead to biases in the data that misrepresents the concentration of herbicides present. Contamination sources include airborne, reagents, equipment, and cross contamination between samples (United States Nuclear Regulatory Commission 2004). Ground and pulverized samples can often result in small particles ($\leq$10 μm) which can suspend in the air and become airborne contaminates. Airborne contamination can be avoided by processing samples under a laboratory hood or in a ventilated area specifically designed to prevent the movement of air borne particles (United States Nuclear Regulatory Commission 2004). Contamination of reagents is especially critical when detecting low concentrations of herbicides. Analysis of a blank or standard to check for contamination of soil, reagents, solvents, and the analytical column is also required (Lehotay et al. 2007). A reagent blank should also be analyzed in each set to check for contamination (Lehotay et al. 2007). Proper care should be taken to ensure equipment is cleaned properly and use disposable containers when possible, to prevent cross contamination. Non-disposable containers can have scratches, cracks, or chips in which residue can be settle and cause cross-contamination. Cross-contamination occurs when a sample contaminates another during simultaneously processing or improper cleaning of equipment between samples (United States Nuclear Regulatory Commission 2004). Khalil et al. (2018b) minimized crop residue sample contamination by cleaning the grinder with a vacuum and an air compressor after sample preparation. Graff (2003) and Westra et al. (2015) avoided contamination at time of soil sampling by utilizing a soil probe equipped with co-polyester liners. Mueller and Senseman (2015) recommended removing the surface of soil sample to prevent the contamination of the subsurface soil zone with herbicides residues that may be present on the soil surface, which may result in false positive herbicide detection in subsurface soil zone due to small amounts of residue being pushed down by the soil probe. An additional method to avoid cross contamination is to use disposable gloves (Boekel and Ek 2022). However, it is critical to remove gloves between tasks or samples. Boekel and Ek (2022) recommended the technique of wearing two layers of gloves, where the first layer of gloves remain contaminant free and the second layer is replaced between samples or tasks.

6.3.5 Methods for soil sampling and residue analysis

To detect the concentration of herbicides in soil for residue analysis, a minimum of three soil samples were collected from each plot immediately following herbicide application and at 8 weeks after treatment (WAT). Other soil sampling times for consideration could be weekly samples taken from 0 to 8 WAT or daily soil samples taken from 0 to 7 days after treatment followed by weekly soil samples to create an herbicide dissipation curve (Mueller et al. 2011). An additional consideration for timing of soil sampling could be at the first appearance of weeds to help determine the herbicide concentration at which weed control begins to subside. However, herbicide residue analysis can be costly as materials, equipment, and expertise are expensive, especially when samples are analyzed in offsite laboratories, so it is important to consider the number of samples that are being analyzed. Soil samples were taken at a depth of 0- to 5-cm with a 10-cm in diameter soil core. It is critical that soil sample size and depth remain consistent. Soil samples were placed in a sealed plastic bag, homogenized, and immediately placed in a cooler for transport. Three dummy samples were taken after samples were collected in each plot using non-treated soil outside of the plot area to prevent cross contamination among plots. However, a better sampling method would be to utilize a soil probe equipped with co-polyester liners. Within 1 hour of sampling, all soil samples were placed in a freezer where the temperature was -18 C. Soil samples remained frozen until extraction to prevent further microbial degradation.

To measure soil moisture content, soil samples were brought to room temperature and homogenized. Soil moisture content was measured by the gravimetric method where a 5 g (+/- 0.5 g) subsample of a moist soil was oven dried at 105 C until weight was constant, and then reweighed. An additional 5 g (+/- 0.5 g) of moist soil was taken from each soil sample for herbicide extraction. Acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor were extracted by utilizing the QuEChERS extraction method as detailed by AOAC Official Method 2007.01 (Lehotay 2007). To calculate percent recovery, quality control spike standards were created for each herbicide by factor interaction utilizing technical grade acetochlor (≥95% purity; Sigma Aldrich, St. Louis, MO), dimethenamid-P (≥98% purity; Sigma Aldrich, St. Louis, MO), pyroxasulfone (99.5% purity; Chem Service, Inc., West Chester, PA), and *S*-metolachlor (≥98% purity; Sigma Aldrich, St. Louis, MO) at a rate of 20,000 µl ml^{-1}. To account for herbicide residues that may have been present prior to trial establishment, composite soil samples were taken prior to herbicide application in each replication. To test for consistency, quality control samples were randomly selected from each replication. HPLC grade water was added to each sample and placed on a reciprocating shaker for 10 min (300 rpm). After removal, 5 ml of acidified acetonitrile (0.1% v/v formic acid + acetonitrile; Thermo Fisher Scientific Inc., Waltham, MA) was added to each sample and place on the reciprocating shaker for 10 min. The entire contents of a QuEChERS packet (6 g magnesium sulfate + 1.5 g sodium acetate; Agilent Technologies, Inc., Santa Clara, CA) was added to each sample and placed on reciprocating shaker for 10 min. Samples were centriguged for 10 minutes at 4000 rpm. Extracted liquid was decanted and filtered through qualitative filter paper (Thermo Fisher Scientific Inc., Waltham, MA). A 3-ml syringe equipped with a 0.2- µm syringe filter (Thermo Fisher Scientific Inc., Waltham, MA) was used to filter a 1-ml aliquot of extracted liquid into a 2-ml autosampler vial with a pre-slit PTFE/silicone LCMS cap. The extracted samples were stored in a cooler at approximately 2 C.

Samples analyzed in this dissertation were analyzed at the Mississippi State Chemical Laboratory in Starkville, MS. Prior to analysis, samples were brought to room temperature and the caps were replaced with caps that had a silicone septum. Acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor concentrations were analyzed with a gas chromatograph equipped with a triple quadrupole mass spectrometer (LC/MS/MS; Shimadzu TQ 8040, Shimadzu Scientific Instrument Inc., Columbia, MD). The analytical column was packed with 1.8 µm of C18 media and was 2.1 mm by 50 mm. All solvents (water + 0.1% formic acid + 5 mM ammonium formate; MeOH + 0.1% formic acid + 5 mM ammonium formate) were HPLC grade. The injection volume was 1-µL and the flow rate was 0.5 ml min^{-1}. Herbicide concentrations were corrected using the internal standard. After analysis, corrected herbicide concentrations were determined utilizing the equations in Table 6.3.

6.4 Conclusion

The VLCFA-inhibiting herbicides are an important group of herbicides for several crops for the control of many broadleaf and grassy weeds. Understanding conditions that facilitate herbicide degradation is key to maximizing the efficacy of VLCFA-inhibiting herbicides. Under dry and/or cool conditions microbial degradation slows which increases the length of persistence of herbicides in the soil. Fine-textured soils with high organic matter content have the greatest ability to adsorb herbicides. Greater herbicide adsorption can lead to reduced weed control and slower degradation as less herbicide is available for plant uptake from the soil solution and for microbes to degrade. Methods to determine degradation and herbicide concentration in soil vary among university laboratories. Modern methods include extraction of herbicides from soil with acetate, methanol, or water saturated toluene and the subsequent shaking, centrifuging, decanting, and filtration prior to analysis with GC/MS, LC/MS, or HPLC. Caution should always be taken when collecting soil samples and sample preparation prior to analysis to avoid contamination. It is critical to avoid contamination as it can lead to biases in data, particularly when working with low concentrations that are often associated with herbicide degradation research. Understanding the principles outlined is essential for collection and interpretation of utilizable data for both, researchers and producers.

6.5 References

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Table 6.1.Water solubility, adsorption coefficients (K_{oc}), and vapor pressure for VLCFA-inhibiting herbicides and dicamba acid.[a]

Herbicide	Water solubility[b]	K_{oc}	Vapor pressure[b]
	Mg L^{-1}		Pa
Acetochlor	223	156[c]	4.53×10^{-6}
Alachlor	200	43-209[d]	2.13×10^{-3}
Dimethenamid-P	1174	55-125[d]	3.68×10^{-2}
Flufenacet	56	113-742[d]	2×10^{-5}
Propachlor	580	112	1.05×10^{-2}
Pyroxasulfone	3.49	57-114[d]	2.4×10^{-6}
S-metolachlor	488	200	1.73×10^{-3}
Dicamba acid	4500	2	4.5×10^{-3}

[a] Values sourced from Shaner et al. (2014).

[b] Measured at 25 C.

[c] Value sourced from Lewis et al. (2016).

[d] Shaner et al. (2014) reported a range of values that varied with soil organic matter content and soil textural class.

Table 6.2. Extraction methods and recovery rates for VLCFA-inhibiting herbicides in literature.

Reference	Trial setting	Extraction method[a]	Analytical technique[b]	Herbicide	Recovery rate (%)
Bouchard et al. 1982	Lab	Soil spiked with C-14 labeled technical grade herbicides and 0.01 M $CaCl_2$ solution	Liquid scintillation spectrometer	Metolachlor	NR[c]
Durovic-Pejcev et al. 2019	Lab	QuEChERS with acetonitrile and water. Add QuEChERS packets (4 g magnesium sulphate, 1 g sodium chloride, 1 g sodium citrate tribasic dihydrate,0.5 g sodium citrate dibasic sesquihydrate), then ultrasonical bath. Added to QuEChERS d-SPE kit (150 mg primary-secondary amine, 150 mg C 18 sorbent, 900 mg magnesium sulphate), then ultrasonical bath, evaporated with nitrogen gas, and reconstituted with acetone	GC-MS	Acetochlor	100 – 103
				Alachlor	97 – 103
				Dimethenamid	79 – 88
Durovic-Pejcev et al. 2019	Lab	Traditional SLE with Na_2SO_4, methanol, and acetone. Stirred, centrifuged, filtered, evaporated, and reconstituted with ethyl acetate-acetone. Filtered through Na_2SO_4 and florisil, rinsed with ethyl acetate-acetone, evaporated, and reconstituted with acetone.	GC-MS	Acetochlor	85 – 91
				Alachlor	82 – 87
				Dimethenamid	71 – 77

Durovic-Pejcev et al. 2019	Lab	Soxhlet with acetone–*n*-hexane. Extraction thimble for 24 hrs and extracted with Soxhlet extractor for 24 hrs. Evaporated and reconstituted with n-hexane and filtered silica gel column and rinsed with n-hexane and diethyl ether–*n*-hexane. Evaporated and reconstituted with acetone.	GC-MS	Acetochlor	54 – 61
				Alachlor	31 – 45
				Dimethenamid	39 – 55
Harvey 1987	Lab	Soxhlet with dichloromethane. Extraction thimble and extracted with Soxhlet extractor for 2 hrs. Evaporated and reconstituted with ethyl acetate.	GC	Alachlor, metolachlor	84
Landry 2022	Field, Lab	SLE with methanol. Shaken for 1 hr, decanted, and filtered	LC-MS	Pyroxasulfone	NR
Long et al. 2014	Lab	SLE with acetone and water. Shaken for 2 hrs, filtered, and evaporated	HPLC	*S*-metolachlor	83.1 – 97.5
Mueller and Steckel 2011	Field	SLE with methanol. Shaken for 14 hrs, decanted, and filtered	LC-MS	Acetochlor, dimethenamid, pyroxasulfone, *S*-metolachlor	85-94
Mueller et al. 1999	Field	SLE with methanol. Shaken for 16 hrs, decanted, and filtered	GC-MS	Acetochlor, alachlor, dimethenamid, metolachlor	80-90

Oliveira et al. 2013	Lab	SLE with methanol. Equilibrate for 24 hrs, centrifuged, and decanted	GC-MS	Acetochlor	70 – 81
Parker et al. 2005	Field	SLE with methanol. Shaken for 24 hrs, decanted, and filtered	GC-MS	Acetochlor, metolachlor, *S*-metolachlor	93
				Encapsulated acetochlor	79
Sanches-Brunete et al. 1994	Lab	SLE with dichloromethane, evaporated, and resuspended with ethyl acetate	GC-MS	Metolachlor	90.4 – 97.5
				Alachlor	91.1 – 96.1
Sanches-Brunete et al. 1994	Lab	SLE with dichloromethane, evaporated, and resuspended with ethyl acetate	GC-NPD	Metolachlor	98 – 101
				Alachlor	98.5 – 99
Sharipov et al. 2021	Lab	SLE with methanol shaken for 24 hrs, centrifuged, and filtered	HPLC	Dimethenamid-P, *S*-metolachlor	84.9 – 118.2
Westra et al. 2015	Lab	SLE with water and water saturated toluene shaken for 24 hrs, decanted, and a 2 ml aliquot was spiked with 10 µl of butylate	GC-MS	Dimethenamid-P, pyroxasulfone, *S*-metolachlor	NR

Zhang et al. 2021	Lab	SLE with acetone and water. Ultrasonical bath, centrifuged, and decanted. Acetone was evaporated, water was filtered, and the filter was rinsed with methanol. Evaporated and resuspended in *n*-hexane	GC-MS	Acetochlor	83.6 – 100.0

[a] QuEChERS = Quick, Easy, Cheap, Effective, Rugged, and Safe; SLE = Solid Liquid Extraction

[b] GC = Gas Chromatography; GC-MS = Gas Chromatography with Mass Spectrometry; GC-NPD = Gas Chromatography with Nitrogen-Phosphorus Detector; HPLC = High Performance Liquid Chromatography; LC-MS = Liquid Chromatography with Mass Spectrometry

[c] NR = Not Reported

Table 6.3. Formulas related to the correction of herbicide concentrations obtained from analysis with a gas chromatograph.

Step	Description	Equation
1	Dry soil weight	$Dry\ soil\ weight\ (g) = \frac{5}{\frac{(Wet\ soil\ weight - Dry\ soil\ weight)}{Dry\ soil\ weight} + 1}$
2	Standardized herbicide concentration for observed, spike, blank, baseline, and quality control	$Herbicide\ concentration\ (ng\ g\ dry\ soil^{-1}) = \frac{(Sample\ Concentration\ (ng\ ml^{-1}) \times 20\ ml)}{dry\ soil\ weight\ (g)}$
3	Final herbicide concentration	$Final\ Herbicide\ Concentration\ (ng\ g\ dry\ soil^{-1}) = Observed\ Standardized\ Herbicide\ Concentration - Baseline\ Standardized\ Herbicide\ Concentration - Nontreated\ Standardized\ Herbicide\ Concentration$
4	Final spike herbicide concentration	$Spike\ Final\ Herbicide\ Concentration\ (ng\ g\ dry\ soil^{-1}) = Spike\ Standardized\ Herbicide\ Concentration - Baseline\ Standardized\ Herbicide\ Concentration$
5	Percent recovered	$Recovery\ (\%) = \frac{Spike\ Final\ Herbicide\ Concentration}{100000} \times 100$
6	Percent difference between quality control and observed	$Difference\ (\%) = \frac{Observed\ Standardized\ Herbicide\ Concentration - - QC\ Standardized\ Herbicide\ Concentration}{Observed\ Standardized\ Herbicide\ Concentration + QC\ Standardized\ Herbicide\ Concentration} \times 100$

Chapter 7 Recommendations

Implementation of multi-pass systems with layered residual herbicides and utilization of herbicide tank mixes that exhibit an additive or synergistic tank mix can be effective in the management of amaranthus species, when future weather conditions are taken into consideration when selecting specific VLCFA-inhibiting herbicides it can increase the likelihood of achieving effective amaranthus species control. Chapters 2 through 5 present research that addresses control of multiple-resistant Palmer amaranth with synergistic tank mixes, the effect of spray volume on residual herbicide premixes, control of Palmer amaranth in dicamba-resistant cotton than 2,4-D-resistant cotton, and the effect of temperature and rainfall on VLCFA-inhibiting herbicides.

In conclusion from the research conducted in Chapter 2, multiple-resistant Palmer amaranth (2,4-D, ALS-, EPSPS-, HPPD-, PPO-, and PS II-inhibitor resistant) may be increased with PRE applications of metribuzin, metribuzin + isoxaflutole or mesotrione, or atrazine + mesotrione. However, research in Chapter 2 was conducted in a greenhouse setting and may not be reproducible under field conditions. These results indicate herbicide combinations can be useful to manage multiple-resistant Palmer amaranth, even if resistance to those herbicides has been confirmed.

Research from Chapters 3 and 4 concluded that Amaranthus control was greater in systems with multiple applications as compared to single applications and layered residual herbicides as compared to single applications of residual herbicides. Additionally, Chapter 3 concluded spray volume had minimal to no impact on the efficacy of Resicore and TriVolt. Resicore resulted in greater amaranthus control in no-tillage systems as compared to TriVolt. The difference may exist due the clopyralid component of Resicore providing foliar control of previously emerged amaranthus. In no-tillage systems, TriVolt provide greater control of grassy weeds in no-tillage systems than Resicore which may be largely attribute to the thiencarbazone-methyl which largely targets annual grass weeds. However, when applied under conventional tillage systems Resicore and TriVolt performed similarly across amaranthus and grass weeds. Spray volume having minimal impact on residual herbicide efficacy is beneficial for growers and applicators, as low spray volumes generally resulted in lower costs and greater effective field capacity. Increasing effective field capacity for residual herbicide applications is critical for growers and applicators as it allows for more timely applications as applicators will be able to cover more acres during busy periods, like corn planting.

Research from Chapter 4 concluded Palmer amaranth control was greater in dicamba-resistant cotton than 2,4-D-resistant cotton. No differences in yield components were detected in the research conducted. Growers need to take into consideration the differences that exist among varieties, whether that be differences in yield potential, disease and pest tolerance, maturity group, seed availability, and the availability of the herbicides associated with the trait system rather than selecting exclusively for the herbicide trait system. Additionally, growers may want to consider what herbicide trait system best fits their location. Both herbicides are susceptible to off-target movement and have potential to injure sensitive vegetation, which has led to the implementation of many counter measures to limit the potential negative impact of these herbicides.

In conclusion from Chapter 5, excessive rainfall and/or high temperatures decreased the probability of successful control of Palmer amaranth with microencapsulated (ME) acetochlor, dimethenamid-P, pyroxasulfone, and *S*-metolachlor, but pyroxasulfone and *S*-metolachlor may have an advantage at high temperatures and high rainfall. In a scenario where the rainfall forecast is predicting little rainfall within 3 WAT, pyroxasulfone and *S*-metolachlor may not be the most effective options. However, ME acetochlor may be the best fit for hot and dry conditions, as less accumulated rainfall was required to achieve high probability of successful weed control. This indicates ME acetochlor may be a good fit in late season POST applications when conditions are typically hot and dry. Dimethenamid-P had a disadvantage in hot and dry conditions but was more likely to have >80% control in cool and wet conditions, indicating dimethenamid-P may be a better fit at plating or prior to planting of corn and soybeans when conditions are cooler. If POST applications are made at or prior to 4 WAT, the VLCFA-inhibiting herbicide selected is less important as Palmer amaranth control remained high and Palmer amaranth remained less than 10-cm in height, which allows for greater efficacy of POST herbicides. However, once 4 WAT is surpassed, pyroxasulfone and *S*-metolachlor resulted in the lowest probabilities of Palmer amaranth reaching 10-cm and the greatest control, which indicates that these herbicides may provide growers and applicators with the greatest flexibility for POST applications.

Appendix A Supplemental information for Chapter 2

Table A.1. Analysis of variance of fixed effects and all interactions 2 weeks after treatment for Palmer amaranth control, expected control, height reduction, expected height reduction, density reduction, and expected density reduction as result of herbicide applications on susceptible and multiple herbicide-resistant Palmer amaranth at PRE and POST.[a]

Fixed effects	Response		
	Control	Height	Density
	——— p-value ———		
Population	<0.0001	<0.0001	<0.0001
Application timing	<0.0001	<0.0001	–
Herbicide	<0.0001	<0.0001	<0.0001
Population x Application timing	<0.0001	<0.0001	–
Population x Herbicide	<0.0001	<0.0001	<0.0001
Application timing x Herbicide	<0.0001	<0.0001	–
Population x Application timing x Herbicide	<0.0001	<0.0001	–

[a] PRE = preemergence; POST = postemergence (4-6 L Palmer amaranth)

Table A.2. Orthogonal contrast means for Palmer amaranth control, height, and density 2 weeks after treatment of susceptible (MSS) and resistant (KCTR) Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied alone and in combination preemergence (PRE) and postemergence (POST).

Contrasts	Control	Height	Density
	————————————*p*-value[a]————————————		
PRE vs. POST	74 vs. 62*	2.1 vs. 4.8**	-
1 vs. 2 herbicides	57 vs. 82**	4.5 vs. 2.0**	3.3 vs. 1.6**
Atrazine vs. Metribuzin	74 vs. 82	2.7 vs. 2.2	2.9 vs. 0.8**
Isoxaflutole vs. Mesotrione	69 vs. 76	3.3 vs. 2.9	2.5 vs. 1.8

** Significant at $\alpha \leq 0.001$

*** Significant at $\alpha \leq 0.0001$

Table A.3. Observed and expected control, height, and density 2 weeks after treatment of susceptible (MSS) and resistant (KCTR) Palmer amaranth when PS II- and HPPD- inhibiting herbicides were applied in combination preemergence (PRE) and postemergence (POST).

Palmer amaranth population[a]	Application timing[b]	Herbicide	Control (%)			Height (cm)			Density (plants pot^{-1})		
			Observed	Expected[c]	p-value[d]	Observed	Expected	p-value	Observed	Expected	p-value
MSS	PRE	Atrazine	99 a[c]	–	–	0.3 kl[c]	–	–	0 hij[b]	–	–
		Metribuzin	96 ab	–	–	0.2 kl	–	–	0 hij	–	–
		Isoxaflutole	82 a-h	–	–	2.8 e-l	–	–	2 d-g	–	–
		Mesotrione	94 a-d	–	–	1.6 f-k	–	–	2 e-i	–	–
		Atrazine + Isoxaflutole	100 a	100	1	0.1 kl	0	0.0024	0 ij	0	0.0033
		Atrazine + Mesotrione	100 a	99	1	0 l	1.9	0.005	0 j	2	0.0044
		Metribuzin + Isoxaflutole	100 a	100	0.3816	0 l	0	0.0045	0 j	0	0.0004
		Metribuzin + Mesotrione	100 a	100	1	0 l	0.3	0.0354	0 j	0	0.0044
		Fomesafen	72 c-i	–	–	3.8 c-h	–	–	4 c-f	–	–

	POST	Non-treated	–	–	–	6.7 a-e	–	–	14 a	–	–
		Atrazine	100 a	–	–	0.6 i-l	–	–	–	–	–
		Metribuzin	68 a-h	–	–	4.9 e-h	–	–	–	–	–
		Isoxaflutole	91 a-d	–	–	3.3 e-l	–	–	–	–	–
		Mesotrione	79 a-g	–	–	4.2 c-j	–	–	–	–	–
		Atrazine + Isoxaflutole	100 a	100	1	0.6 jkl	2	0.0004	–	–	–
		Atrazine + Mesotrione	100 a	100	0.0765	1.3 h-l	1.7	0.005	–	–	–
		Metribuzin + Isoxaflutole	100 a	100	0.3816	0.6 i-l	0.8	0.0046	–	–	–
		Metribuzin + Mesotrione	100 a	100	0.7645	0.4 kl	1.3	0.0008	–	–	–
		Fomesafen	61 b-i	–	–	5.1 b-h	–	–	–	–	–
KCTR	PRE	Non-treated	–	–	–	17.8 a	–	–	–	–	–
		Atrazine	18 i	–	–	5.1 b-f	–	–	8 abc	–	–
		Metribuzin	83 a-d	–	–	1.4 g-l	–	–	1 g-j	–	–
		Isoxaflutole	21 hi	–	–	4.6 b-h	–	–	5 bcd	–	–
		Mesotrione	36 a-i	–	–	4.4 b-h	–	–	5 b-e	–	–
		Atrazine + Isoxaflutole	48 a-i	89	0.00285	3.8 c-i	6.4	0.0038	7 abc	8	0.636

	Atrazine + Mesotrione	89 a-e	86	0.1532	1.7 f-l	5.5	0.0043	2 d-g	6	0.0009
	Metribuzin + Isoxaflutole	93 abc	96	0.0081	1.2 g-l	4.1	0.0009	1 f-j	4	0.0032
	Metribuzin + Mesotrione	87 a-f	86	0.915	1.5 f-l	5.6	0.0011	2 d-h	9	0.0641
	Fomesafen	15 i	–	–	4.7 b-h	–	–	7 abc	–	–
	Non-treated	–	–	–	5.2 a-f	–	–	10 ab	–	–
POST	Atrazine	51 c-i	–	–	5.8 b-h	–	–	–	–	–
	Metribuzin	31 ghi	–	–	8.2 a-d	–	–	–	–	–
	Isoxaflutole	11 i	–	–	9.4 abc	–	–	–	–	–
	Mesotrione	13 i	–	–	10.5 abc	–	–	–	–	–
	Atrazine + Isoxaflutole	31 e-i	51	0.8533	7.1 a-e	13.6	0.0006	–	–	–
	Atrazine + Mesotrione	44 c-i	52	0.7981	5.6 b-g	11.3	0.0021	–	–	–
	Metribuzin + Isoxaflutole	50 c-i	92	0.4168	5.6 b-h	7.6	0.0009	–	–	–
	Metribuzin + Mesotrione	64 a-g	80	0.2652	3.9 d-k	7.8	0.0009	–	–	–
	Fomesafen	15 i	–	–	9.1 abc	–	–	–	–	–
	Non-treated	–	–	–	10.3 ab	–	–	–	–	–

[a] MSS = Mississippi susceptible Palmer amaranth; KCTR = Kansas multiple herbicide-resistant Palmer amaranth

[b] PRE = preemergence; POST = postemergence (4-6 L Palmer amaranth); POST application was applied with 1% v/v crop oil concentrate

[c] Expected values were calculated using Colby's equation (Colby 1967) as follows: $E = (X + Y) - (XY/100)$, where E is the expected control as calculated by the observed control (X and Y) achieved with individual applications of PS II- and HPPD-inhibiting herbicide used in this study

[d] Expected and observed values of the combinations were then compared using Wilcoxon signed-rank test using R package stats. If the expected response is similar to the observed response ($p \geq 0.05$), the combination is considered additive; if the expected response is less than the observed response ($p \leq 0.05$), the combination is considered synergistic; and if the expected response is greater than the observed response the combination is considered antagonistic ($p \leq 0.05$).

[e] Means followed by the same letter within a column are not significantly different (α=.05). Means were separated with the Tukey's honest significant difference test.

Appendix B Supplemental information for Chapter 4

Table B.1. Cotton yield components in herbicide-resistant cotton systems as influenced by residual herbicide applied in PRE fb EPOST systems in 2022.[z]

Residual herbicide[y]	Fruiting nodes plant^{-1}	Total bolls plant^{-1}	Harvestable bolls plant^{-1}	Total dropped bolls m$^{-2,x}$
Acetochlor	3.5 a[w]	3.4 ab	21.2 a	18.8 a
Dimethenamid-P	3.9 a	3.9 ab	19.6 a	18.0 a
Pendimethalin	3.4 a	3.6 ab	24.1 a	22.2 a
S-metolachlor	3.4 a	2.7 b	17.5 a	16.8 a
No over-lapping residual[v]	3.3 a	2.9 b	21.6 a	19.2 a
Non-treated	0.7 b	0.5 c	5.7 b	5.1 b
Weed-free	4.0 a	4.5 a	26.1 a	23.4 a

[z] PRE = preemergence application; fb = followed by; EPOST = early postemergence application (6-Leaf cotton)

[y] PRE residual herbicides were combined with fluometuron *fb* the same residual herbicide combined with glyphosate + trait herbicide EPOST (Trait herbicide in Enlist system = 2,4-D choline; XtendFlex system = dicamba).

[x] Collected from 1 m^{-2} area around 5 plants that were each of the center two rows in each plot.

[w] Means followed by the same letter within a column are not significantly different and means were separated using Tukey's HSD ($\alpha = 0.05$).

[v] No over-lapping residual = fluometuron *fb* glyphosate + trait herbicide.