Control of Palmer Amaranth (*Amaranthus palmeri*) and Common Waterhemp (*Amaranthus rudis*) in Double Crop Soybean and with Very Long Chain Fatty Acid Inhibitor Herbicides

by

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B.S., Iowa State University, 2014

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Agronomy
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

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Abstract

During 2015 and 2016, five site years of research were implemented in double crop soybean after winter wheat at experiment fields in Kansas near Manhattan, Hutchinson, and Ottawa to assess various non-glyphosate herbicide treatments at three different application timings for control of Palmer amaranth (*Amaranthus palmeri* S. Wats.) and common waterhemp (*Amaranthus rudis* Sauer).

Spring-post (SP) treatments with residual control of Palmer amaranth and waterhemp were applied in the winter wheat at Feekes 4 and resulted in less than 50% control of Palmer amaranth and waterhemp at the time of double crop soybean planting. Pre-harvest treatments were applied two weeks before winter wheat harvest. 2,4-D resulted in highly variable Palmer amaranth and waterhemp control whereas flumioxazin resulted in comparable control to PRE treatments that contained paraquat plus a residual herbicide.

Excellent Palmer amaranth and waterhemp control was observed at 1 week after planting (WAP) double crop soybean with a preemergence (PRE) paraquat application; however, reduced control of Palmer amaranth and waterhemp was noted at 8WAP due to extended emergence. Palmer amaranth and waterhemp control was 85% or greater at 8WAP for most PRE treatments that included a combination of paraquat plus residual herbicides. PRE treatments that did not include the combination of paraquat and residual herbicides did not provide acceptable control.

A second set of field experiments were established in 2015 and 2016 near Manhattan, Hutchinson, and Ottawa to assess residual Palmer amaranth and waterhemp control with very-long-chain-fatty acid (VLFCA) inhibiting herbicides. Acetochlor (non-encapsulated and encapsulated), alachlor, dimethenamid-*P*, metolachlor, *S*-metolachlor, and pyroxasulfone as well as the microtubule inhibiting herbicide pendimethalin were applied at three different field use

rates (high, middle, and low) based on labeled rate ranges for soybean as PRE treatments in a non-crop scenario after the plot was clean tilled with a field cultivator.

The experiment was conducted one time in 2015 and four times in 2016 at two different locations for a total of five site years of data. PRE applications were made June 1, 2015, near Manhattan. PRE applications in 2016 were made in April at locations near Hutchinson and Ottawa; the second run of the experiment was applied in June at the same locations on a different set of plot areas.

At Manhattan pyroxasulfone, *S*-metolachlor, and dimethenamid-*P* resulted in the highest Palmer amaranth control at 4WAT. At Hutchinson, pyroxasulfone resulted in superior Palmer amaranth control compared to dimethenamid-*P* and pendimethalin at 4WAT and 8WAT. At Ottawa, acetochlor, *S*-metolachlor, and pyroxasulfone resulted in higher waterhemp control than alachlor and pendimethalin at 4WAT and 8WAT.

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Acknowledgements

I have truly enjoyed my time at K-State as a graduate student in weed science. In addition to finding my passion for weed science, I have been able to grow both as a professional agronomist and as a person during this opportunity. While the thesis is a large part of the degree requirements, the hours spent working as part of a team to overcome challenges and building relationships with the people that comprise that team have facilitated the learning.

While I have learned a tremendous amount and hope that my research will have a positive influence on agricultural production, people matter most at the end of the day. This incredible experience at K-State would never have been possible if Dr. Kevin J. Donnelly had not encouraged me to serve as a teaching assistant – an opportunity I am forever thankful for. Thank you to my major professor Dr. Dallas E. Peterson for providing me with countless opportunities to share my research through extension and professional meetings. Your unwavering commitment to helping me reach new opportunities is admirable and an example for all professors to follow. I extend a special appreciation to Dr. Douglas E. Shoup for serving on my committee as well as mentoring my development as an agronomist.

Thank you to the entire weed science team at K-State, especially Dr. Anita Dille, Dr. Curtis R. Thompson, and Mrs. Cathy L. Minihan, for helping to provide the insight and expertise to facilitate my learning and research. I extend a special thanks to Dr. Kraig L. Roozeboom, Dr. Gary Cramer, and Mr. Jim Kimball for helping with other various aspects of my research.

I also acknowledge the care and support of my parents during this time of my education. While we have missed working with each other on the farm, I am reminded each day that I would not be here without your continuing encouragement. Additionally, I employ the countless lessons that you taught me about respect, hard work, and being passionate each day.

Lastly, I extend a warm appreciation and thanks to my fellow students: Garrison Gundy, Eric Vanloenen, Nate Thompson, Jeffrey Albers, and Peter Bergkamp. We have had a tremendous amount of fun, accomplished a lot of work, and learned a few things not only about agronomy but about life along the way. I feel incredibly blessed to have been able to share this experience with you and believe that this would have been much of a lesser one without your friendship. I am confident that each of you will accomplish great things, and I look forward to sustaining our friendship. Thank you.

Chapter 1 -

Herbicide and Timing Options for Burndown and Residual Control of Palmer Amaranth (*Amaranthus palmeri*) and Common Waterhemp (*Amaranthus rudis*) in Double Crop Soybean

ABSTRACT

Double crop soybean after winter wheat is a component of many cropping systems across eastern and central Kansas. Until recently, control of pigweed (*Amaranthus* spp.), particularly Palmer amaranth (*Amaranthus palmeri* S. Wats.) and common waterhemp (*Amaranthus rudis* Sauer), has been both easy and economical with the use of sequential applications of glyphosate in glyphosate resistant soybean. As a result of this management approach, many populations of Palmer amaranth and common waterhemp in Kansas have become resistant to common use rates of glyphosate. During 2015 and 2016, five site years of research were implemented at experiment fields in Kansas near Manhattan, Hutchinson, and Ottawa, to assess various non-glyphosate herbicide programs at three different application timings for control of Palmer amaranth and waterhemp in a double crop soybean after winter wheat cropping system.

Emergence of Palmer amaranth and common waterhemp begins in April in southern Kansas. Therefore, spring-post treatments of pyroxasulfone and pendimethalin were applied to winter wheat at Feekes 4 to evaluate residual control of Palmer amaranth and waterhemp ahead of double crop soybean. Less than 40% control of pigweed was observed in both treatments 2 weeks after planting (WAP) double crop soybean. Pre-harvest treatments of 2,4-D and flumioxazin were also applied to the winter wheat to assess burndown control of emerged Palmer amaranth and waterhemp. 2,4-D resulted in highly variable Palmer amaranth and waterhemp control; whereas, flumioxazin resulted in comparable control to preemergence (PRE) treatments that contained paraquat plus a residual herbicide.

No-till soybean planting followed by PRE herbicide treatments, occurred within 24 hours of winter wheat harvest at all locations. Excellent control was observed at 2WAP with a PRE paraquat application; however, reduced control of Palmer amaranth and waterhemp was noted at 8WAP due to subsequent emergence. Results from orthogonal contrasts indicate that Palmer amaranth and waterhemp control was 85% or greater at 8WAP for most PRE treatments that included a combination of paraquat plus residual herbicides. PRE treatments that did not include both paraquat and residual herbicides did not provide acceptable control.

INTRODUCTION

Palmer amaranth and waterhemp were ranked as the number 1 and number 4 most troublesome weeds in 2015 based on a survey of weed scientists across the United States (Van Wychen 2016). It is difficult to distinguish common waterhemp and tall waterhemp, and the International Survey of Herbicide Resistant Weeds (Heap 2017; Steckel 2007) combines both species; therefore, they will be referred to collectively as waterhemp. *Amaranthus* spp. (pigweeds) have an aggressive growth rate (Horak and Loughin 2000) and vast seed production abilities which contributes to their competitiveness with crops (Schwartz et al. 2016; Webster and Grey 2015; Sellers et al. 2003; Steckel et al. 2003). In addition, Palmer amaranth and waterhemp have been confirmed resistant to six different herbicide sites of action (Heap 2017).

The emergence of Palmer amaranth and waterhemp closely coincides with that of soybean (Bell et al 2015; Hartzler et al. 2004). Pigweed species utilize the C4 photosynthetic pathway while soybean utilizes the C3 photosynthetic pathway giving pigweed a physiological advantage to soybean in high temperatures and moisture limited conditions (Stoller and Myers

1989; Pearcy and Ehleringer 1984; Ehleringer 1983; Chollet and Ogren 1975). Some pigweed species, such as Palmer amaranth, have physiological and morphological adaptations to shading (Jha et al. 2008) as well as diaheliotropism which aids in light interception through solar tracking (Ehleringer and Forseth 1980). These adaptations result in higher growth rates and more biomass accumulation under high temperatures even in the presence of a competing crop such as soybean when compared to other weed species that do not possess these adaptations. Densities of 8 Palmer amaranth m^{-2} caused a 78% yield reduction in soybean, whereas 11 waterhemp m^{-2} reduced soybean yield by 56% (Bensch et al. 2003).

The critical weed free period in soybean to prevent grain yield loss of no more than 5% has been described as VE through the V3 stage of development (Van Acker et al. 1993). While Palmer amaranth and waterhemp density has been related to yield loss in soybean (Bensch et al. 2003), the time of pigweed emergence was found to be more important than pigweed density in the prediction of yield loss in soybean (Dieleman et al. 1995, 1996). This is likely due to the indeterminate phenological development of pigweed (Ward et al. 2013).

Farmers must consider additional management implications for Palmer amaranth and waterhemp since emergence can occur after the critical weed free period in soybean (Jha and Norsworthy 2009). Late emerging Palmer amaranth and waterhemp can perpetuate the soil seed bank as well as supply seeds for dispersal to other fields with harvest equipment (Cordes et al. 2004). The glyphosate-resistance trait in Palmer amaranth was transferred up to 300 m through pollen from glyphosate resistant male plants to glyphosate-susceptible female plants (Sosnoskie et al. 2012). These are some of the factors that provide the basis for the need to facilitate a community-based pursuit of a zero-tolerance approach to management of herbicide resistant Palmer amaranth (Barber et al. 2015). While high initial upfront costs are associated with a zero-tolerance or a no seed threshold approach to weed management, long term costs should decrease (Norris 1999).

Double crop soybean after winter wheat can be a profitable option (Ibendahl et al. 2015) as well as a way to add diversity to the cropping system for Kansas farmers (Ciampitti et al. 2016). In 2015 and 2016, 187,530 ha and 147,757 ha, respectively, of double crop soybean after winter wheat were planted in Kansas (NASS 2017).

There is considerable uncertainty associated with planting double crop soybean in Kansas. Poor soybean emergence, inadequate soil moisture, and limited profitability are some of the factors that Kansas farmers must assess before choosing to plant double crop soybean. To mitigate some of these challenges, double crop soybean is normally no-till planted into wheat residue immediately after winter wheat harvest (Ciampitti et al. 2016).

Glyphosate resistant soybean brought an option for producers to easily and cost effectively achieve broad-spectrum weed control in double crop soybean without the use of residual herbicides (Krausz and Young 2001, Vangessel et al. 2001). Sequential applications of glyphosate in glyphosate resistant crops without the use of multiple effective modes of action to facilitate weed control have been widely used in most cropping systems (Wilson et al. 2011, Norsworthy et al. 2007, Norsworthy 2003). As a result of widespread glyphosate resistance, the effectiveness of postemergence (POST) glyphosate applications has decreased while weed control expense and seed costs have increased (Gianessi 2008).

Multiple herbicide application options for control of Palmer amaranth and waterhemp in double crop soybean are currently available. Control of both grass and broadleaf weeds in double crop soybean have been achieved with dinitroaniline herbicides applied in the winter wheat at Feekes 4 developmental stage (McHarry and Kapusta 1979). Pyroxasulfone and pendimethalin are labeled for application in winter wheat and can provide residual control of Palmer amaranth and waterhemp in soybean (Anonymous 2016d,f). Pyroxasulfone has been demonstrated to have excellent residual activity on Palmer amaranth and waterhemp in soybean when applied PRE to soybean emergence (Meyer et al. 2016, Mahoney et al. 2014). Pendimethalin has also been shown to provide residual control of Palmer amaranth (Steckel et al. 2002); however, Palmer amaranth resistant to microtubule inhibiting herbicides, such as pendimethalin, has been documented in the mid-south but not confirmed in Kansas (Heap 2017, Gossett et al. 1992).

An additional herbicide application timing is a pre-harvest treatment prior to the harvest of winter wheat. Many pre-harvest treatments are targeted to desiccate the standing wheat crop as well as any other vegetation to aid in harvest (Armstrong 2009). 2,4-D and flumioxazin are labeled for pre-harvest treatment in winter wheat in some states as well as control of emerged pigweed (Anonymous 2016e, 2006). Flumioxazin also provides residual control of Palmer amaranth and waterhemp in soybean (Meyer et al. 2016, Mahoney et al. 2014).

Planting into weed-free fields has been recognized as a best management practice for controlling herbicide resistant weeds (Norsworthy et al. 2012). Paraquat has been demonstrated to control emerged Palmer amaranth and waterhemp (Shoup et al. 2003, Steckel et al. 2002, Gossett et al. 1992) and has been used as a burndown application before no-till planting of double crop soybean into winter wheat stubble (Triplett 1978).

The use of a residual herbicide in combination with a non-selective herbicide such as paraquat has increased double crop soybean grain yield when compared to using only a residual herbicide or paraquat alone (Triplett 1978). The lack of crop canopy in double crop soybean can result in extended emergence of Palmer amaranth and waterhemp. This can warrant the use of a residual herbicide in conjunction with a non-selective herbicide at the time of PRE application.

Considerable mulch can cover the soil surface at the time of PRE application in a no-till system as used in double crop soybean. Compared to other crop residues, winter wheat has a high efficiency of soil coverage per unit weight of biomass (Greb 1967). Residual herbicides such as metolachlor and metribuzin can be spatially separated from the soil surface due to previous crop residue interference (Banks and Robinson 1986, 1982). By increasing the herbicide rate, it is possible to overcome the potential for reduction in weed control (Steinsick and Oliver 1979). While mulches can intercept herbicides, this does not always result in reduced weed control because of the complex interaction of mulches with weed emergence and growth (Crutchfield et al. 1986).

The objectives of this study were to assess the efficacy of Palmer amaranth and waterhemp control in double crop soybean with a) spring-post, pre-harvest, and PRE application timings for various non-glyphosate herbicide combinations and b) the utility of paraquat to control existing weeds as a component of the PRE treatments.

MATERIALS AND METHODS

General

Field experiments were conducted in 2015 and 2016 near Manhattan and Hutchinson, Kansas, and in 2016 near Ottawa, Kansas, for a total of five site years. Palmer amaranth populations at Manhattan and Hutchinson and common waterhemp populations at Ottawa were 20 plants m^{-2} or higher at PRE application at all site years. Soil properties (type, texture, pH, organic matter, and cation exchange capacity), herbicide application dates, and Palmer amaranth and waterhemp details are presented in Table 1.1. Three different herbicide application timings were utilized in this experiment: spring-post, pre-harvest, and PRE. Various labeled treatments were selected to assess the control of pigweed through the burndown as well as possible residual properties of the given herbicides. All treatments were applied using a four nozzle CO_2 pressurized backpack sprayer calibrated to deliver 144 L ha^{-1} at 241 kPa. Experiments were conducted in a randomized complete block design. Plots at all sites were 3 m wide and 9 m long, and staked when the winter wheat was at the Feekes 3 stage. All treatments were replicated four times at each site. Clethodim was applied to all plots as needed at the rate of 56 g ai ha^{-1} for grass weed control in the double crop soybean. Percent Palmer amaranth and waterhemp control was visually evaluated compared to the untreated check 2 WAP, 4 WAP, and 8 WAP. Visual ratings were based on 0% = no Palmer amaranth or waterhemp control and 99% = complete Palmer amaranth or waterhemp control. Soybean grain was harvested from the center two rows of the four row plots and adjusted to 13.5% moisture for yield comparisons.

Data Analysis

Data were analyzed using the Mixed Procedure in JMP Pro 12 (SAS Institute., 100 SAS Campus Drive, Cary, NC 27513-2414) and means were separated using Fisher's Protected Least Significant Difference (LSD) at $\alpha = 0.05$. Site year combinations within a given species (e.g., Palmer amaranth), replications (nested within site year), and all interactions of these effects were considered random effects (Carmer et al. 1989). Treatment was considered as a fixed effect. By considering site year environments as random effects, it has been demonstrated that implications about treatments can be made over a range of environments (Johnson et a. 2014, Zhang et al. 2005, Stephenson et al. 2004a,b, Hager et al. 2003).

Spring-post Application Timing

"Everest" winter wheat was drilled at approximately 56 kg ha^{-1} during the preceding October and November at all sites. When the winter wheat reached the Feekes 4 stage of development, two treatments were applied in March of 2015 and 2016 (Table 1.1). Palmer amaranth and waterhemp had not emerged at the time of application at any of the site years. Application was made using TeeJet (TeeJet Technologies, Springfield, IL) Air Induction Extended Range (AIXR) 110015 nozzles.

Pre-harvest Application Timing

Pre-harvest treatments were applied in June each year two weeks prior to anticipated winter wheat grain harvest (Table 1.1). Turbo TeeJet (TT) 110015 nozzles were used and all appropriate adjuvants were utilized according to label recommendations (Table 1.2). Palmer amaranth and waterhemp height and density at time of application are listed in Table 1.1.

Preemergence Application Timing

"Asgrow 3634" glyphosate-resistant soybean (Monsanto Company, St. Louis, MO 63167) was no-till planted in 76 cm rows into the winter wheat residue after grain harvest (Table 1.1). Thirteen PRE herbicide treatments were applied after soybean was planted, and 1% v/v crop oil concentrate was utilized with all PRE treatments (Table 1.2). Soybean planting and PRE herbicide applications were completed within 24 hours after winter wheat grain harvest. TT 110015 nozzles were used in all PRE treatments. Palmer amaranth and waterhemp height and density at the time of application is listed in Table 1.1.

RESULTS AND DISCUSSION

In Season Precipitation

Thirty year precipitation normals from 1980 to 2010 were referenced for each site from the National Oceanic and Atmospheric Administration (Arugez et al. 2010). Cumulative precipitation percentages of the 30 year normal from January 1 to July 1 and June precipitation (Figure 1.1) indicate that moisture conditions leading into double crop soybean planting in all five site years were slightly dry. This may have contributed to reduced surface moisture at the time of double crop soybean planting; however, adequate rainfall for germination and emergence was received within 1WAP in all site years, except Hutchinson 2015 (Table 1.3). Because of dry soil conditions at planting and lack of moisture until 4WAP at Hutchinson 2015, highly variable double crop soybean emergence was observed.

Ample rainfall for herbicide activation (> 5.0 cm) was received within 1WAP at all site years except for Hutchinson 2015. Periodic moisture events occurred each week (≥ 0.4 cm) up to 8WAP. This helped to contribute to new pigweed emergence at each rating interval.

Spring-post Application Timing

Poor Palmer amaranth and waterhemp control was generally observed at all observation times for both spring-post treatments (Table 1.4, 1.5). The best results were at Ottawa where pyroxasulfone resulted in 40% waterhemp control and pendimethalin resulted in 30% waterhemp control 2WAP but control dropped to 0% 4WAP (Table 1.5). Pyroxasulfone resulted in only 14% control of Palmer amaranth 2WAP whereas pendimethalin resulted in only 5% control of Palmer amaranth 2WAP at Manhattan and Hutchinson (Table 1.4). At 4WAP, spring-post applications resulted in less than 5% Palmer amaranth control, and at 8WAP, 0% Palmer amaranth control was observed (Table 1.4).

The lack of Palmer amaranth and waterhemp control in both of these treatments is not surprising when the application timing is compared to the extended emergence of pigweed in double crop soybean. At the time of double crop soybean planting, both of these treatments had been applied in excess of 90 days.

Pyroxasulfone is susceptible to microbial degradation in the soil and has a half-life of 16 to 26 days (Shaner 2014a). As described by Busi et. al (2012) for pyroxasulfone susceptible rigid ryegrass (*Lolium rigidum* Gaudin), it was possible to select for pyroxasulfone resistant rigid ryegrass through repeated low-dose exposure. While research on this topic has not been conducted with pyroxasulfone in Palmer amaranth and waterhemp, repeated exposure at low-doses, as implemented with a spring-post application of pyroxasulfone, could help in selecting for pyroxasulfone-resistant Palmer amaranth or waterhemp.

Pre-harvest Application Timing

2,4-D resulted in 22% Palmer amaranth control and 41% waterhemp control 2WAP, respectively (Table 1.4, 1.5). Less than 20% Palmer amaranth and waterhemp control was observed at 4WAP. No Palmer amaranth and waterhemp control was observed at any site year at 8WAP (Table 1.4, 1.5). The higher efficacy of 2,4-D 2WAP (41% waterhemp control) could have been due to the lower density of waterhemp at Ottawa at the time of application of the pre-harvest treatments (Table 1.1).

Flumioxazin as a pre-harvest treatment resulted in equivalent Palmer amaranth and waterhemp control when compared to other top performing PRE treatments 2WAP and resulted in similar Palmer amaranth and waterhemp control when compared to top performing PRE treatments through 8WAP. Flumioxazin also provided burndown of emerged Palmer amaranth and waterhemp comparable to the level of control observed with PRE treatments that contained paraquat (Table 1.4, 1.5).

PRE Application Timing

Most PRE treatments that included paraquat resulted in superior burndown control of Palmer amaranth and waterhemp in all treatment combinations and control ratings at 2WAP in all site years compared to those treatments that did not include paraquat. A high level of control was realized despite various sizes of Palmer amaranth and waterhemp present at the time of application. In two of the site years (e.g., Hutchinson 2015 and Manhattan 2016) paraquat was applied to Palmer amaranth that had sustained injury from a 15 cm cutter bar height (Table 1.1). PRE paraquat treatments were applied within twenty-four hours of injury to Palmer amaranth stems without leaves; whereas the herbicide label requires leaf regrowth after such injury before paraquat application (Anonymous 2016b). This indicates that paraquat may have burndown utility when ample time for weed leaf regrowth is not available to producers (e.g., winter wheat harvest and double crop soybean planting).

Pigweed control 2WAP from paraquat alone did not differ from other PRE treatments that included paraquat (≥ 90%) (Table 1.4, 1.5). Numerical reductions in control were observed at some locations; however, this was due to extended emergence rather than recovery of emerged Palmer amaranth and waterhemp at the time of application (data not shown).

PRE treatments that did not include paraquat (e.g., *S*-metolachlor plus metribuzin and *S*-metolachlor plus fomesafen) resulted in less Palmer amaranth control 2WAP when compared to the identical treatments with the addition of paraquat (Table 1.4). This demonstrates that while residual herbicides such as fomesafen and metribuzin have POST Palmer amaranth and waterhemp activity (Bond et al. 2006, Abendroth et al. 2006) the addition of paraquat can increase control when targeting large (> 6 leaves) Palmer amaranth and waterhemp which would otherwise be off label for herbicides such as fomesafen (Anonymous 2016c).

PRE treatments that contained paraquat plus residual herbicides generally resulted in good pigweed control 4WAP and 8WAP, with the exception of the saflufenacil plus paraquat treatment. Reduced control was observed for this treatment for both Palmer amaranth and waterhemp at both the 4WAP and 8WAP observation times (≤ 81%) (Table 1.4, 1.5). This is likely due to the limited residual activity of saflufenacil at the 25 g ai ha^{-1} rate (Morichetti et al. 2012).

Imazethapyr plus dimethenamid-*P* plus saflufenacil plus paraquat resulted in excellent Palmer amaranth and waterhemp control at Manhattan and Hutchinson in all site years, but poor control at Ottawa (Table 1.4, 1.5). This is likely due to resistance to the acetolactate synthase (ALS)-inhibiting herbicide imazethapyr at Ottawa compared to the more susceptible populations at Manhattan and Hutchinson (data not shown). Producers selecting an herbicide for the control of Palmer amaranth and waterhemp in Kansas must carefully consider the potential of an ALS-resistant population when making herbicide decisions (Gaeddert et al. 1997).

Orthogonal contrasts confirm that the combination of paraquat plus residual herbicide(s) improved Palmer amaranth and waterhemp control. (Table 1.6, 1.7). This is due to extended emergence of Palmer amaranth and waterhemp during the development of double crop soybean in combination with poor burndown control of established Palmer amaranth and waterhemp at planting. At 2WAP, Palmer amaranth and waterhemp control with PRE treatments that did not contain paraquat was 68%, whereas, treatments that did contain paraquat resulted in 95% control (Table 1.6). This contrast was significant ($P \leq 0.0001$) through 8WAP where residual herbicide treatments without paraquat resulted in less control (44%); whereas, treatments that included paraquat with at least one residual herbicide resulted in a higher level of control (86%). PRE treatments that did not include paraquat resulted in recovery of emerged Palmer amaranth and waterhemp at the time of application which also contributed to reduced efficacy ratings.

At 8WAP, PRE treatments that included sulfentrazone or flumioxazin plus paraquat resulted in a higher level of Palmer amaranth control (89%) when compared to other PRE treatments that consisted of paraquat plus residual herbicides (81%) (Table 1.6). Similar results were seen with the addition of sulfentrazone or flumioxazin for waterhemp control at Ottawa 4WAP and 8WAP (Table 1.7).

While the addition of sulfentrazone or flumioxazin tended to result in a higher level of control, there was no significant difference in Palmer amaranth and waterhemp control observed between the treatments that contained either of the two herbicides (Table 1.6, 1.7).

Grain Yield

Winter wheat grain yield differences between treatments were not significant; therefore, average wheat grain yield for each site year was reported (Table 1.1). PRE treatments generally resulted in the highest double crop soybean yield when compared to other application timings. Specific treatments at Manhattan and Hutchinson that resulted in the highest soybean yield (> 2,700 kg ha^{-1}) included flumioxazin plus metribuzin plus chlorimuron-methyl plus paraquat, sulfentrazone plus paraquat, sulfentrazone plus metribuzin plus paraquat, *S*-metolachlor plus metribuzin plus paraquat, pyroxasulfone plus flumioxazin plus paraquat, and flumioxazin plus paraquat. Spring-post treatments of pyroxasulfone and pendimethalin did not differ from the weedy check (Table 1.4).

PRE treatments that included residual herbicides without paraquat yielded less (1,907 kg ha^{-1}) than PRE treatments that contained residual herbicides in combination with paraquat (2,667 kg ha^{-1}) as revealed through orthogonal contrast ($P \leq 0.0001$). The inclusion of metribuzin in combination with flumioxazin or sulfentrazone with paraquat in PRE treatments also resulted in higher grain yield ($P = 0.004$) when compared to other PRE treatments comprised of paraquat plus residual herbicides (Table 1.6).

Ottawa 2016 grain yields were highly variable whereas only the PRE treatments of *S*-metolachlor plus metribuzin and *S*-metolachlor plus metribuzin plus paraquat resulted in higher yields than the spring-post treatment of pyroxasulfone, pre-harvest treatment of 2,4-D, and the weedy check. Numerical differences were observed with the grain yield in all other treatments (Table 1.5).

Multiple Effective Sites of Action

Over reliance on a single effective site of action has repeatedly enhanced the development of herbicide resistance (Beckie 2006, Powles et al. 1997). Glyphosate resistant Palmer amaranth and waterhemp was reported after less than 4 and 6 years of repeated glyphosate use without the use of other effective sites of action (Culpepper et al. 2006; Legleiter and Bradley 2008).

Multiple herbicide combinations with varying numbers of effective sites of action on Palmer amaranth and waterhemp from both a foliar and a soil residual perspective were utilized in this experiment (Table 1.8). Treatments were considered to have an effective foliar site of action if an active ingredient provided control of an emerged Palmer amaranth and waterhemp at the time of application; whereas, treatments were considered to have a soil residual site of action if control was provided for Palmer amaranth and waterhemp that had not emerged at the time of application. Treatments that contained an acetolacte synthase (ALS)-inhibiting herbicide (e.g., imazethapyr or chlorimuron-methyl) were not included in effective sites of action counts as most Palmer amaranth and waterhemp populations in Kansas are considered ALS-resistant (Heap 2017, Gaeddert et al. 1997).

Chloroacetamide and dinitroaniline herbicides (e.g., pyroxasulfone, *S*-metolachlor, and pendimethalin) do not control established weeds (Anonymous 2016a,d, Hamm 1974) and were recorded as effective residual sites of action since there is not any confirmed resistance to these herbicides in Kansas (Heap 2017).

Protoporphyrinogen oxidase (PPO)-inhibiting herbicides (e.g., flumioxazin and fomesafen) were recorded as an effective site of action for soil residual as well as for foliar uptake (Table 1.8). Fluthiacet-methyl was not recorded as an effective site of action for foliar uptake because it is not labeled for POST Palmer amaranth control, and due to its high absorption to the soil and short half-life (< 2 days), it is not an effective residual site of action (Shaner 2014a, Anonymous 2012). PPO-resistant waterhemp and Palmer amaranth have been confirmed to be resistant to POST applications of fomesafen due to the target site mechanism of resistance with the presence of the PPO glycine 210 deletion gene. Waterhemp populations that express this gene are still susceptible to PPO-inhibiting herbicides PRE, and it is speculated that the same is true for Palmer amaranth (Salas et al. 2016, Wuerffel et al. 2015). PPO-resistant waterhemp has been confirmed in Kansas (Shoup et al. 2003), and it is speculated that isolated populations of PPO-resistant Palmer amaranth exist, but have not been confirmed. Therefore, while resistant populations may exist in Kansas, they are spatially variable and a high-level of efficacy can still be expected with PPO-inhibiting herbicide applications.

Many pigweed populations may be susceptible to various sites of action that were not reported as effective (Table 1.8). Local expertise must be consulted when making herbicide recommendations in regards to effective sites of action.

As seen in the orthogonal contrast (Table 1.6, 1.7), PRE treatments that included metribuzin plus sulfentrazone or flumioxazin resulted in significantly higher Palmer amaranth control ($P = 0.0012$) as well as waterhemp control ($P = 0.10$) when compared to other residual herbicide treatments. Whitaker et al. (2010) reported that the addition of metribuzin plus chlorimuron-methyl to *S*-metolachlor increased Palmer amaranth control by 22% in a PRE application in soybean. Therefore, metribuzin should be considered in PRE applications as an additional effective site of action for residual pigweed control.

Some PRE treatments included two effective sites of action on emerged pigweed but only one residual effective site of action (e.g., sulfentrazone plus paraquat with 90% Palmer amaranth control 8WAP). Many of these treatments resulted in numerical differences in Palmer amaranth when control when compared to treatments that contained multiple residual effective sites of action (e.g., sulfentrazone plus metribuzin plus paraquat with 93% Palmer amaranth control 8WAP). However, when the data were pooled in contrast, it revealed that PRE treatments containing multiple residual sites of action resulted in greater control 8WAP when compared to treatments that utilized only one residual effective site of action ($P = 0.009$). The same pattern was observed with waterhemp control at Ottawa 8WAP ($P = 0.10$). Significant differences were not observed for this contrast at 2 and 4WAP; however, by the 8WAP observations, it was realized that by adding effective sites of action at adequate rates can help in pigweed control later in the season (Table 1.4, 1.5).

Models indicate that combining multiple effective sites of action in tank mixes is more effective than rotating two different sites of action from year to year in managing against the selection of herbicide resistant weeds (Becki and Rebound 2009). Resistance models indicate when an average of 2.5 effective sites of action are used per year compared to 1.5 effective sites of action, the selection of glyphosate-resistant weeds was 83 times less likely to occur (Evans et al. 2015). Additional cost is associated with utilizing additional sites of action in tank mixes, and growers tend to only manage herbicide resistant weeds after they have already become herbicide resistant (Peterson 1999). To contrast this, using multiple effective sites of action as a tank mix can increase grower profitability through time as a result of improved weed control, plus facilitate long term resistance management (Weirich et al. 2011a,b).

Practical Implications for Integrated Weed Management

Spring-post applications of residual herbicides such as pyroxasulfone and pendimethalin can provide some suppression of Palmer amaranth and waterhemp at planting of double crop soybean; however, when compared to other herbicides at different application timings, this application timing resulted in less Palmer amaranth and waterhemp control. Spring-post herbicide applications could be combined with other spring treatments in winter wheat to reduce application costs; however, the repeated exposure of a low dose of these herbicides at the time of Palmer amaranth and waterhemp emergence could select resistant biotypes. It is recognized as a best management practice of managing herbicide resistance to avoid recurrent low dose exposure to herbicides (Norsworthy et al. 2012).

As a pre-harvest treatment for Palmer amaranth and waterhemp control, flumioxazin performed superior to 2,4-D in all site years and observation timings. Flumioxazin has additional utility as pre-harvest treatment with both foliar and residual activity. By treating earlier to the planting of double crop soybean, the chances for receiving activating rainfall are also increased; however, complete control of emerged Palmer amaranth and waterhemp at the time of double crop soybean planting was not observed in any of the site years. Therefore, a sequential treatment, such as a POST application, would need to be implemented to control the remainder of emerged Palmer amaranth and waterhemp if a pre-harvest treatment of flumioxazin were to be effectively implemented.

Paraquat was an effective site of action with superior control of emerged pigweed prior to the emergence of double crop soybean. As a result of this research, paraquat combined with residual herbicides for multiple effective sites of action and applied in a PRE application to double crop soybean is recommended.

While herbicides with a POST application timing in double crop soybean were not utilized in this experiment, the potential utility of a POST herbicide application is suggested by the reduced Palmer amaranth and waterhemp control observed 8WAP in all treatments in all site years. None of the treatments facilitated complete Palmer amaranth and waterhemp control 8WAP and the inclusion of a POST application of herbicides with an effective site of action such as auxinic herbicides (e.g., 2,4-D and dicamba), glufosinate, or PPO-inhibiting herbicides (e.g., fomesafen) would likely increase the overall efficacy of pigweed control.

Cultural control methods, while outside the objective of this experiment, must also be considered in addition to effective herbicide treatments when implementing double crop soybean after winter wheat. Wide row spacing (76 cm) was utilized in this experiment. It is understood that narrow rows (≤ 38 cm) can aid in Palmer amaranth and waterhemp suppression (Butts et al. 2016, Bell et al. 2015, Schultz et al. 2015, Knezevic et al. 2003). The winter wheat ecology should also be considered in terms of Palmer amaranth and waterhemp management. As seen at Hutchinson 2015, the winter wheat grain crop resulted in low grain yield, and because of a lack of crop competition, the Palmer amaranth and waterhemp size was large (> 75 cm) at the time of winter wheat grain harvest (Table 1.1). As a result, limited Palmer amaranth and waterhemp emergence was observed at this site after the emergence of double crop soybean (data not shown) when compared to other site years where emergence of weeds was normally more extended throughout the summer. The effect of a preceding cereal crop on the emergence pattern of Palmer amaranth and waterhemp in soybean should be considered when planning a weed control program. DeVore et al. (2013) reported that the residue from a winter wheat grain crop reduced Palmer amaranth emergence by 40% in the double crop soybean. Therefore, a high yielding wheat grain crop could have utility in managing Palmer amaranth and waterhemp in double crop soybean.

It is imperative for double crop soybean producers to give careful selection to proper tank mixes of multiple effective sites of action for driver weeds, such as Palmer amaranth and waterhemp. Unfortunately, regardless of any chemical control tactic, herbicide resistance is inevitable (Shaner 2014b). Therefore, it is imperative that producers implement an integrated system which encompasses all possible control methods to suppress the long-term influence of weeds on agricultural productivity (Owen 2016).

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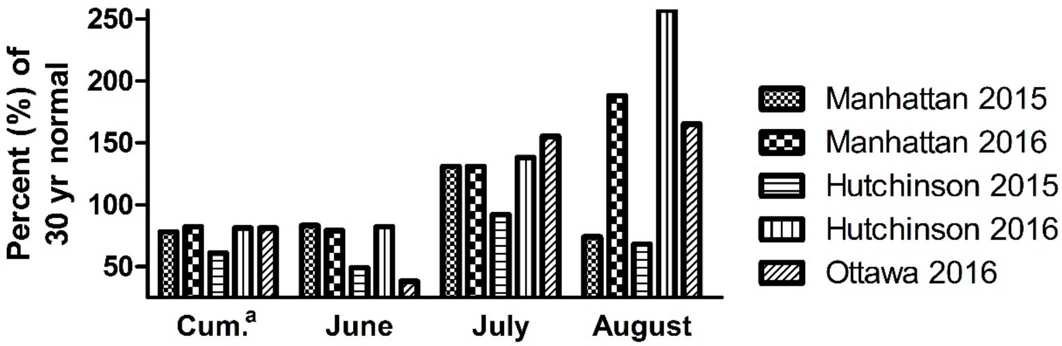

Figure 1.1. Rainfall at five site years as a percentage of the 30 yr normal from 1980 to 2010 for June, July, and August from the National Oceanic and Atmospheric Administration (Arugez et al. 2010).

[a] Cum: cumulative rainfall percentage of 30 yr normal from January 1 to July 1 for each site year.

Table 1.1. Planting and herbicide application dates, soil characteristics, winter wheat grain yield, and Palmer amaranth and waterhemp densities and heights at experiment sites.[a,b]

	2015		2016		
Site characteristics	Manhattan	Hutchinson	Manhattan	Hutchinson	Ottawa
SP application date	March 31	March 17	March 24	March 24	March 24
PH application date	June 17	June 22	June 13	June 15	June 13
PRE application date	July 1	July 6	June 27	June 29	June 29
Density at SP	-	-	-	-	-
Height at SP	-	-	-	-	-
Density at PH	2 m^{-2}	30 m^{-2}	4 m^{-2}	120 m^{-2}	4 m^{-2}
Height at PH	8 cm	75 cm	8 cm	10 cm	10 cm
Density at PRE	35 m^{-2}	25 m^{-2}	50 m^{-2}	50 m^{-2}	20 m^{-2}
Height at PRE	10 cm	[†]15 cm	[†]15 cm	14 cm	10 cm
Soil series	Reading [c]	Farnum [d]	Reading	Darlow [e]	Woodson [f]
Soil texture	silt loam	loam	silt loam	silt loam	silt loam
Soil organic matter [g] (%)	3.5	2.4	2.6	2.6	2.4
Soil pH	6.1	5.0	6.1	5.9	6.0
Soil cation exchange capacity (meq/100g) [h]	19.1	16.8	20.9	20.0	19.5
Average winter wheat grain yield (ton ha^{-1}) [i]	4.0	1.8	3.8	3.5	4.1

[a] Abbreviations: SP, spring postemergence; PH, pre-harvest; PRE, preemergence; meq, milliequivalents.

[b] All soil characteristics assessed from a 0 to 7.6 cm soil sampling depth.

[c] Fine-silty, mixed superactive, mesic Pachic Argiudolls

[d] Fine-loamy, mixed superactive, mesic Pachic Argiustolls.

[e] Fine-loamy, mixed, superactive, mesic Vertic Natrustalfs.

[f] Fine, smectic, thermic Abruptic Argiaquolls.

[g] Loss-on-ignition (Ball 1964).

[h] Adjusted to 7 pH (Rich 1969).

[h] Wheat grain moisture content adjusted to 12.5%.

[†] Pigweed height determined by the 15 cm cutter bar height at wheat harvest.

Table 1.2. Herbicides, rates, and adjuvants for spring postemergence, pre-harvest, and PRE application timings. [a]

Herbicide	Trade Name	Rate	Manufacturer	Location	Application Timing	Adjuvant [b]
		g ai or ae ha $^{-1}$				
Pyroxasulfone	Zidua®	119	BASF Corporation	Research Triangle Park, NC	SP	-
Pendimethalin	Prowl® H2O	1065	BASF Corporation	Research Triangle Park, NC	SP	-
2,4-D	Shredder™ 2,4-D LV4	561	Winfield Solutions LLC	St. Paul, MN	PH	-
Flumioxazin	Valor® SX	107	Valent U.S.A. Corporation	Walnut Creek, CA	PH	AMS + MSO
Paraquat	Gramoxone® SL 2.0	841	Syngenta Crop Protection, LLC	Greensboro, NC	PRE	COC
S-met + metr	Boundary® 6.5 EC	1472 + 350	Syngenta Crop Protection, LLC	Greensboro, NC	PRE	COC
S- met + fome	Prefix®	1217 + 266	Syngenta Crop Protection, LLC	Greensboro, NC	PRE	COC
S- met + sulf	BroadAxe® XC	1435 + 160	Syngenta Crop Protection, LLC	Greensboro, NC	PRE	COC
Sulf + chlo	Authority® XL	152 + 19	FMC Corporation	Philadelphia, PA	PRE	COC
Sulf + metr	Authority® MTZ DF	202 + 303	FMC Corporation	Philadelphia, PA	PRE	COC
Flum + pyro	Fierce®	70 + 89	Valent U.S.A. Corporation	Walnut Creek, CA	PRE	COC
Imaz + dime + safl	OpTill® PRO	70 + 526 + 25	BASF Corporation	Research Triangle Park, NC	PRE	COC
Flum + metr + chlo	Trivence™	72 + 250 + 22	E.I. du Pont de Nemours and Co.	Wilmington, DE	PRE	COC
Flut + pyro	Anthem®	4 + 146	FMC Corporation	Philadelphia, PA	PRE	COC
Flumioxazin	Valor® SX	70	Valent U.S.A. Corporation	Walnut Creek, CA	PRE	COC
Sulfentrazone	Spartan® 4F	202	FMC Corporation	Philadelphia, PA	PRE	COC
Saflufenacil	Sharpen®	25	BASF Corporation	Research Triangle Park, NC	PRE	COC

[a] Abbreviations: *S*-met, *S*-metolachlor; metr, metribuzin; fome, fomesafen; para, paraquat; sulf, sulfentrazone; chlo, chlorimuron-methyl; flum, flumioxazin; pyro, pyroxasulfone; imaz, imazethapyr; dime, dimethenamid-*P*; safl, saflufenacil; flut, fluthiacet-methyl; SP, spring postemergence; PH, pre-harvest; PRE, preemergence; AMS, ammonium sulfate; MSO, methylated seed oil; COC, crop oil crop concentrate.
[b] Adjuvant rates: AMS, 2.8 kg ai ha^{-1} (N-Pak, Winfield, St. Paul, MN); MSO, 1% v/v (Destiny, Winfield Solutions LLC, St. Paul, MN); COC, 1% v/v (Prime Oil, Winfield Solutions LLC, St. Paul, MN).

Table 1.3. Rainfall data for each week after PRE application.

			Rainfall							
			Weeks after PRE application							
Location	Year	PRE [a]	1	2	3	4	5	6	7	8
			cm							
Manhattan	2015	July 1	7.8	0.8	2.3	0.9	1.9	3.1	1.7	1.1
Manhattan	2016	June 27	6.7	1.62	5.1	0.2	4.1	3.4	1.9	4.6
Hutchinson	2015	July 6	0.7	0.4	0.7	5.4	1.5	0.5	3.1	0.3
Hutchinson	2016	June 29	5.6	1.1	2.1	1.3	2.7	5.1	5.5	0.0
Ottawa	2016	June 29	8.4	3.8	0.13	2.9	0.6	2.8	4.6	3.7

[a] Date of PRE application for each site year.

Table 1.4. Palmer amaranth control and double crop soybean grain yield at Manhattan and Hutchinson, KS.[a,b]

Herbicide treatment	Application timing[c]	Rate	Visual Control 2WAP	4WAP	8WAP	Grain yield
		g ai or ae ha^{-1}		%		kg ha^{-1}
Pyroxasulfone	SP	119	14cd	2.5f	0e	1278jk
Pendimethalin	SP	1065	5d	1f	0e	1135jk
2,4-D	PH	561	22c	18e	5e	1348j
†Flumioxazin	PH	107	90a	86ab	84ab	1946hi
Paraquat	PRE	841	91a	64c	41d	1952hi
S-met + metr	PRE	1472 + 350	60b	47d	46d	2020ghi
S-met + fome	PRE	1217 + 266	75b	52d	41d	1794i
S-met + metr + para	PRE	1472 + 350 + 841	93a	90ab	82b	2824abcd
S-met + fome + para	PRE	1217 + 266 + 841	98a	94a	88ab	2691bcde
†*S*-met + sulf + para	PRE	1435 + 160 + 841	95a	89ab	81ab	2175fghi
†Sulf + chlo + para	PRE	152 + 19 + 841	99a	93ab	87ab	2428defg
Sulf + metr + para	PRE	202 + 303 + 841	98a	96a	93a	2898abc
Flum + pyro + para	PRE	70 + 89 + 841	97a	94a	90ab	2734def
Imaz + dime + safl + para	PRE	70 + 526 + 25 + 841	98a	95a	90ab	2583cdef
Flum + metr + chlo + para	PRE	72 + 250 + 22 + 841	98a	96a	93a	3051a
Flut + pyro + para	PRE	4 + 146 + 841	97a	92ab	83ab	2511def
†Flum + para	PRE	70 + 841	99a	92ab	89ab	2713abcde
†Sulf + para	PRE	202 + 841	99a	94ab	90ab	3035ab
†Safl + para	PRE	25 + 841	94a	81b	61c	2355efgh
Not treated weedy check	-	-	-	-	-	952k
P-value			< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a] Abbreviations: SP, spring-post; PH, pre-harvest; PRE, preemergence; *S*-met, *S*-metolachlor; metr, metribuzin; fome, fomesafen; para, paraquat; sulf, sulfentrazone; chlo, chlorimuron-methyl; flum, flumioxazin; pyro, pyroxasulfone; imaz, imazethapyr; dime, dimethenamid-*P*; safl, saflufenacil; flut, fluthiacet-methyl; WAP, weeks after planting; NS, not significant.

[b] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD ($\alpha = 0.05$).

[c] Application timing: SP, Feekes 4 stage; PH, 2 weeks prior to wheat harvest; PRE, at soybean planting.

†Treatment only present in 2016 site years.

Table 1.5. Waterhemp control and double crop soybean grain yield at Ottawa, KS 2016.[a,b]

Herbicide treatment	Application timing[c]	Rate	Visual Control			Grain yield
			2WAP	4WAP	8WAP	
		g ai or ae ha^{-1}		%		kg ha^{-1}
Pyroxasulfone	SP	119	40b	0h	0f	1407bcd
Pendimethalin	SP	1065	30b	0h	0f	1461abcd
2,4-D	PH	561	41b	13h	0f	1404cd
Flumioxazin	PH	107	91a	86abc	83ab	2235ab
Paraquat	PRE	841	99a	30g	25g	1841abc
S-met + metr	PRE	1472 + 350	94a	69e	60cd	2282a
S-met + fome	PRE	1217 + 266	96a	80bcd	73abc	1626abcd
S-met + metr + para	PRE	1472 + 350 + 841	99a	75de	71abc	2279a
S-met + fome + para	PRE	1217 + 266 + 841	99a	86abc	79abc	1929abc
S-met + sulf + para	PRE	1435 + 160 + 841	99a	91a	85ab	1746abcd
Sulf + chlo + para	PRE	152 + 19 + 841	99a	86abc	73abc	2042abc
Sulf + metr + para	PRE	202 + 303 + 841	99a	88abc	83ab	1809abcd
Flum + pyro + para	PRE	70 + 89 + 841	99a	86abc	78abc	1891abc
Imaz + dime + safl + para	PRE	70 + 526 + 25 + 841	99a	55f	41de	2185ab
Flum + metr + chlo + para	PRE	72 + 250 + 22 + 841	99a	90ab	85ab	2081abc
Flut + pyro + para	PRE	4 + 146 + 841	99a	85abcd	81ab	1557abcd
†Flum + para	PRE	70 + 841	99a	79cde	68bc	1687abcd
†Sulf + para	PRE	202 + 841	99a	91a	90a	2035abc
†Safl + para	PRE	25 + 841	99a	40g	35e	1846abcd
Not treated weedy check	-	-	-	-	-	994d
P-value			< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a] Abbreviations: SP, spring-post; PH, pre-harvest; PRE, preemergence; *S*-met, *S*-metolachlor; metr, metribuzin; fome, fomesafen; para, paraquat; sulf, sulfentrazone; chlo, chlorimuron-methyl; flum, flumioxazin; pyro, pyroxasulfone; imaz, imazethapyr; dime, dimethenamid-*P*; safl, saflufenacil; flut, fluthiacet-methyl; WAP, weeks after planting; NS, not significant.

[b] Means followed by the same letter within a column are not statistically different according to Fisher's Protected LSD ($\alpha = 0.05$).

[c] Application timing: SP, Feekes 4 stage; PH, 2 weeks prior to wheat harvest; PRE, at soybean planting.

Table 1.6. Orthogonal contrasts of various treatments for Palmer amaranth control and double crop soybean grain yield at Manhattan and Hutchinson, KS.[a]

Orthogonal Contrasts [b,c]	Visual Control 2WAP	4WAP	8WAP	Grain yield
PRE treatments containing sulf or flum + para vs. other PRE treatments containing residual herbicide(s) w/ para.	98 vs. 95 NS	93 vs. 90 NS	89 vs. 81 ***	2719 vs. 2593 NS
PRE treatments containing para + residual herbicide(s) vs. PRE treatments containing residual herbicide(s) w/o para.	95 vs. 68 ****	92 vs. 50 ****	86 vs 44 ****	2667 vs. 1907 ****
PRE treatments containing sulf or flum + metr + para vs. other PRE treatments containing residual herbicide(s) w/ para.	98 vs. 94 NS	96 vs. 91 *	93 vs. 84 ***	2975 vs. 2607 ***
PRE treatments containing sulf vs. PRE treatments containing flum.	98 vs. 98 NS	93 vs. 94 NS	88 vs. 91 NS	2634 vs. 2838 *
PRE treatments containing para + 2 residual herbicides vs. PRE treatments containing para + 1 residual herbicide.	93 vs. 97 NS	93 vs. 90 NS	88 vs. 81 ***	2673 vs. 2654 NS

[a] Abbreviations: WAP, weeks after planting; sufl, sulfentrazone; flum, flumioxazin; para, paraquat; metr, metribuzin; NS, not significant.

[b] Means of contrast different at *P = 0.1 to 0.05, **P = 0.05 to 0.01, ***P = 0.01 to 0.0001, ****P $\leq$ 0.0001 levels.

[c] Residual herbicide only counted if listed as an effective site of action in Table 1.8.

Table 1.7. Orthogonal contrasts of various treatments for waterhemp control and double crop soybean grain yield at Ottawa, KS.[a]

Orthogonal Contrasts [b,c]	Visual Control 2WAP	Visual Control 4WAP	Visual Control 8WAP	Grain yield
PRE treatments containing sulf or flum + para vs. other PRE treatments containing residual herbicide(s) w/ para.	99 vs. 99 NS	87 vs. 68 ***	80 vs. 61 ***	1898 vs. 1959 NS
PRE treatments containing para + residual herbicide(s) vs. PRE treatments containing residual herbicide(s) w/o para.	99 vs. 95 NS	79 vs. 75 *	72 vs. 67 **	1924 vs 1954 NS
PRE treatments containing sulf or flum + metr + para vs. other PRE treatments containing residual herbicide(s) w/ para.	99 vs. 97 NS	89 vs. 77 *	84 vs. 70 *	1945 vs. 1920 NS
PRE treatments containing sulf vs. PRE treatments containing flum.	99 vs. 99 NS	89 vs. 85 NS	83 vs. 77 NS	1908 vs. 1886 NS
PRE treatments containing para + 2 residual herbicides vs. PRE treatments containing para + 1 residual herbicide.	99 vs. 99 NS	82 vs. 74 NS	74 vs. 69 *	1995 vs. 1781 NS

[a] Abbreviations: WAP, weeks after planting; sufl, sulfentrazone; flum, flumioxazin; para, paraquat; metr, metribuzin; NS, not significant.

[b] Means of contrast different at *P = 0.1 to 0.05, **P = 0.05 to 0.01, ***P = 0.01 to 0.0001, ****P ≤ 0.0001 levels.

[c] Residual herbicide only counted if listed as an effective site of action in Table 1.8.

Table 1.8. Effective herbicide sites of action on Palmer amaranth and waterhemp for various herbicide combinations for soil residual and foliar action. [a]

Herbicide treatment[a]	Application timing[d]	Rate	Effective Sites of Action[b,c] Residual	Foliar
		g ai or ae ha^{-1}		
Pyroxasulfone	SP	119	1	-
Pendimethalin	SP	1065	1	-
2,4-D	PH	561	1	1
Flumioxazin	PH	107	1	1
Paraquat	PRE	841	-	1
S-met + metr	PRE	1472 + 350	2	1
S-met + fome	PRE	1217 + 266	2	1
S-met + metr + para	PRE	1472 + 350 + 841	2	2
S-met + fome + para	PRE	1217 + 266 + 841	2	2
S-met + sulf + para	PRE	1435 + 160 + 841	2	2
Sulf + chlo + para	PRE	152 + 19 + 841	2	2
Sulf + metr + para	PRE	202 + 303 + 841	2	3
Flum + pyro + para	PRE	70 + 89 + 841	2	2
Imaz + dime + safl + para	PRE	70 + 526 + 25 + 841	2	2
Flum + metr + chlo + para	PRE	72 + 250 + 22 + 841	2	3
Flut + pyro + para	PRE	4 + 146 + 841	1	1
Flum + para	PRE	70 + 841	1	2
Sulf + para	PRE	202 + 841	1	2
Safl + para	PRE	25 + 841	1	2

[a] Abbreviations: SP, spring postemergence; PH, pre-harvest; PRE, preemergence; *S*-met, *S*-metolachlor; metr, metribuzin; fome, fomesafen; para, paraquat; sulf, sulfentrazone; chlo, chlorimuron-methyl; flum, flumioxazin; pyro, pyroxasulfone; imaz, imazethapyr; dime, dimethenamid-*P*; safl, saflufenacil; flut, fluthiacet-methyl; WAP, weeks after planting.

[b] Effective sites of action listed with an assumed ALS-inhibiting herbicide resistant population.

[c] Soil residual control listed of Palmer amaranth and waterhemp that had not emerged at the time of application. Foliar control listed for Palmer amaranth and waterhemp that had emerged at time of application.

[d] Application timing: SP, Feekes 4 stage; PH, 2 weeks prior to wheat harvest; PRE, at soybean planting.

Chapter 2 -

Palmer Amaranth (*Amaranthus palmeri*) and Common Waterhemp (*Amaranthus rudis*) Control with Very Long Chain Fatty Acid Inhibitor Herbicides

ABSTRACT

Increased herbicide resistance in Palmer amaranth (*Amaranthus palmeri* S. Wats.) and common waterhemp (*Amaranthus rudis* Saur) across multiple herbicide sites of action (SOA) requires a change in management to facilitate weed control. Very long chain fatty acid (VLCFA) inhibitor herbicides have been mostly used for residual grass control. It is often overlooked that these herbicides also can provide residual control of Palmer amaranth and common waterhemp.

Field experiments were established in 2015 and 2016 near Manhattan, Hutchinson, and Ottawa, Kansas to assess residual control of Palmer amaranth and waterhemp with VLCFA herbicides. Acetochlor (non-encapsulated and encapsulated), alachlor, dimethenamid-*P*, metolachlor, *S*-metolachlor, and pyroxasulfone, as well as the microtubule inhibiting herbicide pendimethalin, were applied at three different rates (high, middle, and low) based on labeled rate ranges for soybean. The experiment was a randomized complete block design with a factorial arrangement of herbicides and rates with four replications. All treatments were applied PRE in a non-crop scenario after the plot area was clean tilled with a field cultivator. The experiment was conducted one time in 2015 and four times in 2016 at two locations for a total of five site years of data. PRE applications were made June 1, 2015 near Manhattan. PRE applications in 2016 were made on April 12 and 13, 2016 at locations near Hutchinson and Ottawa. The second run of the experiment was applied on June 6, 2016 at locations near Hutchinson and Ottawa as well. Percent Palmer amaranth and common waterhemp control was visually evaluated at 4 and 8 weeks after treatment (WAT).

Analysis of fixed effects revealed no significance for three and two-way interactions of herbicide by rate by timing and herbicide by rate for each site at both 4 and 8WAT; therefore,

percent Palmer amaranth and waterhemp control was compared using means for each product across rates. At Manhattan pyroxasulfone, *S*-metolachlor, and dimethenamid-*P* resulted in the highest Palmer amaranth control at both 4 and 8WAT. At Hutchinson and Ottawa, pyroxasulfone, *S*-metolachlor, and non-encapsulated acetochlor resulted in the highest Palmer amaranth and common waterhemp control at both 4 and 8WAT. Pyroxasulfone and *S*-metolachlor were often the most effective herbicides; whereas, pendimethalin resulted in the least effective Palmer amaranth and common waterhemp control at all sites and observation times. The high use rate across all herbicides resulted in superior control when compared to the low use rate across all herbicides at all sites and observation times. This research demonstrates the value of utilizing VLCFA herbicides as an effective site of action for residual control of Palmer amaranth and common waterhemp as part of integrated weed management plan in various cropping systems.

INTRODUCTION

The very-long-chain-fatty acid (VLFCA) inhibiting herbicides have been a staple in many weed management programs as an effective site of action for many troublesome grass and broadleaf weeds for decades (Kearney and Kaufman 1988). Chloroacetamide, oxyacetamide, and pyrazole chemical families encompass most of the VLCFA herbicides used in Midwest cropping systems (Sprague 2017; Shaner 2014).

Discovered in 1952 by Monsanto Company, the chloroacetamide family was the first of the VLCFA herbicides (Hamm 1974). In contrast to 2,4-D, a popular herbicide in the 1950’s, the VLCFA herbicides offered residual weed control options; whereas, 2,4-D was utilized primarily for control of emerged weeds (Peterson et al. 2016; Hamm 1974). *N,N*-diallyl-2chloracetamide (CDAA) was first made available for public use in 1956, and this was the first time that a herbicide could be applied PRE to a crop to provide control of annual grass species (Timmons 2005; Hamm 1974).

VLCFA herbicides are absorbed after germination during internode elongation in emerging seedlings, but do not provide control of emerged weeds (Fuerst 1987). Susceptible seedlings seldom emerge from the soil (Cobb and Reade 2010). Grass seedlings absorb herbicide through the coleoptile while dicotyledonous weeds absorb the herbicide through the radicle (Kearney and Kaufman 1988; Duke et al. 1975). Root and shoot development is thereby impeded, stopping seedling emergence (Fuerst 1987; Dhillon and Anderson 1972).

Much uncertainty has been associated with the specific mechanism of action of the VLCFA herbicides (Böger 1997; Deal and Hess 1980; Deal et al. 1980). Recent research has specified that this class of herbicides inhibit VLCFA biosynthesis. Cultured rice (*Oryza sativa* L.) cells treated with pyroxasulfone showed a decrease in VLCFA levels and a buildup of medium chain and long chain fatty acids, which are required for synthesizing VLCFA (Tanetani et al. 2009; Böger et al. 2000). Plant cell death is likely due to reduced functionality of the plasmalemma as VLCFAs are its primary constituents (Matthes and Böger 2002). The plasmalemma enables a cell to export and retain solutes, ions, and metabolites as well as provide structure to specialized organelles (Taiz and Zeiger 2006).

Detoxification of VLCFA herbicides in crop species is facilitated through numerous pathways, some of which are specific to the given VLCFA herbicide. However, enhanced herbicide metabolism from glutathione conjugation is considered to be the primary mechanism (Breaux 1987; Fuerst 1987; Jaworski, 1969). Selectivity among weed species has been linked to morphological characteristics such as seed size (e.g., *Amaranthus retroflexus* L. compared to *Xanthium strumarium* L.) as well as the rate of herbicide metabolism through glutathione conjugation (Ruberson 1999; Breaux 1987; Fuerst 1987; Jaworski 1969).

The primary fate of VLCFA herbicides in the soil is microbial degradation, which is influenced by the type of soil as well as the moisture content and temperature (Beestman and Deming 1974). Specific soil properties such as the variable net negative charge of organic matter as well as the clay minerology can heavily influence the adsorption of VLCFA herbicides within the soil (Obrigawitch et al. 1981; Helling et al. 1964). Increased adsorption to organic matter can dictate the application rate of VLCFA herbicide necessary to ensure residual herbicidal activity (Vasilakoglou and Eleftherohorinos 1997; Weber and Peter 1982; Peter and Weber 1985). In peat or muck type soils that consist predominantly of organic matter, applications of some VLCFA herbicides are prohibited due to poor weed control (Anonymous 2016).

Seed applied safeners (e.g., fluxofenim in grain sorghum (*Sorghum bicolor* L. Moench)) as well as those included in the formulation of some VLCFA herbicides (e.g., benoxacor in *S*-metolachlor) have expanded the number of crops available for VLCFA herbicide applications (Hatzios and Burgos 2004). Encapsulation of some VLCFA herbicides (e.g., acetochlor) have improved crop safety as well as influenced the residual control the herbicide can provide in a variety of conditions (Parker et al 2005; Vasilakoglou and Eleftherohorinos 1997; Peterson et al. 1988). The revision of certain active ingredients (e.g., metolachlor to *S*-metolachlor and dimethenamid to dimethenamid-*P*) to include more of the biologically active isomer have reduced the net amount of VLCFA herbicide entering the environment and increased weed control efficacy (Shaner et al. 2006; O’Connell et al. 1998; Couderchet et al. 1997).

VLCFA herbicides provide residual control of a variety of weed species including monocotyledonous, dicotyledonous, and sedge type plants (Grichar et al. 1996; Kearney and Kaufman 1988; Banks 1983). From 1990 to 2006, the percent of planted soybean area receiving a VLCFA herbicide decreased dramatically (Figure 2.1; NASS 2017). This decline is likely due to an increased use of POST applied herbicides in soybean (e.g., imazethapyr and glyphosate) (Young 2006; Shaner 2000; Vangessel et al. 2001; Johnson et al. 1998). In 2015, almost 25% of the planted soybean acres received a VLCFA herbicide. Increased use is likely due to the prevalence of Palmer amaranth and waterhemp resistant to acetolactate synthase (ALS) and 5-enolypyruvyl-shikimate-3-phosphate (EPSP) synthase inhibiting herbicides (NASS 2017; Heap 2017).

Palmer amaranth and common waterhemp have been confirmed resistant to six different herbicide sites of action (Heap 2017). Because common waterhemp (*Amaranthus rudis* Saur) and tall waterhemp (*Amaranthus tuberculatus* Moq. Saur) are difficult to distinguish and the International Survey of Herbicide Resistant Weeds combines both species, they will be collectively referred to as waterhemp (Heap 2017; Steckel 2007; Pratt and Clark 2001).

While numerous cases of VLCFA herbicide resistance have been reported in monocotyledonous species such as barnyardgrass (*Echinochloa crus-galli* L. var. *crus-galli*) and rigid ryegrass (*Lolium rigidum* Gaudin), no VLCFA herbicide resistance has been reported in dicotyledonous species (Heap 2017).

Drastic yield losses in many cropping systems can be expected if Palmer amaranth or waterhemp is left uncontrolled in fields (Bensch et al. 2003). Characteristics such as an aggressive growth rate, extended emergence, and vast seed production abilities have enabled Palmer amaranth and waterhemp to become driver weeds in many cropping systems (Horak and

Loughin 2000; Schwartz et al. 2016; Webster and Grey 2015; Sellers et al. 2003; Steckel et al. 2003).

Best management practices for herbicide resistance indicate that multiple effective herbicide sites of action should be used in combination with an integrated weed management strategy (Norsworthy et al. 2012). The high probability of developing herbicide resistance in Palmer amaranth and waterhemp combined with a lack of grower understanding of herbicide mode of action, makes this approach difficult to implement for producers (Norsworthy et al. 2017; Owen et al. 2017). VLCFA herbicides can provide excellent efficacy on Palmer amaranth and waterhemp when applied prior to weed emergence (Vizantinopoulos and Katranis 1998; Whitaker et al. 2010; Meyers et al. 2010; Fuerst et al. 1986; Clewis et al. 2006). VLCFA herbicides also provide the needed flexibility for crop rotational restrictions as well as preharvest intervals for in-season applications to facilitate a layered residual approach (Anonymous 2017; Steckel et al. 2002).

Differences exist between VLCFA herbicides and their formulations in the amount of precipitation required for activation as well as their residual persistence in a soil (Hart et al. 1995; Shrefler and Chandler 1994). The objectives of this study were to a) determine the efficacy of various VLCFA herbicides for Palmer amaranth and waterhemp control and 2) determine the importance of VLCFA herbicide application rate in obtaining a high level of Palmer amaranth and waterhemp control through the growing season.

MATERIALS AND METHODS

General

Field experiments were implemented at three different locations in Kansas near Manhattan, Hutchinson, and Ottawa during 2015 and 2016. A single, June application timing was utilized at Manhattan in 2015; whereas, two different April and June application timings were made at Hutchinson and Ottawa in 2016. Two application timings were assessed since VLCFA herbicides may be applied at a variety of timings to accommodate early preplant, preemergence (PRE), and post emergence (POST) application timings. The June application timings were applied to plot areas separate from the April application timings, and treatments were re-randomized and analyzed as separate experiments. Across all sites and application timings, five site years of data were considered in this project (Table 2.1).

Palmer amaranth populations at Manhattan and Hutchinson and waterhemp populations at Ottawa exceeded 50 plants m^{-2} in untreated checks at 8 weeks after treatment (WAT) at both the April and June application timings (data not shown). Soil properties (type, texture, pH, organic matter, and cation exchange capacity) are reported for all plot areas (Table 2.1). All treatments were applied PRE in the absence of a crop after the ground was clean tilled with a field cultivator.

Seven VLCFA herbicides and one microtubule inhibiting herbicide for comparison were applied in a randomized complete block design in a factorial of three rates for a total of 24 treatments. Rates were designated as high, middle, and low based on the labeled rate structure for soybean for each herbicide (Table 2.2). The rate structure of non-encapsulated acetochlor was based on corn (*Zea mays* L. ssp. *indentata*) as it is not labeled for use in soybean, and was included for comparison to encapsulated acetochlor (Anonymous 2012).

Treatments were applied to plots 3 m wide and 9 m long and replicated 4 times per site. Treatments were applied using a 4 nozzle CO_2 pressurized backpack sprayer calibrated to deliver 144 L ha^{-1} at 241 kPa with TeeJet (TeeJet Technologies, Springfield, IL 62703) Air Induction Extended Range or Turbo TeeJet Air Induction 110015 nozzles. Percent control of Palmer amaranth and waterhemp was visually evaluated compared to the untreated check 4 and 8WAT. Visual ratings were based on 0% = no Palmer amaranth and waterhemp control and 99% = complete Palmer amaranth and waterhemp control.

Data Analysis

Data were analyzed using the mixed procedure in JMP Pro 12 (SAS Institute., 100 SAS Campus Drive, Cary, NC 27513-2414) and means were separated using Fisher's Protected Least Significant Difference (LSD) at α=0.05. Analysis of interaction of main effects of herbicide, rate, and timing by location and observation timing did not reveal a significant interaction, while only the main effects of herbicide and rate were significant (Table 2.3). Therefore, herbicide and rate were considered fixed effects and application timing and replication (nested within application timing) were considered random effects (Carmer et al. 1989).

In a separate analysis, data for *S*-metolachlor and metolachlor were extracted and pooled across site and application timing to understand implications about these two specific herbicides over a range of environments (Johnson et a. 2014; Zhang et al. 2005; Stephenson et al. 2004a,b; Hager et al. 2003). Analysis of main effects of herbicide and rate for both observation timings did not reveal significant interactions (Table 2.4). Site, application timing, and replication (nested within site and application timing) were considered random effects for the fixed effects of herbicide and rate.

RESULTS AND DISCUSSION

In-Season Precipitation and Temperature

Thirty-year precipitation normals from 1980 to 2010 were referenced from the National Oceanic Atmospheric Administration (Arugez et al. 2010), and cumulative rainfall values as a percent of normal for each month by site were calculated. All months received a greater amount of precipitation when compared to the 30 year normal, except for June 2016 at Hutchinson and Ottawa which were slightly drier (Figure 2.2).

Activating rainfall ($\geq$ 4.5 cm) was received within the first week after application for Manhattan and for the April application timings at Hutchinson and Ottawa. The June application timings at Hutchinson and Ottawa did not receive activation until 2WAT. Hutchinson received 7.7 cm which provided excellent activation; whereas, Ottawa received 2.6 cm (Table 2.5). Because of the lack of activation and increased exposure to sunlight on the soil surface, photodegradation and volatilization of some VLCFA herbicides is possible (Kearney and Kaufman 1988). The combination of dry conditions after the 2 week delay in activation probably accounted for the reduced level of waterhemp control at Ottawa. After 2WAT, each site received at least 1.6 cm of rainfall biweekly through 8WAT (Table 2.5). This enabled the continued emergence of Palmer amaranth and waterhemp.

Average daily temperatures were calculated by month for each site (Figure 2.3). Temperatures were generally warmer for June and July when compared to April and May. While temperature influences Palmer amaranth and waterhemp emergence (Jha and Norsworthy 2009;

Hartzler et al. 1999) and herbicide adsorption and degradation (Zimdahl and Clark 1982), the daily temperature swings experienced within the microclimate within the germination zone for Palmer amaranth and waterhemp (e.g., upper 1 cm of soil) within a field can be variable (Buhler et al. 1997,1996). Because of these variable factors that can change from year to year, producers have a limited probability of predicting the ideal application timing for a VLCFA herbicide (i.e., from an April vs. June timing).

Palmer Amaranth and Waterhemp Control by Herbicide and Rate

Pyroxasulfone, *S*-metolachlor, and dimethenamid-*P* resulted in the highest level of Palmer amaranth control when compared to encapsulated acetochlor and pendimethalin 4WAT and 8WAT at Manhattan (Table 2.6).

Dimethenamid-*P* and pendimethalin resulted in less Palmer amaranth control than pyroxasulfone 4WAT at Hutchinson. At 8WAT acetochlor, encapsulated acetochlor, *S*-metolachlor, and pyroxasulfone resulted in the highest level of control (≥ 83%) when compared to alachlor, dimethenamid-*P*, and metolachlor. Of the herbicides evaluated, pendimethalin provide the least amount of control (Table 2.6).

At Ottawa 4WAT, acetochlor, *S*-metolachlor, and pyroxasulfone resulted in the highest level of waterhemp control. Acetochlor provided higher control (80%) when compared to encapsulated acetochlor (68%) at the 4WAT observation time; this is likely due to the differences in rate structure between the two formulations used in soybean versus corn (Table 2.2). *S*-metolachlor and pyroxasulfone provided superior control compared to alachlor, dimethenamid-*P*, metolachlor, and pendimethalin at 8WAT (Table 2.6).

A lower level of waterhemp control was observed at Ottawa across all treatments when compared to the Palmer amaranth control observed at Hutchinson and Manhattan. This is likely an effect of weather rather than a species interaction. Producers can occasionally observe poor performance of VLCFA herbicides because of lack of activation at the time of weed germination and emergence; however, as demonstrated at Ottawa, there is still value in terms of waterhemp control after activating rainfall is received. In the case of extended emergence in waterhemp or Palmer amaranth (Jha and Norsworthy 2009; Hartzler et al. 1999), activation weeks after the application can still offer a substantial amount of weed control.

Across all sites and observation times, pyroxasulfone and *s*-metolachlor tended to result in the highest level of Palmer amaranth and waterhemp control. Pendimethalin resulted in the lowest level of Palmer amaranth and waterhemp control at all sites and observation times.

Analysis of the main effect of rate (Table 2.3) revealed differences across the high, middle, and low rates, and data were pooled across herbicides because of the lack of an interaction of herbicide by rate (Table 2.7). The high rate, regardless of site or observation time, resulted in a higher level of Palmer amaranth and waterhemp control when compared to the low rate. The middle rate performed better than the low rate except for Hutchinson 8WAT and Ottawa 4WAT where control was the same and the high rate was better than the middle rate at Hutchinson 8WAT and at Ottawa 8WAT (Table 2.7). Increasing the rate of VLCFA herbicide has been demonstrated to increase weed control at later observation timings (Grey et al. 2014; Knezevic et al. 2009; Meyers et al. 2010; Geier et al. 2006; Walker and Zimdahl 1981).

S-metolachlor and Metolachlor Compared

Data for *S*-metolachlor and metolachlor were extracted from the bulk data set and pooled across sites and application timings for both observation times (Table 2.4). At both observation times, *S*-metolachlor provided a higher level of Palmer amaranth and waterhemp control than metolachlor (Table 2.8). Numerical differences between the high, middle, and low rates of each herbicide reveal that the high rate of metolachlor (1068 g ai ha^{-1}) was required to deliver comparable control to that of the low rate of *S*-metolachlor (2136 g ai ha^{-1}). The high and middle rates of *S*-metolachlor resulted in better control when compared to all rates of metolachlor (Table 2.8). Differences in efficacy observed between *S*-metolachlor and metolachlor is likely due to the biological function of the proportion of the resolved *S*-isomer as found in *S*-metolachlor (Shaner et al. 2006; Blaser 2002; O’Connell et al. 1998).

Practical Implications and Conclusions

VLCFA herbicides should not be used as a stand-alone treatment. An inhibitor of photosystem II (e.g., metribuzin or atrazine) or an inhibitor of protoporphyrinogen oxidase (e.g., fomesafen) are often tank mixed with a VLCFA herbicide as an additional effective site of action (Wuerffel et al 2015; Whaley et al. 2009; Steckel et al. 2002; Akobundu et al. 1975). Timely rainfall for activation is required. Because VLCFA herbicides generally do not provide reach back control for flushes of weeds that emerged after application but before activation, producers can be reluctant to invest in this class of herbicides. In this study, delayed activation did contribute to reduced control. However, it is important to communicate that weeks of control of later emerging weeds can still be observed, once the herbicide is activated.

Because of extended emergence, the 4WAT observation times resulted in a higher level of Palmer amaranth and waterhemp control when compared to 8WAT. In addition to herbicide leaching out of the zone of germination for Palmer amaranth and waterhemp, decreasing control over time is due to the various degradation mechanisms (e.g., microbial) of VLCFA herbicides (Beestman and Deming 1974). Therefore, when producers make sequential applications (e.g, PRE followed by POST), additional control could be expected if a VLCFA herbicide is utilized in the tank mix in both applications (Steckel et al. 2002). By increasing the amount of VLCFA herbicide in soil solution, the potential to select for resistant biotypes through repeated low dose exposure would be reduced (Busi et al. 2012).

The high to middle rate, regardless of herbicide, tended to result in a superior level of Palmer amaranth and waterhemp control when compared to the low rate; therefore, the low rate range should be avoided when making VLCFA herbicide applications. Unfortunately, it can be difficult for producers to implement this recommendation as many premixes that contain a VLCFA herbicide are formulated with a reduced rate of VLFCA herbicide. Producers should consider the amount of active ingredient that will be applied when selecting an herbicide premix (Owen 2016). The high, middle, and low rates for this experiment were based around labeled soybean recommendations and the soils at the experiment sites (Table 2.1, 2.2). Rate structure of VLCFA herbicide will change depending on crop and soil type. Control of Palmer amaranth and waterhemp could be affected by the total amount of VLCFA herbicide applied as well as the adsorption and persistence of the VLCFA herbicide in a soil.

S-metolachlor and metolachlor are often used synonymously when making weed management recommendations; however, a higher degree of Palmer amaranth and waterhemp control should be expected with *S*-metolachlor compared to metolachlor. The high rate of metolachlor will tend to result in less Palmer amaranth and waterhemp control when compared to middle and high rates of *S*-metolachlor. Therefore, producers must consider the additional value of *S*-metolachlor when selecting a VLCFA herbicide. Unfortunately, it can be difficult for producers to make this value differentiation when metolachlor is often priced much lower than *S*-metolachlor (Thompson et al. 2017). *S*-metolachlor is often available in premixes with other herbicides which could offset the additional cost of *S*-metolachlor as well as provide the producer with additional effective sites of action for herbicide resistance management.

As an outcome of this study, VLCFA herbicides should be utilized as part of an integrated weed management plan for control of small seeded broadleaf weeds such as Palmer amaranth and waterhemp. Best management practices for managing herbicide resistance, such as using multiple effective sites of action, should always be implemented to help ensure the long-term resilience of VLCFA herbicides and control of driver weeds. All VLCFA herbicides provided superior control when compared to the microtubule-inhibiting herbicide pendimethalin. Of the VLCFA herbicides compared, pyroxasulfone and *S*-metolachlor tended to provide the highest level of control across sites and observation times for both Palmer amaranth and waterhemp.

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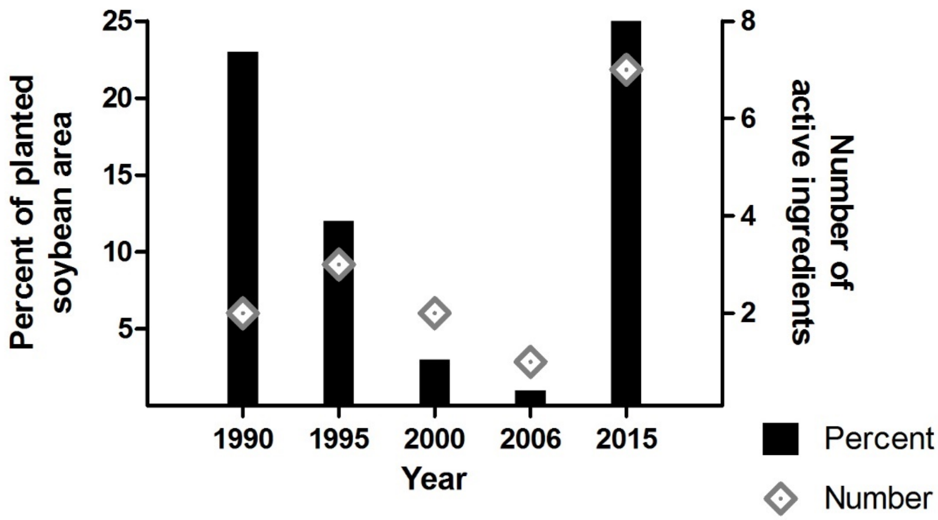

Figure 2.1 VLCFA herbicide usage as a percentage of planted soybean area in the Midwest as well as number of VLCFA active ingredients reported per survey year (NASS 2017).

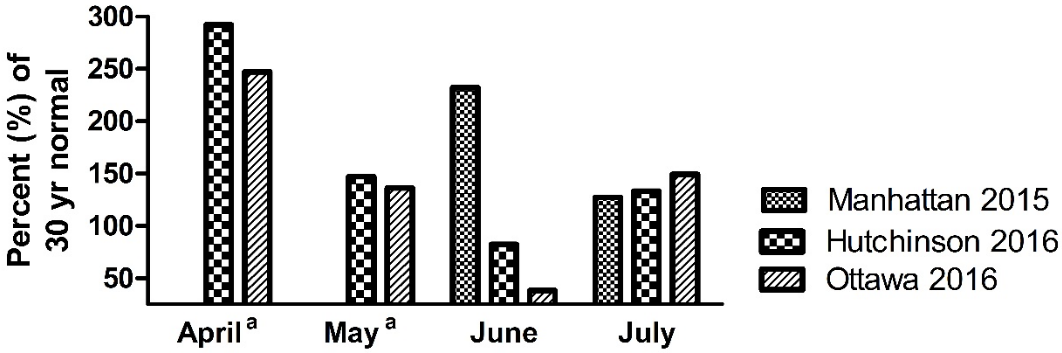

Figure 2.2. Precipitation at Manhattan, Hutchinson, and Ottawa, KS as a percentage of the 30 yr normal from 1980 to 2010 (Arugez et al. 2010) for April, May, June, and July.

[a] April and May precipitation data is excluded for Manhattan 2015 because treatments were not applied until June 1, 2015.

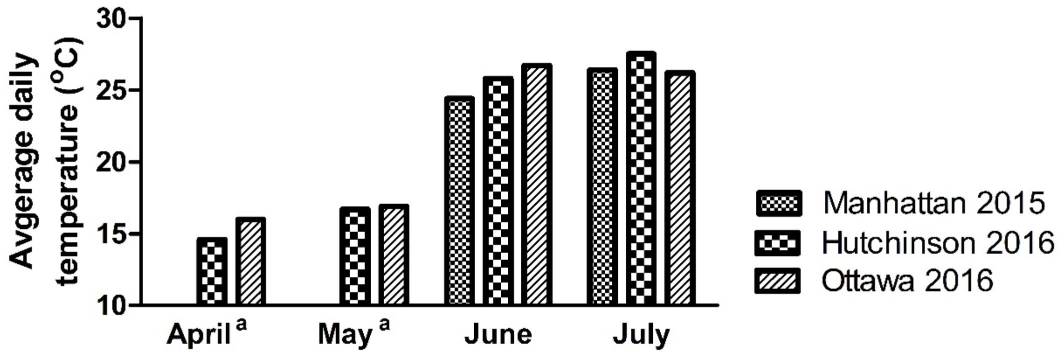

Figure 2.3. Average daily air temperature (ºC) at Manhattan, Hutchinson, and Ottawa, KS, for April, May, June, and July.

[a] April and May temperature data is excluded for Manhattan 2015 because treatments were not applied until June 1, 2015.

Table 2.1. Herbicide application dates and soil characteristics at experiment sites.[a,b]

	June 2015	April 2016		June 2016	
Site characteristics	Manhattan	Hutchinson	Ottawa	Hutchinson	Ottawa
PRE application date	June 1	April 12	April 13	June 6	June 6
Soil series	Reading [c]	Ost [d]	Woodson [e]	Ost	Woodson
Soil texture	silt loam	loam	silt loam	loam	silt loam
Sand (%)	16	30	6	30	8
Silt (%)	60	46	64	46	64
Clay (%)	24	24	30	24	28
Soil organic matter [f] (%)	2.6	2.6	3.3	2.6	3.5
Soil pH	7.3	5.0	7.0	6.3	6.6
Soil cation exchange capacity (meq/100g)[g]	17.0	24.7	18.5	22.6	17.9

[a] Abbreviations: meq, milliequivalents.

[b] All soil characteristics assessed from a 0 to 7.6 cm soil sampling depth.

[c] Fine-silty, mixed superactive, mesic Pachic Argiudolls

[d] Fine-loamy, mixed superactive, mesic Udic Argiustolls.

[e] Fine, smectic, thermic Abruptic Argiaquolls.

[f] Loss-on-ignition (Ball 1964).

[g] Adjusted to 7 pH (Rich 1969).

Table 2.2. Factorial of herbicides and rates used for PRE applications. [a]

Herbicide	Trade Name	Rate Low	Rate Middle	Rate High	Manufacturer	Location
			g ai ha $^{-1}$			
†Acetochlor	Harness®	1471	2207	2943	Monsanto Company	St. Louis, MO
Acetochlor (encapsulated)	Warrant®	1051	1367	1682	Monsanto Company	St. Louis, MO
†Alachlor	Intrro®	1682	2523	3364	Monsanto Company	St. Louis, MO
Dimethenamid-P	Outlook®	630	841	1052	BASF Corporation	Research Triangle Park, NC
Metolachlor	Stalwart®	1121	1682	2242	Sipcam Agro USA, Inc.	Roswell, GA
S-metolachlor	Dual Magnum®	1068	1602	2136	Syngenta Crop Protection, LLC	Greensboro, NC
Pendimethalin	Prowl® H2O	799	1198	1598	BASF Corporation	Research Triangle Park, NC
Pyroxasulfone	Zidua®	89	134	179	BASF Corporation	Research Triangle Park, NC

†Treatment only used in 2016 experiments.

Table 2.3. Analysis of significance of fixed effects and all interactions for Palmer amaranth control at Manhattan and Hutchinson, KS and waterhemp control at Ottawa, KS.[a]

Fixed Effects	Manhattan 2015				Hutchinson 2016				Ottawa 2016			
	4WAT		8WAT		4WAT		8WAT		4WAT		8WAT	
	P Value	F Ratio	P Value	F Ratio	P Value	F Ratio	P Value	F Ratio	P Value	F Ratio	P Value	F Ratio
Timing	-	-	-	-	<0.0001	67.53	0.0923	2.872	0.5967	0.2812	0.0762	3.190
Herbicide	<0.0001	97.80	<0.0001	77.55	<0.0001	16.91	<0.0001	17.0641	<0.0001	5.054	<0.0001	6.434
Rate	<0.0001	20.09	0.0002	10.12	<0.0001	7.300	0.0006	7.858	0.0002	8.935	<0.0001	11.88
Rate by timing	-	-	-	-	0.0862	1.006	0.0736	4.551	0.1584	10.67	0.0641	2.802
Herbicide by timing	-	-	-	-	0.0111	2.724	<0.0001	4.941	<0.0001	7.432	0.0005	3.977
Herbicide by rate	0.0833	1.805	0.3677	1.118	0.9648	0.4245	0.9333	0.4941	0.0725	1.652	0.9740	0.3967
Herbicide by rate by timing	-	-	-	-	0.9216	0.5146	0.5321	0.9266	0.9303	0.4996	0.9386	0.4840

[a] Abbreviations: WAT, weeks after treatment.

Table 2.4. Analysis of significance of fixed effects and all interactions for Palmer amaranth and waterhemp control for *S*-metolachlor and metolachlor.[a]

Observation time	Fixed effect	F-Ratio	P-Value
4WAT	Herbicide	9.9000	0.0021
	Rate	4.2324	0.0170
	Herbicide by rate	0.3252	0.7231
8WAT	Herbicide	17.6189	<0.0001
	Rate	4.7824	0.0102
	Herbicide by rate	0.3980	0.6726

[a] Abbreviations: WAT, weeks after treatment.

Table 2.5. Rainfall data for each week after PRE application.

			Rainfall							
			Weeks after PRE application							
Location	Year	PRE	1	2	3	4	5	6	7	8
			cm							
Manhattan	2015	June 1	4.5	4.5	0.9	0.7	1.3	7.3	1.9	1.1
Hutchinson	2016	April 13	6.3	0.3	4.9	0.2	1.7	8.1	6.7	0.0
	2016	June 6	0.0	7.7	2.4	5.6	1.1	2.1	0.0	4.0
Ottawa	2016	April 13	4.5	4.5	0.9	0.7	1.3	7.3	1.9	1.1
	2016	June 6	0.0	2.6	0.2	8.2	3.3	0.7	0.0	3.5

Table 2.6. Palmer amaranth control at Manhattan and Hutchinson, KS and waterhemp control at Ottawa, KS.[a,b]

	Manhattan 2015		Hutchinson 2016 [c]		Ottawa 2016 [c]	
Herbicide	4WAT	8WAT	4WAT	8WAT	4WAT	8WAT
			%			
[†]Acetochlor	-	-	94abc	87a	80ab	65bc
Acetochlor (encapsulated)	68c	56c	93bc	84a	68cd	64bc
[†]Alachlor	-	-	94abc	76b	65d	51d
Dimethenamid-*P*	92a	85a	91cd	73b	70bcd	54cd
Metolachlor	83b	73b	93bc	73b	69cd	56cd
S-metolachlor	92a	87a	93bc	83a	78abc	69ab
Pendimethalin	48d	26d	79e	67c	62d	46d
Pyroxasulfone	96a	91a	95ab	87a	82a	78a

[a] Abbreviations: WAT, weeks after treatment.
[b] Means followed by the same letter within a column are not statistically different per Fisher's Protected LSD (α = 0.05).
[c] April and June application timing data per site pooled for analysis.
[†]Herbicide only present in 2016 site years.

Table 2.7. Palmer amaranth control at Manhattan and Hutchinson, KS and waterhemp control at Ottawa, KS by application rate pooled across herbicides.[a,b]

	Manhattan 2015		Hutchinson 2016 [c]		Ottawa 2016 [c]	
Rate	4WAT	8WAT	4WAT	8WAT	4WAT	8WAT
	%					
Low	73b	63b	89b	76b	66b	52c
Middle	81a	71a	92a	78b	72ab	60b
High	84a	75a	93a	82a	78a	70a

[a] Abbreviations: WAT, weeks after treatment.

[b] Means followed by the same letter within a column are not statistically different per Fisher's Protected LSD ($\alpha = 0.05$).

[c] April and June application timing data per site pooled for analysis.

Table 2.8. Palmer amaranth and waterhemp control with *S*-metolachlor and metolachlor pooled across sites and application timings.[a,b]

	4WAT				8WAT			
Herbicide	High	Middle	Low	Average of herbicides	High	Middle	Low	Average of herbicides
				%				
S-metolachlor	92	89	86	87a	84	81	75	79a
Metolachlor	87	80	76	79b	76	66	63	66b

[a] Abbreviations: WAT, weeks after treatment.

[b] Means followed by the same letter within a column are not statistically different per Fisher's Protected LSD ($\alpha = 0.05$).