HORSEWEED (*ERIGERON CANADENSIS*) CONTROL IN NO-TILL SOYBEAN SYSTEMS ON A COARSE TEXTURED SOIL

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

April 2020

Fargo, North Dakota

North Dakota State University
Graduate School

Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Horseweed (*Erigeron canadensis*) is a competitive winter or summer annual broadleaf weed. When uncontrolled, horseweed can reduce soybean (*Glycine max*) yields by 93%. Research was conducted to advance our knowledge on horseweed growth stage response to foliar-active and residual herbicides, fall applications, and the utility of differing herbicide technologies. Greenhouse results determined that herbicide efficacy was greatest when applied to early rosette horseweed providing an average control of 70% across herbicide treatments. Field trials determined that preventing new emergence with flumioxazin, added with dicamba or paraquat to kill existing plants in the fall, increased control to 99% the following spring. Field trials also determined that dicamba, applied PRE or POST, provided excellent horseweed control and was an effective soybean technology system for horseweed-infested fields. Saflufenacil controlled existing plants, but residual benefits were unclear. Further research must be done to investigate residual activity of PRE herbicides applied before horseweed emergence.

ACKNOWLEDGEMENTS

I would first like to express my deep and sincere gratitude my research supervisor Dr. Kirk Howatt for providing me his guidance, knowledge, patience, and support throughout my undergraduate and graduate degrees. I would also like thank my exceptional committee members Dr. Brian Jenks, Dr. Ted Helms, and Dr. Tom DeSutter for all of their professionalism, knowledge, guidance, and time spent throughout my thesis development. I would also like to thank Steve Valenti for his knowledge, support, and time provided with my trial development and treatment lists.

I would like to extend my sincere gratitude to Joseph Mettler, Kelly Satrom, and Sandy Mark for their patience and assistance with my greenhouse and field research management and development. It was a blast working alongside all of you and I will remember the summers of 2018 and 2019 for years to come.

Furthermore, I would like to thank my amazing wife Morgan for dealing with my sporadic work schedule and stress over the last two years. I could not have done it without your love, support, and encouragement. I must also thank my fellow NDSU alumni Nathan Haugrud, Dylan Barry, and Peder Schmitz for making my time at NDSU a fun and unforgettable experience. You were always there to talk about football or movies when I needed a break from writing.

Lastly, I would especially like to thank my parents Kerry and Jodie, siblings Tyler, Ryan, and Jeremy, and grandparents Argil, Holly, Ray, and Evonne for all of their love, support, and encouragement. Without their support, guidance, and lessons taught, I would not have become the person that I am today.

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RATIONALE/SIGNIFICANCE

Horseweed [*Erigeron canadensis (L.) Cronq.*], also known as marestail, has become an increasingly troublesome weed in no-till soybean [*Glycine max* (L.) Merr.]cropping systems. Horseweed has a competitive growth habit and has the ability to infest entire fields in as little as one growing season. Horseweed has also developed resistance to ALS Inhibitors, making it difficult to control in soybean. Due to over-reliance and over-use of glyphosate, horseweed has also developed resistance to glyphosate, which makes postemergence control of horseweed extremely difficult in glyphosate-resistant soybean.

Herbicide resistance has increased the need for alternative chemical methods in no-till soybean systems. Preemergence (PRE) and fall-applied herbicides have become increasingly popular and important as herbicide resistance has grown and possibly are extremely important for horseweed control. These herbicides need to have moderate soil persistence, a broad spectrum of weed control, and must be safe for the crop. More research is needed to test the efficacy of different PRE and fall-applied herbicides for control of established horseweed and the residual benefits to control successive cohorts. The knowledge gained from this research will help soybean producers control horseweed in their fields, with the goal to improve yield and grain quality.

CHAPTER 1. REVIEW OF LITERATURE

Soybean

Soybean [*Glycine max* (L.) Merr.] is one of the most important oilseed crops in the agricultural industry, providing roughly 90% of the U.S. oilseed production (USDA-ERS 2018). Soybean is the second most widely raised crop in the U.S. and was grown on about 36 million hectares in 2018. The Upper Midwest portion of the U.S. contains more than 80% of the soybean hectarage.

Soybean originated in southeast Asia and was first domesticated around 1100 BC by Chinese farmers (NCSPA 2014a). Soybean then spread to Japan and other countries by the first century AD where it was grown to produce products such as soy sauce. In 1851, soybean seed had finally found its way to the U.S. Corn Belt states where it was mostly grown for animal feed. It was not until 1904 when an American chemist named George Washington Carver found that soybean had useful oil and protein qualities that the rise of the soybean oil industry began.

Soybean is an extremely important food crop for today's growing population and is used to make many different, widely used, food and industrial products. Two major products derived from soybean are animal feed and biodiesel (NCSPA 2014b). Biodiesel is a growing soybean product that burns cleaner and is more environmentally sustainable than petroleum-based fuel. A few other examples of products made from soybean-derived constituents are margarine, soymilk, crayons, paints, hydraulic fluid, and cooking oil. Soybean has many other uses in products that contain soybean-derived materials allowing it to be the second most grown crop in the U.S. Since soybean is such an important crop, not only domestically but also internationally, it must provide high yield and quality to fulfill our needs. Because of this great demand, it is imperative that weed and stress influences be minimal for the greatest yields.

Weed management is extremely important in agricultural systems in order to achieve high quality and maximum yield potential of any crop. According to Halford et al. (2001), the critical period of weed control in no-till soybean is between 13 to 40 (V1 and R1 stage) days after soybean emergence. This is the interval in the soybean life cycle when weed interference will cause yield loss (Halford et al. 2001). Weed interference can reduce soybean yield up to 93% depending on the weed species, density, and extent of time weeds remain in the field (Saberali and Mohammadi 2015). The reason for this drastic yield reduction is due to weed competition with soybean for soil water, sunlight, and soil nutrients such as nitrogen (N), phosphorus (P), and potassium (K). Numerous management strategies can be utilized to help reduce the weed influence on a crop. Some of the most effective strategies include herbicide application, tillage, crop rotation, and hand pulling (Bajwa et al. 2016). The use of each specific strategy depends on the environment and weed species present in the field. If left unmanaged, a weed population will grow and produce seed that will enter the seed bank for subsequent growing seasons (Harder et al. 2007). The soil seed bank will be much higher and more time and money will be spent to control the vast amount of weeds that may be present within the field in subsequent years.

Horseweed

Horseweed (*Erigeron canadensis (L.) Cronq.*), also known as marestail, horseweed fleabane, Canada fleabane, and Canadian horseweed, is a competitive winter or summer annual weed within the Asteraceae family (Bajwa et al. 2016). Winter annual biotypes produce a basal rosette during the beginning of its life cycle in the fall and then bolts in early spring, whereas summer annual plants bolt immediately in the spring without basal rosette development (Budd et al. 2017). Bolting plants have a densely haired, single, erect stem with alternate leaf arrangement

(Stubbendieck et al. 2003). Mature leaves have bristly hairs, are simple with linear to oblanceolate leaf shape, and can grow to a length of 3- to 10-cm and a width of 2- to 10-mm.

Flowering for both winter and summer annual ecotypes usually occurs between June and September and is sporadic due to summer annual seedlings ability to emerge throughout the season (Stubbendieck et al. 2003; Bajwa et al. 2016). Horseweed has a panicle inflorescence of several heads that are comprised of numerous white ray florets and 20 to 50 yellow disk florets (Stubbendieck et al. 2003). About 95% of these florets are self-compatible and have the capability to self-pollinate (Bajwa et al. 2016; Budd et al. 2017). Mature seeds are shed in late July to the start of October and can immediately germinate when exposed to a rain or irrigation event (Bajwa et al. 2016). Horseweed seeds have non-deep dormancy meaning they convert to dormancy in the presence of changing microsite conditions. In a field setting, a horseweed plant can produce about 230,000 seeds per plant and can grow up to 180 cm in height (Budd et al. 2017). The seeds are 1- to 1.5-mm long and have small hairs that form a pappus allowing easy seed distribution by wind or water vectors (Stubbendieck et al. 2003). Since the seeds readily move by wind, they have been shown to travel up to 500 m away from the parent plant (Norsworthy et al. 2009).

Because of its robust biological features, successful ecological adaptations, and strong interference ability, horseweed is one of the most problematic weed species in agriculture to date (Bajwa et al. 2016). When uncontrolled, horseweed can reduce soybean yields by up to 93% (Byker et al. 2013a). In addition to competition for resources such as N, P, and K, horseweed also releases phenolic acids with allelopathic effects that suppress the growth and germination of many crops such as wheat and maize (Bajwa et al. 2016). Horseweed also harbors numerous destructive insects and pathogens that can reduce crop yield and quality. In continuous glyphosate cropping systems, horseweed was the first broadleaf weed to develop resistance in the United States and has been accepted as the most extensive glyphosate-resistant (GR) weed in modern cropping systems (Byker et al. 2013a).

Weed Control with Herbicides

Herbicides have been used for the purpose of weed control since the beginning of the 20th century (Cobb and Reade 2010). Some of the first chemicals used to control weeds were copper sulphate, corrosive fertilizers such as calcium cyanamide, and industrial chemicals such as sodium chlorate and sulfuric acid. In 1932, modern synthetic herbicides made their first appearance in France. In 1934, the first widely used herbicides called 2,4-Dichlorophenoxyacetic acid (2,4-D) and 2-methyl-4-chlorophenoxyacetic acid (MCPA) were discovered and are still used today. Herbicides are the most widely used type of pesticide, and in 2012, more than five billion dollars worth of product was sold in the U.S. alone (USEPA 2017).

A resistant weed is a weed that has the capability to grow and reproduce following a normal lethal dose of herbicide (Heap 1997). In 1996, Monsanto released glyphosate-resistant (GR) soybean, which increased glyphosate sales and usage due to its extensive weed control ability (Cobb and Reade 2010). In result of the increase of glyphosate use, weed resistance became an increased issue. There have been 14 reports of GR weed species in the U.S. alone (Flessner et al. 2015). As the number of GR weed species increases, there is an increasing need for different chemical, physical, and cultural weed management strategies to be developed within soybean production systems.

One of the most difficult GR weeds to control in soybean is horseweed since it has developed resistance to both 5-enolpyruvylshikimate 3-phosphate synthase (EPSPS) inhibitors and acetolactate synthase (ALS) enzyme inhibitors (Byker et al. 2013b). Resistant horseweed populations are challenging to control in no-till conventional soybean systems and have shown the highest levels of glyphosate-resistance at 8- to 13-fold over the sensitive biotype (Feng et al. 2004). This resistance was first thought to be due to enhanced metabolism of the treated plant, but research has shown that resistance is due to reduced translocation throughout the plant. When GR plants were treated with glyphosate, the glyphosate became localized at application sites causing reduced leaf loading and export. Ge et al. (2011) observed similar results. In their findings, when GR plants were treated with glyphosate, the glyphosate molecules became localized and sequestered within the vacuoles of the plant. This localization reduced translocation throughout the plant and therefore, reduced glyphosate efficacy. Ge et al. (2011) did find a limitation to this sequestration of glyphosate within the vacuole. They determined that vacuole sequestration was significantly suppressed in GR horseweed at low temperatures (~12°C) allowing an application of glyphosate to once again be lethal. Therefore, in North Dakota, an application of glyphosate in early spring or late fall may once again control GR horseweed.

Because of GR weeds such as horseweed, there has been an increase of glufosinate, dicamba, and 2,4-D herbicide usage in no-till soybean systems. In 2009, Bayer released the glufosinate (Liberty Link®) cropping system allowing glufosinate (Liberty®) to be applied postemergence (POST) to soybean. Glufosinate is a non-selective glutamine synthetase inhibitor herbicide that produces rapid desiccating action in horseweed. Then in 2017, Monsanto released the dicamba plus glyphosate (Roundup Ready® Xtend) cropping system allowing dicamba (Engenia®, Xtendimax®, or FeXapan®) and glyphosate (Roundup PowerMAX® II) to be applied POST to soybean. Dicamba is a selective plant growth regulator herbicide that is excellent for control of most broadleaf plants and can effectively control many GR weed species. Most recently in 2018, Corteva released the 2,4-D plus glyphosate plus glufosinate (Enlist E3™) cropping system allowing 2,4-D and glyphosate (Enlist Duo™) along with glufosinate to be applied POST to soybean. This herbicide combination allows for good control of most dicotyledonous plants while being effective on many monocotyledonous plants as well.

In no-till soybean systems, herbicide applications are highly relied on for season long weed control. This has led to an increase in preemergence (PRE) herbicide applications to control troublesome weeds since there are limited herbicide options for POST control (Norsworthy et al. 2009). These PRE herbicides have been effective for resistance management because they have different sites of action than most POST herbicides and generally have beneficial soil residual properties to control later emerging horseweed cohorts. As result of horseweed's developed herbicide resistance, there is great need for further research to evaluate current herbicide options for horseweed control.

CHAPTER 2. GREENHOUSE EXPERIMENTS TO EVALUATE HERBICIDE EFFICACY AT DIFFERING HORSEWEED GROWTH STAGES

Introduction

Herbicide application timing is imperative in terms of horseweed control. Previous research has shown that horseweed's level of glyphosate resistance (GR) varied with horseweed growth stage requiring 12, 11, and 20 kg ha^{-1} glyphosate to achieve 85% control at seedling, large rosette, and bolting growth stages, respectively (VanGessel et al. 2009). Shrestha et al. (2007) determined that percent mortality of GR horseweed, when treated with 2,240 to 4,480 g ai ha^{-1} glyphosate, was greatest during early rosette growth stage (5 to 8 leaves) resulting in greater than 50% mortality and decreased drastically after bolting to less than 20% mortality. VanGessel et al. (2009) experienced similar results observing decreased sensitivity of bolting GR horseweed to glyphosate compared to plants in the rosette growth stage. Both of these experiments determined that glyphosate efficacy varied depending on horseweed growth stage, but supplementary research needs to be done in order to determine if similar results will occur with differing herbicide technologies.

Fomesafen is a common postemergence herbicide used in soybean, but minimal research has been done to evaluate horseweed growth stage response to fomesafen application. In a trial conducted by Falk et al. (2006), common waterhemp control was 42% greater when fomesafen was applied at the 2-leaf stage than at the 8- to 10- leaf stage. Falk et al. (2006) also stated that common waterhemp resistance to POST-applied protox-inhibiting herbicides did not occur until the 8-leaf growth stage. Research must be done to determine if a similar response will be observed at differing horseweed growth stages with multiple common herbicides used in soybean. The objective of this trial was to evaluate horseweed growth stage response to herbicide technologies.

Materials and Methods

To identify control of horseweed in various development stages with various herbicides, a greenhouse experiment was established in randomized complete block design (RCBD) with four replicates repeated two times. Treatment factors were A) horseweed growth stage and B) herbicide. Factor A included three growth levels: early rosette, late rosette, and bolting. Factor B had ten levels representing different herbicides (Table 2.1). A factorial arrangement was chosen to evaluate the efficacy each herbicide treatment has on each of the three horseweed growth stages. Placement of both factors was randomized independently using the ARM Software (Agriculture Research Management 2018, 405 Martin Boulevard, Brookings, South Dakota 57006).

Table 2.1. Herbicide product information for greenhouse treatments applied at three horseweed growth stages in 2018 and 2019.

Treatments[a]	Rate	Trade name	Manufacturer	Address
	g ai ha^{-1}			
Control	-	-	-	-
Imazamox + HSMOC	35	Raptor	BASF	Research Triangle Park, NC
2,4-D	560	2,4-D Amine 4	United Suppliers	St. Eldora, IA
Dicamba	560	Xtendimax	Monsanto	St. Louis, MO
Halauxifen + HSMOC	5	Elevore	Dow	Indianapolis, IN
Fomesafen + HSMOC	200	Reflex	Syngenta	Greensboro, NC
Flumioxazin + HSMOC	70	Valor SX	Valent	Walnut Creek, CA
Saflufenacil + HSMOC	25	Sharpen	BASF	Research Triangle Park, NC
Glufosinate + AMS-D	810	Liberty 280 SL	Bayer	Research Triangle Park, NC
Paraquat + NIS	560	Gramoxone 2.0 SL	Syngenta	Greensboro, NC

[a]Adjuvants: (HSMOC) high surfactant methylated oil concentrate at 1.2 L ha^{-1} (Destiny HC, Winfield Solutions LLC, St. Paul, MN); (AMS-D) ammonium sulfate-dry at 3360 g ha^{-1} (AMS Plus Dry, Coastal AgroBusiness, Greenville, NC); (NIS) nonionic surfactant at 0.3 L ha^{-1} (Prefer 90, West Central, Willmar, MN).

Horseweed seed was collected in southeastern North Dakota near Sheldon, 46°28'20.1"N, 97°29'43.4"W, in a field that was suspected to have a native infestation of horseweed with resistance to both glyphosate and acetolactate synthase (ALS) inhibitors. The seed was placed on the soil surface into 10- by 15- by 5-cm pots that contained a peat-based soil media (Sunshine Mix #1, Sun Gro Horticulture 770 Silver Street Agawam, MA 01001). The emerged plants were thinned to five plants per pot. Natural light supplemented with multi-vapor 1000-watt metal halide lamps at a 14-h photoperiod along with a maintained greenhouse temperature of 24 to 27°C were utilized to promote horseweed growth. All plants were watered daily and fertilized on a weekly basis with 20-20-20 water-soluble plant food at a rate of 1 tablespoon fertilizer per gallon of water (Jack's Classic All Purpose, Jack's Classic, 6656 Grant Way Allentown, PA 18106). To encourage bolting in the appropriate treatment, the plants (10- to 12.7-cm) were placed within a vernalization growth chamber to induce bolting at a temperature of 0 °C for 5 weeks. Plants within the vernalization chamber were watered when needed and did not receive any fertilizer throughout the rest of the experiment. After 5 weeks, plants were removed from the vernalization chamber and placed back in the greenhouse, lightly watered every other day, and bolting began approximately 3 weeks later. Throughout the experiment, pots were randomized weekly to minimize greenhouse microenvironment effects.

Since all ten treatments were applied at all three of the different growth stages, there were thirty treatments total for each replication. Treatments were delivered via a greenhouse chamber sprayer (Research Track Sprayer, DeVries Manufacturing, Hollandale, MN. Serial number SB8-095) at a speed of 5 km hr^{-1} with 276 kPa of pressure to deliver 94 L ha^{-1} at a height of 66 cm to the horseweed canopy using a Turbo TeeJet 11001 nozzle (TeeJet®, Spraying Systems Co., 200 W. North Ave., Glendale Heights, IL 60139). Herbicide was applied to early rosette plants at a width of 5- to 7.6-cm, late rosette at a width of 10- to 12.7-cm, and at a height of 14- to 16-cm for the bolted plants.

Plants were visually evaluated 1 and 3 weeks after herbicide application for percent control on a scale of 0 (no control) to 100 (complete plant death). Aboveground biomass was collected 4 weeks after herbicide application for all treatments, dried at 35 °C, and weighed. Height was measured 3 weeks after herbicide application for bolted plants. Stems did not elongate at all for the two rosette stages, therefore, height was not measured.

SAS 9.4 (SAS Institute, Cary, NC) ANOVA procedure was used to conduct the analysis of variance along with treatment mean separation using Fisher's F-protected LSD at $\alpha=0.05$. Mean squares were equated to expected mean squares to determine the proper denominators for the different F-tests. A randomized complete block design was used allowing herbicide and horseweed growth stage to be fixed effects, whereas replication and run were random effects. Values within treatment did not vary between replications in the 1- and 3-week visual evaluations. This nonexistent replication effect caused issues within the analysis of variance; therefore, replication effect was removed from the analysis of variance. A separate analysis of variance for dry weight, and height was conducted that included replications within runs and runs as sources of variation for those evaluations. Data were combined across runs if mean square error values between runs were within a factor of ten.

Results and Discussion

Horseweed growth stage, herbicide, and growth stage by herbicide interaction were statistically significant for the 1 and 3 week after application (WAA) evaluations as determined by p-values (Tables 2.2 and 2.3). However, growth stage was not significant when horseweed was harvested for dry weight (Table 2.4). Herbicide efficacy varied among horseweed growth stages showing decreased control as the horseweed matured (Table 2.3). Overall, herbicide efficacy to horseweed was greatest when applied to the early rosette growth stage. On average, 70% control was observed 3 weeks after herbicide application to early rosette horseweed, 34% control to late rosette horseweed, and 41% control to bolted horseweed. In other research, horseweed control decreased as plant maturity increased (Flessner et al. 2015). A possible reason for the slightly reduced control when comparing late rosette to bolted horseweed in this trial is due to differences in plant morphology. Late rosette plants were compact with many overlapping leaves; therefore, a larger percentage of plant tissue would be protected from herbicide application. For bolted plants, the nodes were elongated and the plant tissue is more outspread. This would allow for a greater percentage of plant tissue to be contacted by herbicide, therefore leading to increased herbicide damage.

Imazamox provided poor control at all three growth stages with no difference compared to the control 1 WAA (Table 2.2). Shoup et al. (2012) observed similar results with a field application of imazamox providing 30% control 1 WAA. Due to the lack of control provided by an application of cloransulam (FirstRate®) to the horseweed population in the field by the grower, ALS resistance was suspected.

Table 2.2. Interaction of growth stage and herbicide on horseweed control 1 week after application in the greenhouse.

	Herbicide[a]								
Growth stage	Ima	2,4-D	Dica	Hala	Fome	Flum	Safl	Gluf	Para
	%								
Early rosette	8mn[b]	45ef	48ef	48ef	15klm	43ef	99a	98a	99a
Late rosette	0n	25ij	25ij	35gh	20jkl	23ijk	65bc	90a	60c
Bolting	0n	30hi	35gh	40fg	13lm	15klm	58cd	70b	50de

ANOVA	Growth stage	Herbicide	Growth stage * herbicide
	p value		
	0.0374	< 0.0001	< 0.0001

[a]Abbreviations: (Ima) Imazamox, (Dica) Dicamba, (Hala) Halauxifen, (Fome) Fomesafen, (Flum) Flumioxazin, (Safl) Saflufenacil, (Gluf) Glufosinate, (Para) Paraquat.
[b]Means among columns that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Due to slow activity of the plant growth regulator (PGR) herbicides, dicamba, 2,4-D, and halauxifen, only slight visible symptoms were observed 1 WAA resulting in less than 50% control for all three growth stages (Table 2.2). Visible symptoms from the PGR herbicides were similar to what Flessner et al. (2015) observed, which included stem swelling and malformed tissue development at the shoot apex.

Application of fomesafen provided weak control across all growth stages resulting in sparse, small, necrotic lesions on tissue (Table 2.2). Less than 50% control was observed with flumioxazin, expressed as spotty necrotic tissue for all three horseweed growth stages with control decreasing as the plant matured. Flumioxazin was not expected to provide adequate control of horseweed since it primarily is applied as a PRE for its residual benefits, although foliar activity has been observed (Tahmasebi et al. 2018). Tahmasebi et al. (2018) confirmed similar results when flumioxazin was applied to horseweed with six to eight true leaves providing low dry weight reduction and zero plant mortality 4 WAA.

Saflufenacil, glufosinate, and paraquat provided the greatest control of early rosette horseweed with greater than 98% control (Table 2.2). Efficacy of saflufenacil and paraquat at the late rosette growth stage was only 65 and 60%, respectively, with glufosinate providing adequate control at 90%. Saflufenacil and paraquat provided only 58 and 50% control, respectively, when applied to bolted horseweed while glufosinate provided significantly greater control, but not sufficient, at 70%.

Control from all three PGR herbicides on early rosette horseweed was greater than 90% 3 WAA (Table 2.3). Early rosette growth was halted after PGR application and tissue became necrotic resulting in low dry weight for all three PGR herbicides (Table 2.4). Control with 2,4-D, dicamba, and halauxifen substantially decreased by about half when applied to late rosette horseweed resulting in high dry weight per pot (Tables 2.3 and 2.4). Control with these herbicides was similar or slightly better when applied to bolted compared with late rosette horseweed. After PGR application, bolted plant growth ceased and height remained less than 16 cm (LSD=4.7) for all three PGR herbicides (data not shown). As a result of this, seed production would likely be reduced or stopped completely. Control of late rosette and bolted horseweed from PGR herbicides possibly would have been similar to that of Kruger et al. (2010) if subsequent evaluations were performed. Kruger et al. (2010) found that applications of dicamba and 2,4-D to 7- to 15-cm tall horseweed provided greater than 90% control 4 WAA.

Table 2.3. Interaction of growth stage and herbicide on horseweed control 3 weeks after application in the greenhouse.

	Herbicide[a]								
Growth stage	Ima	2,4-D	Dica	Hala	Fome	Flum	Safl	Gluf	Para
	------------	------------	------------	------------	%	------------	------------	------------	------------
Early rosette	33fgh[b]	93a	99a	93a	0k	15ijk	99a	99a	99a
Late rosette	0k	35fg	45ef	45ef	18hij	18hij	35fg	85ab	23ghi
Bolting	3jk	41f	59cde	61cd	8ijk	15ijk	70bc	66c	46def
ANOVA		Growth stage			Herbicide		Growth stage * herbicide		
		------------	------------	------------	*p value*	------------	------------	------------	------------
		0.0262			< 0.0001		< 0.0001		

[a]Abbreviations: (Ima) Imazamox, (Dica) Dicamba, (Hala) Halauxifen, (Fome) Fomesafen, (Flum) Flumioxazin, (Safl) Saflufenacil, (Gluf) Glufosinate, (Para) Paraquat.
[b]Means among columns that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Table 2.4. Interaction of growth stage and herbicide on horseweed dry weight 4 weeks after application in the greenhouse.

	Herbicide[a]									
Growth stage	Cont	Ima	2,4-D	Dica	Hala	Fome	Flum	Safl	Gluf	Para
	g/pot									
Early rosette	3.08cd[b]	1.12b	1.14b	0.12a	0.77ab	2.57c	2.32c	0a	0a	0a
Late rosette	6.39hijk	5.90fgh	6.04ghi	5.12e	5.15ef	6.27ghij	7.01jkl	3.40d	1.37b	3.53d
Bolting	9.69m	7.57l	5.95gh	5.85efgh	5.87efgh	7.07kl	6.80ijkl	5.61efg	2.75cd	3.49d

ANOVA	Growth stage	Herbicide	Growth stage * herbicide
	p value		
	0.1488	< 0.0001	0.0010

[a]Abbreviations: (Cont) Control, (Ima) Imazamox, (Dica) Dicamba, (Hala) Halauxifen, (Fome) Fomesafen, (Flum) Flumioxazin, (Safl) Saflufenacil, (Gluf) Glufosinate, (Para) Paraquat.
[b]Means among columns that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

At 3 WAA, imazamox, fomesafen, and flumioxazin provided poor control at all growth stages with fomesafen and flumioxazin providing less than 20% control (Table 2.3). Imazamox provided 33% control to early rosette horseweed resulting in reduced dry weight at 1.12 g per pot compared to the control at 3.08 g per pot (Table 2.4). Plants did not display chlorotic/necrotic tissue, but growth was stunted when compared to the untreated control.

Control of early rosette horseweed with saflufenacil, glufosinate, and paraquat remained excellent at 99% 3 WAA and reduced horseweed dry biomass to 0 g per pot (Tables 2.3 and 2.4). Control with saflufenacil and paraquat drastically decreased when applied to late rosette horseweed while glufosinate remained at 85% control. Rapid horseweed regrowth from axillary buds was initiated 1 week after saflufenacil application to late rosette plants. This rapid regrowth of late rosette plants was responsible for the decrease in saflufenacil efficacy providing 35% control 3 WAA. Application of the contact herbicides glufosinate and paraquat led to chlorotic/necrotic leaf tissue, but failed to damage the apical meristem. Therefore, apical meristematic growth went uninterrupted.

PPO-inhibiting herbicides such as fomesafen and flumioxazin have limited symplastic phloem movement causing only contact necrosis to treated plant tissue (Grossmann et al. 2011). Saflufenacil, also a PPO-inhibiting herbicide, has a broader systemic mobility and herbicidal action due to an added side-chain bearing an acidic proton. This acidic proton increases systemic mobility and therefore, has the ability to increase apical meristem damage. Damage to the apical meristem by saflufenacil would then break apical dominance and initiate the rapid axillary meristematic regrowth mentioned in the previous paragraph (Gurevitch et al. 2006).

Control of bolted plants from saflufenacil increased by 35% when compared to late rosette plants 3 WAA (Table 2.3). Bolted plants were stunted and height was reduced to less than 12 cm (LSD=4.7) compared to the 29.9 cm tall untreated control 3 WAA (data not shown). Approximately 10 days after saflufenacil application, the apical meristems of bolted plants became necrotic. New shoots began to emerge from auxiliary meristems approximately 17 days after saflufenacil application due to the loss of apical dominance as stated in the previous paragraph. Control of bolted plants with paraquat increased by 23% when compared to control of late rosette plants. This increase in control could be due to the differences in plant morphology as stated in the beginning of the chapter. Control with glufosinate to bolted plants decreased to 66% when compared to the control of late rosette plants. Paraquat and glufosinate-treated leaf tissue of bolted plants became necrotic, but the apical meristem remained healthy and vertical growth continued. Regrowth of bolted plants was similar, but not as rapid, when compared to late rosette plants after application of saflufenacil, paraquat and glufosinate.

CHAPTER 3. FIELD EXPERIMENTS TO EVALUATE THE EFFECT OF FALL APPLIED HERBICIDE APPLICATION ON HORSEWEED MANAGEMENT

Introduction

Postemergence (POST) applied herbicide options for horseweed management in soybean are dwindling because of development of resistant biotypes with minimal effective herbicide options remaining (Byker et al. 2013b). Previously, POST applications of cloransulam and glyphosate were relied on heavily for horseweed control in soybean. This over-reliance has allowed horseweed to develop resistance to both 5-enolpyruvylshikimate 3-phosphate synthase (EPSPS) and acetolactate synthase (ALS) herbicide sites of action. As result of horseweed's resistance or tolerance to many POST herbicides used in soybean, producers have begun to manage horseweed in the fall after harvest or as a preemergence (PRE) application.

Horseweed's capability to emerge throughout the season makes control with PRE herbicides difficult since sufficient soil residual for horseweed control does not extend through the entire germination period (Davis et al. 2010). This sporadic emergence can lead to varying plant sizes early in the spring resulting in further management issues when solely relying on herbicide applications before soybean emergence. In past research by Bond et al. (2014), fall-applied herbicide treatments have been promising when it comes to control of Italian ryegrass as they provided greater than or equal to 93% control 180 days after application. An ideal fall-applied herbicide treatment should consist of a herbicide that controls already emerged plants along with a long residual herbicide to control emerging plants in late fall and early spring (Norsworthy et al. 2009). Winter annual horseweed is most common in North Dakota; therefore, if controlled in the fall, horseweed presence in the field the following spring should be minimal. Winter annual horseweed plants are typically in the early rosette growth stage at the time of a fall herbicide application. Past research has shown that this is the ideal time to chemically control horseweed for maximum efficacy because the plant is in the juvenile growth stage (Shrestha et al. 2007). More research is needed to evaluate fall-applied herbicide utility and timing of fall herbicide application. The objective of this trial was to evaluate the importance of fall-applied herbicides for horseweed control in the field.

Materials and Methods

To determine herbicide residual efficacy on horseweed with treatments applied in the fall, a field experiment was established in 2018 in randomized complete block design (RCBD) with four replicates. Treatment factors were A) herbicide. Factor A had six levels of herbicide or combinations plus an untreated control (Table 3.1). Each experimental unit, or plot, was 3 m wide by 9 m long. Placement of herbicide factor was randomized independently using the ARM software (Agriculture Research Management 2018, 405 Martin Boulevard, Brookings, South Dakota 57006).

Table 3.1. Herbicide product information for field treatments applied in the fall in 2018.

Treatment[a]	Rate	Trade name	Manufacturer[b]
	g ai ha^{-1}		
Control	-	-	-
Dicamba	280	Xtendimax	Monsanto
Dicamba + flumioxazin + HSMOC	280 + 70	Xtendimax + Valor SX	Monsanto + Valent
Saflufenacil + HSMOC	25	Sharpen	BASF
Saflufenacil + flumioxazin + HSMOC	25 + 70	Sharpen + Valor SX	BASF + Valent
Paraquat + NIS	560	Gramoxone 2.0 SL	Syngenta
Paraquat + flumioxazin + NIS	560 + 70	Gramoxone 2.0 SL + Valor SX	Syngenta + Valent

[a]Adjuvants: (HSMOC) high surfactant methylated oil concentrate at 1.2 L ha^{-1} (Destiny HC, Winfield Solutions LLC, St. Paul, MN); (NIS) nonionic surfactant at 0.3 L ha^{-1} (Prefer 90, West Central, Willmar , MN).
[b]Manufacturer information: Monsanto Company, St. Louis, MO; BASF Corporation, Research Triangle Park, NC; Valent Corporation, Walnut Creek, CA; Syngenta Crop protection, Greensboro, NC.

Field experiments were conducted at two locations in southeastern North Dakota near Sheldon, 46°28'20.1"N, 97°29'43.4"W on a Towner soil series and 46°29'47.4"N, 97°29'29.3"W on a Hecla soil series (Table 3.2). These locations were separated by 3 km and were selected due to sufficient native infestation of horseweed. Towner was a sandy over loamy, mixed, superactive, frigid Calcic Hapludoll and Hecla was a sandy, mixed, frigid Oxyaquic Hapludoll.

Table 3.2. Soil series descriptions for environments in 2018.

Soil series[a]	Texture	pH	OM	Sand	Silt	Clay
			----------------------	------------%	----------------------	
Towner	Sandy Loam	5.6	2.5	74.4	20.0	5.6
Hecla	Loamy Sand	5.7	2.3	81.3	14.3	4.4

[a]Soil series obtained from (USDA-NRCS, 2019).

Since all six of the herbicides were applied to each replication, there were seven treatments total including an untreated control per replication. Treatments were delivered on October 24 via a CO_2-pressurized backpack sprayer at a speed of 5 km hr^{-1} with 276 kPa of pressure to deliver 94 L ha^{-1} to each 3- by 9-m plot. The sprayer consisted of a four-nozzle boom with nozzles spaced 51 cm apart that covered 2 m leaving a 1 m running check between plots. Turbo TeeJet 11002 nozzles were used for all herbicide applications (TeeJet®, Spraying Systems Co., 200 W. North Ave., Glendale Heights, IL 60139). Environmental data was collected at the time of herbicide application (Table 3.3).

Table 3.3. Environmental data recorded at fall herbicide application at two locations in 2018.

Factor	Towner	Hecla
Treatment Date	10/24	10/24
Application Time	1:30 AM	1:50 AM
Air temp	10.6°C	10.6°C
Soil temp	5.0°C	5.0°C
Soil moisture	dry	dry
Dew point	0°C	0°C
Humidity	49%	49%
Cloud cover	10%	10%
Wind velocity	16.1 km hr^{-1}	16.1 km hr^{-1}
Wind direction	146°	146°
Horseweed width	1-4 cm	1-4 cm
Horseweed density	20 0.25-m^{-2}	30 0.25-m^{-2}

Horseweed density was evaluated in three random 0.25-m^{-2} quadrats per experiment in the fall before herbicide application. In the following spring, plant density was counted two times per plot in a 0.5-m^{-2} quadrat and visible percent control was determined on a scale of 0 (no control) to 100 (complete plant death).

SAS 9.4 (SAS Institute, Cary, NC) ANOVA procedure was used to conduct the analysis of variance along with treatment mean separation using Fisher's F-protected LSD at α=0.05. Mean Squares were equated to expected mean squares to determine the proper denominators for the different F-tests. A randomized complete block design was used allowing herbicide treatment to be a fixed effect, whereas replication and environment were random effects. A separate analysis of variance for plant density and visible percent control was conducted that included replications within locations and locations as sources of variation for those evaluations. Data were combined across environments if mean square error values between environments were within a factor of 10.

Results and Discussion

Herbicide treatment was statistically significant for the plant density and percent control evaluations as determined by p-values of 0.0002 and less than 0.0001, respectively. A sole application of dicamba at 280 g ai ha^{-1} in late October, was able to control horseweed that had already emerged, but failed to provide long enough residual benefit to control later emerging winter annual cohorts (Tables 3.4 and 3.5). As a result, 76% control and 9 plants 0.5-m^{-2} were observed the following spring. Dicamba generally has moderate residual activity, but when applied at a low rate (280 g ai ha^{-1}), residual activity would decrease (Anonymous 2018). A sole application of paraquat was similar to dicamba and was able to control emerged plant tissue, but failed to control later emerging winter annual horseweed resulting in 11 plants 0.5-m^{-2} and provided 64% control the following spring. Since paraquat is a strict contact, non-residual herbicide, it does not provide any residual benefit in the soil and, therefore, is unable to control non-emerged winter annual horseweed (Anonymous 2016). A sole application of saflufenacil controlled emerged plants while also providing a long enough residual benefit to control later emerging plants in the fall. As a result, 99% control was observed the following spring.

Table 3.4. Main effect of herbicide treatment on horseweed plant density in the spring following fall herbicide application in 2018.

	Herbicide[a]						
Application date	Cont	Dica	Dica + flum	Safl	Safl + flum	Para	Para + flum
	-----------	-----------	-----------	plants 0.5-m^{-2}	-----------	-----------	-----------
Late October	29c[b]	9b	0a	0a	0a	11b	0a

[a]Abbreviations: (Cont) Control, (Dica) Dicamba, (Flum) Flumioxazin, (Safl) Saflufenacil, (Para) Paraquat.
[b]Means that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Table 3.5. Main effect of herbicide treatment on horseweed control in the spring following fall herbicide application in 2018.

	Herbicide[a]					
Application date	Dica	Dica + flum	Safl	Safl + flum	Para	Para + flum
	-----------	-----------	-----------	%	-----------	-----------
Late October	76b[b]	99a	99a	99a	64b	99a

[a]Abbreviations: (Dica) Dicamba, (Flum) Flumioxazin, (Safl) Saflufenacil, (Para) Paraquat.
[b]Means that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Fall-applied herbicide treatments that contained flumioxazin or saflufenacil significantly reduced horseweed density to 0 plants 0.5-m^{-2} and provided 99% control the following spring (Tables 3.4 and 3.5). Flumioxazin does not provide additional control of existing horseweed, but it does provide up to 56 days of residual control (Norsworthy et al. 2009). Dicamba and paraquat controlled emerged plants at the time of application while the residual of flumioxazin controlled later emerging winter annual cohorts. In previous research by Falk et al. (2006), a POST application of flumioxazin failed to control already emerged common waterhemp resulting in 20% control 28 days after treatment. Falk et al. (2006) demonstrated the importance of tank-mixing flumioxazin with a POST-applied foliar herbicide if plants are emerged at the time of herbicide application. Due to saflufenacil efficacy, the added residual benefit that flumioxazin provided when tank-mixed was not observed.

CHAPTER 4. FIELD EXPERIMENTS TO EVALUATE SOYBEAN ROW WIDTH AS A METHOD FOR HORSEWEED CONTROL

Introduction

Herbicide-tolerant cultivars offer a myriad of benefits, such as flexibility and efficiency in weed management, and better economic returns (Manalil et al. 2016). These benefits make it easy for farmers to rely too much on a single herbicide technology without diversity of control strategy, which has led to the emergence of many problematic resistant weeds. Due to this increasing number of resistant weeds, additional cultural control methods must be incorporated within weed control programs. Some common methods used may include weed-competitive cultivars, adjusting crop row orientation, adjusting plant density, and adjusting row width.

Soybean row width can vary depending on the specific pest within the field. A narrow row width is preferred in terms of weed control due to more rapid soybean canopy closure resulting in decreased light availability for weed growth (Harder et al. 2007). When row width is narrowed, there is more equidistant plant distribution within the field resulting in decreased intraspecific competition for water, nutrients, and light leading to a healthier crop. In previous research by Harder et al. (2007), soybean leaf area index (LAI) 8 to 12 weeks after planting was greater in 19- and 38-cm rows compared with 76-cm rows when soybean was seeded at a range of 185,000 to 445,000 seeds ha^{-1}. This increased LAI in the 19- and 38-cm rows intercepted a greater percentage of solar radiation (Harder et al. 2007). Weed seed germination and weed growth is stimulated by this solar radiation; therefore, if solar radiation is restricted from reaching the soil surface, there will be a decrease in weed seed germination and growth. Soybean row width is a useful and effective cultural weed management method; therefore, additional research is needed to determine soybean row width effects on horseweed growth and development. The objective of this trial was to evaluate the impact of soybean row width on horseweed growth.

Materials and Methods

To identify the influence soybean row width has on horseweed growth, a field experiment was established in 2018 and 2019 in randomized complete block design (RCBD) with four replicates. Treatment factors were A) soybean row width and B) herbicide. Factor A included three row width levels: 19, 38, and 76 cm. Factor B had three levels representing different herbicides (Table 4.1). Both the dicamba and paraquat treatments were applied at a reduced rate to allow some horseweed to survive for row width evaluation. A split-plot arrangement was chosen to evaluate soybean row width influence on horseweed growth and emergence. Soybean row width represented the whole plot factor while herbicide treatment represented the subplot factor. Each experimental unit, or subplot, was 3 m wide by 9 m long. Placement of both factors was randomized independently using the ARM software (Agriculture Research Management 2018, 405 Martin Boulevard, Brookings, South Dakota 57006).

Table 4.1. Herbicide product information for field treatments applied to three soybean row widths in 2018 and 2019.

Treatment[a]	Rate	Trade Name	Manufacturer	Address
	g ai ha^{-1}			
Control	-	-	-	-
Dicamba	280	Xtendimax	Monsanto	St. Louis, MO
Paraquat + NIS	350	Gramoxone 2.0 SL	Syngenta	Greensboro, NC

[a]Adjuvants: (NIS) nonionic surfactant at 0.3 L ha^{-1} (Prefer 90, West Central, Willmar, MN).

Field experiments were conducted at two locations in southeastern North Dakota near Sheldon, 46°28'20.1"N, 97°29'43.4"W on a Towner soil series and 46°37'21.4"N 97°30'30.8"W on a Embden soil series (Table 4.2). These locations were separated by 10 km and were selected due to sufficient native infestation of horseweed. Towner is a sandy over loamy, mixed, superactive, frigid Calcic Hapludoll and Embden is a coarse-loamy, mixed, superactive, frigid Pachic Hapludoll.

Table 4.2. Soil series descriptions for environments in 2018 and 2019.

Soil series[a]	Texture	pH	OM	Sand	Silt	Clay
			-------------------------------	---%---	-------------------------------	
Towner	Sandy Loam	5.6	2.5	74.4	20.0	5.6
Embden	Loamy Sand	5.1	2.3	82.2	13.4	4.4

[a]Soil series obtained from (USDA-NRCS, 2019).

The trials for both years were seeded with AG08X8 (Monsanto, 800 N. Lindbergh Boulevard, St. Louis, MO 63167) soybean that is resistant to glyphosate and dicamba at a population of 350,000 seeds ha^{-1}. A 3P600 Great Plains drill was used for all field trials to plant into soybean stubble (Great Plains Ag 1525 E. North Street Salina, KS 67401). The drill is 1.52 m wide and consists of nine feeder cups spaced 19 cm apart. Covers were placed on feeder cups to prevent seed from dropping in all rows depending on desired row width. The drill was set at drive type three for all row widths with cup size two. To achieve the correct seed rate population for desired row width, the seed rate handle was set at 24, 41, and 66 for row widths 19, 38, and 76 cm, respectively. Since whole plots were planted horizontally through each subplot, five drill passes were needed for both the 18 and 38 cm row widths while four passes were needed for the 76 cm row width to fill the 9- by 9-m whole plot. For ease of planting, a 6 m alley was placed between replicates. A 3 m buffer was placed around the whole trial to reduce herbicide drift from the surrounding soybean crop.

Since all three treatments were applied to each of the row widths, there were nine treatments total for each replication. Herbicide treatments were delivered immediately after planting via a CO_2-pressurized backpack sprayer at a speed of 5 km hr^{-1} with 276 kPa of pressure to deliver 94 L ha^{-1} to each 3- by 9-m subplot. The sprayer consisted of a four-nozzle boom with nozzles spaced 51 cm apart that covered 2 m leaving a 1 m running check between subplots. Turbo TeeJet 11001 nozzles were used for all treatments. Environmental data was collected at the time of herbicide application for both years (Table 4.3).

Table 4.3. Environmental data recorded at preemergence application at two locations in 2018 and 2019.

	2018		2019	
Factor	Embden	Towner	Embden	Towner
Treatment Date	5/10	5/11	5/20	5/20
Application Time	5:30 PM	11:15 PM	6:40 PM	2:45 PM
Air temp	15.0°C	14.4°C	20.6°C	19.4°C
Soil temp	20.0°C	15.6°C	17.8°C	16.7°C
Soil moisture	dry	dry	dry	moist
Dew point	15.6°C	-1.1°C	3.9°C	5.6°C
Humidity	99%	30%	33%	34%
Cloud cover	90%	95%	50%	10%
Wind velocity	4.8 km hr^{-1}	11.3 km hr^{-1}	14.5 km hr^{-1}	12.9 km hr^{-1}
Wind direction	35°	135°	90°	90°
Horseweed width	5-7 cm	5-7 cm	5-7 cm	5-7 cm
Horseweed density	105 0.5-m^{-2}	60 0.5-m^{-2}	80 0.5-m^{-2}	40 0.5-m^{-2}

Horseweed density was evaluated 3 and 6 weeks after soybean emergence in two 0.5-m^{-2} quadrats per subplot. Horseweed height was also measured 6 weeks after soybean emergence, and aboveground biomass was collected in one 0.5-m^{-2} quadrat per subplot, dried at 35°C, and weighed.

SAS 9.4 (SAS Institute, Cary, NC) ANOVA procedure was used to conduct the analysis of variance along with treatment mean separation using Fisher’s F-protected LSD at α=0.05. Mean squares were equated to expected mean squares to determine the proper denominators for the different F-tests. A randomized complete block design was used allowing row width and herbicide to be fixed effects, whereas replication and environment were random effects. A separate analysis of variance for plant density, height, and biomass was conducted that included replications within locations and locations as sources of variation for those evaluations. Data were combined across environments if mean square error values between environments were within a factor of 10.

Results and Discussion

Soybean row width and row width by herbicide interaction was not statistically significant for all evaluations as determined by p-values (Table 4.4). Therefore, row width by herbicide interactions was not included within the text or table. Soybean row width had little to no impact on horseweed growth as determined by emergence, height, and biomass. This lack of horseweed suppression is possibly due to the horseweeds establishment in the soil before soybean planting had occurred and herbicide impediments. The application rates of the two herbicides applied at planting may not have been appropriate for the evaluation among horseweed and soybean row width.

Table 4.4. Main effect of soybean row width on horseweed plant density, height, and biomass in 2018 and 2019.

	Density[a]			
Row width	3 WAA	6 WAA	Height	Biomass
cm	------------plants 0.5-m^{-2}------------		cm	g 0.5-m^{-2}
19	34a[b]	34a	20a	43a
38	34a	38a	21a	53a
76	45a	37a	20a	41a
ANOVA	-------------------------------------*p value*-------------------------------------			
Row width	0.5379	0.8696	0.8772	0.5222
Herbicide	0.0093	0.0043	< 0.0001	0.0037
Row width * herbicide	0.5888	0.8876	0.2715	0.1500

[a]Rating separation was run independently.

[b]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

The dicamba treatment applied at a low rate was initially chosen to control emerged plants while providing little to no residual benefit to allow spring annual horseweed to emerge later in the growing season. The efficacy of dicamba, even applied at a low rate, killed the majority of horseweed present and allowed few plants to emerge and grow later in the season. As a result, there were no differences in horseweed growth among row widths. The paraquat treatment applied at a low rate was initially chosen to damage emerged plants while providing no residual benefit to allow emerged plants to grow back along with the emergence of summer annual cohorts. Paraquat provided minimal horseweed control when applied at the reduced rate and allowed many of the already established plants to flourish and outcompete the soybean resulting in no difference among row widths. The dicamba and paraquat herbicide treatments possibly would have allowed more interpretation of soybean row width if the dicamba was applied at an even lower rate of 140 g ai ha^{-1} and the paraquat was applied at a higher rate of 560 g ai ha^{-1}.

A soybean study conducted over a span of two years by Schultz et al. (2015) found that visible waterhemp control was greater in 19- and 38-cm rows than 76-cm rows. In both years, waterhemp density was also lower in 19- and 38-cm compared to 76-cm row widths. This more visible response from the waterhemp to the row widths may have been due to the later emergence period of waterhemp or the two tillage passes performed before soybean seeding allowing direct competition among waterhemp and soybean. Beginning the growing season with a weed-free field would allow the soybean to germinate and emerge without weed competition, allowing the soybean to get established before weed emergence. This is unlike this trial where the winter annual horseweed was already established before soybean seeding, leading to different results. Harder et al. (2007) confirmed similar results in soybean with decreased weed densities of 10-cm tall yellow rocket and wild mustard when comparing 19- and 38-cm rows to 76-cm rows following glyphosate application. Yellow rocket and wild mustard have similar growth habits as horseweed, as they can both complete their life cycle as a winter annual. Therefore, if herbicide applications were to be adjusted within this treatment list, similar results may have been observed.

CHAPTER 5. FIELD EXPERIMENTS TO EVALUATE RESPECTIVE HERBICIDE TECHNOLOGY CROPPING SYSTEMS

Introduction

Soybean production was greatly simplified with the introduction of glyphosate-resistant (GR) soybean in 1996 (Schultz et al. 2015). Glyphosate-resistant soybean allowed producers to apply glyphosate, an effective non-selective herbicide, postemergence over soybean. Efficacy of glyphosate reduced production costs by means of fewer tillage passes and preemergence herbicide applications needed throughout the growing season (Byker et al. 2013a). Due to glyphosate efficacy, producers readily adapted it as their primary weed control method and eliminated the use of different herbicide sites of action within herbicide applications (Schultz et al. 2015). This led to an excessive use of glyphosate and increased selection pressure to encourage evolution of herbicide resistance. In order to manage these glyphosate-resistant cohorts, producers were forced to incorporate various herbicide technologies and additional cultural weed management methods leading to increased production costs.

Horseweed is effectively controlled if tillage can be utilized within an integrated pest management plan (Nandula et al. 2006). After tillage, horseweed seed is buried deeper within the soil profile decreasing seed germination and emergence. Horseweed seed is only 1.0-1.3 mm long with an average weight of 0.07 mg (Bajwa et al. 2016). This small size limits seed reserves and increases reliance on light stimulation for germination; therefore, seeds can only emerge from shallow soil depths (Nandula et al. 2006). Previous research has determined that horseweed emergence is at its maximum 14 days after planting when seeds are placed on the soil surface. Emergence drastically decreased when the seeds were planted 0.25 cm deep while no seedlings emerged at a soil depth of 0.5 cm or deeper.

Glyphosate-resistant horseweed is especially problematic to manage in no-till soybean systems. Without tillage, a combination of fall-applied, preplant (PP), preemergence (PRE), or postemergence (POST) herbicide applications are imperative for GR horseweed control (Vollmer et al. 2019). However, more than one of these application timings must be implemented each year for effective management of both winter and summer annual ecotypes. Winter annual horseweed produces a basal rosette during the beginning of its life cycle in the fall and then bolts in early spring (Budd et al. 2017). Previous research has shown that these populations have been controlled by fall and PP herbicide applications when plants are small (Vollmer et al. 2019). However, if these applications are not utilized, horseweed may be too large to solely rely on PRE and POST herbicide applications for acceptable control (Vollmer et al. 2019; Byker et al. 2013a). Summer annual populations bolt immediately in the spring without basal rosette development and may be difficult to control with fall-applied and PP herbicide applications (Budd et al. 2017; Vollmer et al. 2019). Since summer annual horseweed populations have the ability to emerge before or weeks after soybean planting, the residual of soil applied herbicides, applied in the fall or PP, may not extend late enough into the growing season for long-term control (Vollmer et al. 2019). Therefore, PRE or POST herbicide applications must also be implemented within integrated pest management practices for adequate control.

With the development of 5-enolpyruvylshikimate 3-phosphate synthase (EPSPS) and acetolactate synthase (ALS) resistant horseweed, many POST herbicides are ineffective in conventional and glyphosate-resistant soybean (Byker et al. 2013b). Two of the remaining effective POST herbicides are glufosinate (Liberty®) and dicamba (Xtendimax®, Engenia®, FeXapan®) in their respective cropping platform technologies (Eubank et al. 2008; Byker et al. 2013a). Previous research has shown that glufosinate provided 90 to 94% horseweed control 4 weeks after application in a glufosinate-based burndown program (Eubank et al. 2008). Dicamba applied PP followed by a POST application in dicamba-resistant soybean also provided consistent horseweed control of greater than 86% 4 to 8 weeks after application (Byker et al. 2013a). Both of these herbicide technologies have effectively managed horseweed, but minimal research has been done to determine which technology has the greatest efficacy in a management system when applied POST along with a PRE herbicide application. The objective of this trial was to evaluate the efficacy of different herbicide programs (PRE + POST) in distinctive herbicide crop systems (glufosinate, glyphosate, dicamba) for horseweed control in soybean.

Materials and Methods

To evaluate horseweed control with unique herbicide-resistant technology crop systems, a field experiment was established in 2018 and 2019 in randomized complete block design (RCBD) with four replications. Treatment factors were A) soybean herbicide technology platform and B) PRE herbicide. Factor A included three platform levels: glufosinate resistant, glyphosate resistant, and dicamba plus glyphosate resistant soybean. Factor B had four levels representing different herbicide PRE treatments (Table 5.1). A randomized complete nested block arrangement was selected in order to evaluate different herbicide platforms since each specific herbicide treatment cannot be applied over the other two soybean platforms. Soybean herbicide technology platform represented the whole plot factor while the specific PRE herbicide treatment represented the subplot factor. Each experimental unit, or subplot, was 3 m wide by 9 m long. Placement of both factors was randomized independently using the ARM software (Agriculture Research Management 2018, 405 Martin Boulevard, Brookings, South Dakota 57006).

Table 5.1. Herbicide product information for field treatments applied to three soybean technology platforms in 2018 and 2019.

PRE herbicide	Treatment[ab]: PRE[c] fb POST	Rate
		g ai ha^{-1}
	Glufosinate-resistant (Liberty Link)	
None	Paraquat + NIS fb	560 fb
	glufosinate + AMS-D	810
Saflufenacil	Paraquat + saflufenacil + HSMOC fb	560 + 25 fb
	glufosinate + AMS-D	810
Flumioxazin	Paraquat + flumioxazin + HSMOC fb	560 + 70 fb
	glufosinate + AMS-D	810
Sulfentrazone	Paraquat + sulfentrazone + HSMOC fb	560 + 210 fb
	glufosinate + AMS-D	810
	Glyphosate-resistant (Roundup Ready)	
None	Glyphosate + AMS-D fb	840 fb
	bentazon + glyphosate + HSMOC	560 + 840
Saflufenacil	Glyphosate + saflufenacil + HSMOC + AMS-D fb	840 + 25 fb
	bentazon + glyphosate + HSMOC	560 + 840
Flumioxazin	Glyphosate + flumioxazin + HSMOC + AMS-D fb	840 + 70 fb
	bentazon + glyphosate + HSMOC	560 + 840
Sulfentrazone	Glyphosate + sulfentrazone + HSMOC + AMS-D fb	840 + 210 fb
	bentazon + glyphosate + HSMOC	560 + 840
	Dicamba- and glyphosate-resistant (Xtend)	
None	Glyphosate + AMS-D fb	840 fb
	dicamba + glyphosate	560 + 840
Saflufenacil	Glyphosate + saflufenacil + dicamba + HSMOC fb	840 + 25 + 560 fb
	dicamba + glyphosate	560 + 840
Flumioxazin	Glyphosate + flumioxazin + dicamba + HSMOC fb	840 + 70 + 560 fb
	dicamba + glyphosate	560 + 840
Sulfentrazone	Glyphosate + sulfentrazone + dicamba + HSMOC fb	840 + 210 + 560 fb
	dicamba + glyphosate	560 + 840

[a]Adjuvants: (HSMOC) high surfactant methylated oil concentrate at 1.2 L ha^{-1} (Destiny HC, Winfield Solutions LLC, St. Paul, MN); (AMS-D) ammonium sulfate-dry at 953 and 3360 g ha^{-1} for glyphosate and glufosinate (AMS Plus Dry, Coastal AgroBusiness, Greenville, NC); (NIS) nonionic surfactant at 0.3 L ha^{-1} (Prefer 90, West Central, Willmar, MN).
[b]Herbicide manufacturer information: (Paraquat) Gramoxone 2.0 SL, Syngenta Crop Protection, Greensboro, NC; (glufosinate) Liberty 280 SL, Bayer Crop Science, Research Triangle Park, NC; (saflufenacil) Sharpen, BASF Corporation, Research Triangle Park, NC; (flumioxazin) Valor SX, Valent Corporation, Walnut Creek, CA; (sulfentrazone) Spartan 4F, FMC Corporation, Philadelphia, PA; (glyphosate) Roundup PowerMAX, Monsanto Company, St. Louis, MO; (bentazon) Basagran, Winfield Solutions LLC,St. Paul, MN; (dicamba) Xtendimax, Monsanto Company, St. Louis, MO.
[c]Abbreviations: (PRE) preemergence, (POST) postemergence, (fb) followed by.

Field experiments were conducted at two locations in southeastern North Dakota near Sheldon, 46°28'20.1''N, 97°29'43.4''W on a Towner soil series and 46°37'21.4''N 97°30'30.8''W on a Embden soil series (Table 5.2). These locations were separated by 10 km and were selected due to sufficient native infestation of horseweed. Towner was a sandy over loamy, mixed, superactive, frigid Calcic Hapludoll and Embden was a coarse-loamy, mixed, superactive, frigid Pachic Hapludoll.

Table 5.2. Soil series descriptions for environments in 2018 and 2019.

Soil series[a]	Texture	pH	OM	Sand	Silt	Clay
			-----------------------------%-----------------------------			
Towner	Sandy Loam	5.6	2.5	74.4	20.0	5.6
Embden	Loamy Sand	5.1	2.3	82.2	13.4	4.4

[a]Soil series obtained from (USDA-NRCS, 2019).

The trial was seeded with three different soybean platforms at a population of 350,000 seeds ha^{-1}. A 3P600 Great Plains drill was used to plant into soybean stubble (Great Plains Ag 1525 E. North Street Salina, KS 67401). The drill was 1.52 m wide and consisted of nine feeder cups spaced 19 cm apart. Covers were placed within feeder cups to prevent seed from dropping in all rows for desired row width. Rows were 76 cm apart across the entire experiment. Soybean for herbicide technology platforms were ‘CZ0201LL’ and ‘CZ0301LL’ with resistance to glufosinate for growing seasons 2018 and 2019, respectively (Liberty Link; BASF Corporation 100 Park Ave., Florham Park, NJ 07932). Soybean ‘AG0934’ with resistance to glyphosate (Roundup Ready 2 Yield; Monsanto, 800 N. Lindbergh Boulevard, St. Louis, MO 63167) and ‘AG08X8’ with resistance to dicamba and glyphosate (Roundup Ready 2 Xtend; Monsanto, 800 N. Lindbergh Boulevard, St. Louis, MO 63167) were used for both years. To reduce the amount of dicamba drift on the two susceptible platforms, replicates were 6 m apart and whole plots within replicate were 3 m apart. A 3 m buffer was also placed around the whole trial to reduce herbicide drift from the surrounding soybean crop. Trials were harvested for grain yield using a plot combine (Hege 125B) with a 1.37-m-wide grain header.

Since all three of the soybean platforms included four herbicide PRE treatments, there were twelve treatments per replication. Treatments were delivered via a CO_2-pressurized backpack sprayer at a speed of 5 km hr^{-1} with 276 kPa of pressure to deliver 94 L ha^{-1} to each 3- by 9-m subplot. The sprayer consisted of a four nozzle boom with nozzles spaced 51 cm apart that covered 2 m leaving a 1 m running check between subplots. Turbo TeeJet 11001 nozzles were used for all PRE treatments (TeeJet®, Spraying Systems Co., 200 W. North Ave., Glendale Heights, IL 60139). POST applications that included dicamba were applied with Turbo TeeJet Induction 110015 nozzles while Turbo TeeJet 11001 nozzles were used for all other POST applications. PRE treatments were applied immediately after soybean planting. POST applications were applied at the fourth soybean trifoliolate growth stage. Environmental data was collected at the time of each herbicide application (Tables 5.3 and 5.4).

Table 5.3. Environmental data recorded at preemergence application at two locations in 2018 and 2019.

	2018		2019	
Factor	Embden	Towner	Embden	Towner
Treatment Date	5/10	5/11	5/20	5/20
Application Time	5:50 PM	1:45 PM	6:50 PM	3:15 PM
Air temp	13.9°C	15.6°C	20.6°C	19.4°C
Soil temp	20°C	21.1°C	17.8°C	16.7°C
Soil moisture	dry	dry	dry	moist
Dew point	15.6°C	-2.2°C	3.9°C	5.6°C
Humidity	99%	26%	33%	34%
Cloud cover	95%	95%	50%	10%
Wind velocity	9.7 km hr^{-1}	3.2 km hr^{-1}	14.5 km hr^{-1}	12.9 km hr^{-1}
Wind direction	35°	65°	90°	90°
Horseweed width	5-7 cm	5-7 cm	5-7 cm	5-7 cm
Horseweed density	105 0.5-m^{-2}	60 0.5-m^{-2}	80 0.5-m^{-2}	40 0.5-m^{-2}

Table 5.4. Environmental data recorded at postemergence application at two locations in 2018 and 2019.

	2018		2019	
Factor	Embden	Towner	Embden	Towner
Treatment Date	6/18	6/18	6/24	6/24
Application Time	1:18 PM	2:45 PM	9:23 AM	12:10 PM
Air temp	25.6°C	26.7°C	22.2°C	22.2°C
Soil temp	26.7°C	28.3°C	21.1°C	22.8°C
Soil moisture	moist	dry	moist	moist
Dew point	13.9°C	12.2°C	17.2°C	15°C
Humidity	47%	40%	87%	67%
Cloud cover	40%	50%	100%	80%
Wind velocity	6.4 km hr^{-1}	6.4 km hr^{-1}	1.6 km hr^{-1}	4.8 km hr^{-1}
Wind direction	15°	0°	335°	325°
Horseweed height	27-30 cm	27-30 cm	27-30 cm	27-30 cm

Visible percent control was evaluated on a scale of 0 (no control) to 100 (complete plant death) and horseweed density was determined 3 weeks after PRE herbicide application in two 0.5-m^{-2} quadrats per subplot. Horseweed density and visible percent control was also evaluated 3 and 7 weeks after POST herbicide application in two 0.5-m^{-2} quadrats per subplot. Horseweed aboveground biomass was collected 7 weeks after POST herbicide application in one 0.25-m^{-2} quadrat per subplot, dried at 35°C, and weighed. Soybean seed yield was determined by harvesting the center 1.37 m of each subplot, dried down to an average of 13% moisture at a temperature of 35°C, and weighed.

SAS 9.4 (SAS Institute, Cary, NC) ANOVA procedure was used to conduct the analysis of variance along with treatment mean separation using Fisher's F-protected LSD at α=0.05. Mean squares were equated to expected mean squares to determine the proper denominators for the different F-tests. A randomized complete block design was used allowing herbicide platform and herbicide application to be fixed effects, whereas replication and environment were random effects. A separate analysis of variance for visible percent control, plant density, horseweed aboveground biomass, and seed yield was conducted that included replications within location as sources of variation for those evaluations. Mean square error values between environments did not fall within a factor of 10; therefore, environments were not combined for analysis. Due to the construction of a randomized complete nested block arrangement, comparisons can only be made between the four herbicide treatments within soybean platform, and among soybean platforms averaged across herbicide treatment. Comparisons cannot statistically be made between single herbicide treatments between soybean platforms.

Results and Discussion

Horseweed Stand Counts

Herbicide within soybean system was statistically significant for all locations but Embden19 (2019) for the three weeks after PRE application evaluation as determined by p-values (Table 5.5). For the 3 and 7 weeks after POST application evaluations, herbicide within soybean system was significant for all locations (Tables 5.6 and 5.7). Horseweed plant density at Embden18, Towner18, Embden19, and Towner19 at the time of PRE herbicide application was 105, 60, 80, and 40 plants 0.5-m^{-2}, respectively (Table 5.3). Plant density at Embden18 was much higher than the other three locations; therefore, a sole application of paraquat applied alone as a PRE within the Liberty system provided poor coverage that resulted in poor control (Table 5.5). The compact horseweed population had a lot of overlapping plant tissue that decreased herbicide contact for many small rosettes. Since paraquat is strictly a contact herbicide, it failed to provide effective coverage resulting in poor horseweed control (Anonymous 2016). Eubank et al. (2008) determined similar results when a treatment of paraquat was applied to a field with 25- to 30-cm-tall horseweed. He theorized that this limited control from paraquat might also be due to poor herbicide contact (Eubank et al. 2008). Horseweed, both rosette and bolted plants, is densely covered with pubescence that can help protect the plant apical meristem from herbicide application. When a contact herbicide such as paraquat is applied to horseweed, some of the herbicide will be suspended within the pubescence and therefore, decrease herbicide contact with the plant cuticle. The native infestation of horseweed at Towner18, Embden19, and Towner19 was not as severe as Embden18; therefore, the addition of paraquat in all four PRE herbicide treatments within the Liberty system adequately decreased rosette horseweed density to fewer than 13 plants 0.5-m^{-2}.

Table 5.5. Main effects of herbicide treatment within system and system on horseweed plant density 3 weeks after PRE application at four locations in 2018 and 2019.

		2018[b]		2019	
System	Herbicide[a]	Embden	Towner	Embden	Towner
		---------------------------plants 0.5-m^{-2}	------------------------------		
Liberty					
	Para	59ab[ce]	1a	12a	6a
	Para + safl	32a	1a	1a	0a
	Para + flum	79b	3a	12a	4a
	Para + sulf	88b	2a	9a	3a
Roundup					
	Glyt	86b	57c	41b	12c
	Glyt + safl	15a	1a	7a	1a
	Glyt + flum	85b	32b	39b	8bc
	Glyt + sulf	92b	28b	46b	5b
Xtend					
	Glyt	100b	30b	17a	16b
	Dica + glyt + safl	1a	0a	0a	0a
	Dica + glyt + flum	0a	0a	1a	1a
	Dica + glyt + sulf	0a	0a	1a	0a
Liberty	-	65b[d]	1a	8a	3a
Roundup	-	70b	29b	33b	6a
Xtend	-	25a	8a	4a	4a
ANOVA		--------------------------------*p value*	--------------------------------		
System		0.0021	< 0.0001	< 0.0001	0.1808
Herbicide(System)		0.0005	< 0.0001	0.0836	0.0002

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin, (Sulf) Sulfentrazone.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Flumioxazin and sulfentrazone were included for their residual benefit and have limited foliar activity on horseweed. Since horseweed populations were established before PRE herbicide treatment, additions of flumioxazin and sulfentrazone within the Liberty system were not effective leaving 79 or more plants 0.5-m^{-2} at Embden18 (Table 5.5). The majority of this horseweed population is likely winter annuals. Therefore, the residual benefit from flumioxazin and sulfentrazone would not be observed in the spring since the majority of the horseweed population is already emerged before herbicide application. When residual herbicides are applied in the fall, many winter annual horseweed plants would not be emerged at the time of application, therefore, the added residual benefit would control later emerging cohorts. In previous research, POST applications of flumioxazin and sulfentrazone, when tank-mixed with glyphosate, only provided 50 and 53% control 4 weeks after application to 25- to 30-cm-tall GR horseweed, respectively (Eubank et al. 2008). It is not stated what the horseweed symptoms were, but symptoms from the two treatments mentioned above may be similar to this experiment. Since flumioxazin and sulfentrazone both have limited foliar activity and the horseweed was also GR, no foliar symptoms were observed. Horseweed plants within the treated subplot area were slightly stunted compared to the plants in the 1 m running check between subplots. Saflufenacil is labeled to have foliar activity on horseweed, but residual length is limited (Anonymous 2017). Saflufenacil efficacy on already emerged horseweed reduced horseweed density to 32 plants 0.5-m^{-2} at Embden18 and had the greatest efficacy out of all four PRE herbicide treatments within the Liberty system.

The only PRE herbicide treatment that considerably decreased plant density within the Roundup system was glyphosate plus saflufenacil, which resulted in 15 or fewer plants 0.5-m^{-2} at all four locations (Table 5.5). This lack of efficacy from glyphosate further reinforces the consideration that this was a GR horseweed population. Additions of flumioxazin and sulfentrazone in the Roundup system at Embden18 and Embden19 did not affect horseweed density due to their lack of foliar activity when compared to glyphosate alone. At Towner18, the addition of flumioxazin and sulfentrazone did reduce plant density to 32 or fewer plants 0.5-m^{-2}

when compared to glyphosate alone. Only slight statistical differences were observed at Towner19 when comparing flumioxazin and sulfentrazone to the glyphosate alone PRE treatments. Perhaps the horseweed population at Embden consisted mostly of the winter annual biotype where plants would already be emerged at the time of PRE herbicide application. This would explain the high horseweed density at the time of PRE application and the lack of control provided by flumioxazin and sulfentrazone when comparing to glyphosate alone (Table 5.5).

In the Xtend system, a sole application of glyphosate left many plants 0.5-m^{-2} at Embden18, Towner18, and Towner19 when compared to treatments that contained dicamba (Table 5.5). Dicamba is able to control already emerged plants while also providing a residual benefit as well. In previous research, an application of dicamba plus glyphosate to emerged GR horseweed provided greater than 90% control 6 weeks after application (Norsworthy et al. 2009). This high level of control demonstrated dicamba's ability to control already emerged plant foliage. In the same article, an application of dicamba also reduced horseweed emergence by 66 to 76% over a 10 week period. This high emergence reduction demonstrated the residual benefit that dicamba provided, but residual duration may vary depending on soil type, environmental factors, and rate. In this research, efficacy of dicamba on horseweed masked the efficacy of saflufenacil so there was no difference among the treatments that contained saflufenacil, flumioxazin, and sulfentrazone within the Xtend system at all four locations.

When systems averaged across PRE herbicide treatments at Embden18 were compared, the Xtend system removed the most horseweed plants and reduced the population from 105 to 25 plants 0.5-m^{-2} (Tables 5.3 and 5.5).The residual benefit that dicamba provided helped to control non-emerged plants along with emerged plants at the time of application. Due to the high horseweed density at Embden18, paraquat coverage on emerged plant foliage was reduced.

Therefore, the Liberty system was not significantly different from the Roundup system, which struggled because of suspected resistance, at this location. Both the Liberty and Xtend systems at Towner18 and Embden19 reduced the horseweed population to 8 or fewer plants 0.5-m^{-2}. The Roundup system at Towner18 and Embden19 lacked control leaving 29 and 33 plants 0.5-m^{-2}, respectively. The horseweed population at Towner19 was less severe than the other three locations. This was the second year that this trial was conducted at the Towner location, so it had to be placed at a different area within the field. The new area did not have as high of a horseweed population. This decreased native horseweed population led to no differences when comparing systems averaged across PRE herbicide treatment at Towner19.

Horseweed plant density in the Liberty system at all four locations was drastically reduced to 12 or fewer plants 0.5-m^{-2} after POST application of glufosinate for both the 3 and 7 week evaluations (Tables 5.6 and 5.7). Due to glufosinate efficacy, there were no differences in PRE followed by POST herbicide application for all four treatments within the Liberty system at all four locations. Even though glufosinate and paraquat are both considered contact herbicides, previous research has shown that glufosinate generally is more effective in terms of weed control (Wibawa et al. 2007; Eubank et al. 2008). When both glufosinate and paraquat were applied to multiple broadleaf weeds at a rate of 600 g ha^{-1}, glufosinate provided greater control at 98% while paraquat provided 88% control 4 weeks after application (Wibawa et al. 2007). Eubank et al. (2008) also observed a similar difference in control between glufosinate and paraquat 4 weeks after application when applied to 15- to 20-cm-tall horseweed. An application of paraquat and glufosinate provided 55 and 96% control when applied at 840 and 470 g ai ha^{-1}, respectively (Eubank et al. 2008).

Table 5.6. Main effects of herbicide treatment within system and system on horseweed plant density 3 weeks after POST application at four locations in 2018 and 2019.

	Herbicide[a]		2018[b]		2019	
System	PRE	POST	Embden	Towner	Embden	Towner
			------------------plants 0.5-m^{-2}	--------------------		
Liberty						
	Para	Gluf	9a[ce]	0a	2a	1a
	Para + safl	Gluf	1a	1a	1a	0a
	Para + flum	Gluf	12a	0a	1a	0a
	Para + sulf	Gluf	4a	0a	1a	0a
Roundup						
	Glyt	Glyt + bent	102b	25b	45b	14b
	Glyt + safl	Glyt + bent	13a	4a	5a	0a
	Glyt + flum	Glyt + bent	83b	21b	52b	11b
	Glyt + sulf	Glyt + bent	101b	29b	45b	1a
Xtend						
	Glyt	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + safl	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + flum	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + sulf	Dica + glyt	0a	0a	0a	0a
Liberty	-	-	6a[d]	1a	1a	1a
Roundup	-	-	75b	20b	37b	7b
Xtend	-	-	0a	0a	0a	0a
ANOVA			------------------------*p value*	-------------------------		
System			< 0.0001	< 0.0001	< 0.0001	< 0.0001
Herbicide(System)			< 0.0001	0.0421	0.0026	0.0004

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin , (Sulf) Sulfentrazone, (Gluf) Glufosinate, (Bent) Bentazon.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE + POST herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Table 5.7. Main effects of herbicide treatment within system and system on horseweed plant density 7 weeks after POST application at four locations in 2018 and 2019.

	Herbicide[a]		2018[b]		2019	
System	PRE	POST	Embden	Towner	Embden	Towner
			---plants 0.5-m^{-2}---			
Liberty						
	Para	Gluf	12a[ce]	0a	2a	1a
	Para + safl	Gluf	3a	0a	1a	0a
	Para + flum	Gluf	10a	0a	4a	1a
	Para + sulf	Gluf	9a	0a	1a	0a
Roundup						
	Glyt	Glyt + bent	126b	33b	44b	14b
	Glyt + safl	Glyt + bent	21a	1a	4a	1a
	Glyt + flum	Glyt + bent	114b	21b	34b	15b
	Glyt + sulf	Glyt + bent	115b	17b	38b	3a
Xtend						
	Glyt	Dica + glyt	0a	0a	1a	0a
	Dica + glyt + safl	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + flum	Dica + glyt	0a	0a	1a	0a
	Dica + glyt + sulf	Dica + glyt	0a	0a	0a	0a
Liberty	-	-	9b[d]	0a	2a	1a
Roundup	-	-	94c	18b	30b	8b
Xtend	-	-	0a	0a	0a	0a
ANOVA			---*p value*---			
System			< 0.0001	< 0.0001	< 0.0001	< 0.0001
Herbicide(System)			< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin , (Sulf) Sulfentrazone, (Gluf) Glufosinate, (Bent) Bentazon.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE + POST herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

In the Roundup system, POST application of glyphosate plus bentazon was ineffective at all four locations to kill horseweed (Tables 5.6 and 5.7). As a result, addition of saflufenacil as a PRE was the only PRE followed by POST treatment that significantly decreased plant density to 21 or fewer plants 0.5-m^{-2}. Since the POST application of glyphosate plus bentazon did not decrease plant density in the other three treatments within the Roundup system, it is likely that the addition of saflufenacil in the PRE treatment was largely responsible for the substantially reduced plant density at all four locations.

In the Xtend system, when the PRE application of glyphosate was followed by a POST application of dicamba plus glyphosate, plant density was reduced to 1 or fewer plants 0.5-m^{-2} at all four locations (Tables 5.6 and 5.7). This demonstrates the efficacy of a POST application of dicamba on horseweed since these plots contained a high population of horseweed before POST application.

When systems averaged across PRE followed by POST herbicide treatments were compared, the Xtend and Liberty systems reduced horseweed density to 6 or fewer plants 0.5-m^{-2} at all four locations for the 3 week after POST application evaluation (Table 5.6). At the 7 week after POST application evaluation, the Xtend system was statistically different from the Liberty system at only the Embden18 location (Table 5.7). In fields with high horseweed densities, the Xtend system was the more reliable option. Although the majority of the horseweed population was of the winter annual ecotype, summer annual populations that bolted immediately without basal rosette development were also observed. Therefore, dicamba was able to control emerged plant foliage while also providing a residual benefit to control later emerging summer annual populations. The POST application of glufosinate was likely influenced in a similar manner as the PRE application of paraquat due to their reliance on foliar contact. The dense horseweed canopy at Embden18 likely prevented the glufosinate from penetrating deeper within the canopy, which reduced herbicide contact with plant foliage, therefore, young horseweed plants were protected and not controlled due to the lack of foliar herbicide contact. Glufosinate was able to control large horseweed plants when contacted by herbicide, but two POST applications of glufosinate are likely needed for acceptable control throughout the growing season. The Roundup system on the other hand had substantially more plants 0.5-m^{-2} than both the Xtend and Liberty systems at all locations for both the 3 and 7 week after POST herbicide application evaluations (Tables 5.6 and 5.7).

Horseweed Control

Herbicide within soybean system was statistically significant for all locations for all three control evaluations as determined by p-values (Tables 5.8, 5.9, 5.10). Horseweed control 3 weeks after PRE herbicide application in the Liberty system was also influenced by the dense horseweed population at both Embden locations (Table 5.8). All four PRE applications at Embden18 lacked acceptable control; however, paraquat with the addition of saflufenacil did show significantly greater control than the other three PRE herbicide treatments providing 45% control. Embden19 showed similar results as Embden18 with the addition of saflufenacil providing excellent control at 98%. The native infestation of horseweed at Embden19 was less than Embden18; therefore, control was greater due to increased canopy penetration and coverage with paraquat and saflufenacil.

Table 5.8. Main effects of herbicide treatment within system and system on horseweed control 3 weeks after PRE application at four locations in 2018 and 2019.

		2018[b]		2019	
System	Herbicide[a]	Embden	Towner	Embden	Towner
		---%	---	---	---
Liberty					
	Para	6b[ce]	95a	53b	83b
	Para + safl	45a	99a	98a	97a
	Para + flum	8b	80b	50b	88ab
	Para + sulf	13b	92a	53b	89ab
Roundup					
	Glyt	5b	5b	23b	75b
	Glyt + safl	55a	97a	95a	98a
	Glyt + flum	6b	10b	21b	75b
	Glyt + sulf	6b	8b	20b	81b
Xtend					
	Glyt	5b	11b	28b	63b
	Dica + glyt + safl	99a	99a	99a	99a
	Dica + glyt + flum	99a	99a	99a	99a
	Dica + glyt + sulf	99a	99a	98a	99a
Liberty	-	18b[d]	92a	63b	89ab
Roundup	-	18b	30c	40c	82b
Xtend	-	75a	77b	81a	90a
ANOVA		---*p value*	---	---	---
System		< 0.0001	< 0.0001	< 0.0001	0.0693
Herbicide(System)		< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin, (Sulf) Sulfentrazone.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

In the Roundup system, glyphosate with the addition of saflufenacil provided greater than 90% control at Towner18, Embden19, and Towner19 (Table 5.8). The addition of saflufenacil at Embden18 resulted in increased control compared to the other three PRE herbicide treatments at that location, but was still low due to the high horseweed population. Every PRE herbicide treatment that contained saflufenacil at Towner18, Embden19, and Towner19 provided greater control than the other three PRE treatments. The low control provided by an application of glyphosate plus flumioxazin was similar to what Eubank et al. (2008) observed with glyphosate plus flumioxazin providing 50% control 4 weeks after application. Eubank et al. (2008) also observed poor control (53%) with an application of glyphosate plus sulfentrazone 4 weeks after application. Flumioxazin and sulfentrazone were not effective on already emerged and established horseweed. Since the populations were also glyphosate-resistant, these two treatments were not able to control emerged horseweed plants resulting in poor control.

In the Xtend system, PRE herbicide treatment that included dicamba provided excellent control at 99% (Table 5.8). This was similar to an experiment which found that dicamba applied at 400 g ha^{-1} provided 100% control of rosette horseweed 4 weeks after application (Keeling et al. 1989).

When systems averaged across PRE followed by POST herbicide treatments were compared, the Xtend system provided significantly greater control at 75 and 81% for both Embden18 and Embden19 locations, respectively, than other crop technologies (Table 5.8). Due to the less dense native horseweed infestation at Towner18, paraquat effectively controlled this horseweed population providing an average of 92% control. Control provided by the Xtend system at Towner18, when averaged across the four PRE herbicide treatments, decreased to 77%. This reduction in control was due to the sole PRE application of glyphosate which provided only 11% control compared to 99% control when dicamba was included. This poor glyphosate control decreased the Xtend system average and allowed the Liberty system to provide greater control overall than either the Xtend or Roundup systems at Towner18. The native horseweed infestation at Towner19 was less dense than the three other locations.

Therefore, all three systems provided 82% or greater control. This resulted in no differences among the Liberty and Xtend, and the Liberty and Roundup systems while the Xtend system remained greater than the Roundup system.

Horseweed control 3 weeks after POST herbicide application in the Liberty system provided 74% or greater control at Embden18 and 93% or greater control at the other three locations (Table 5.9). In Towner18, Embden19, and Towner19 no difference was observed between PRE followed by POST herbicide treatments while significance was observed at Embden18 in the treatments that contained the PRE herbicides saflufenacil and sulfentrazone. The high horseweed population at Embden18 allowed more horseweed plants to survive the PRE herbicide applications within the Liberty system. Therefore, at the time of glufosinate application, plants were larger and more mature, which decreased glufosinate control.

Table 5.9. Main effects of herbicide treatment within system and system on horseweed control 3 weeks after POST application at four locations in 2018 and 2019.

	Herbicide[a]		2018[b]		2019	
System	PRE	POST	Embden	Towner	Embden	Towner
			--------------------------%	--------------------------		
Liberty						
	Para	Gluf	74b[ce]	99a	95a	99a
	Para + safl	Gluf	84a	99a	99a	99a
	Para + flum	Gluf	75b	99a	93a	98a
	Para + sulf	Gluf	80a	99a	97a	99a
Roundup						
	Glyt	Glyt + bent	11b	13bc	35b	46c
	Glyt + safl	Glyt + bent	68a	80a	88a	97a
	Glyt + flum	Glyt + bent	11b	19b	36b	46c
	Glyt + sulf	Glyt + bent	11b	18bc	30b	82b
Xtend						
	Glyt	Dica + glyt	85b	89b	95a	99a
	Dica + glyt + safl	Dica + glyt	99a	99a	99a	99a
	Dica + glyt + flum	Dica + glyt	99a	99a	99a	99a
	Dica + glyt + sulf	Dica + glyt	99a	99a	98a	98a
Liberty	-	-	78b[d]	99a	96a	99a
Roundup	-	-	25c	32b	47b	68b
Xtend	-	-	96a	96a	98a	99a
ANOVA			-----------------------*p value*	-----------------------		
System			< 0.0001	< 0.0001	< 0.0001	< 0.0001
Herbicide(System)			< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin , (Sulf) Sulfentrazone, (Gluf) Glufosinate, (Bent) Bentazon.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE + POST herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

In the Roundup system 3 and 7 weeks after POST herbicide application, the treatment that contained saflufenacil within the PRE herbicide treatment provided greater control than all other treatments, providing 68% or greater control at all four locations (Tables 5.9 and 5.10). Horseweed displayed little to no foliar symptoms after application of glyphosate plus bentazon at all four locations. The addition of saflufenacil within the PRE herbicide application was likely responsible for that treatment's efficacy within the Roundup system since both glyphosate and bentazon had little to no influence on horseweed growth.

Table 5.10. Main effects of herbicide treatment within system and system on horseweed control 7 weeks after POST application at four locations in 2018 and 2019.

	Herbicide[a]		2018[b]		2019	
System	PRE	POST	Embden	Towner	Embden	Towner
			----------------------------%----------------------------			
Liberty						
	Para	Gluf	82a[ce]	99a	90b	98a
	Para + safl	Gluf	92a	99a	99a	99a
	Para + flum	Gluf	86a	99a	89b	98a
	Para + sulf	Gluf	85a	99a	95ab	98a
Roundup						
	Glyt	Glyt + bent	5b	13c	23b	20c
	Glyt + safl	Glyt + bent	68a	89a	89a	88a
	Glyt + flum	Glyt + bent	5b	20b	25b	20c
	Glyt + sulf	Glyt + bent	5b	24b	23b	71b
Xtend						
	Glyt	Dica + glyt	99a	99a	99a	99a
	Dica + glyt + safl	Dica + glyt	99a	99a	99a	99a
	Dica + glyt + flum	Dica + glyt	99a	99a	98a	99a
	Dica + glyt + sulf	Dica + glyt	99a	99a	99a	99a
Liberty	-	-	86b[d]	99a	93b	98a
Roundup	-	-	21c	36b	40c	50b
Xtend	-	-	99a	99a	98a	99a
ANOVA			------------------------*p value*------------------------			
System			< 0.0001	< 0.0001	< 0.0001	< 0.0001
Herbicide(System)			< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin , (Sulf) Sulfentrazone, (Gluf) Glufosinate, (Bent) Bentazon.

[b]Environment separation was run independently.

[c]Comparison among the four unique PRE + POST herbicide treatments within system.

[d]Comparison among systems averaged across the four unique herbicide treatments.

[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

In the Xtend system, the only differences observed were at Embden18 and Towner18 in the PRE followed by POST treatments that did not include dicamba within the PRE herbicide application (Table 5.9). These plots contained larger, more mature horseweed plants that remained standing for a longer duration of time before dicamba application; therefore, a few horseweed plants looked as if they could survive at the 3 weeks after POST evaluation. Dicamba completely controlled all horseweed plants providing 99% control for all treatments within the Xtend system at the 7 weeks after POST control evaluation at all locations (Table 5.10). This is similar to what Kruger et al. (2010) observed with a preplant (PP) followed by POST application of dicamba providing 100, 99, and 95% control at three sites 8 weeks after POST application. Kruger et al. (2010) also determined that dicamba applied PP, or dicamba applied PP followed by a POST application provided the most consistent horseweed control at 86% or greater. This consistency was similar to observations in this experiment with a PRE followed by POST application of dicamba providing 99% control 7 weeks after application.

When systems averaged across PRE followed by POST herbicide treatments were compared, similar results were observed between the two control evaluations at all locations but Embden19 (Tables 5.9 and 5.10). At Embden19, a slight decrease in control for the 7 week evaluation in the Liberty system was enough to show a significant difference among all three systems with the Xtend system providing the greatest control at 98% (Table 5.10). Similar significance was observed at Embden18 with the Xtend system providing the highest control at 99% and the Roundup system providing the lowest at 21%. No substantial difference was observed between the Liberty and Xtend systems at Towner18 and Towner19 (Tables 5.9 and 5.10). The less dense horseweed population at these two locations allowed a POST application of glufosinate to effectively penetrate the horseweed canopy and provide excellent control. At

Embden18 and Embden19, the denser horseweed population allowed a few horseweed plants to escape the POST application of glufosinate.

Horseweed Plant Biomass

Herbicide within soybean system was statistically significant for all locations as determined by p-values (Table 5.11). Horseweed biomass generally mirrored the results of the plant density and control evaluations (Tables 5.7, 5.10, and 5.11). Glufosinate and dicamba POST application efficacy eliminated many horseweed plants within the Liberty and Xtend systems reducing overall biomass (Tables 5.7 and 5.11). Therefore, no differences were observed within these systems at all four locations (Table 5.11). The addition of saflufenacil applied PRE within the Roundup system reduced horseweed biomass at all four locations when compared with other treatments. When systems averaged across PRE followed by POST herbicide treatments were compared, no differences were observed between the Liberty and Xtend systems at all four locations and horseweed biomass was reduced to 17 or fewer g 0.25 m^{-2}.

Table 5.11. Main effects of herbicide treatment within system and system on horseweed aboveground biomass 7 weeks after POST application at four locations in 2018 and 2019.

	Herbicide[a]		2018[b]		2019	
System	PRE	POST	Embden	Towner	Embden	Towner
			---------------------g 0.25-m^{-2}	---------------------		
Liberty						
	Para	Gluf	19a[ce]	0a	10a	1a
	Para + safl	Gluf	5a	0a	2a	0a
	Para + flum	Gluf	24a	0a	9a	0a
	Para + sulf	Gluf	19a	0a	7a	1a
Roundup						
	Glyt	Glyt + bent	444b	311c	123b	81b
	Glyt + safl	Glyt + bent	146a	18a	41a	6a
	Glyt + flum	Glyt + bent	482b	247b	146b	59b
	Glyt + sulf	Glyt + bent	504b	252bc	139b	27a
Xtend						
	Glyt	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + safl	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + flum	Dica + glyt	0a	0a	0a	0a
	Dica + glyt + sulf	Dica + glyt	0a	0a	1a	0a
Liberty	-	-	17a[d]	0a	7a	1a
Roundup	-	-	394b	207b	112b	43b
Xtend	-	-	0a	0a	1a	0a
ANOVA			----------------------*p value*	----------------------		
System			< 0.0001	< 0.0001	< 0.0001	< 0.0001
Herbicide(System)			< 0.0001	< 0.0001	< 0.0001	0.0009

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin , (Sulf) Sulfentrazone, (Gluf) Glufosinate, (Bent) Bentazon.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE + POST herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

Soybean Seed Yield

Herbicide within soybean system was statistically significant at Towner18 and Towner19 as determined by p-values (Table 5.11). Soybean seed yield for all four herbicide treatments within the Liberty system were similar within each of the four locations (Table 5.12).

Glufosinate managed the horseweed well throughout the POST growing season to limit competition between the horseweed and soybean and therefore, effect on yield was limited. In the Roundup system, the addition of saflufenacil within the PRE herbicide treatment increased soybean seed yield at Embden18, Towner18, and Embden19. In the Xtend system, no differences were observed among all four treatments at Embden18, Towner18, and Embden19. When systems averaged across PRE followed by POST herbicide treatments were compared, the Xtend system yield was greater than either the Liberty or Roundup systems at Towner18, Embden19, and Towner19. At Embden18, there was no difference between the Xtend and Liberty systems. No dicamba injury symptoms were observed in any of the non-dicamba-resistant whole plots at either location for both years.

Table 5.12. Main effects of herbicide treatment within system and system on soybean seed yield at four locations in 2018 and 2019.

	Herbicide[a]		2018[b]		2019	
System	PRE	POST	Embden	Towner	Embden	Towner
			----------kg ha^{-1}----------			
Liberty						
	Para	Gluf	1096a[cef]	1190a	716a	1167a
	Para + safl	Gluf	1273a	1337a	734a	1151a
	Para + flum	Gluf	1196a	1378a	840a	1323a
	Para + sulf	Gluf	1232a	1501a	860a	1374a
Roundup						
	Glyt	Glyt + bent	532b	842b	423b	928ab
	Glyt + safl	Glyt + bent	1149a	1704a	844a	1161a
	Glyt + flum	Glyt + bent	509b	1130b	382b	821b
	Glyt + sulf	Glyt + bent	399b	1176b	379b	1173a
Xtend						
	Glyt	Dica + glyt	1356a	1721a	905a	1595a
	Dica + glyt + safl	Dica + glyt	1494a	1633a	1005a	1254b
	Dica + glyt + flum	Dica + glyt	1381a	1883a	1082a	1395ab
	Dica + glyt + sulf	Dica + glyt	1432a	1764a	1092a	1582a
Liberty	-	-	1167a[d]	1352b	788b	1253b
Roundup	-	-	1151b	1213b	507c	1020c
Xtend	-	-	1323a	1750a	1021a	1457a
ANOVA			----------*p value*----------			
System			< 0.0001	< 0.0001	< 0.0001	< 0.0001
Herbicide(System)			0.1524	0.0031	0.0747	0.0267

[a]Abbreviations: (Para) Paraquat, (Glyt) Glyphosate, (Dica) Dicamba, (Safl) Saflufenacil, (Flum) Flumioxazin , (Sulf) Sulfentrazone, (Gluf) Glufosinate, (Bent) Bentazon.
[b]Environment separation was run independently.
[c]Comparison among the four unique PRE + POST herbicide treatments within system.
[d]Comparison among systems averaged across the four unique herbicide treatments.
[e]Weight was calculated to an average moisture of 13%.
[f]Means in each column that do not share the same lowercase letter are significantly different according to Fisher's F protected LSD at α=0.05.

CHAPTER 6. CONCLUSIONS

Greenhouse experiments determined that efficacy of different herbicide technologies does vary by horseweed growth stage (Table 2.3). Herbicide efficacy was greatest when applied to 5- to 7.6-cm-wide horseweed (early rosette) providing a total average control of 70%. For producers, this would be the best time to apply herbicides for effective control. When herbicide was applied to late rosette or bolted horseweed, total average control decreased by 40 and 29%, respectively. Therefore, if producers do not manage horseweed when in the early rosette growth stage, they may not effectively manage the weed and experience crop yield loss. When comparing specific herbicides, 2,4-D, dicamba, halauxifen, saflufenacil, glufosinate, and paraquat all provided greater than 90% control to early rosette horseweed. Control drastically decreased when herbicides were applied to late rosette horseweed. Applications of saflufenacil and paraquat applied at later growth stages initially desiccated aboveground foliage, but failed to kill the plants. About 1 week later, plants that were treated with saflufenacil and paraquat began to regrow new leaf tissue, which then decreased overall control rating at the 3 week evaluation. Late rosette horseweed plants treated with the plant growth regulator (PGR) herbicides 2,4-D, dicamba, and halauxifen all displayed severe stem swelling and malformed tissue development at the shoot apex, but lacked control due to the amount of green leaf tissue remaining 3 weeks after application. These PGR herbicides possibly would have resulted in greater control if subsequent evaluations were performed. In conclusion, it is important for producers to control horseweed in the early rosette growth stage with the selected herbicides stated above in their unique crop platform technology.

Field experiments that evaluated control of horseweed with fall herbicide applications determined that applications of dicamba or paraquat in the fall controlled existing plants, but lacked residual properties to control later emerging winter annual horseweed. As a result, dicamba and paraquat only provided 76 and 64% control the following spring, respectively. When flumioxazin was tank-mixed with dicamba or paraquat, control increased to 99% the following spring. Flumioxazin provided a residual benefit to control later emerging cohorts while dicamba or paraquat controlled existing plants. This demonstrates the importance of including a long residual herbicide along with short residual or contact herbicides in the fall. A sole application of saflufenacil controlled existing plants while also providing a long enough residual duration to control later emerging winter annual horseweed resulting in 99% control the following spring. Due to saflufenacil efficacy, the added benefit of flumioxazin tank-mixed with saflufenacil was not observed. In North Dakota, the majority of observed horseweed population is winter annual. Therefore, if horseweed is controlled in the fall with contact and residual herbicides, fields will be cleaner the following spring.

Field experiments that evaluated the impact of soybean row width on horseweed growth determined that soybean row width had little to no impact on horseweed growth as determined by emergence, height, and biomass (Table 4.4). These results were not similar to previous literature, which determined that row width does influence weed growth. At both locations the horseweed was established in the soil before soybean planting had occurred. This provided horseweed a competitive advantage over the untreated control soybean subplots. The application rates of the two herbicides applied at planting also may not have been appropriate for the evaluation among horseweed and soybean row width. The application of dicamba, when applied at a low rate, killed the majority of the horseweed present and allowed few plants to emerge and grow later in the season. Therefore, few plants were present within those subplots for row width evaluation. The application of paraquat, when applied at a low rate, provided minimal horseweed control and allowed many of the already established plants to flourish and outcompete the soybean resulting in no difference among row widths. A better interpretation of the effect of soybean row width may have occurred if the dicamba was applied at an even lower rate of 140 g ha^{-1} and the paraquat was applied at a higher rate of 560 g ha^{-1}.

Field experiments that evaluated horseweed control with distinct herbicide technology crop systems confirmed that dicamba, applied PRE or POST, provided greater than 97% control and is an effective system for horseweed-infested fields (Table 5.10). Glufosinate is also effective and provided greater than 80% control, but two POST applications in the soybean season are likely needed for adequate control in heavily infested fields. Saflufenacil controlled existing plants, but residual benefits of saflufenacil, flumioxazin, and sulfentrazone were unclear in this experiment. Since the horseweed population was already established at the time of PRE herbicide application, residual benefits from flumioxazin and sulfentrazone were not effective. Further research must be done to investigate residual activity of PRE herbicides applied before horseweed emergence.

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APPENDIX A. SAS CODES

Greenhouse Trial SAS Codes

```
options pageno=1;
data cmbloc;
input stg $ trt run control;
datalines;
;;
ods graphics off;
ods rtf file='cmb_loc_anova.rtf';
proc anova;
class run stg trt;
model control=run stg run*stg trt run*trt stg*trt;
test h=stg e=run*stg;
test h=trt e=run*trt;
means stg/lsd e=run*stg;
means trt/lsd e=run*trt;
means stg*trt/lsd;
title 'Green House 1 Week % Control';
run;
ods rtf close;
```

Fall Trial SAS Codes

```
options pageno=1;
data cmbloc;
input trt rep loc control;
datalines;
;;
ods graphics off;
ods rtf file='cmb_loc_anova.rtf';
proc anova;
class loc rep trt;
model control=loc rep(loc) trt loc*trt;
test h=trt e=loc*trt;
means trt/lsd e=loc*trt;
title '2018 Fall % Control';
run;
ods rtf close;
```

Row Width Trial SAS Codes

```
options pageno=1;
data spplot;
input a  b  rep loc count;
datalines;
;;
ods graphics off;
ods rtf file='split_plot.rtf';
proc anova;
class rep a b loc;
model count=loc rep(loc) a a*loc b b*loc a*b loc*a*b;
test H=a E=loc*a;
test H=b E=loc*b;
test H=a*b E=loc*a*b;
means a/lsd E=loc*a;
means b/lsd E=loc*b;
means a*b/lsd E=loc*a*b;
title 'Row Spacing 3 Week Stand Counts';
run;
ods rtf close;
```

Program Trial SAS Codes

```
options pageno=1;
data nested;
input S $ T rep loc control @@;
datalines;
;;
ods graphics off;
ods rtf file='cmb_sys_anova.rtf';
proc sort;
by loc;
proc anova;
by loc;
class rep T;
model control=rep T;
means T/lsd;
title1'Program 3 Week PRE % Control';
title2'LSD for Treatment Comparison';
run;
proc sort;
by loc;
proc anova;
by loc;
class rep S T;
model control=rep S T(S);
means S/lsd;
title1'Program 3 Week PRE % Control';
title2'LSD for System Comparison';
run;
ods rtf close;
```

APPENDIX B. GREENHOUSE PICTURES OF LATE ROSETTE HORSEWEED 3 WEEKS AFTER HERBICIDE APPLICATION

Control

Dicamba

Glufosinate

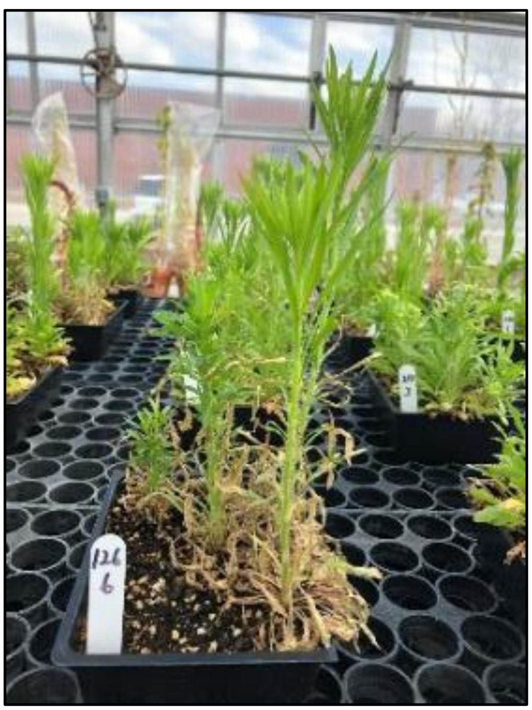
Saflufenacil

APPENDIX C. GREENHOUSE PICTURES OF BOLTED HORSEWEED 3 WEEKS AFTER HERBICIDE APPLICATION

Control

Dicamba

Glufosinate



Saflufenacil

APPENDIX D. FIELD PICTURES OF THE LIBERTY, ROUNDUP, AND DICAMBA SYSTEMS 7 WEEKS AFTER POST APPLICATION

Para + safl fb gluf

Glyt + safl fb glyt + bent

Dica + safl fb dica + glyt

APPENDIX E. FIELD PICTURES OF THE ROUNDUP SYSTEM 7 WEEKS AFTER POST APPLICATION

Glyt fb glyt + bent

Glyt + safl fb glyt + bent

Glyt + flum fb glyt + bent

Glyt + sulf fb glyt + bent