Influence of Water Quality on Glyphosate Performance and Evaluation of Enlist™ Weed Control Systems in Texas High Plains Cotton

by

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DEDICATION

To Tucker (Rufus, June Bug, Stink, and Monkey). If it wasn't for our adventures, I never would have finished this. Thank you for taking such good care of me, for teaching me how to love so big, and for bringing me Seth. What a gift.

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CHAPTER I

LITERATURE REVIEW

The history of weed control is co-existent with the history of agricultural technology as humans have been battling weeds since they first started cultivating crops 10,000 years ago (Bell 2015). Effective and economical weed management is crucial to a profitable cropping system. Weeds compete with crops for water, nutrients, light, and space (Aldrich 1987; Spitters and Aerts 1983). Weeds also contribute to decreases in crop yields, crop quality, and harvest efficiency, and can harbor insects and pathogens.

Weeds were first managed with physical/mechanical and cultural strategies and more recently with herbicides. Hildebrand (1946) discussed early herbicide developments in the mid 1800s. Becker (1840) reported that lime was recommended for control of horsetail (*Equisetum* spp.) and the use of salt (sodium chloride) as a herbicide was recommended in Germany in 1854 (Meyn 1854). Around the same time, significant progress was made in biological control of weeds (Timmons 2005). The insect *Cactoblastis cactorum*, which was introduced to Australia from Argentina (Dodd 1927; Miller 1936), eliminated over 24 million hectacres of prickly pear cactus (*Opuntia* spp.) from 1926 to 1940 (Dodd 1940).

The development of new weed management strategies continued to progress steadily; however, the discovery of the phenoxyacetic herbicides in Britain and the United States during 1942 and 1944 (Blackman 1948; Hamner and Tukey 1944; Mitchell and Hamner 1944) marked the real beginning of the “Chemical Era of Agriculture”. The phenoxyacetic herbicides transformed agriculture by selectively controlling many weeds with small and relatively inexpensive quantities and are considered to be amongst the greatest scientific discoveries of the twentieth century (Fryer 1980).

The use of herbicides in cotton began in the 1950s with petroleum fractions called naphthas to control young grasses and broadleaf weeds postemergence (POST) (Holstun and McWhorter 1965). However, the use of naphthas quickly declined as more effective, inexpensive, and selective herbicides were developed at the end of the 1950s and 1960s. Chlorpropham, diuron, and dalapon were developed in the 1950s, which allowed for selective control of broadleaf weeds in cotton. However, these herbicides were still moderate to highly phytotoxic to cotton and did not gain widespread acceptance (Reed 2012).

In 1963, trifluralin, a dinitroaniline herbicide, was introduced and rapidly accepted. In cotton, trifluralin may be applied preplant incorporated (PPI) to selectively control annual grass and small-seeded broadleaf weeds. Mono-sodium methyl arsenic acid (MSMA) also was developed during this time, which allowed for POST control of annual grasses, johnsongrass (*Sorghum halepense* (L.) Pers.), and nutsedge (*Cyperus* spp.) with minimal crop injury. A number of other herbicides were introduced during the 1960s that were of great economic benefit to cotton producers including, linuron, fluometuron, prometryn, and paraquat (Buchanan 1992).

In 1974, glyphosate, a non-selective herbicide that provides excellent control of a vast number of weeds, was introduced. Glyphosate was used for preplant burndown, POST-directed, and "spot" treatments in cotton throughout the 1980s. Few POST herbicide options were available to selectively control broadleaf weeds in cotton until the introduction of pyrithiobac in 1993. Pyrithiobac was a significant improvement over previous technologies because it controlled broadleaf weeds POST over-the-top in cotton with little or no injury to the crop (Jordan et al. 1993; Keeling et al. 1993).

Effective and economical weed control is crucial to a profitable cotton production system. Weeds decrease cotton lint yield and quality by competing for nutrients, water, and light (Stuart et al. 1984). In 2007, the release and wide adoption of glyphosate tolerant cotton changed weed management systems in cotton. Glyphosate tolerant cotton systems provided growers with broad-spectrum weed control and flexibility in application timings (Norsworthy et al. 2007). Other benefits included reduced time and labor inputs, less reliance on tillage, reduced herbicide costs, and less complicated weed management systems compared with previous weed control practices (Bradley et al. 2004; CTIC 2004; Johnson et al. 2000; Reddy and Whiting 2000).

Traditionally, weed management in cotton relied on a combination of soil applied herbicides, cultivation, and POST-directed herbicides (Wilcut et al. 1996). Trifluralin and fluometuron were applied to over 50 and 25% of treated cotton hectares from 1992 to 1999. However, glyphosate use started to increase rapidly in 1998, a year after the introduction of glyphosate tolerant cotton. By 2000, glyphosate had replaced trifluralin as the herbicide applied to the greatest percentage of cotton hectares (Young 2006).

A survey conducted in the spring of 2006 indicated that approximately two-thirds of cotton producers in the southern United States had planted glyphosate tolerant cotton continuously for three to five years (Foresman and Glasgow 2008). Of the cotton producers surveyed, 21% applied glyphosate alone, 21% applied glyphosate in a tank mixture, and 52% applied glyphosate after a preemergence (PRE) herbicide. This increase in glyphosate use placed an extreme selection pressure for glyphosate resistance on Palmer amaranth (*Amaranthus palmeri* S. Wats.) populations and other weeds frequently found in cotton cropping systems (Neve et al. 2011).

Palmer amaranth was ranked as the most troublesome cotton weed in the southern United States in 2009, occurring in nine of 10 states surveyed (Webster and Nichols 2012). Cotton yield loss due to Palmer amaranth competition has been well-documented and ranges between 6 and 65% depending on the date of emergence and its subsequent density levels (MacRae et al. 2008; Morgan et al. 2001; Rowland et al. 1999; Smith et al. 2000). Palmer amaranth also is among the most difficult-to-control weeds in Texas. In 1996 and 1997, Morgan et al. (2001) reported that cotton lint yield decreased from 13 to 54% for 1 to 10 Palmer amaranth plants per 9.1 m of row, respectively.

Palmer amaranth is an erect, branched summer annual broadleaf weed capable of reaching 2 m in height. Rapid erect growth, a deep root system, high water use efficiency (Davis et al. 1964), and allelopathic potential (Menges 1987, 1988) enable Palmer amaranth to compete effectively with crops for light, water, space, and nutrients. Large Palmer amaranth plants also can clog harvest equipment, which reduces harvest efficiency (Reed et al. 2014).

Today, Palmer amaranth management is more complicated than ever before as it has become one of the most economically damaging glyphosate-resistant weed species in the United States (Beckie 2006). Glyphosate resistant Palmer amaranth was first confirmed in Georgia in 2004 (Culpepper et al. 2006) and subsequently reported in Arkansas, North and South Carolina, and Tennessee (Norsworthy et al. 2008; Scott et al. 2007; Steckel et al. 2008; York et al. 2007). It is now widespread across the South and is spreading rapidly.

Glyphosate resistant Palmer amaranth was confirmed on the Texas High Plains in 2011 (Heap 2016a). Since then, resistant Palmer amaranth biotypes have increased and spread dramatically throughout the region, causing cotton growers to change their management inputs in order to maintain sustainable cotton production systems. Growers who are successfully controlling weeds including glyphosate resistant Palmer amaranth are using a systems-based approach that involves starting clean, multiple application timings, multiple herbicide modes of action, and the addition of soil residual herbicides as well as the incorporation of mechanical, cultural, and biological methods where appropriate.

The number of tools to combat glyphosate resistant Palmer amaranth and other difficult-to-control weeds in Texas High Plains cotton may increase as early as the 2016 growing season with the release of auxin tolerant cotton (XtendFlex® and Enlist™ systems). Bollgard II® XtendFlex® cotton is a triple-stack variety from Monsanto with tolerance to dicamba, glyphosate, and glufosinate. Enlist™ technology developed by Dow AgroSciences will have tolerance to 2,4-D choline, glyphosate, and glufosinate. For the 2016 growing season, All-Tex®, Americot®, Cropland Genetics®, Deltapine®, Dyna-Gro®, and NextGen® will feature the XtendFlex® technology while Phytogen® will have the only Enlist™ variety.

Understanding how to maximize the use of these technologies will not only improve weed control and cotton yields, but also may reduce selection pressure for resistant weeds. Currently, 32 weeds are confirmed resistant to herbicides in the synthetic auxin family (Heap 2016b). The quality of water used as the spray carrier, tank-mix combinations, weed size at the time of application, and tank cleanout are four factors among many others that will impact the success of these new auxin tolerant systems.

The quality of water used as the spray carrier can play an important role in herbicide performance, especially for weak acid herbicides such as glyphosate. The XtendFlex® and Enlist™ systems will offer a premixes of dicamba or 2,4-D choline plus glyphosate, respectively. Glyphosate antagonism caused by hard water (water containing cations) has been well-documented in a number of weed species. Cations that create complexes with glyphosate and ultimately decrease its effectiveness include aluminum, calcium, iron, magnesium, potassium, and zinc (Aliverdi et al. 2014; Bailey et al. 2002; Bernards et al. 2005; Buhler and Burnside 1983a; Chahal et al. 2012; Gauvrit 2003; Mueller 2006; Nalewaja and Matysiak 1991; Scroggs et al. 2009; Stahlman and Phillips 1979; Thelen et al. 1995).

Overcoming hard water antagonism of glyphosate often can be achieved by increasing the glyphosate rate, decreasing the carrier volume (Buhler and Burnside 1983a; Nalewaja and Matysiak 1993; O'Sullivan 1981; Ramsdale et al. 2003; Sandberg 1978; Stahlman and Phillips 1979), acidifying the spray solution (Buhler and Burnside 1983b; Nalewaja and Matysiak 1991), and/or adding a stronger chelator or water conditioner (Aliverdi et al. 2014; Gauvrit 2003; Nalewaja and Matysiak 1991, 1992, 1993; O'Sullivan et al. 1981; Shea and Tupy 1984; Thelen et al. 1995). Some growers in the Texas High Plains use reverse osmosis (RO) water as a spray carrier to prevent potential antagonism of glyphosate due to poor water quality. However, no data supporting the benefit of using RO water as the carrier has been documented.

The addition of 2,4-D or dicamba to exisiting weed management systems will likely improve overall weed control. In dicamba resistant cotton in North Carolina, greater Palmer amaranth control and cotton yields were obtained with dicamba applied early postemergence (EPOST), mid-postemergence (MPOST), or EPOST fb MPOST compared with standard herbicides in glyphosate based systems (Cahoon et al. 2015). Inman et al. (2016) also observed increased weed control with the addition of dicamba in glyphosate systems. Out of five treatments, they found that the lowest population of Palmer amaranth was observed when glyphosate + dicamba was applied regardless of PRE herbicides or inclusion of acetochlor POST.

While comparing 2,4-D, glyphosate, and glufosinate systems in Georgia cotton, Merchant et al. (2014) found that Palmer amaranth was controlled 98 to 99% at harvest when a PRE herbicide was followed by sequential applications of 2,4-D + glufosinate, and Palmer amaranth was controlled 95 to 96% following sequential applications of 2,4-D + glyphosate. In Missouri soybean, Craigmyle et al. (2014) found that the addition of 2,4-D to POST applications of glufosinate improved control of common waterhemp (*Amaranthus rudis* Sauer) and common cocklebur (*Xanthium strumarium* L.) up to 6 and 11%, respectively.

In addition to Palmer amaranth, Russian-thistle (*Salsola tragus* L.) and kochia (*Kochia scoparia* L.) also are difficult-to-control weeds in Texas High Plains cotton. Russian-thistle, an annual broadleaf weed that is prevalent in the western United States, is extremely competitive due in part to its aggressive root system (Young 1988; Pan et al. 2001). The competitiveness of kochia, a troublesome summer annual broadleaf weed in croplands and noncroplands over the Great Plains of North America, is attributed to its early seedling emergence, C_4 photosynthesis, rapid growth rate, heat and salt tolerance, prolific seed production (greater than 50,000 seeds plant^{-1}), and long distance seed dispersal by tumbling (Baker et al. 2010; Christoffoleti et al. 1997; Eberlein and Fore 1984; Forcella 1985; Friesen et al. 2009; Schwinghamer and Van Acker 2008; Wicks et al. 1994).

Although auxin tolerant cotton systems will provide growers with a new tool to manage weeds, it is still critical to make timely applications with these new systems. Everitt and Keeling (2007) found that dicamba rates of 0.14 and 0.28 kg ae ha^{-1} controlled 3 to 8 cm horseweed at least 93% 28 DAT. However, reduced control was observed with these same rates when applied to 10 to 15 and 25 to 46 cm horseweed. A similar response was observed when using 2,4-D (Everitt and Keeling 2007). In the XtendFlex® system, it will be recommended that applicators apply dicamba to broadleaf weeds before they reach 10 cm in height (Anonymous 2016a) while the Enlist system will suggests that applicators apply 2,4-D choline + glyphosate (Enlist Duo®) to actively growing weeds that are 7.5 to 15 cm in height (Anonymous 2016b).

The effect of weed size on 2,4-D also has been reported with other weed species such as red morningglory (*Ipomoea coccinea* L.) and dogfennel [*Eupatorium capillifolium* (Lam.) Small] (Sellers et al. 2009; Siebert et al. 2004). Siebert et al. (2004) observed 100% control of 30 cm red morningglory; however, a 6 to 19% reduction in control was observed when 2,4-D was applied to 60 cm plants. Dogfennel control was reduced from 85 to 70% to 6% when applications of 2,4-D and dicamba were applied to plants 36, 72, and 154 cm in height, respectively (Sellers et al. 2009).

Water carrier, weed management system, and weed size are not the only factors that should be considered when making an auxin application. Two other challenges that will exist with these new systems are the risk of drift and spray tank contamination to non-auxin tolerant cotton and other sensitive crops and/or vegetation. Risk of drift and spray tank contamination of dicamba and 2,4-D in cotton is already a major concern in areas where grain crops, leguminous crops such as alfalfa and peanut, and pastureland are grown near where cotton is produced.

Multiple studies have reported the extreme sensitivity of cotton that is not tolerant to dicamba and 2,4-D (Byrd 2015; Everitt and Keeling 2009; Johnson et al. 2012; Marple et al. 2007, 2008). Byrd (2015) observed injury greater than 50% when 2,4-D amine rates of 2 and 40 g ae ha^{-1} were applied to four leaf and nine leaf cotton. As cotton matured beyond the two weeks after first bloom stage, visual injury from the 2 and 40 g ha^{-1} rates was less than 10% and 25%, respectively. Yield loss greater than 20% was observed at 5 of 12 locations when 2 g ha^{-1} of 2,4-D was applied to cotton between four leaf and two weeks after first bloom. At 40 g ha^{-1} averaged over 12 locations, yield was 45, 58, 66, 45, 16, and 7% less than the nontreated control when applied at four leaf, nine leaf, first bloom, two weeks after first bloom, four weeks after first bloom, and six weeks after first bloom, respectively.

Marple et al. (2008) observed greater 2,4-D amine and dicamba injury when herbicides were applied at the three to four leaf stage compared with the 8, 14, and 18-node stages. For three to four leaf cotton 28 DAT, 61 and 76% injury was observed for 2,4-D amine simulated drift rates of 1.4 and 2.8 g ae ha^{-1}, respectively. For cotton sprayed with dicamba at rates of 1.4 and 2.8 g ae ha^{-1}, 15 and 28% injury was observed. No adverse yield effects were observed except when 2,4-D was applied at the 2.8 g ha^{-1} rate at the three to four leaf growth stage.

Everitt and Keeling (2009) observed that simulated drift rates of 2,4-D amine as low as 2.8 g ae ha^{-1} applied at the cotyledon to two leaf stage injured cotton 50% 14 DAT, and injury increased to greater than 90% with 280 g ae ha^{-1}. The simulated drift rate of 2.8 g ha^{-1} had little effect on yield reduction (less than 10%) across application timing; however, yield reductions of 61 to 97% were observed after 280 g ha^{-1} was applied.

In another study, Johnson et al. (2012) observed 36 to 90% visual injury two weeks after treatment when 20 to 30 cm cotton was sprayed with 2,4-D amine simulated drift rates of 1, 5, 20, 78, and 269 g ae ha^{-1}. For the three greatest rates, seed cotton yield loss occurred. For dicamba, visual injury ranged from 47 to 75% when sprayed with simulated drift rates of 0.6, 3, 11, 41, and 140 and yield loss occurred at 41 and 140 g ha^{-1}.

In order to minimize the risk of drift while using these new technologies, applicators will be required to use appropriate nozzle and pressure combinations, only tank-mix with permissible tank-mix partners, spray when temperature, relative humidity, wind speed, and wind direction are suitable, and respect buffer zone requirements and sensitive habitats. The current Enlist Duo® label in corn and soybean includes a chart of the acceptable nozzle pressure combinations and instructs applicators to use the minimum boom height based upon the nozzle manufacturer's directions (Anonymous 2016b). A spray volume of 94 to 104 L ha^{-1} is recommended and applicators are instructed to only apply Enlist Duo® herbicide when winds are less than 24 km per hour. Applicators must also maintain a 9 m downwind buffer from any area except roads, planted agricultural fields (planted or prepared for planting), or areas covered by the footprint of a building. Permissible tank-mix partners can be found at EnlistTankmix.com.

One herbicide that will be labeled for XtendFlex® crops is the product M1691, a diglycolamine salt formuation of dicamba developed by Monsanto. The proposed label instructs applicators to only use the TTI11004 nozzle (TeeJet® Technologies, Glendale Heights, IL), use a spray volume ranging from 94 to 104 L ha^{-1}, and not exceed a ground speed of 24 km per hour (Anonymous 2016a). A boom height of 61 cm should not be exceeded and a 30 m buffer or 67 m buffer needs to be maintained from all outer edges of the field when applying 0.56 or 1.12 kg ae ha^{-1}, respectively. No tank-mix partners are permitted on this label. To avoid tank contamination of either product, a triple rinse is suggested. Further information for Enlist™ and XtendFlex® systems can be found on herbicide labels and industry websites.

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CHAPTER II

INFLUENCE OF WATER QUALITY AND AMMONIUM SULFATE ON GLYPHOSATE EFFICACY

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The effects of water quality and ammonium sulfate on glyphosate efficacy were assessed in six field trials near Lubbock, TX in 2012 and 2013. The objectives of these trials were to 1) determine if glyphosate efficacy is affected by water carrier source, 2) determine if there is a benefit using reverse osmosis water as the carrier, and 3) determine if the addition of ammonium sulfate will improve glyphosate control when water quality

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is poor. Overall, water source affected glyphosate control in three of the six trials when evaluated 21 DAT. The RO water source (11 ppm) was the top performing water source at 21 DAT for 30 cm wheat in 2013; however, in the same year, it controlled 20 cm winter wheat similar to the poorest water quality source. For 61 cm Palmer amaranth in 2012, the RO water source (11 ppm) was similar to the top performing water sources. Additionally, an increase in glyphosate rate and the addition of AMS increased weed control for all six trials.

Nomenclature: Glyphosate.

Key words: Reverse osmosis, hard water, antagonism, cations.

INTRODUCTION

The quality of water used as the spray carrier can play an important role in herbicide performance, especially for weak acid herbicides such as glyphosate. Glyphosate antagonism caused by hard water (water containing cations) has been well-documented in a number of weed species. Cations that create complexes with glyphosate and ultimately decrease its effectiveness include aluminum, calcium, iron, magnesium, potassium, and zinc (Aliverdi et al. 2014; Bailey et al. 2002; Bernards et al. 2005; Buhler and Burnside 1983a; Chahal et al. 2012; Gauvrit 2003; Mueller 2006; Nalewaja and Matysiak 1991; Scroggs et al. 2009; Stahlman and Phillips 1979; Thelen et al. 1995).

Overcoming hard water antagonism of glyphosate often can be achieved by increasing the glyphosate rate, decreasing carrier volume (Buhler and Burnside 1983a; Nalewaja and Matysiak 1993; O'Sullivan 1981; Ramsdale et al. 2003; Sandberg 1978; Stahlman and Phillips 1979), acidifying the spray solution (Buhler and Burnside 1983b; Nalewaja and Matysiak 1991), and/or adding a stronger chelator or water conditioner (Aliverdi et al. 2014; Gauvrit 2003; Nalewaja and Matysiak 1991, 1992, 1993; O'Sullivan et al. 1981; Shea and Tupy 1984; Thelen et al. 1995).

Some growers in the Texas High Plains use reverse osmosis (RO) water as a spray carrier to prevent potential antagonism of glyphosate due to poor water quality. However, no data supporting the benefit of using RO water as the carrier has been documented. To better understand the relationship between water quality and glyphosate efficacy in the semi-arid Texas Southern High Plains, research was conducted to: 1) determine if glyphosate efficacy is affected by water carrier source, 2) determine if there is a benefit using RO water as the carrier, and 3) determine if the addition of ammonium sulfate will improve glyphosate control when water quality is poor.

MATERIALS AND METHODS

In the fall of 2011, 23 water sources were collected from wells in 14 counties in the Texas Southern High Plains. Water sources were stored in the dark at room temperature. All water sources were analyzed by A&L Plains Agricultural Laboratories of Lubbock, which included parts per million (ppm) concentrations of calcium, magnesium, sodium, manganese, iron, and zinc. From these 23 sources, five water sources ranging in cation concentrations of 185 to 1,046 ppm were selected and used as water carriers in six field trials conducted in 2012 and 2013 at the Texas A&M AgriLife Research and Extension Center (33.4151319°N, -101.483274°W, 1,001 m elevation) in Lubbock, TX (Table 2.1).

Four studies were conducted in 2012, where two studies utilized winter wheat (*Triticum aestivum* L.) and two studies utilized Palmer amaranth (*Amaranthus palmeri* S. Wats.) as the test species. Two additional winter wheat studies were conducted in 2013. For winter wheat trials, 'TAM 111' (Lazar et al. 2004) was planted with a standard Tye grain drill with 25 cm centers on September 9, 2011 and on September 19, 2012 at a density of 56 kg ha^{-1}. Natural populations of glyphosate-susceptible Palmer amaranth were used from non-crop, rainfed areas that contained emergence densities estimated at 100 plants m^{2}. The soil type was an Amarillo fine sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs). All studies were arranged in a randomized complete block design with four replications. Each replication was 21.3 by 24.4 m and each plot was 3.0 by 6.1 m. Annual rainfall in 2012 was 290 mm while rainfall in 2013 was 320 mm (National Weather Service, Lubbock, TX Weather Forecast Office, 2579 S. Loop 280 Lubbock, TX 79423).

The five pre-selected water sources ranging in total water hardness from 185 to 1,046 ppm plus a reverse osmosis (RO) water source (11 ppm) were used as carriers for the following four herbicide treatments: glyphosate (Roundup PowerMAX® herbicide, Monsanto Company, St. Louis, MO) applied at 0.43 or 0.86 kg ae ha^{-1} with and without dry ammonium sulfate (AMS) at 2.04 kg 100 L^{-1}. All applications were made at 4.8 km per hour with a CO_2-pressurized backpack sprayer equipped with TT110015 spray tips (TeeJet® Technologies, Glendale Heights, IL) calibrated to deliver 94 L ha^{-1} at 165 kPa. The nontreated control did not receive a herbicide application. Visual control estimates were recorded 14, 21, and 28 days after treatment using a scale of 0 to 100 percent, where 0 was no control and 100 was complete control (Frans et al. 1986). Foliar chlorosis, necrosis, tissue distortion, and plant stunting were considered when making visual estimates.

A univariate analysis was performed on all responses in order to test for stable variance (Version 9.3, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513). No data sets were transformed as transformation did not increase stabilization. Data sets were analyzed using PROC MIXED with the pdmix 800 macro described by Saxton (1998) and treatments were separated by Fisher's Protected LSD at an alpha level of $P < 0.05$.

RESULTS AND DISCUSSION

Two winter wheat trials were conducted in 2012 (trials one and two) and two were conducted in 2013 (trials three and four). Two Palmer amaranth trials also were conducted in 2012 (trials five and six). All trials were analyzed independently. No three way-interactions were significant; however, there was a glyphosate rate by AMS interaction for trial one at the 14 DAT assessment and for trial three at the 14 and 21 DAT assessments. For all other assessments, main effects were evaluated.

2012 – Trial 1 (15 cm winter wheat). Winter wheat control following glyphosate treatments ranged from 54 to 67% 14 DAT (Table 2.2). Winter wheat was controlled 67% when the Lubbock (185 ppm) and Dawson (519 ppm) water sources were used as carriers and 54 to 56% control was observed when the Garza I (804 ppm) and Garza II (1046 ppm) water sources were used as carriers. A glyphosate rate by AMS interaction was present. For the greater glyphosate rate, the addition of AMS improved winter wheat control from 71 to 81% (Table 2.3). While at the reduced glyphosate rate, the addition of AMS improved winter wheat control from 35 to 59%. At 21 DAT, winter wheat control following glyphosate treatments ranged from 75 to 80% and was similar for all water sources (Table 2.2). The greater glyphosate rate and the addition of AMS improved control from 66 to 90% and from 72 to 85%, respectively (Tables 2.4 and 2.5).

2012 – Trials 2 (20 cm winter wheat). Winter wheat control following glyphosate treatments ranged from 28 to 31% 14 DAT and from 42 to 46% 21 DAT, but was similar for all water sources (Table 2.2). A glyphosate rate by AMS interaction was present at 14 and 21 DAT (Table 2.3). For the low glyphosate rate, the addition of AMS improved winter wheat control from 39 to 63% 14 DAT; however, at the greater glyphosate rate, the addition of AMS did not improve winter wheat control. At 21 DAT, winter wheat control following glyphosate treatments ranged from 42 to 46% and was similar for all water sources (Table 2.2). The addition of AMS improved control for the low glyphosate rate from 48 to 73% and improved control for the greater glyphosate rate from 82 to 95%.

2013 – Trial 3 (20 cm winter wheat). Winter wheat control following glyphosate treatments ranged from 57 to 67% and was similar for all water sources 14 DAT (Table 2.2). The greater rate of glyphosate and the addition of AMS improved control from 51 to 74% and from 56 to 70%, respectively (Tables 2.4 and 2.5). At 21 DAT, winter wheat was controlled 68 to 80% (Table 2.2). Winter wheat control ranged from 75 to 80% and was similar with the exception of the RO (11 ppm) and Garza II (1046 ppm) water sources, which was less effective at controlling winter wheat (68 to 70%). The greater glyphosate rate and the addition of AMS improved control from 60 to 89% and from 65 to 84%, respectively (Tables 2.4 and 2.5).

2013 – Trial 4 (30 cm winter wheat). At 14 DAT, the greatest winter wheat control (52 to 61%) was observed for the RO (11 ppm), Garza I (804 ppm), and Reeves (839 ppm) water sources while control was less and similar (42%) for all other water sources (Table 2.2). The greater glyphosate rate and the addition of AMS improved winter wheat control from 29 to 68% and from 40 to 57%, respectively (Tables 2.4 and 2.5). At 21 DAT, water source, glyphosate rate, and AMS affected control (Tables 2.2, 2.4, and 2.5). Winter wheat control ranged from 44 to 71% for all water sources. The RO water source (11 ppm) controlled winter wheat the greatest (71%) while control using all other water sources was less than 60%. The greater glyphosate rate and the addition of AMS improved control from 30 to 78% and from 44 and 64%, respectively.

2012 – Trial 5 (61 cm Palmer amaranth). Water source, glyphosate rate, and the addition of AMS affected Palmer amaranth control when evaluated 14 and 21 DAT (Tables 2.6, 2.7, and 2.8). At 14 DAT, Palmer amaranth was controlled 85 to 90% when RO, Lubbock, Dawson, and Reeves water sources (11, 185, 519, and 839 ppm, respectively) were used as carriers and the least control (77%) was observed when the Garza I water source (804 ppm) was used as the carrier. At 21 DAT, all water sources controlled Palmer amaranth at least 86% except for the Garza water sources (804 and 1046 ppm), which controlled Palmer amaranth 78 to 83%. The greater glyphosate rate and the addition of AMS improved control from 75 to 94% and from 77 to 92%, respectively, at 14 DAT and from 75 to 96% and from 78 to 93%, respectively, at 21 DAT.

2012 – Trial 6 (104 cm Palmer amaranth). Water source, glyphosate rate, and the addition of AMS affected the control of Palmer amaranth 14 DAT (Tables 2.6, 2.7, and 2.8). Palmer amaranth was controlled 37% with the RO and Lubbock water sources (11 and 185 ppm, respectively), while all other water sources provided less than 30% control. At 14 DAT, the greater glyphosate rate improved control from 12 to 45%, while the addition of AMS improved control from 23 to 33%. At 21 DAT, Palmer amaranth control following all water sources was similar (32 to 44%), while the increased glyphosate rate and addition of AMS positively affected control (Tables 2.6, 2.7, and 2.8). The greater glyphosate rate and the addition of AMS improved control from 24 to 54% and from 34 to 44%, respectively.

Overall, water source affected glyphosate control in three of the six trials when evaluated 21 DAT. The RO water source (11 ppm) was the top performing water source at 21 DAT for 30 cm wheat in 2013; however, in the same year, it controlled 20 cm winter wheat similar to the poorest water quality source. For 61 cm Palmer amaranth in 2012, the RO water source (11 ppm) was among the top performing water sources 21 DAT. Chahal et al. (2012) observed that Palmer amaranth control by glyphosate was not affected when glyphosate was applied at 0.95 kg ae ha^{-1} in different water sources compared with glyphosate applied in deionized water; however, hardness values for water sources used in the study did not exceed 440 ppm.

As expected, an increase in glyphosate rate increased weed control for all six trials 21 DAT. The greater glyphosate rate used in this study reflects a rate that was recommended during the initial design of this trial while the lower rate was included in order to observe the effects of water quality on glyphosate efficacy. Today, these rates might be considered low depending on one's target cropping system and weed specie(s). Using labeled glyphosate rates is important for herbicide resistance management and from the standpoint of water quality. A similar study using greater glyphosate rates would compliment this work.

The addition of AMS also increased weed control for all six trials. When studying the effects of water conditioners on glyphosate and imazethapyr activity, Aliverdi et al. (2014) found that AMS was the most effective additive. Gauvrit (2003) also observed that AMS restored the foliar uptake of glyphosate when calcium ions were present in solution at concentrations of 100 to 400 ppm. Ammonium sulfate is often used in glyphosate applications because the sulfate anion is thought to compete with glyphosate for the antagonistic cations, thus deterring the formation of glyphosate cation complexes (Thelen et al. 1995). Nalewaja and Matysiak (1991) suggest that the addition of AMS also may enhance glyphosate efficacy in the absence of antagonistic salts (Nalewaja and Matysiak 1991). Enhanced glyphosate efficacy in the absence of salts was observed in this study as the addition of AMS increased winter wheat and Palmer amaranth control for all water sources evaluated including the RO source (11 ppm).

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Table 2.1. Cation concentration and total water hardness of five selected water sources used to evaluate glyphosate efficacy.[a]

	Cations						
Water source	Ca^{2+}	Mg^{2+}	Na^{+}	Mn^{2+}	Fe^{2+}	Zn^{2+}	Total water hardness
	ppm						
RO	< 0.01	< 0.01	11	< 0.01	< 0.01	< 0.01	11
Lubbock	54	63	68	< 0.01	< 0.01	0.04	185
Dawson	150	197	171	< 0.01	0.78	0.02	519
Garza I	144	180	480	0.02	0.05	0.06	804
Reeves	118	35	686	< 0.01	< 0.01	0.03	839
Garza II	160	229	656	0.04	0.46	0.01	1046

[a]Abbreviations: ppm, parts per million; RO, reverse osmosis.

Table 2.2. Effects of water source on winter wheat control in 2012 and 2013 near Lubbock, TX.[a]

Water source (total water hardness)	2012 (15 cm) 1	2012 (15 cm) 2	2012 (20 cm) 1	2012 (20 cm) 2	2013 (20 cm) 1	2013 (20 cm) 2	2013 (30 cm) 1	2013 (30 cm) 2
	4 DAT[b]	1 DAT	4 DAT	1 DAT	4 DAT	1 DAT	4 DAT	1 DAT
	---- % ----							
RO (11 ppm)	63 ab	80	31	42	60	68 b	61 a	71 a
Lubbock (185 ppm)	67 a	80	28	46	65	80 a	42 b	52 bc
Dawson (519 ppm)	67 a	79	28	42	67	76 a	42 b	44 c
Garza I (804 ppm)	54 b	76	29	46	65	77 a	52 a	52 bc
Reeves (839 ppm)	62 ab	80	30	45	63	75 a	57 a	58 b
Garza II (1046 ppm)	56 b	75	30	46	57	70 b	42 b	46 c

[a]Abbreviations: ppm, parts per million; DAT, days after treatment.

[b]Water source means pooled over glyphosate rate and ammonium sulfate for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other ($P < 0.05$).

Table 2.3. Effects of glyphosate rate and ammonium sulfate on winter wheat control in 2012 and 2013 near Lubbock, TX.

		2012 (15 cm)	2013 (20 cm)	
Glyphosate rate	AMS rate	14 DAT[b]	14 DAT	21 DAT
kg ae ha^{-1}	kg 100 L^{-1}	----------------------------------	%	----------------------------------
0.43	0	35 d	39 c	48 c
0.43	2.04	59 c	63 b	73 b
0.86	0	71 b	72 ab	82 b
0.86	2.04	81 a	77 a	95 a

[a]Abbreviations: AMS, ammonium sulfate; DAT, days after treatment.

[b]Glyphosate and ammonium sulfate means pooled over water source for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other ($P < 0.05$).

Table 2.4. Effects of glyphosate rate on winter wheat control in 2012 and 2013 near Lubbock, TX.[a]

Glyphosate rate	2012 (15 cm)	2013 (20 cm)		2013 (30 cm)	
	21 DAT	14 DAT	21 DAT	14 DAT	21 DAT
kg ae ha^{-1}	----------	----------	%	----------	----------
0.43	66 b	51 b	60 b	29 b	30 b
0.86	90 a	74 a	89 a	68 a	78 a

[a]Abbreviations: DAT, days after treatment.

[b]Glyphosate rate means pooled over water source and ammonium sulfate for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other (P < 0.05).

Table 2.5. Effects of ammonium sulfate on winter wheat control in 2012 and 2013 near Lubbock, TX.[a]

AMS rate	2012 (15 cm)	2013 (20 cm)		2013 (30 cm)	
	21 DAT	14 DAT	21 DAT	14 DAT	21 DAT
kg 100 L^{-1}	---------------	---------------	%	---------------	---------------
0	72 b	56 b	65 b	40 b	44 b
2.04	85 a	70 a	84 a	57 a	64 a

[a]Abbreviations: AMS, ammonium sulfate; DAT, days after treatment.

[b]Ammonium sulfate means pooled over water source and glyphosate rate for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other (P < 0.05).

Table 2.6. Effects of water source on Palmer amaranth control in 2012 and 2013 near Lubbock, TX.[a]

Water source (total water hardness)	2012 (61 cm)		2013 (104 cm)	
	14 DAT[b]	21 DAT	14 DAT	21 DAT
	--- % --------------------------------------- ---------			
RO (11 ppm)	86 ab	90 a	37 a	42
Lubbock (185 ppm)	89 ab	88 ab	37 a	44
Dawson (519 ppm)	90 a	88 ab	21 b	33
Garza I (804 ppm)	77 c	78 c	24 b	32
Reeves (839 ppm)	85 ab	86 ab	28 ab	38
Garza II (1046 ppm)	80 bc	83 bc	23 b	44

[a]Abbreviations: ppm, parts per million; DAT, days after treatment.

[b]Water source means pooled over glyphosate rate and ammonium sulfate for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other ($P < 0.05$).

Table 2.7. Effects of glyphosate rate on Palmer amaranth control in 2012 and 2013 near Lubbock, TX.[a]

Glyphosate rate	2012 (61 cm)		2013 (104 cm)	
	14 DAT[b]	21 DAT	14 DAT	21 DAT
kg ae ha^{-1}	-- % --------------------------------------			
0.43	75 b	75 b	12 b	24 b
0.86	94 a	96 a	45 a	54 a

[a]Abbreviations: DAT, days after treatment.

[b]Glyphosate rate means pooled over water source and ammonium sulfate for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other (P < 0.05).

Table 2.8. Effects of ammonium sulfate on Palmer amaranth control in 2012 and 2013 near Lubbock, TX.[a]

	2012 (61 cm)		2013 (104 cm)	
AMS rate	14 DAT[b]	21 DAT	14 DAT	21 DAT
kg 100 L^{-1}	--- % --			
0	77 b	78 b	23 b	34 b
2.04	92 a	93 a	33 a	44 a

[a]Abbreviations: AMS, ammonium sulfate; DAT, days after treatment.

[b]Ammonium sulfate means pooled over water source and glyphosate rate for each observation date followed by the same lower case letter (a, b, c) are not significantly different from each other ($P < 0.05$).

CHAPTER III

ENLIST™ WEED CONTROL SYSTEMS IN TEXAS HIGH PLAINS COTTON

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Weed management systems were established near Lubbock, TX in 2013, 2014, and 2015 to assess the effectiveness of 2,4-D choline + glyphosate (Enlist Duo®) alone and in combination with glufosinate and several soil-residual herbicides for control of Palmer amaranth. Systems consisted of trifluralin applied preplant incorporated followed by an early postemergence application followed by a mid-postemergence application. Visual control of Palmer amaranth was recorded 14, 21, and 28 days after treatment. Palmer amaranth control 21 days after the early postemergence application in 2013 ranged from 75 to 90% for all treatments that included Enlist Duo® or 2,4-D choline alone or in a tank-mixture. Twenty-eight days after the mid-postemergence application, Palmer amaranth was controlled 85 to 99% for all herbicide systems with the exception of

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systems that included a mid-postemergence application of glufosinate alone. Combined across 2014 and 2015, Palmer amaranth control 21 days after the early postemergence application ranged from 96 to 98% for all systems that included Enlist Duo® or 2,4-D choline alone or in a tank-mixture. Combined across 2014 and 2015, Palmer amaranth control 28 days after the mid-postemergence application ranged from 95 to 100% with the exception of trifluralin preplant incorporated followed by glufosinate with or without acetochlor applied early postemergence followed by glufosinate mid-postemergence and trifluralin preplant incorporated followed by glyphosate early postemergence followed by glyphosate mid-postemergence. Overall, seed cotton yields were similar for all treatments with the exception of trifluralin alone preplant incorporated and the nontreated control.

Nomenclature: Cotton, *Gossypium hirsutum* L.; 2,4-D choline; glyphosate; glufosinate; Palmer amaranth, *Amaranthus palmeri* S. Wats.

Key words: Resistance, tank mixtures.

INTRODUCTION

Effective and economical weed control is crucial to a profitable cotton production system. Weeds decrease cotton lint yield and quality by competing for nutrients, water, and light (Stuart et al. 1984). In 2007, the release and wide adoption of glyphosate tolerant cotton changed weed management systems in cotton. Glyphosate tolerant cotton systems provided growers with broad-spectrum weed control and flexibility in application timings (Norsworthy et al. 2007). These systems also were widely adopted due to their simplicity and convenience.

Prior to the release of glyphosate tolerant cotton, weed control in cotton was dominated by soil residual herbicides. Trifluralin and fluometuron were applied to over 50 and 25% of treated cotton hectares, from 1992 to 1999. However, glyphosate use started to increase rapidly in 1998, the year after the commercial introduction of glyphosate tolerant cotton. By 2000, glyphosate had replaced trifluralin as the herbicide applied to the greatest percentage of cotton hectares (Young 2006).

A survey conducted in the spring of 2006 indicated that approximately two-thirds of cotton producers in the southern United States had planted glyphosate tolerant cotton continuously for three to five years (Foresman and Glasgow 2008). Of the cotton producers surveyed, 21% applied glyphosate alone, 21% applied glyphosate in a tank mixture, and 52% applied glyphosate after a preemergence (PRE) herbicide. This increase in glyphosate use decreased tillage (Young 2006) and placed an extreme selection pressure for glyphosate resistance in Palmer amaranth (*Amaranthus palmeri* S. Wats.) and other weeds frequently found in cotton cropping systems (Neve et al. 2011).

Glyphosate resistant Palmer amaranth was confirmed on the Texas High Plains in 2011 (Heap 2016), although confirmation in Georgia occurred seven years earlier (Culpepper et al. 2006). Resistant Palmer amaranth biotypes have increased and spread dramatically throughout the Texas High Plains, causing cotton growers to change their management inputs in order to maintain sustainable cotton production systems. Growers who are successful at controlling weeds including Palmer amaranth are using a systems approach that involves multiple application timings, multiple herbicide modes of action, and the addition of soil residual herbicides as well as the incorporation of mechanical, cultural, and biological methods where appropriate.

The list of available modes of action in cotton may increase as early as the 2016 growing season with the registration of Enlist™ technology developed by Dow AgroSciences. Enlist™ technology utilizing 2,4-D choline + glyphosate (Enlist Duo®) and glufosinate tolerance has the potential to effectively manage glyphosate resistant Palmer amaranth. Cotton tolerant to 2,4-D choline was conferred by the insertion of a gene (AAD-12) that codes for an aryloxyalkanoate dioxygenase enzyme (Wright et al. 2010). Plants transformed to include this gene can metabolize certain auxin herbicides including 2,4-D to a nonlethal form (Richburg et al. 2012). The availability of Enlist™ cotton would provide growers with a new tool to effectively manage glyphosate resistant Palmer amaranth, Russian-thistle (*Salsola tragus* L.), and other difficult-to-control weeds in Texas High Plains cotton.

Understanding how to maximize the use of this technology with existing herbicides will not only improve weed control and cotton yields, but also may reduce selection pressure for 2,4-D resistant weeds. The objective of this study was to identify effective weed management systems for the control of Palmer amaranth in glyphosate, 2,4-D, and glufosinate tolerant cotton.

MATERIALS AND METHODS

Field experiments were conducted in 2013, 2014, and 2015 in Lubbock, TX at the Texas Tech New Deal Research Farm (33.441376°N, -101.435804°W, elevation 994 m). The cultivar 'Phytogen 490 W3FE' (Dow AgroSciences, Indianapolis, IN) was planted with a John Deere 1700 MaxEmerge XP Planter on May 16, 2013, June 3, 2014, and June 4, 2015 at 10 seed per m of row spaced 101 cm apart. The soil type was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) with less than 1% organic matter and pH of 7. All studies were arranged in a randomized complete block design with four replications. Individual plots were 4.1 m wide by 6.1 m in length. In-season rainfall was 292 mm in 2013, 460 mm in 2014, and 354 mm in 2015. Water was applied as needed through sub-surface drip irrigation. In-season irrigation was 318, 36, and 244 mm in 2013, 2014, and 2015, respectively.

Weed control systems included trifluralin applied preplant and incorporated 5 to 8 cm with a rolling cultivator. Early postemergence (EPOST) applications consisted of Enlist Duo® at two rates; Enlist Duo® + glufosinate; glufosinate; *S*-metolachlor + glufosinate; acetochlor + glufosinate; Enlist Duo® + acetochlor; 2,4-D choline + glufosinate; and glyphosate. Mid-postemergence (MPOST) applications consisted of Enlist Duo®; Enlist Duo® + glufosinate; glufosinate; 2,4-D choline + glufosinate; and glyphosate. Herbicides and application rates are listed in Table 3.1.

Early postemergence applications were made when Palmer amaranth was approximately 5 to 10 cm in height while MPOST applications were made 21 days after EPOST applications. The nontreated control did not receive any herbicide applications. All applications were made with a CO_2-pressurized backpack sprayer equipped with AIXR11002 spray tips (TeeJet® Technologies, Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} at 205 kPa. No adjuvants were included with any application. Insect control, fertilization, and defoliation practices were standard for cotton production in the Texas High Plains (Bronson 2004; Kelley et al. 2014; Kerns et al. 2009).

Visual control estimates were recorded 14, 21, and 28 days after treatment using a scale of 0 to 100 percent, where 0 equals no weed control and 100 equals complete control (Frans et al. 1986). Cotton was harvested with a small-plot stripper on October 31, 2013, November 11, 2014, and November 6, 2015.

A univariate analysis was performed on all responses in order to test for stable variance (Version 9.3, SAS Institute Inc., SAS Campus Drive, NC). No data sets were transformed as transformation did not increase stabilization. Data sets were analyzed using PROC MIXED with the pdmix 800 macro described by Saxton (1998) and treatments were separated by Fisher's Protected LSD at an alpha level of $P < 0.05$.

RESULTS AND DISCUSSION

For Palmer amaranth control 21 days after EPOST and 28 days after MPOST applications, 2014 and 2015 trials were averaged over year due to no significant year effect ($P > 0.05$); however, the 2013 trial was analyzed independently. For seed cotton yields, 2013 and 2015 trials were averaged over year due to no significant year effect (P > 0.05); however, the 2014 trial was analyzed independently.

Palmer amaranth control. In 2013, Palmer amaranth control 21 days after the EPOST application ranged from 75 to 90% for all treatments that included Enlist Duo® or 2,4-D choline alone or in a tank-mixture (Table 3.2). Treatments that did not include Enlist Duo® or 2,4-D choline EPOST only controlled Palmer amaranth 59 to 66%. Palmer amaranth control 28 days after the MPOST application ranged from 85 to 97% for all systems with the exception of treatments that included glufosinate only at the MPOST timing, where control ranged from 59 to 61% (Table 3.3).

When averaged over the 2014 and 2015 growing seasons, Palmer amaranth control 21 days after the EPOST application was at least 96% for all systems that included Enlist Duo® or 2,4-D choline alone or in a tank-mixture (Table 3.2). All other treatments controlled Palmer amaranth 84 to 93%. Palmer amaranth control 28 days after the MPOST application ranged from 95 to 100% for all systems with the exception of trifluralin PPI followed by glufosinate with or without acetochlor EPOST followed by glufosinate MPOST and trifluralin PPI followed by glyphosate EPOST followed by glyphosate MPOST (Table 3.3).

Craigmyle et al. (2014) and Merchant et al. (2014) also observed increased weed control with the addition of 2,4-D to postemergence (POST) applications. When comparing 2,4-D, glyphosate, and glufosinate systems in Georgia cotton, Merchant et al. (2014) found that Palmer amaranth was controlled 98 to 99% at harvest when a PRE herbicide was followed by sequential applications of 2,4-D + glufosinate, and Palmer amaranth was controlled 95 to 96% following sequential applications of 2,4-D +

glyphosate. In Missouri soybean, Craigmyle et al. (2014) found that the addition of 2,4-D to POST applications of glufosinate improved control of common waterhemp (*Amaranthus rudis* Sauer) and common cocklebur (*Xanthium strumarium* L.) up to 6 and 11%, respectively.

Seed cotton yield. In 2013/2015, seed cotton yields ranged from 5,222 to 6,896 kg ha^{-1} for all treatments with the exception of trifluralin PPI and the nontreated control, which ranged from 0 to 1,342 kg ha^{-1} (Table 3.4). In 2014**,** seed cotton yields ranged from 3,455 to 4,820 kg ha^{-1} for all treatments with the exception of trifluralin PPI and the nontreated control, where yield ranged from 2,428 to 2,474 kg ha^{-1}. Although yields were similar among systems due to variability, Merchant et al. (2014) found that the greatest yields were achieved when systems included a PRE herbicide followed by sequential POST applications of 2,4-D + glyphosate or 2,4-D + glufosinate or when glufosinate + 2,4-D was the POST option.

Cotton technology with tolerance to glyphosate, 2,4-D, and glufosinate will improve grower flexibility and POST management of Palmer amaranth (Merchant et al. 2014). In these studies, numerous effective systems were identified; however, systems containing Enlist Duo® or 2,4-D choline EPOST and MPOST were among the most effective, providing 85 to 97% control while systems that relied on glufosinate alone MPOST only achieved 28 to 66% control. Control of certain weeds with glufosinate such as *Amaranthus* species has been inconsistent, especially under poor growing conditions (Steckel et al. 1997), which is commonly observed in the Texas High Plains.

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Table 3.1. Herbicides and application rates for 2013, 2014, and 2015 systems trials near Lubbock, TX.

Herbicide common names	Brand names or designations	Application rates	Manufacturer
Trifluralin	Trifluralin 4 EC	0.84 kg ai ha^{-1}	Albaugh, Inc., Ankeny, IA, http://albaughllc.com
2,4-D choline + glyphosate	Enlist Duo®	2.19 kg ae ha^{-1}	Dow AgroSciences, Indianapolis, IN, http://www.dowagro.com
Glufosinate	Liberty® 280 SL	0.59 kg ai ha^{-1}	Bayer CropScience, Research Triangle Park, NC, https://www.cropscience.bayer.com
S-metolachlor	Dual MAGNUM®	1.09 kg ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC, https://www.syngenta.com
Acetochlor	Warrant®	1.26 kg ai ha^{-1}	Monsanto Company, St. Louis, MO, http://www.monsanto.com
2,4-D choline	GF-3355	1.07 kg ae ha^{-1}	Dow AgroSciences
Glyphosate	Roundup PowerMAX®	1.12 kg ae ha^{-1}	Monsanto Company

Table 3.2. Palmer amaranth control 21 days after the early postemergence application in 2013, 2014, and 2015 systems trials near Lubbock, TX.[a]

Weed control system		Palmer amaranth control	
PPI[b]	EPOST[c]	2013[d]	2014/2015
		------------------------------- % -------------------------------	
Trifluralin	Enlist Duo®	84 ab	98 a
Trifluralin	Enlist Duo® + glufosinate	83 abc	96 a
Trifluralin	Glufosinate	59 d	84 c
Trifluralin	*S*-metolachlor + glufosinate	66 cd	93 abc
Trifluralin	Acetochlor + glufosinate	65 d	89 bc
Trifluralin	Enlist Duo® + acetochlor	90 a	98 ab
Trifluralin	2,-4-D Choline + glufosinate	75 a-d	97 ab
Trifluralin	Glyphosate	66 bcd	84 c
Trifluralin	-	28 e	13 d

[a]Abbreviations: PPI, preplant incorporated; EPOST, early postemergence.

[b]Trifluralin was applied at 0.84 kg ai ha^{-1}. Enlist Duo®; glufosinate; glyphosate; *S*-metolachlor; acetochlor; and 2,4-D choline applied at 2.19, 0.59, 1.12, 1.09, 1.26, and 1.07 kg ha^{-1}, respectively.

[c]EPOST application made once Palmer amaranth reached 5 to 10 cm in height.

[d]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P < 0.05$. Data pooled over 2014 and 2015.

Table 3.3. Palmer amaranth control 28 days after the mid-postemergence application in 2013, 2014, and 2015 systems trials near Lubbock, TX.[a]

Weed control system			Palmer amaranth control	
PPI[b]	EPOST[c]	MPOST	2013[d]	2014/2015
			------------------- %	-------------------
Trifluralin	Enlist Duo®	Enlist Duo®	94 a	100 a
Trifluralin	Enlist Duo® + glufosinate	Enlist Duo®	95 a	97 a
Trifluralin	Glufosinate	Enlist Duo®	95 a	95 a
Trifluralin	Enlist Duo®	Glufosinate	59 b	99 a
Trifluralin	Enlist Duo® + glufosinate	Glufosinate	61 b	98 a
Trifluralin	Enlist Duo®	Enlist Duo® + glufosinate	93 a	99 a
Trifluralin	Enlist Duo® + glufosinate	Enlist Duo® + glufosinate	89 a	99 a
Trifluralin	*S*-metolachlor + glufosinate	Enlist Duo®	97 a	99 a
Trifluralin	Acetochlor + glufosinate	Enlist Duo®	98 a	97 a
Trifluralin	Acetochlor + Enlist Duo®	Enlist Duo®	99 a	99 a
Trifluralin	2,4-D choline + glufosinate	2,4-D choline + glufosinate	86 a	99 a
Trifluralin	Glyphosate	Glyphosate	85 a	81 b

Trifluralin	Glufosinate	Glufosinate	33 c	90 ab
Trifluralin	Acetochlor + glufosinate	Glyphosate	97 a	96 a
Trifluralin	Acetochlor + glufosinate	Glufosinate	55 bc	87 ab
Trifluralin	-	-	9 d	13 c

[a]Abbreviations: EPOST, early postemergence; MPOST, mid-postemergence.

[b]Trifluralin was applied at 0.84 kg ai ha^{-1}. Enlist Duo®; glufosinate; glyphosate; *S*-metolachlor; acetochlor; and 2,4-D choline were applied at 2.19, 0.59, 1.12, 1.09, 1.26, and 1.07 kg ha^{-1}, respectively.

[c]EPOST application made once Palmer amaranth reached 5 to 10 cm in height; MPOST application made 21 days after the initial application.

[d]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P < 0.05$. Data pooled over 2014 and 2015.

Table 3.4. Seed cotton yield in 2013, 2014, and 2015 systems trials near Lubbock, TX.[a]

Weed control system			Seed cotton yield	
PPI[b]	EPOST[c]	MPOST	2013/2015[d]	2014
			---------------- $kg\ ha^{-1}$ ----------------	
Trifluralin	Enlist Duo®	Enlist Duo®	6690 ab	4435 ab
Trifluralin	Enlist Duo® + glufosinate	Enlist Duo®	6530 a-d	3455 c
Trifluralin	Glufosinate	Enlist Duo®	6438 a-d	4023 bc
Trifluralin	Enlist Duo®	Glufosinate	5800 b-e	4820 a
Trifluralin	Enlist Duo® + glufosinate	Glufosinate	5732 cde	4637 ab
Trifluralin	Enlist Duo®	Enlist Duo® + glufosinate	6552 a-d	4380 ab
Trifluralin	Enlist Duo® + glufosinate	Enlist Duo® + glufosinate	6438 a-d	4719 a
Trifluralin	*S*-metolachlor + glufosinate	Enlist Duo®	6873 ab	4270 ab
Trifluralin	Acetochlor + glufosinate	Enlist Duo®	6515 a-d	4307 ab
Trifluralin	Acetochlor + Enlist Duo®	Enlist Duo®	6483 a-d	4307 ab
Trifluralin	2,4-D choline + glufosinate	2,4-D choline + glufosinate	6896 ab	4664 ab
Trifluralin	Glyphosate	Glyphosate	5240 e	4426 ab
Trifluralin	Glufosinate	Glufosinate	5222 e	3519 c

Trifluralin	Acetochlor + glufosinate	Glyphosate	6987 a	4307 ab
Trifluralin	Acetochlor + glufosinate	Glufosinate	5516 de	4408 ab
Trifluralin	-	-	1342 f	2474 d
-	-	-	0 g	2428 d

[a]Abbreviations: PPI, preplant incorporated; EPOST, early postemergence; MPOST, mid-postemergence.

[b]Trifluralin applied at 0.84 kg ai ha^{-1}. Enlist Duo®, glufosinate, glyphosate, *S*-metolachlor, acetochlor, and 2,4-D choline applied at 2.19, 0.59, 1.12, 1.09, 1.26, and 1.07 kg ha^{-1}, respectively.

[c]EPOST application made once Palmer amaranth reached 5 to 10 cm in height; MPOST application made 21 days after the initial application.

[d]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P < 0.05$. Data pooled over 2014 and 2015.

CHAPTER IV

ENLIST DUO® EFFICACY AS INFLUENCED BY WEED SIZE IN THE TEXAS HIGH PLAINS

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Postemergence timing trials based on weed size were conducted near Lubbock, TX to assess the effectiveness of 2,4-D choline + glyphosate (Enlist Duo®) on control of Palmer amaranth, Russian-thistle, and kochia at three growth stages (3 to 5 cm, 10 to 15 cm, and 20 to 30 cm). The greatest level of weed control for all three weed species was achieved at the 3 to 5 cm timing; however, weed size was most critical for Palmer amaranth and Russian-thistle compared to kochia. Averaged over all three years, Palmer amaranth control decreased from 93 to 74% when applications of 2,4-D choline alone or in a tank-mixture were applied to plants 3 to 5 and 10 to 30 cm, respectively. For Russian-thistle, control decreased from 98 to 78% when applications of 2,4-D choline

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alone or in a tank-mixture were applied to plants 3 to 5 and 10 to 30 cm, respectively. For kochia, control decreased from 98 to 84% when applications of 2,4-D choline or in a tank-mixture were applied to plant 3 to 5 and 10 to 30 cm, respectively.

Nomenclature: 2,4-D choline; glyphosate; glufosinate; Palmer amaranth, *Amaranthus palmeri* S. Wats; Russian-thistle, *Salsola tragus* L.; kochia, *Kochia scoparia* (L.) Schrad.

Key words: Application timing, growth stage, tank mixtures.

INTRODUCTION

Effective, economical, and sustainable weed management is crucial to a profitable cotton production system. Weeds decrease cotton lint yield and quality by competing for nutrients, water, and light (Stuart et al. 1984). Palmer amaranth (*Amaranthus palmeri* S. Wats.), Russian-thistle (*Salsola tragus* L.), and kochia (*Kochia scoparia* L.) are among the most difficult-to-control weeds in Texas High Plains cotton. Palmer amaranth was ranked as the most troublesome cotton weed in the southern United States in 2009, occurring in nine of 10 states surveyed (Webster and Nichols 2012). It also has become one of the most economically damaging glyphosate-resistant weed species in the United States (Beckie 2006).

Russian-thistle, an annual broadleaf weed that is prevalent in the western United States, is extremely competitive due in part to its aggressive root system (Pan et al. 2001; Young 1988). The competitiveness of kochia, a troublesome summer annual broadleaf weed in croplands and noncroplands over the Great Plains of North America, is attributed to its early seedling emergence, C_4 photosynthesis, rapid growth rate, heat and salt tolerance, prolific seed production (greater than 50,000 seeds $plant^{-1}$), and long distance seed dispersal by tumbling (Baker et al. 2010; Christoffoleti et al. 1997; Eberlein and Fore 1984; Forcella 1985; Friesen et al. 2009; Schwinghamer and Van Acker 2008; Wicks et al. 1994).

The list of available modes of action to control these species in cotton is limited; however, options may increase as early as the 2016 growing season with the release of Enlist™ technology. Enlist™ technology utilizes cotton tolerance to 2,4-D choline, glyphosate, and glufosinate. Cotton tolerant to 2,4-D choline was conferred by the insertion of a gene (AAD-12) that codes for an aryloxyalkanoate dioxygenase enzyme (Wright et al. 2010). Plants transformed to include this gene can metabolize certain auxin herbicides, including 2,4-D, to a nonlethal form (Richburg et al. 2012). The availability of Enlist™ cotton would provide growers with a new tool to effectively manage Palmer amaranth, Russian-thistle, kochia, and other difficult-to-control weeds in Texas High Plains cotton.

Weed size at the time of application (Bellinder et al. 2003; Craigmyle et al. 2013; Mellendorf et al. 2013; Schuster et al. 2007) and tank-mix combinations (Everman et al. 2007; Merchant et al. 2014; Richardson et al. 2006) are two factors that often impact the success of a herbicide. The importance of weed size at the time of 2,4-D application has been well-documented (Everitt and Keeling 2007; Siebert et al. 2004). Therefore, weed size should be considered when making 2,4-D choline + glyphosate (Enlist Duo®) applications. The objective of this research was to evaluate the effectiveness of mixtures of 2,4-D choline with glyphosate, glufosinate, *S*-metolachlor, and/or acetochlor on control of Palmer amaranth, Russian-thistle, and kochia at different growth stages.

MATERIALS AND METHODS

Field experiments were conducted in 2013, 2014, and 2015 in Lubbock, TX at the Texas A&M AgriLife Research Farm (33.415319°N, -101.483274°W, elevation 1,001 m). The soil type was an Amarillo fine sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) with less than 1% organic matter and pH of 7.5. All studies were arranged in a randomized complete block design with four replications. Individual plots were 3.0 m wide by 6.1 m in length. Annual rainfall was 292 mm in 2013, 460 mm in 2014, and 354 mm in 2015. No supplemental irrigation was provided.

On average over all three years, there were 1,200 Palmer amaranth, 30 Russian-thistle, and 10 kochia plants per plot. In 2013, postemergence (POST) applications were made to 3 to 5, 10 to 15, and 20 to 30 cm Palmer amaranth, Russian-thistle, and kochia (Table 4.1). In 2014, applications were made to 10 to 15 and 20 to 30 cm Palmer amaranth and 3 to 5 and 20 to 30 cm Russian-thistle and kochia. In 2015, applications were made to 3 to 5, 10 to 15, and 20 to 30 cm Palmer amaranth and 10 to 15 and 20 to 30 cm Russian-thistle. Kochia was not evaluated in 2015 as a late frost controlled most of the populations at this location. The nontreated control did not receive a herbicide application. All applications were made at 4.8 km per hour with a CO_2-pressurized backpack sprayer equipped with AIXR11002 spray tips (TeeJet® Technologies, Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} at 205 kPa. No adjuvants were included with any application.

Treatments consisted of a single POST application of Enlist Duo® at two rates, Enlist Duo® at two rates + glufosinate, Enlist Duo® + *S*-metolachlor, Enlist Duo® + acetochlor, 2,4-D choline + glufosinate, glyphosate, or glufosinate. Herbicides and application rates are listed in Table 4.2. Visual control estimates were recorded 14, 21, and 28 days DAT using a scale of 0 to 100 percent, where 0 was no weed control and 100 was complete control (Frans et al. 1986). Foliar chlorosis, necrosis, tissue distortion, and plant stunting were considered when making visual control estimates.

A univariate analysis was performed on all responses in order to test for stable variance (Version 9.3, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513). No data sets were transformed as transformation did not increase stabilization. Data sets were analyzed using PROC MIXED with the pdmix 800 macro described by Saxton (1998) and treatments were separated by Fisher's Protected LSD at an alpha level of P < 0.05.

RESULTS AND DISCUSSION

For Palmer amaranth, Russian-thistle, and kochia control, trials were analyzed independently due to a significant year effect (P < 0.05) across all possible year combinations. Within year (2013, 2014, and 2015), 10 to 15 and 20 to 30 cm Palmer amaranth control ratings were combined due to no difference in control based on weed height at application (P > 0.05). In 2013, 10 to 15 and 20 to 30 cm Russian-thistle and kochia control ratings were combined due to no difference in control based on weed height at application (P > 0.05). All other control ratings were analyzed independently due to a significant weed height effect (P < 0.05).

Palmer amaranth control. In 2013, Enlist Duo® at 1.64 kg ae ha^{-1}, Enlist Duo® at 2.19 kg ae ha^{-1}, Enlist Duo® at 2.19 kg ha^{-1} + *S*-metolachlor, and Enlist Duo® at 2.19 kg ha^{-1} + acetochlor controlled 3 to 5 cm Palmer amaranth 95 to 98% 21 DAT while glufosinate alone controlled Palmer amaranth 58% (Table 4.3). For 10 to 30 cm Palmer amaranth, Enlist Duo® at 2.19 kg ha^{-1}, Enlist Duo® at 2.19 kg ha^{-1} + *S*-metolachlor, and Enlist Duo® at 2.19 kg ha^{-1} + acetochlor controlled Palmer amaranth the greatest (71 to 77%) while glufosinate alone again provided the least control (5%).

In 2014, Enlist Duo® at 1.64 kg ha^{-1} + glufosinate, Enlist Duo® at 2.19 kg ha^{-1} + glufosinate, and Enlist Duo® at 2.19 kg ha^{-1} + acetochlor controlled 10 to 30 cm Palmer amaranth 88 to 90% 21 DAT while glufosinate alone achieved the least control (54%)

(Table 4.3). In 2015, Enlist Duo® at 2.19 kg ha^{-1}, Enlist Duo® at 2.19 kg ha^{-1} + *S*-metolachlor, and Enlist Duo® at 2.19 kg ha^{-1} + acetochlor achieved the greatest Palmer amaranth control (97 to 98%) 21 DAT while glyphosate alone achieved the least control (82%) (Table 4.3). Enlist Duo® at 2.19 kg ha^{-1} and Enlist Duo® at 2.19 kg ha^{-1} + *S*-metolachlor achieved the greatest control (86 to 87%) of 10 to 30 cm Palmer amaranth while glufosinate alone achieved the least control (44%).

Russian-thistle control. In 2013 at 21 DAT, all treatments controlled 3 to 5 cm Russian-thistle 96 to 99% with the exception of glufosinate alone, which controlled Russian-thistle 75% (Table 4.4). All treatments achieved similar control (81 to 85%) of 10 to 30 cm Russian-thistle with the exception of Enlist Duo® at 1.64 kg ha^{-1} alone (70%), glyphosate alone (34%), and glufosinate alone (28%).

In 2014 at 21 DAT, all treatments controlled 3 to 5 cm Russian-thistle 95 to 100% and 20 to 30 cm Russian-thistle 71 to 76% with the exception of glyphosate alone and glufosinate alone (Table 4.4). Glyphosate alone controlled 3 to 5 and 20 to 30 cm Russian-thistle 69 and 61%, respectively, while glufosinate alone controlled 3 to 5 and 20 to 30 cm Russian-thistle 0 and 23%, respectively. In 2015, Enlist Duo® at 2.19 kg ha^{-1} and Enlist Duo® at 2.19 kg ha^{-1} + *S*-metolachlor achieved the greatest 10 to 15 cm Russian-thistle control (81 to 88%) 21 DAT while glufosinate alone achieved the least control (16%) (Table 4.4).

Kochia control. In 2013 at 21 DAT, all treatments controlled 3 to 5 cm kochia 95 to 100% with the exception of glufosinate alone, which controlled kochia 79% (Table 4.5). All treatments achieved 76 to 90% control of 10 to 30 cm kochia with the exception of glufosinate alone (49%). In 2014, all treatments controlled 3 to 5 cm kochia 97 to 99% 21

DAT with the exception of glufosinate alone, which only controlled kochia 3% (Table 4.5). Enlist Duo® at 2.19 kg ha^{-1}, Enlist Duo® at 2.19 kg ha^{-1} + glufosinate, Enlist Duo® at 2.19 kg ha^{-1} + *S*-metolachlor, and Enlist Duo® at 2.19 kg ha^{-1} + acetochlor achieved the greatest 20 to 30 cm kochia control (84 to 90%) while glufosinate alone controlled kochia the least (53%).

Similarly, Everitt and Keeling (2007) found that 2,4-D at 0.56 and 1.12 kg ha^{-1} controlled 3 to 8 cm horseweed at least 92% 28 days after treatment (DAT); however, reduced horseweed control was observed with these same rates of 2,4-D when applied to 10 to 15 cm and 25 to 46 cm-tall horseweed. A comparable response to 2,4-D also has been reported with other weed species such as red morningglory (*Ipomoea coccinea* L.) and dogfennel [*Eupatorium capillifolium* (Lam.) Small] (Siebert et al. 2004). Siebert et al. (2004) observed 100% control of 30 cm red morningglory; however, a 6 to 19% reduction in control was observed when 2,4-D was applied to 60 cm plants. Dogfennel control was reduced from 85 to 70 to 6% when applications of 2,4-D and dicamba were applied to plants 36, 72, and 154 cm in height, respectively (Sellers et al. 2009).

Regardless of weed size, applications that consisted of 2,4-D choline alone or in a tank-mixture were the most successful. Among these treatments, tank-mixtures of 2,4-D choline or Enlist Duo® + glufosinate achieved the greatest level of weed control. Glyphosate alone applications were inconsistent, especially for larger weeds and glufosinate alone performed poorly across weed species with the exception of 3 to 5 cm Palmer amaranth in 2015 and 10 to 15 cm Russian-thistle in 2015.

The greatest level of weed control for all three weed species was achieved at the 3 to 5 cm timing; however, weed size was most critical for Palmer amaranth and Russian-thistle compared to kochia. Averaged over all three years, Palmer amaranth control decreased from 93 to 74% when applications of 2,4-D choline alone or in a tank-mixture were applied to plants 3 to 5 and 10 to 30 cm, respectively. For Russian-thistle, control decreased from 98 to 78% when applications of 2,4-D choline alone or in a tank-mixture were applied to plants 3 to 5 and 10 to 30 cm, respectively. For kochia, control decreased from 98 to 84% when applications of 2,4-D choline or in a tank-mixture were applied to plant 3 to 5 and 10 to 30 cm, respectively.

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Table 4.1. Dates of Palmer amaranth, Russian-thistle, and kochia applications at several weed sizes near Lubbock, TX.

	Palmer amaranth			Russian-thistle/kochia		
Weed size (cm)	2013	2014	2015	2013	2014	2015
3 to 5	June 14	-	June 3	April 13	May 15	-
10 to 15	June 27	July 23	June 18	May 14	-	April 21
20 to 30	July 8	August 19	June 24	June 13	June 3	May 4

Table 4.2. Herbicide treatments and application rates for 2013, 2014, and 2015 application timing trials near Lubbock, TX.

Herbicide common names	Brand names or designations	Application rates	Manufacturer
2,4-D choline + glyphosate	Enlist Duo®	1.64 or 2.19 kg ae ha^{-1}	Dow AgroSciences, Indianapolis, IN, http://www.dowagro.com
Glufosinate	Liberty® 280 SL	0.59 kg ai ha^{-1}	Bayer CropScience, Research Triangle Park, NC, https://www.cropscience.bayer.com
S-metolachlor	Dual MAGNUM®	1.09 kg ai ha^{-1}	Syngenta Crop Protection, Greensboro, NC, https://www.syngenta.com
Acetochlor	Warrant®	1.26 kg ai ha^{-1}	Monsanto Company, St. Louis, MO, http://www.monsanto.com
2,4-D choline	GF-3355	1.07 kg ae ha^{-1}	Dow AgroSciences
Glyphosate	Roundup PowerMAX®	1.12 kg ae ha^{-1}	Monsanto Company

Table 4.3. Influence of weed height and herbicide treatment on Palmer amaranth control 21 days after treatment in 2013, 2014, and 2015 near Lubbock, TX.[a]

Treatments	Rate (kg ae or ai ha^{-1})	2013		2014	2015	
		3 to 5 cm	10 to 30 cm	10 to 30 cm	3 to 5 cm	10 to 30 cm
		%				
Enlist Duo®	1.64	95 ab	66 b	80 bc	94 c	79 b
Enlist Duo®	2.19	96 ab	77 a	82 b	97 ab	87 a
Enlist Duo® + glufosinate	1.64 + 0.59	80 cd	48 cd	90 a	95 bc	66 c
Enlist Duo® + glufosinate	2.19 + 0.59	78 d	54 c	90 a	95 bc	69 c
Enlist Duo® + *S*-metolachlor	2.19 + 1.09	98 a	71 ab	79 bc	98 a	86 a
Enlist Duo® + acetochlor	2.19 + 1.26	95 ab	72 ab	75 c	98 a	81 b
2,4-D choline + glufosinate	1.07 + 0.59	86 cd	44 d	88 a	94 c	64 c
Glyphosate	1.12	88 bc	63 b	74 c	82 d	59 d
Glufosinate	0.59	58 e	5 e	54 d	93 c	44 e

[a]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD at $P < 0.05$. Data pooled for 10 to 15 cm and 20 to 30 cm Palmer amaranth control ratings within each year.

Table 4.4. Influence of weed height and herbicide treatment on Russian-thistle control 21 days after treatment in 2013, 2014, and 2015 near Lubbock, TX.[a]

Treatments	Rate (kg ae or ai ha^{-1})	Russian-thistle control					
		2013		2014		2015	
		3 to 5 cm	10 to 30 cm	3 to 5 cm	20 to 30 cm	10 to 15 cm	20 to 30 cm
		%					
Enlist Duo®	1.64	96 ab	70 b	97 ab	71 a	100 a	70 cd
Enlist Duo®	2.19	99 ab	85 a	100 a	75 a	100 a	88 a
Enlist Duo® + glufosinate	1.64 + 0.59	96 b	84 a	95 b	73 a	99 ab	68 d
Enlist Duo® + glufosinate	2.19 + 0.59	97 ab	85 a	99 a	73 a	100 a	74 cd
Enlist Duo® + *S*-metolachlor	2.19 + 1.09	99 ab	83 a	100 a	75 a	100 a	81 ab
Enlist Duo® + acetochlor	2.19 + 1.26	98 ab	81 a	98 a	76 a	100 a	70 cd
2,4-D choline + glufosinate	1.07 + 0.59	99 a	81 a	100 a	73 a	100 a	70 cd
Glyphosate	1.12	98 ab	34 c	69 c	61 b	99 a	75 bc

Glufosinate	0.59	75 c	28 c	0 d	23 c	98 b	16 e

[a]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD at $P < 0.05$. In 2013, 10 to 15 and 20 to 30 cm Russian-thistle control ratings were combined due to no weed height effect ($P > 0.05$).

Table 4.5. Influence of weed height and herbicide treatment on kochia control 21 days after treatment in 2013, 2014, and 2015 near Lubbock, TX.[a]

Treatment	Rate (kg ae or ai ha^{-1})	Kochia control			
		2013		2014	
		3 to 5 cm	10 to 30 cm	3 to 5 cm	20 to 30 cm
		%			
Enlist Duo®	1.64	98 a	76 b	98 a	76 d
Enlist Duo®	2.19	98 a	90 a	98 a	90 abc
Enlist Duo® + glufosinate	1.64 + 0.59	95 a	84 ab	97 a	81 d
Enlist Duo® + glufosinate	2.19 + 0.59	95 a	88 ab	99 a	84 a-d
Enlist Duo® + *S*-metolachlor	2.19 + 1.09	100 a	85 ab	98 a	90 ab
Enlist Duo® + acetochlor	2.19 + 1.26	98 a	86 ab	98 a	91 a
2,4-D choline + glufosinate	1.07 + 0.59	98 a	77 ab	98 a	83 bcd
Glyphosate	1.12	100 a	79 ab	88 b	82 cd

Glufosinate	0.59	79 b	49 c	3 c	53 e

[a]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD at $P < 0.05$. In 2013, 10 to 15 and 20 to 30 cm kochia control ratings were combined due to no weed height effect ($P > 0.05$). Kochia was not evaluated in 2015.

CHAPTER V

NON-2,4-D TOLERANT COTTON RESPONSE TO ENLIST DUO® TANK CONTAMINATION

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Field trials were conducted near Lubbock, TX in 2013, 2014, and 2015 to evaluate non-2,4-D tolerant cotton response to low rates of 2,4-D choline + glyphosate (Enlist Duo®). Cotton was sprayed with five rates of Enlist Duo® (0.0183, 0.183, 1.83, 18.3, and 183 g ae ha^{-1}) at two application timings (nine leaf and first bloom). These rates correspond to Enlist Duo® contamination rates of 0.0008, 0.008, 0.08, 0.8, and 8%, respectively. Visual cotton injury, boll retention, lint yield, and fiber properties were

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recorded. Leaf curling, petiole and stem epinasty, stunting, and chlorosis were considered when making visual injury estimates. When averaged over contamination rates, visual injury for nine leaf cotton was greater than first bloom cotton in three of three years and yield loss was greater for nine leaf cotton than first bloom cotton in two of three years. Contamination rates of 0.0008, 0.008, 0.08, and 0.8% did not affect fiber quality; however, a contamination rate of 8% decreased micronaire, fiber length, fiber length uniformity, and fiber strength.

Nomenclature: 2,4-D; Cotton, *Gossypium hirsutum* L.

Key words: Simulated drift, off-target movement, synthetic auxin.

INTRODUCTION

The discovery of the herbicidal properties of the phenoxyacetic acids in Britain and the United States during 1942 and 1944 (Blackman 1948; Hamner and Tukey 1944; Mitchell and Hamner 1944) marked the beginning of the herbicide phase of the "Chemical Era of Agriculture." The phenoxyacetic herbicides transformed agriculture by selectively controlling many weeds in small and relatively inexpensive quantities and are considered to be amongst the greatest scientific discoveries of the twentieth century (Fryer 1980). One of the most important phenoxyacetic herbicides, 2,4-D, has provided economical, selective, preemergence (PRE), and POST control of broadleaf weeds in grass crops and noncropland for the past six decades and remains a widely used herbicide throughout the world (Shaner 2014).

The wide use of 2,4-D will likely continue to expand in the future with the release of 2,4-D choline tolerant corn (*Zea mays* L.), soybean (*Glycine max* (L.) Merr.), and cotton *(Gossypium hirsutum* L.) (Enlist™ Technology). Enlist™ cotton will be tolerant to preplant, PRE, and POST applications of 2,4-D choline. Cotton tolerant to 2,4-D choline was conferred by the insertion of a gene (AAD-12) that codes for an aryloxyalkanoate dioxygenase enzyme (Wright et al. 2010). Plants transformed to include this gene can metabolize certain auxin herbicides, including 2,4-D, to a nonlethal form (Richburg et al. 2012). This new salt of 2,4-D is less prone to drift and volatilization (EPA 2015).

Enlist™ technology utilizing 2,4-D choline + glyphosate (Enlist Duo®) and glufosinate crop tolerance, has the potential to effectively manage Palmer amaranth, Russian-thistle, and other difficult-to-control weeds in Texas High Plains cotton; however, like all tools, there will be challenges associated with this technology. One challenge is the risk of spray tank contamination to non-2,4-D tolerant cotton. Risk of spray tank contamination of 2,4-D in cotton is already a major concern in Texas as grain crops, leguminous crops such as alfalfa and peanut, and pastureland also are grown where cotton is produced. Multiple studies have reported the extreme sensitivity of cotton that is not tolerant to 2,4-D (Everitt and Keeling 2009; Johnson et al. 2012; Marple et al. 2007, 2008). Many of these studies have observed that visual injury is a poor indicator of yield loss (Everitt and Keeling 2009; Johnson et al. 2012). In order to better understand this relationship, field trials were conducted to evaluate non-2,4-D tolerant cotton response to low rates of Enlist Duo® at two application timings (nine leaf and first bloom).

MATERIALS AND METHODS

Field experiments were conducted in 2013, 2014, and 2015 in Lubbock, TX at the Texas Tech New Deal Farm (33.441376°N, -101.435804°W, elevation 994 m). The cultivar 'Phytogen 499 WRF' (Dow AgroSciences, Indianapolis, IN) was planted at 10 seed per m of row spaced 101 cm apart on May 10, 2013, June 5, 2014, and May 27, 2015 with the use of a John Deere 1700 MaxEmerge XP Planter. The soil type was a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) with less than 1% organic matter and pH of 7. Seventy pounds of 28-0-0-5 (N-P-K-S) fertilizer was applied in two in-season applications. All studies were arranged in a randomized complete block design with four replications. Each replication was 26 by 98 m and each plot was 4 by 12 m. Rainfall was 292 mm in 2013, 460 mm in 2014, and 354 mm in 2015. Water was applied as needed through sub-surface drip irrigation. In-season irrigation was 307, 35, and 188 mm in 2013, 2014, and 2015, respectively. Two tillage passes were made throughout the trial with a field sweep cultivator.

Cotton plants were sprayed with five rates of Enlist Duo® (0.0183, 0.183, 1.83, 18.3, and 183 g ae ha^{-1}) at two application timings (nine leaf and first bloom). These rates correspond to Enlist Duo® contamination rates of 0.0008, 0.008, 0.08, 0.8, and 8%, respectively. The nontreated control did not receive a 2,4-D choline application. All applications were made at 4.8 km per hour with a CO_2-pressurized backpack sprayer equipped with AIXR11002 spray tips (TeeJet® Technologies, Glendale Heights, IL) calibrated to deliver 140 L ha^{-1} at 205 kPa. No adjuvants were included with any application. Insect control, fertilization, and defoliation practices were standard for cotton production in the Texas High Plains (Kerns et al. 2009; Kelley et al. 2014; Bronson 2004). Visual injury evaluations were recorded throughout the season using a scale of 0 (no injury) to 100% (complete crop death). Leaf curling, petiole and stem epinasty, stunting, and chlorosis were considered when making visual estimates.

At crop maturity based on the non-treated control, cotton was defoliated following local extension recommendations (Kelley et al. 2014). After defoliation and prior to harvest, 10 consecutive plants from each plot were removed by cutting the main stem directly above the soil surface. The plant was divided into 0.3 m sections of the main stem and the number of open and closed bolls were quantified. Bolls were attributed to the 0.3 m section in which the reproductive branch originated. Plots were harvested at the end of the season with a two row plot harvester and seed cotton yield was measured after harvest. A 40 g lint sample was subjected to fiber quality tests, which included micronaire, fiber length, length uniformity, and fiber strength at the Texas Tech University Fiber and Biopolymer Research Institute, Lubbock, TX.

A univariate analysis was performed on all responses in order to test for stable variance (Version 9.3, SAS Institute Inc., SAS Campus Drive, Cary, NC). No data sets were transformed as transformation did not increase stabilization with the exception of boll retention from 0.3 to 0.6 m in 2014. A value of one was added to these values before applying the natural log transformation. Adding a value of one to the values of this data set was necessary in order to include values of zero in the natural log transformation analysis. Data sets were analyzed using PROC MIXED with the pdmix 800 macro described by Saxton (1998) and treatments were separated by Fisher's Protected LSD at an alpha level of $P < 0.05$.

RESULTS AND DISCUSSION

Visual injury. For visual injury, 2014 and 2015 trials were averaged over year due to no significant year effect ($P > 0.05$) while the 2013 trial was analyzed independently. The two-way-interaction between application timing and Enlist Duo® contamination rate was not significant; therefore, main effects are discussed below.

In 2013 when averaged over contamination rate, visual injury increased from 15% for cotton sprayed at the first bloom timing to 27% for cotton sprayed at the nine leaf timing (Table 5.1). Averaged over application timing 28 days after treatment (DAT), visual injury following contamination rates of 0.0008 and 0.008% ranged from 2 to 3% and were similar (Table 5.2). However, cotton was injured 20, 41, and 62% when sprayed with contamination rates of 0.08, 0.8, and 8%, respectively.

Averaged over 2014 and 2015, visual injury increased from 4% for cotton sprayed at the first bloom timing to 18% for cotton sprayed at the nine leaf timing when averaged over all contamination rates (Table 5.1). Averaged over application timing, contamination rates of 0.0008 and 0.008 were similar and did not exceed 1% (Table 5.2). Contamination rates of 0.08, 0.8, and 8% caused 4, 19, and 44% visual injury, respectively.

Byrd (2015) observed injury greater than 50% when 2,4-D amine rates of 2 and 40 g ae ha^{-1} were applied to four leaf and nine leaf cotton. As cotton matured beyond the two weeks after first bloom stage, visual injury from the 2 and 40 g ha^{-1} rates was less than 10% and 25%, respectively. Marple et al. (2008) also observed greater 2,4-D amine injury when applied at the three to four leaf stage compared with the 8, 14, and 18-node stages. For three to four leaf cotton 28 DAT, 61 and 76% injury was observed for simulated drift rates of 1.4 and 2.8 g ae ha^{-1}, respectively.

Additionally, Everitt and Keeling (2009) observed that simulated drift rates of 2,4-D amine as low as 2.8 g ae ha^{-1} applied at the cotyledon to two leaf stage injured cotton 50% 14 DAT with injury increasing to greater than 90% with 280 g ae ha^{-1}. In another study, Johnson et al. (2012) observed 36 to 90% visual injury two weeks after treatment when 20 to 30 cm cotton was sprayed with 2,4-D amine simulated drift rates of 1, 5, 20, 78, and 269 g ae ha^{-1}.

Boll retention. For boll retention from 0 to 0.3 m, 2013 and 2014 trials were averaged due to no significant year effect ($P > 0.05$). The 2015 trial was analyzed independently. For boll retention from 0.3 to 0.6 m, 2013, 2014, and 2015 trials were analyzed independently. The two-way-interaction between application timing and Enlist Duo® contamination rate was not significant; therefore, main effects are discussed below.

Application timing and contamination rate affected boll retention from 0 to 0.3 m when averaged over 2013 and 2014 (Tables 5.1 and 5.2). Boll retention, averaged over contamination rate, was greater for first bloom cotton than nine leaf cotton. When averaged over application timing, boll retention following contamination rates of 0.0008, 0.008, and 0.08% were similar to the nontreated control. For contamination rates of 0.8 and 8%, boll retention decreased by 0.9 and 1.4 bolls, respectively. In 2015, boll retention was similar following applications made at the nine leaf and first bloom timings (Table 5.1), but was affected by contamination rate (Table 5.2). When averaged over application timing, contamination rates of 0.8 and 8% decreased boll retention by 1.7 and 2.9 bolls, respectively.

In 2013, application timing did not affect boll retention from 0.3 to 0.6 m (Table 5.1); however, contamination rate did have an effect (Table 5.2). When averaged over application timing, boll retention was similar to the nontreated control at contamination rates of 0.0008, 0.008, and 0.08%. At contamination rates of 0.8 and 8%, boll retention decreased by 1.4 and 2.2 bolls, respectively. In 2014, application timing did not affect boll retention from 0.3 to 0.6 m (Table 5.1), but was affected by contamination rate (Table 5.2). Boll retention for all contamination rates was similar to the nontreated control with the exception of the 8% contamination rate, which retained no bolls from 0.3 to 0.6 m. In 2015, boll retention was not affected by application timing (Table 5.1), but was affected by contamination rate (Table 5.2). Boll retention for contamination rates of

0.0008, 0.008, and 0.08% were similar to the nontreated control. At contamination rates of 0.8 and 8%, boll retention decreased by 2.8 and 4.1 bolls, respectively.

Lint yield. For cotton lint yield, 2013, 2014 and 2015 trials were analyzed independently due to a significant year affect across all year combinations ($P \leq 0.05$). The two-way-interaction between application timing and Enlist Duo® contamination rate for each year was not significant; therefore, main effects are discussed below.

Averaged over application timing in 2013, lint yield following Enlist Duo® contamination rates of 0.0008 and 0.008% were not different than the nontreated control while contamination rates of 0.08, 0.8 and 8% decreased yield by 3, 45, and 80% (Table 5.2). In 2014, lint yield following Enlist™ contamination rates of 0.0008 and 0.008% were similar to the nontreated control (Table 5.2). Contamination rates of 0.8, 0.8 and 8% decreased lint yield by 25, 58, and 86%, respectively. In 2015 when averaged over application timing, lint yield for Enlist Duo® contamination rates of 0.0008 and 0.008% were similar to the nontreated control while contamination rates of 0.8, and 8% decreased lint yield by 48 and 78%, respectively (Table 5.2). When averaged over tank contamination rates, lint yields for nine leaf and first bloom cotton were similar in 2013, 2014, or 2015 (Table 5.1).

Marple et al. (2008) found that 2,4-D amine had no adverse effect on lint yield except when applied at 2.8 g ae ha^{-1} at the three to four leaf application timing. Everitt et al. (2009) also observed that at rates of 2.8 g ae ha^{-1} of 2,4-D amine and lower had little effect on yield reduction (< 10%) across all application timings (two leaf, four to five leaf, pinhead square, and early bloom); however, yield reductions of 61 to 97% were observed after 280 g ae ha^{-1} was applied. Conversely, Byrd (2015) observed yield loss greater than 20% at 5 of 12 locations when 2 g ae ha^{-1} of 2,4-D was applied to cotton between four leaf and two weeks after first bloom. At 40 g ae ha^{-1}, averaged over 12 locations yield was 45, 58, 66, 45, 16, and 7% less than the nontreated control when applied at four leaf, nine leaf, first bloom, two weeks after first bloom, four weeks after first bloom, and six weeks after first bloom, respectively.

Fiber quality. For micronaire and fiber length uniformity 2013, 2014 and 2015 trials were analyzed independently due to a significant year effect across all year combinations ($P \leq 0.05$). For fiber staple length and fiber strength, 2014 and 2015 trials were averaged over year due to no significant year effect ($P > 0.05$) while 2013 trials were analyzed independently. The two-way-interaction between application timing and Enlist Duo® contamination rate for each year was not significant; therefore, main effects are discussed below.

Micronaire, length, uniformity, and strength were quantified with the High Volume instrument (HVI) line. Micronaire is a measure of the air permeability of compressed cotton fibers. It is often used as an indication of fiber fineness and maturity (Cotton Incorporated 2016). In 2013, micronaire values following Enlist Duo® contamination rates of 0.0008, 0.008, 0.08, and 0.8% were similar to the nontreated control while a contamination rate of 8% decreased micronaire by 0.83 (Table 5.3). Application timing and contamination rate did not affect micronaire in 2014 (Table 5.3) In 2015, micronaire values following Enlist Duo® contamination rates of 0.0008, 0.008, and 0.08% were similar to the nontreated control while a contamination rate of 0.08 and 8% decreased micronaire by 0.34 and 1.15, respectively, compared to the nontreated control (Table 5.3).

Fiber staple length is the average of the longest 50% of the fibers (Upper Half Mean Length) (Cotton Incorporated 2016). In 2013, lengths following 0.0008, 0.008, 0.08, and 0.8% contamination rates were similar to the nontreated control; however, a contamination rate of 8% decreased length by 0.16 cm (Table 5.2). Averaged over 2014 and 2015, application timing and contamination rate did not affect fiber length.

Fiber length uniformity index is the ratio (given as a percent) of the average length to the upper half-mean-length. Length uniformity index is an indicator of how fibers will perform in the spinning of yarn (Cotton Incorporated 2016). In 2013, application timing and contamination rate affected fiber length uniformity. Across all contamination rates, the length uniformity for nine leaf cotton was 1.14% greater than for first bloom cotton (data not shown). Averaged over application timing, fiber length was similar for all contamination rates with the exception of the 8% contamination rate, which was 2.18% less than the nontreated control (Table 5.3). Fiber length uniformity was not affected by application timing or contamination rate in 2014 (Table 5.3). In 2015, application timing and contamination rate affected fiber length uniformity. Averaged over all contamination rates, the length for nine leaf cotton was 1.14% greater than for first bloom cotton (data not shown). Averaged over application timing, length for contamination rates of 0.0008, 0.008, and 0.08 and 0.8% was similar to the nontreated control. At the 8% contamination rate, fiber length decreased by 2.8% compared to the nontreated control (Table 5.3).

Fiber strength reports the force, in grams, required to break a bundle of fiber one tex unit size. A tex unit is the weight in grams of 1,000 m of fiber (Cotton incorporated 2016). Averaged over 2013, 2014, and 2015, Enlist Duo® contamination affected fiber strength (Table 5.3). Fiber strength was similar for contamination rates of 0.0008, 0.008, 0.08, and 0.8%; however, a contamination rate of 8% decreased fiber strength by 1.86 g. Marple et al. (2008) found that simulated drift of 2,4-D on cotton did not affect average micronaire, fiber length, fiber strength, fiber color, or trash; however, 2,4-D treatments did reduce fiber elongation.

In general, visual injury for nine leaf cotton was greater than first bloom cotton in three of three years and nine leaf cotton yield loss was greater than first bloom cotton in two of three years. Others have reported that yield loss is the most severe when 2,4-D drift injury occurred during early growth stages, particularly those prior to bloom (Egan et al. 2014; Everitt and Keeling 2009; Marple et al. 2008). When predicting yield loss, boll load as noted by plant mapping may be a better indiciator than visual injury (Byrd 2015; Johnson et al. 2012). This research continues to support the statements that non-2,4-D tolerant cotton is extremely sensitive to 2,4-D injury and that predicting yield loss based on visual injury is unreliable.

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Table 5.1. Visual injury 28 days after treatment, boll retention, and lint yield as influenced by application timing in 2013, 2014, and 2015.[a]

	Injury		Boll Retention					Lint yield		
Application timing	2013	2014/15	2013/14	2015	2013	2014	2015	2013	2014	2015
	----------- % -----------		---- 0 to 0.3 m ----		-------- 0.3 to 0.6 m --------			--------- kg ha^{-1} ---------		
Nine leaf	27 a	18 a	1.9 b	3.0	1.9	0.7	3.7	1113	347 c	2741 c
First Bloom	15 b	4 b	2.1 a	4.0	1.7	0.7	3.9	1197	415 abc	3223 abc

[a]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P < 0.05$.

Table 5.2. Visual injury 28 days after treatment, boll retention, and lint yield as influenced by Enlist Duo® tank contamination rate in 2013, 2014, and 2015.[a]

	Injury		Boll Retention					Lint yield		
Contamination rate	2013	2014/15	2013/14	2015	2013	2014	2015	2013	2014	2015
----------- % -----------	--------- % --------		---- 0 to 0.3 m ----		------ 0.3 to 0.6 m ------			----------- kg ha^{-1} -----------		
0	-	-	2.4 a	4.2 ab	2.5 a	1.2 a	4.7 a	1477 a	549 a	3702 b
0.0008	2 d	0 d	2.4 a	4.2 ab	2.4 a	0.9 a	5.3 a	1476 a	478 a	3777 b
0.008	3 d	1 d	2.4 a	4.9 a	2.2 a	1.0 a	5.3 a	1435 a	517 a	3773 b
0.08	20 c	4 c	2.2 a	3.7 b	2.5 a	1.0 a	5.1 a	1437 b	438 b	3900 a
0.8	41 b	19 b	1.5 b	2.6 c	1.0 b	0 ab	1.8 b	813 c	229 c	1919 c
8	62 a	44 a	0.98 c	1.3 d	0.3 c	0 b	0.6 c	294 d	75 d	822 d

[a]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P < 0.05$.

Table 5.3. Fiber quality measurements as influenced by Enlist Duo® tank contamination rate in 2013, 2014, and 2015.[a]

	MIC			LEN		LUI			STR
Contamination rate	2013[b]	2014	2015	2013	2014/15	2013	2014	2015	2013/14/15
------- % -------				-------- cm --------		--------------- % ---------------			----- g/t -----
0	4.11 ab	3.14	3.93 a	2.76 a	2.63	80.14 a	78.41	80.96 ab	28.31 a
0.0008	4.13 ab	3.04	3.91 a	2.74 a	2.65	80.11 a	78.66	81.91 a	28.69 a
0.008	4.03 b	3.14	3.99 a	2.72 a	2.65	79.63 a	79.18	81.24 ab	28.53 a
0.08	4.11 ab	2.98	4.03 a	2.71 a	2.63	79.60 a	78.14	81.64 a	28.19 a
0.8	4.15 a	3.05	3.69 b	2.72 a	2.66	79.29 a	78.48	80.55 b	28.10 a
8	3.29 c	2.95	2.88 c	2.60 b	2.60	77.95 b	78.81	78.69 c	26.45 b

[a]abbreviations MIC, micronaire; LEN, length; LUI, length uniformity; STR, strength.

[b]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD test at $P < 0.05$.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Understanding how to use herbicides in the new auxin-tolerant cotton technologies will not only improve weed control and cotton yields, but also may reduce the impacts on sensitive crops and the selection pressure for resistant weeds. The quality of water used as the spray carrier, tank-mix combinations, weed size at application, and appropriate tank cleanout procedures are four factors among many others that will impact the success of auxin tolerant weed control systems.

Overall, water source affected glyphosate control in three of the six trials when evaluated 21 DAT. The RO water source (11 ppm) was the top performing water source for control of 30 cm wheat in 2013; however, in the same year, it controlled 20 cm winter wheat similar to the poorest water quality source. For control of 61 cm Palmer amaranth in 2012, the RO water source (11 ppm) was among the top performing water sources.

As expected, an increase in glyphosate rate increased weed control for all six trials 21 DAT. The greater glyphosate rate used in this study reflects a rate that was recommended during the initial design of this trial while the lower rate was included in order to observe the effects of water quality on glyphosate efficacy. Today, these rates might be considered low depending on one's target cropping system and weed specie(s). Using labeled glyphosate rates is important for herbicide resistance management and from the standpoint of water quality. A similar study using greater glyphosate rates would compliment this work.

The addition of AMS also increased weed control for all six trials. Ammonium sulfate is often used in glyphosate applications because the sulfate anion is thought to compete with glyphosate for the antagonistic cations, thus deterring the formation of glyphosate cation complexes (Thelen et al. 1995). Nalewaja and Matysiak (1991) suggest that the addition of AMS also may enhance glyphosate efficacy in the absence of antagonistic salts (Nalewaja and Matysiak 1991). Enhanced glyphosate efficacy in the absence of salts was observed in this study as the addition of AMS increased winter wheat and Palmer amaranth control for all water sources evaluated including the RO source (11 ppm).

When considering weed management systems, auxin-tolerant cotton technology will improve grower flexibility and POST management of Palmer amaranth (Merchant et al. 2014). In these studies, numerous effective systems were identified; however, systems containing Enlist Duo® or 2,4-D choline EPOST and MPOST were among the most effective, providing 85 to 97% control while systems that relied on glufosinate alone MPOST only achieved 28 to 66% control. Control of certain weeds such as *Amaranthus* species with glufosinate has been documented to be inconsistent, especially under poor growing conditions (Steckel et al. 1997), which are often observed in the Texas High Plains. Cotton yields were similar among systems due to variability; however, Merchant et al. (2014) found that the greatest cotton yields were achieved when systems included a PRE herbicide followed by sequential POST applications of 2,4-D + glyphosate or 2,4-D + glufosinate or when glufosinate + 2,4-D was the POST option.

When evaluating Palmer amaranth, Russian-thistle, and kochia control with Enlist™ in non-crop, single POST application studies, treatments that consisted of Enlist Duo® or 2,4-D choline alone or in a tank-mixture were the most successful. Among these treatments, tank-mixtures of 2,4-D choline or Enlist Duo® + glufosinate achieved at least 78% Palmer amaranth, Russian-thistle, and kochia control at the 3 to 5 cm timing. Glyphosate alone applications were inconsistent, especially for larger weeds and glufosinate alone performed poorly across weed species with the exception of 3 to 5 cm Palmer amaranth in 2015 and 10 to 15 cm Russian-thistle in 2015.

The greatest level of weed control for all three weed species was achieved at the 3 to 5 cm timing; however, weed size was most critical for Palmer amaranth and Russian-thistle compared to kochia. Averaged over all three years, Palmer amaranth control decreased from 93 to 74% when applications of 2,4-D choline alone or in a tank-mixture were applied to plants 3 to 5 and 10 to 30 cm, respectively. For Russian-thistle, control decreased from 98 to 78% when applications of 2,4-D choline alone or in a tank-mixture were applied to plants 3 to 5 and 10 to 30 cm, respectively. For kochia, control decreased from 98 to 84% when applications of 2,4-D choline alone or in a tank-mixture were applied to plant 3 to 5 and 10 to 30 cm, respectively.

When considering drift and tank contamination of Enlist Duo® on non-tolerant cotton in the Texas High Plains, nine leaf cotton is more sensitive than first bloom cotton. Others also have reported that yield loss is the most severe when 2,4-D drift injury occurred during early growth stages, particularly those prior to bloom (Egan et al. 2014; Everitt and Keeling 2009; Marple et al. 2008). When predicting yield loss, boll load as noted by plant mapping may be a better indicator than visual injury (Byrd 2015; Johnson et al. 2012). This research continues to support the statements that non-2,4-D tolerant cotton is extremely sensitive to 2,4-D injury and that predicting yield loss based on visual injury is unreliable. In order to minimize the risk of drift while using these new technologies, applicators must use appropriate nozzle and pressure combinations, only tank-mix with permissible tank-mix partners, spray when temperature, relative humidity, wind speed, and wind direction are suitable, and respect buffer zone requirements and sensitive habitats. All of this information will be outlined on herbicide labels and industry websites.

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