Chapter 4

Using Herbicide Programs to Control Weeds in Corn (*Zea mays* L.) and Cotton (*Gossypium hirsutum* L.)

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Additional information is available at the end of the chapter

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Abstract

Field studies were conducted to evaluate control of Amaranthus species and other weeds in corn and cotton. In corn, Palmer amaranth control was at least 90% with preemergence applications of fluthiacet-methyl plus pyroxasulfone, atrazine plus either acetochlor, alachlor, dimethenamid-P, *S*-metolachlor, or *S*-metolachlor plus mesotrione, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione. When using postemergence herbicides applied to Palmer amaranth less than 5 cm tall, atrazine, prosulfuron, and topramezone alone or the combinations of atrazine plus *S*-metolachlor plus glyphosate, diflufenzopyr plus dicamba, dimethenamid plus glyphosate, halosulfuron-methyl plus dicamba, mesotrione plus *S*-metolachlor plus glyphosate, pyroxasulfone plus glyphosate, and thiencarbazone-methyl plus tembotrione provided at least 91% control. In cotton, pyrithiobac applied preemergence resulted in no greater than 63% of control of Palmer amaranth and common waterhemp at the early season rating. Pendimethalin applied preemergence provided varied levels of control of common waterhemp. Trifluralin, applied preplant incorporated, consistently provided at least 86% or greater control of both species. A decreased level of control of both Palmer amaranth and common waterhemp was observed with pendimethalin applied preemergence followed by pyrithiobac-applied early postemergence and followed by glufosinate applied mid-post. Systems which included an early postemergence and mid-postemergence application of glyphosate plus 2,4-D choline provided at least 94% season-long Palmer amaranth control.

Keywords: annual grasses, broadleaf weeds, weed efficacy, crop response, *Amaranthus palmeri* S. Wats, *Amaranthus rudis* Sauer

1. Introduction

During the past 20 years, the use of glyphosate-resistant crop production systems has been adopted and used extensively in various regions of the USA [1]. In 2009, nearly 61 million ha of soybean [*Glycine max* (L.) Merr.], cotton (*Gossypium hirsutum* L), and corn (*Zea mays* L.) contained a modified 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) gene that confers resistance to glyphosate [2]. The wide use of row crops with glyphosate-resistance, the reduction of traditional herbicide and cultivation practices, and the use of intense management of weeds using glyphosate as the predominant control strategy has caused a shift in weed populations and created a selective advantage for glyphosate-resistant weeds [3, 4].

The development of herbicide-resistant crops allows weed control by nonselective postemergence (POST) herbicides, such as glyphosate and glufosinate, widening the array of weed management programs available to producers [5–7]. Both glyphosate and glufosinate control a wide range of weeds in herbicide-resistant crops [7] with little, if any, crop injury [8, 9]. POST applications of glyphosate or glufosinate provide consistent and greater control of large-seeded broadleaf weed species including velvetleaf (*Abutilon theophrasti* Medik.), giant ragweed (*Ambrosia trifida* L.), common cocklebur (*Xanthium strumarium* L.), and morningglory spp. (*Ipomoea* spp.) compared with preemergence (PRE) herbicides [9]. Even though the performance of glyphosate and glufosinate is similar, glufosinate is less likely to succeed in a single POST application program since glufosinate is less effective on larger weeds, needs an increased spray volume, and a need for high humidity at application [7].

Glyphosate-resistant weeds, specifically Amaranthus species, have become an issue across all the USA corn and cotton-producing areas [10]. Estimates are that more than 1.2 million ha of cropland in the USA are now affected by glyphosate-resistant Amaranthus species [10]. In cotton, Palmer amaranth (*Amaranthus palmeri* S. Wats.) has been shown to reduce lint yield by 57% when growing at a density of 10 plants per 9.1 m of row [11]. Additionally, with Palmer amaranth growing at densities greater than six plants per 9.1 m of row, cotton may not be harvestable due to the potential for damage to harvest equipment [11]. A study by Smith et al. [12] found that Palmer amaranth densities of 650–3260 plants ha^{-1} in dryland stripper-harvested cotton increased harvesting time by 2- to 3.5-fold.

Weed resistance to photosystem II (PSII)-inhibiting herbicides, such as atrazine, has also been documented across many corn-growing areas of the USA [10]. Resistance to PSII inhibitors has been documented in 7 monocot and 17 dicot species in the corn-producing regions [13]. Also, populations of tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] have been identified with resistance to herbicides that inhibit acetolactate synthase (ALS), PSII, protoporphyrinogen oxidase (PPO), 5-enolpyruvylshikimate-3-phosphate-synthase (EPSPS), and 4-hydroxyphenyl-pyruvate-dioxygenase (HPPD) in Illinois and Iowa, and Palmer amaranth populations resistant to ALS, PSII, and HPPD inhibitors have been identified in Kansas [13], indicating the continued need for alternative modes of action in corn to reduce the chance of herbicide resistance. The HPPD-inhibiting herbicides have become popular among corn producers because of their broad-spectrum weed control, flexible application timings, tank-mix compatibilities, and crop safety [14–16].

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Cotton growers have experienced more problems with weed resistance because of cotton's slower emergence after planting and fewer registered herbicides compared with other major crops [17]. The first documented cases of glyphosate-resistant (GR) Palmer amaranth in cotton occurred in 2000 in Lauderdale County, TN [18] and in 2003 in Edgecombe County, NC [19]. The first confirmed case of GR Palmer amaranth was documented in a biotype of Palmer amaranth growing in a Macon County, GA cotton field, where six- to eightfold levels of resistance to glyphosate were observed [3].

With the widespread adoption of glyphosate-resistant cotton after its introduction in 1997, cotton weed management practices largely shifted away from the use of soil-applied residual herbicides to POST herbicide programs based on glyphosate [20]. Studies conducted in 2006 and 2007 by Legleiter and Bradley [21] confirmed glyphosate resistance in a biotype of common waterhemp (*Amaranthus rudis* Sauer) found in a Missouri soybean field following multiple glyphosate applications. Currently, glyphosate-resistant Palmer amaranth and common waterhemp have been reported in 27 and 18 USA states, respectively [10]. Through surveys sent to weed scientists across the USA, Culpepper [3] revealed that 50% of respondents indicated that weeds of the genus Amaranthus had increased significantly in cotton. The respondents also provided the following four recommendations for managing glyphosate-induced weed species shifts: tank-mix combinations of other herbicides with glyphosate for POST applications, rotating with non-glyphosate-resistant crops (though there was some disagreement among respondents), use of POST herbicides other than glyphosate, and using preplant-incorporated (PPI) or (PRE) soil-applied herbicides.

Amaranthus species are some of the most common weed species found in annual crop production throughout the USA [22]. Palmer amaranth is now ranked as the most troublesome weed found in the USA [23]. It is a common weed in many major crops around the world and is found in all areas of Texas [24]. Up until the 1990s, its distribution in North America was the southern half of the USA [24]; however, since then, it has become established in every state with the exception of the northwestern USA, including Washington, Oregon, Montana, and North Dakota [25]. In Texas, Palmer amaranth can be found in all areas of the state [26] and is one of the two Amaranthus species with confirmed resistant to glyphosate across Texas (common waterhemp is the other) [27]. It is a dioecious, summer-annual species that is native to the desert southwest region of the USA [28, 29]. Plants of the genus Amaranthus are often very problematic weeds in agronomic crops due to their ability to germinate under a wide range of conditions, grow rapidly, and produce large numbers of seed, all while competing with the crop for sunlight, moisture, and nutrients. Despite its origin, Palmer amaranth is able to survive in many diverse environments because of its biological characteristics [6, 30]. It has a lengthy germination window, robust growth habit, and is a prolific seed producer [31–33], and these characteristics make control of this weed difficult. Common waterhemp is an obligate outcrossing annual broadleaf weed that is capable of long-distance pollen dispersal [34]. It germinates optimally between 20/25 and 30/35°C [35], has an aggressive growth habit and may grow 1.6 mm per growing degree day [32], and is capable of producing more than 250,000 seeds per plant [30]. These factors make it a strong competitor with most crops.

Traditional corn and cotton weed management programs have relied on PRE applications of a broadleaf and grass herbicide for residual season-long weed control [36–41]. In corn, these PRE programs usually have included atrazine in combination for broad-spectrum weed control. Atrazine is used in over 60% of the USA corn, and its doses have gotten lower with most doses of no more than 1.12 kg ha^{-1} with some growers applying no more than 0.84 kg ha^{-1} [42]. Atrazine and 4-hydroxylphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides are commonly used for weed control in corn and are effective in controlling glyphosate-resistant weeds, including Palmer amaranth [36, 43, 44]. Atrazine can be applied PRE or POST alone or in tank-mixtures with several herbicides [16].

Since POST herbicides are applied after the weed species and severity are known, this allows growers to assess the problem before making a herbicide application; therefore, POST herbicides are an essential component of an integrated weed management system to combat the herbicide-resistant weeds [45]. In addition, POST herbicides typically do not require rainfall for herbicide activation, making performance less dependent on environmental conditions [45]. Also, POST herbicides can reduce the potential for water pollution [46]. A Minnesota study showed reduced atrazine concentrations in runoff water when applied POST compared with soil-applied applications because of the increased plant residue and cover, limiting the amount of herbicide reaching the soil [47].

Two new herbicide systems have recently become important in POST weed control in cotton [48–53]. Dicamba (3,6-dichloro-2-methoxybenzoic acid) is synthetic auxin herbicide that controls glyphosate-resistant Palmer amaranth and other broadleaf weeds alone or in sequential combinations with glyphosate or glufosinate [48]. An enzyme, dicamba O-demethylase, was discovered in a soil bacterium (*Pseudomonas maltophilia*) that converts dicamba to 3,6-dichlorosalicylic acid (DCSA) [49]. The enzyme DCSA has no significant herbicidal properties. The gene responsible for this enzyme is known as DMO (dicamba monooxygenase). This gene was successfully inserted into mouse-ear cress [*Arabidopsis thaliana (L). Heynh*.], tomato (*Solanum lycopersicum* L.), and tobacco (*Nicotiana tabacum* L.) and showed to provide these plants with effective tolerance to foliar applications of dicamba [49]. Dicamba-tolerant cotton, coupled with existing glyphosate- and glufosinate-tolerant traits, was deregulated in the USA in 2015 and has since become significant portion of the cotton planted in the USA, comprising over 40% of the crop planted in 2016 [50, 51].

Enlist Duo herbicide, a premix formulation containing 195 g ae L^{-1} of 2,4-D choline and 205 g ae L^{-1} of glyphosate dimethylamine, was developed for use in Enlist corn, cotton, and soybean. Resistance to 2,4-D is conferred by the insertion of a gene that codes for the enzyme aryloxyalkanoate dioxygenase. Plants transformed to include this gene can metabolize 2,4-D to a nonlethal form [52]. Developed during World War II, 2,4-D was the first selective herbicide widely used in agriculture [53]. Since that time, researchers have demonstrated control of a large number of dicotyledonous weed species with 2,4-D [54–57].

The adoption of 2,4-D in Enlist crops will be influenced by yield potential of the crop, weed species infesting fields, and, most notably, the ability of growers to mitigate off-target movement of 2,4-D [58–60]. Although Enlist cotton is resistant to 2,4-D [61], all other cotton cultivars, including cotton resistant to dicamba, are extremely sensitive to the herbicide, with reports of cotton injury due to 2,4-D drift dating back to the time of development [62]. Multiple studies showed that exposure to 2,4-D resulted in cotton injury with sensitivity increasing at earlier growth stages and higher herbicide concentrations [63–65].

The prime strategy for managing herbicide resistance in weeds is to reduce the selection pressure for resistance evolution by any one selecting agent, while managing adequate weed control [66]. Selection pressure has the greatest impact on herbicide-resistance evolution and is a factor that growers can control. Selection pressure imposed by an herbicide is the product of efficacy and persistence in the soil [67]. Herbicides applied in crop generally result in the greatest selection pressure compared with other application timings. Selection pressure against a weed population over time, resulting in increasing frequency of resistant individuals that collectively possess one or more resistance mechanisms, is a function of frequency of application [66]. Herbicide sequences, rotations, or mixtures generally have the greatest effect in delaying resistance when the mechanism conferring resistance is target-based, the weed species are highly self-pollinated, and seed spread is restricted [68, 69] and herbicide mixtures may delay resistance longer than rotations [70].

The rapid increase in resistant weeds in corn and cotton and the concerns pertaining to the overuse of atrazine in corn, including detection in surface and groundwater, rotational crop injury, and the development of triazine-resistant weeds, calls for the development of appropriate and effective management techniques. Also, growing questions about the renewed use of PRE and POST herbicides for early season and possibly season-long weed control in corn and cotton have also become a major topic of discussion. Therefore, the objective of this research was to evaluate the effect of various PRE and POST herbicides alone and in combinations for crop tolerance and weed control efficacy in the Texas corn and cotton-producing regions. In cotton, several herbicide programs in glyphosate-, glufosinate-, and dicamba-tolerant cotton were evaluated for their efficacy on both Palmer amaranth and common waterhemp.

2. Materials and methods

2.1. Corn PRE studies in central and south Texas

These studies were conducted during the 2013 through 2015 growing season in central Texas near Taylor (30.5326° N, 97.4548° W) and in south-central Texas near Ganado (29.0438° N, 96.4849° W). Study sites were located in different fields within the same general area of each year. Soils at the Taylor location were a Burleson clay (fine, montmorillonitic, and thermic Udic Pellusterts) with less than 1% organic matter and 7.6 pH, while soils at the Ganado location were a Houston Black clay (fine, montmorillonitic, and thermic Udic Pellusterts) with less than 1% organic matter and 7.4 pH.

Studies were arranged in a randomized complete block design with three replicates. Plot dimensions were two or four corn rows, wide spaced 76–97 cm apart, and 6.3 or 7.9 m long (depending on location). The corn hybrids BH 8846RR (2013), BH 8844VTTP (2014), and BH 8475SS (2015) were planted mid- to late February near Taylor and late February to early March near Ganado in each year to a depth of 2.5–3.5 cm at the rate of 54,000–65,500 seeds ha^{-1}.

Herbicides were applied within 5–7 days after planting with a CO_2-pressurized backpack sprayer with TeeJet 11002 flat-fan nozzles (Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60188) using a pressure of 180 kPa and calibrated to deliver 140 or 187 L ha^{-1} (depending on location). An untreated check was included for comparison at each location. All herbicide doses were based on the USA label dose with the exception of the acetochlor (74.8% formulation) dose which was applied at 2X of the labeled rate throughout the study by mistake. Once the error was realized, it was decided to maintain this dose throughout the study.

Weed populations varied from year to year and were from naturally occurring soil seed bank populations. At the Taylor location, browntop panicum [*Panicum fasciculatum* Sw. var. *reticulatum* (Torr.) Beal] populations in 2013 were moderate (3–4 plants/m^2), while in 2014 populations were higher (6–8 plants/m^2). Common barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] populations in 2015 ranged from 4–8 plants/m^2. At Ganado, Texas millet [*Urochloa texana* (Buckley) R. Webster] populations ranged from 6–10 plants/m^2. Palmer amaranth populations varied from 4–8 plants/m^2 at the Taylor location to 2–10 plants/m^2 at the Ganado location. Hophornbeam copperleaf (*Acalypha ostryifolia* Riddell) populations at Taylor in both years were low to moderate (2–6 plants/m^2), while common sunflower (*Helianthus annuus* L.) populations ranged from 2–6 plants/m^2 depending on the year.

Crop injury and weed control were estimated visually on a scale of 0–100 (0 indicating no control or injury and 100 indicating complete control or plant death). Crop injury consisted of plant stunting and early season (30 days after herbicide application) and late season (95–140 days after application) crop injury was recorded. Late season weed control ratings (95–140 days after herbicide application) are presented for all weeds with the exception of Palmer amaranth control at Ganado in 2015 where populations of this weed were low (<4 plants/m^2) and somewhat inconsistent. Crop yield was determined by hand-harvesting 3.8 m of each plot, shelling the kernels from the corn ear, and weighing the kernels. Crop weights were adjusted to 15% moisture.

Visual estimates of weed control and corn injury were transformed to the arcsine square root prior to analysis of variance but are expressed in their original form for clarity because the transformation did not alter interpretation. Means were compared with Fisher's Protected LSD test at the 5% probability level [71]. The non-treated check was not included in the weed control analysis but was included in corn yield analysis.

2.2. Corn POST studies in central and south Texas

Field studies were conducted during the 2013 through 2015 growing season at two locations in central Texas including near Taylor (30.5326° N, 97.4548° W) and Beyersville (30.3036° N, 97.1947° W) and at three locations in south-central Texas near Kendleton (29.44786° N, 95.99961° W), Ganado (29.0438° N, 96.4849° W), and Yoakum (29.1827° N, 97.0929° W). Where study sites were similar over years, these studies were located in different fields within the same general area. Soils at the central Texas locations near Taylor were a Burleson clay (fine, montmorillonitic, and thermic Udic Pellusterts) with less than 1% organic matter and 7.6 pH, while soils at the Beyersville location soils were a Houston Black clay (fine, smectitic, and thermic Udic

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Haplusterts) with less than 3% organic matter and 7.8 pH. Soils at the south-central locations near Ganado were a Laewest clay (fine, montmorillonitic, and thermic Udic Pellusterts) with less than 1% organic matter and 7.4 pH, soils at Kendleton were a Bernard-Edna complex (fine, smectitic, and hyperthermic Oxyaquic Vertic Argiudolls) with less than 3% organic matter and 6.8 pH. Soils at the Yoakum location were a Cuero sandy clay loam (fine, loamy, mixed, superactive, and thermic Pachic Argiustolls) with less than 2% organic matter and 7.2 pH.

Studies were arranged in a randomized complete block design with three replicates of treatments. Plot dimensions were either two or four rows (depending on location), spaced 76–97 cm apart by 6.3–7.9 m long. The corn varieties BH 8846RR (2013), BH 8844 VTTP (2014), and BH 8475 SS (2015) were planted from mid-February to mid-March depending on locations and environmental conditions to a depth of approximately 2.5–3.5 cm at the rate of 54,000–65,500 seeds ha^{-1}.

Herbicides were applied POST with a CO_2-pressurized backpack sprayer using TeeJet 11002 flat-fan nozzles (Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60188) with a pressure of 180 kPa and calibrated to deliver 140–187 L ha^{-1} (depending on location). An untreated check was included for comparison at each location. All herbicide doses were based on the USA label and included an adjuvant and either ammonium nitrate or sulfate per label requirements.

Weed populations varied from location to location and were from natural seed bank populations in the soil. At the Taylor location, browntop panicum populations in 2013 were sparse (3–4 plants/m^2), while Texas millet populations at Beasley were extremely dense (16–18 plants/m^2) and moderate at Beyersville (6–8 plants/m^2). Common barnyardgrass pressure at Taylor was low to moderate (4–8 plants/m^2). Palmer amaranth populations at the Yoakum and Ganado locations was dense (16–20 plants/m^2), while populations at the Taylor locations were low (4–6 plants/m^2). Pitted morningglory (*Ipomoea lacunose* L.), hophornbeam copperleaf, and Asiatic dayflower (*Commelina communis* L.) populations were low to moderate (4–8 plants/m^2). Approximately 50% of the Palmer amaranth population at the Ganado location was glyphosate resistant.

Weed size at the time of treatment varied by location. Browntop panicum was no greater than 15 cm tall when treated, while Texas millet and common barnyardgrass were less than 20 cm tall at the time of herbicide application. Palmer amaranth at the Yoakum location was less than 5 cm tall at herbicide application, while at Taylor weed size was less than 20 cm. However, at the Ganado location, Palmer amaranth height varied from 40 to 60 cm due to rains which prevented entry into the field in a timely manner. Pitted morningglory length ranged from 5 to 20 cm, while hophornbeam copperleaf and Asiatic dayflower were less than 20 cm in height at the time of treatment. Corn height varied from location to location but was typically in the V4–V8 stage.

Crop injury and weed control were visually estimated on a scale of 0–100 (0 indicating no control or injury and 100 indicating complete control or plant death). Mid- to late season weed control ratings (31–98 days after herbicide application) are presented for all weeds. Crop yield was determined by hand-harvesting 3.8 m of each plot, shelling the kernels from the corn ear, and weighing the kernels. Crop weights were adjusted to 15% moisture.

Visual estimates of weed control and corn injury were transformed to the arcsine square root prior to analysis of variance but are expressed in their original form for clarity because the transformation did not alter interpretation. Means were compared with Fisher's Protected LSD test at the 5% probability level [71]. The non-treated check was not included in the weed control analysis but was included in corn yield analysis.

2.3. Cotton studies in south-central Texas

Studies were conducted in Burleson County, TX (30.3257° N, 96.2615° W) at the Texas A&M AgriLife Research Farm in 2012 and 2013 to investigate management strategies for controlling Palmer amaranth and common waterhemp in cotton possessing glyphosate-, glufosinate-, and dicamba-tolerant transgenic traits. Studies were in the same general area in each year. Soils at this site are characterized as a Westwood silty clay loam (fine, silty, mixed, superactive, and thermic Udifluventic Haplustepts) with 2% organic matter and 8.1 pH. The experiment included 12 treatments arranged as a randomized complete block design with 4 replications. Plots were four rows wide and 9.1 m in length with 102 cm row spacing. Buffers 4.5 m wide were maintained between blocks to facilitate lateral movement of equipment.

This experiment was conducted on a furrow-irrigated field with large seed bank populations of both Palmer amaranth and common waterhemp. Both Palmer amaranth and common waterhemp were naturally occurring populations with 10–15 plants/m^2. In 2012, none of the Palmer amaranth or common waterhemp populations were glyphosate resistant, while in 2013 approximately 10% of the Palmer amaranth population was resistant; however, none of the waterhemp populations were resistant. Treatments included preplant-incorporated (PPI), PRE, and two POST application timings of an early POST (EPOST) and mid-POST (MPOST). Plots receiving PPI applications of trifluralin were subjected to two passes of a rolling cultivator immediately following application to thoroughly incorporate the herbicide into the soil. Preemergence herbicide applications included fomesafen, pendimethalin, prometryn, pyrithiobac, and *S*-metolachlor, while POST applications included acetochlor, dicamba, glufosinate, glyphosate, pyrithiobac, and trifloxysulfuron. Early postemergence applications in 2012 were made when weeds were approximately 12 cm tall and in 2013 when weeds were 10 cm in height, while MPOST treatments in 2012 were made when weeds were 25 cm tall and in 2013 when 15 cm in height. An untreated check was included in all studies.

For the 2012 experiment, PPI applications were made on May 7, cotton was planted on May 22, EPOST applications were made on June 21, and MPOST applications were made on July 4. In 2013, PPI applications were made on May 8, cotton was planted on May 9, EPOST applications were made on June 7, and MPOST applications were made on June 16. The cotton variety was an experimental dicamba-glyphosate tolerant entry from Monsanto. Herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} total spray volume. Preplant-incorporated and PRE applications were made using TeeJet 11003 Drift Guard flat-fan nozzles, while EPOST and MPOST applications were made with TeeJet 110015 Turbo TeeJet Induction flat-fan nozzles (TeeJet Technologies, Wheaton, Illinois 60187).

Control of Palmer amaranth and common waterhemp was estimated visually at the time of the EPOST application, at the time of MPOST application, and 14 days after the MPOST application.

These observations are reported as early, mid, and late, respectively. Plots were managed throughout the season according to standard crop management practices for this region. The center two rows of all plots were mechanically harvested and seed cotton yields were recorded. Means were compared with Fisher's Protected LSD test at the 5% probability level [71].

2.4. Cotton studies in the High Plains of Texas

Field studies were conducted near New Deal (33.4413° N, 101.4358° W) and Halfway, TX (34.1881° N, 101.9522° W) during the 2015 and 2016 growing seasons to investigate management strategies for controlling Palmer amaranth in cotton possessing glyphosate-, glufosinate-, dicamba-, and 2,4-D choline-tolerant transgenic traits. Soils at the New Deal site are characterized as a Pullman clay loam (fine, mixed, and superactive thermic Torrertic Paleustolls) with less than 1% organic matter and 7.9 pH, while soils at New Deal are a Olton clay loam (fine, mixed, and thermic Aridic Paleustoll) with less than 1% organic matter and a 7.4 pH. These experiments were conducted under center pivot irrigation at Halfway and 102 cm spacing of sub-surface drip tape at New Deal with large populations of Palmer amaranth (8–10 plants/m^2). These studies were conducted as a randomized complete block design with four replications. Plots were four rows wide and 9.1–12.7 m in length, with 102 cm row spacing.

Treatments for the glyphosate plus 2,4-D choline study (Enlist Duo) included PPI treatments of trifluralin and EPOST and MPOST treatments of glyphosate, glufosinate, glyphosate plus 2,4-D choline, *S*-metolachlor, and 2,4-D choline salt. Plots receiving PPI applications of trifluralin were subjected to two passes of a rolling cultivator immediately following application. Postemergence applications were made when Palmer amaranth was 15 cm or less in height. This study was conducted in 2016. The cotton variety was an experimental from Dow AgroSciences (9330 Zionsville Rd, Indianapolis, IN 46268) and was planted on May 26 at a seeding rate of 13.1 seeds m^{-1} of row.

Treatments for the glyphosate systems study included preplant applications of glyphosate plus either flumioxazin, fomesafen, the premix of rimsulfuron plus thifensulfuron-methyl, or diruron, PRE applications of either flumeturon, pyrithiobac, acetochlor, or flumeturon plus paraquat, EPOST applications of glyphosate alone or plus either acetochlor, *S*-metochlor, dimethenamid-P, or pyrithiobac, MPOST applications of glyphosate alone or plus acetochlor, dimethenamid-P, or S-metochlor, and LPOST treatments of diruron plus MSMA. Postemergence applications were made when Palmer amaranth was 10 cm or less in height. This study was conducted in 2015 and 2016. Fibermax 2322GL was planted in both years with the same seeding rate as in the previous study.

Herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 93–140 L ha^{-1} total spray volume. PPI and PRE applications were made using TeeJet 11002 Drift Guard flat-fan nozzles, while EPOST and MPOST applications were made with TeeJet 110015 Turbo TeeJet Induction flat-fan nozzles. A Redball® tractor-mounted hooded sprayer (Willmar Fabrication, LLC; Willmar, MN 56201) was used for LPOST herbicide applications.

Control of Palmer amaranth was estimated visually as in previous studies. Plots were managed throughout the season according to standard crop management practices for this region.

The center two rows of all plots were mechanically harvested, and lint cotton yields were recorded. Means were compared with Fisher's Protected LSD test at the 5% probability level [71].

3. Results and discussion

Although the primary emphasis in this chapter is the discussion on controlling Palmer amaranth and, to some extent, common waterhemp which have become troublesome weeds in corn and cotton, other weed species will be discussed since they are/can become problematic weeds as well.

3.1. Corn PRE studies

Since not all treatments were included in each year of the study, no attempt was made to combine results over years or locations. Also, rainfall amounts varied from site to site and year to year affecting herbicide response (**Table 1**). Rainfall during the 7 days after the application of PRE herbicide treatments occurred at all locations with the exception of Ganado in 2013 and 2014 when no rainfall occurred. Rainfall between 8 and 14 days after the PRE application varied from no rainfall at Ganado in 2013 to 78.2 mm at Ganado in 2015 (**Table 1**). Rainfall 15–21 days after the PRE application was low at Taylor in 2013 and Ganado in 2015, and no rainfall occurred at the other sites.

With respect to annual grasses, browntop panicum and Texas millet were present in 2013 and 2014 at the Taylor and Ganado sites, respectively. Common barnyardgrass was present at Taylor only in 2015. Broadleaf weeds were present at the Taylor and Ganado locations. Palmer amaranth was present in 2013 and 2015, while hophornbeam copperleaf and common sunflower were present in 2013 and 2014. Although this chapter discusses the control of herbicide-resistant weeds, the control of other weeds will also be discussed since they are also a large part of the problem when providing effective weed control under normal growing conditions.

3.1.1. Annual grass control

Atrazine alone controlled common barnyardgrass 33%, while acetochlor (74.8%) or pendimethalin alone, acetochlor plus atrazine, *S*-metolachlor plus mesotrione, or *S*-metolachlor plus

	2013		**2014**		**2015**	
	Taylor	**Ganado**	**Taylor**	**Ganado**	**Taylor**	**Ganado**
Day	**Mm**					
1–7	29.5	0	2.8	0	7.4	3.3
8–14	6.6	0	0.5	18.6	65.6	78.2
15–21	7.3	0	0	0	0	3.3

Table 1. Rainfall amounts at test locations for 21 days following application of PRE herbicides.

atrazine plus mesotrione provided 90–97% control (**Table 2**). The dinitroaniline herbicides, such as pendimethalin, are registered for use in over 40 crops [72]. These herbicides usually provide excellent control of annual grasses [73–75].

In 2013, pendimethalin alone, alachlor plus atrazine, *S*-metolachlor plus mesotrione, or *S*- metolachlor plus atrazine plus mesotrione provided 96% or better browntop panicum control, while isoxaflutole, *S*-metolachlor, and pyroxasulfone alone, and *S*-metolachlor plus atrazine controlled this weed 80–88% (**Table 2**). In 2014, only the dose of acetochlor (74.8%) provided acceptable control (83%). The lack of effective control in 2014 can be attributed to greater plant populations at the test site in 2014 compared to 2013 and also the low rainfall amounts after the PRE application in 2014 (**Table 1**). Since many of the PRE herbicides can volatilize and photodecompose on the soil surface over time, these herbicides need to be mechanically incorporated or need rainfall or irrigation to move these herbicides into the weed seed zone [76–78], which explains the erratic control noted with these herbicides under the droughty conditions observed at Taylor in 2014.

		Browntop panicum		**Texas millet**		**Barnyardgrass**
	Dose	**2013**	**2014**	**2013**	**2014**	**2015**
Treatment	**Kg ai ha^{-1}**	**Taylor**		**Ganado**		**Taylor**
		Days after treatment				
		95	138	109	112	101
		%				
Atrazine (A)	1.1	33	3	23	0	33
Fluthiacet-methyl (FM)+pyroxasulfone (P)	0.006+0.2	-	-	-	-	58
(FM)+(P)+(A)	0.004+0.2+1.3	-	-	-	-	40
S-metolachor (S)	1.3	82	57	78	75	68
Isoxaflutole	0.05	80	38	94	80	67
(S)+(A)	1.4+1.8	85	53	86	83	63
Alachlor+(A)	2.5+1.5	99	-	89	-	-
Mesotrione (M)	0.1	37	8	53	88	55
Thiencarbazone-methyl+isoxaflutole	0.02+0.06	47	15	98	72	73
Acetochlor+(A)	2.1+1.3	72	0	98	86	90
(S)+(A)+(M)+bicyclopyrone	0.4+0.8+0.09+0.02	-	-	-	-	65
Dimethenamid-P+(A)	1.6+3.2	55	45	85	58	89
Acetochlor (74.8%)	6.9	-	83	-	73	97
Rimsulfuron+(M)	0.02+0.2	60	33	77	47	-
Rimsulfuron+thifensulfuron-methyl	0.02+0.02	74	10	60	61	40
(S)+(A)+(M)	1.5+1.5+0.2	98	44	83	73	92

		Browntop panicum		Texas millet		Barnyardgrass
	Dose	2013	2014	2013	2014	2015
Treatment	Kg ai ha^{-1}	Taylor		Ganado		Taylor
Dimethenamid-P	0.8	78	53	55	63	73
Pendimethalin	1.6	96	52	86	99	97
Saflufenacil	0.05	69	7	81	23	33
Saflufenacil+dimethenamid-P	0.08+0.7	61	28	92	78	57
Acetochlor (33%)	1.7	75	10	78	96	63
(S)+(M)	2.8+0.3	98	65	67	95	96
(P)	0.1	88	37	75	99	42
Untreated	-	0	0	0	0	0
LSD (0.05)		33	33	22	48	29

Table 2. Annual grass control in corn with PRE herbicides.

In 2013, isoxaflutole alone, thiencarbazone-methyl plus isoxaflutole, acetochlor plus atrazine, or saflufenacil plus dimethenamid-P controlled Texas millet at least 92% (**Table 2**). Pendimethalin or saflufenacil alone, atrazine plus either *S*-metolachlor, alachlor, or dimethenamid-P, and the three-way combination of *S*-metolachlor plus atrazine plus mesotrione provided 81–89% control. In 2014, acetochlor, pendimethalin, or pyroxasulfone alone or *S*-metolachlor plus mesotrione controlled this weed at least 95%, while isoxaflutole or mesotrione alone and atrazine plus either acetochlor or *S*-metolachlor controlled 83–89% (**Table 2**). In the two years, *S*-metolachlor alone provided 75–78% Texas millet control compared with 75–99% control with pyroxasulfone. Typically, *S*-metolachlor alone provides poor control of this weed [79, 80]. With high populations of Texas millet, Grichar et al. [79] reported less than 70% control with 1.7 and 3.4 kg ha^{-1} of metolachlor in dryland peanut (*Arachis hypogaea* L.) and 25–76% control under irrigated conditions. Steele et al. [80] reported that pyroxasulfone, at a 10-fold lower use rate than *S*-metolachlor, controlled Texas millet 84–96%, while *S*-metolachlor provided 75–85% control when rated 9 weeks after treatment. They attributed the results to the longer residual activity of pyroxasulfone [81].

3.1.2. Broadleaf weed control

At Taylor in 2013, under moderate weed pressure (4 plants m^2), all herbicides, with the exception of atrazine (73%), provided at least 97% Palmer amaranth control, while in 2015 under increased populations (8 plants m^2), atrazine controlled Palmer amaranth 79%, while isoxaflutole, mesotrione, or saflufenacil provided no better than 71% control (**Table 3**). All other herbicide treatments provided at least 96% control. At the Ganado location, in 2013 and 2015, control was more erratic than at the Taylor location. This may be due to the greater weed populations noted in 2013 (10 plants m^2) and variable populations in 2015. In 2013, either atrazine or isoxaflutole alone, acetochlor, alachlor, *S*-metolachlor, or dimethenamid-P plus atrazine, or

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the three-way combination of *S*-metolachlor plus atrazine plus mesotrione provided 97–100% control, while mesotrione, dimethenamid-P, or acetochlor (33%) alone and rimsulfuron plus mesotrione controlled this weed 61% or less (**Table 3**). In 2015, acetochlor (74.8%) alone, dimethenamid-P plus atrazine, fluthiacet-methyl plus pyroxasulfone, and saflufenacil plus dimethenamid-P controlled Palmer amaranth at least 95%, while isoxaflutole, mesotrione, *S*-metolachlor, and pendimethalin alone and rimsulfuron plus thifensulfuron-methyl controlled this weed less than 70%.

In previous research, mesotrione applied PRE controlled smooth pigweed (*Amaranthus hybridus* L.), but control of morningglory species (*Ipomoea* spp.) and common lambsquarter (*Chenopodium album* L.) was inconsistent and dependent upon a timely rainfall following application [38, 82]. Armel et al. [38] reported improved weed control with mixtures of mesotrione plus acetochlor or atrazine over that of mesotrione alone. As seen in this study, the combination of mesotrione with metolachlor plus atrazine has enhanced weed control in other studies [38].

		2013		**2015**	
Treatment	**Dose**	**Taylor**	**Ganado**	**Taylor**	**Ganado**
	Kg ai ha^{-1}	Days after treatment			
		95	109	101	44
		%			
Atrazine (A)	1.1	73	99	79	72
Fluthiacet-methyl (F)+pyroxasulfone (P)	0.006 + 0.2	-	-	99	98
(F)+(P)+(A)	0.004 + 0.2 + 1.3	-	-	40	93
Isoxaflutole	0.05	100	98	51	67
S-metolachlor (S)	1.35	100	76	99	69
(S)+(A)	1.4 + 1.8	100	99	99	92
Alachlor+(A)	2.5 + 1.5	100	99	-	-
Mesotrione (M)	0.1	99	61	71	52
Thiencarbazone-methyl+isoxaflutole	0.02 + 0.06	100	92	99	83
(S)+(A)+(M)+bicyclopyrone	0.4 + 0.8	-	-	99	72
	0.09 + 0.02				
Acetochlor+(A)	2.1 + 1.3	100	100	99	93
Dimethenamid-P+(A)	1.6 + 3.2	100	100	99	95
Acetochlor (74.8%)	6.9	-	-	100	100
Rimsulfuron+(M)	0.02 + 0.2	100	27	-	-
Rimsulfuron+thifensulfuron-methyl	0.02 + 0.02	99	90	98	37
(S)+(A)+(M)	1.5 + 1.5 + 0.2	100	97	99	90

		2013		2015	
Treatment	**Dose**	**Taylor**	**Ganado**	**Taylor**	**Ganado**
Dimethenamid-P	0.8	98	53	96	92
Pendimethalin	1.6	97	83	98	47
Saflufenacil	0.05	99	72	70	73
Saflufenacil+dimethenamid-P	0.08 + 0.7	100	95	99	100
Acetochlor (33%)	1.7	100	50	99	88
(S)+(M)	2.8 + 0.3	100	91	100	94
(P)	0.12	100	91	99	84
Untreated	-	0	0	0	0
LSD (0.05)		17	27	22	24

Table 3. Palmer amaranth control in corn with PRE herbicides.

In 2013, thiencarbazone-methyl plus isoxaflutole provided perfect control (100%) of hophornbeam copperleaf while acetochlor (33%), saflufenacil or pyroxasulfone alone, alachlor plus atrazine, rimsulfuron plus thifensulfuron-methyl, *S*-metolachlor plus atrazine plus mesotrione, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione controlled this weed at least 92% (**Table 4**). Atrazine and mesotrione alone and rimsulfuron plus mesotrione provided unacceptable control (<60%). In 2014, either acetochlor (74.8%), isoxaflutole, saflufenacil, or pyroxasulfone alone controlled hophornbeam copperleaf at least 93% (**Table 4**). The combinations of *S*-metolachlor plus either atrazine or mesotrione and saflufenacil plus dimethenamid-P controlled this weed 90–98%, while rimsulfuron plus either mesotrione or thifensulfuron-methyl and acetochlor (33%) provided 67–70% control.

In 2013, under low common sunflower pressure (2–3 plants m^2), all herbicides, with the exception of atrazine alone (73%) and rimsulfuron plus thifensulfuron-methyl (87%), controlled this weed at least 95% (**Table 4**). In 2014, under slightly greater common sunflower populations (4–6 plants m^2), control was more variable. Acetochlor (74.8%) alone, thiencarbazone-methyl plus isoxaflutole, rimsulfuron plus thifensulfuron-methyl, saflufenacil plus dimethenamid-P, and *S*-metolachlor plus mesotrione controlled this weed at least 97%. Mesotrione, pendimethalin, or pyroxasulfone alone provided unacceptable control (<60%). The development of ALS-resistant common sunflower has limited the options for growers having to control common sunflower with POST herbicides [83, 84]. Results from this study are consistent with previous findings which found that common sunflower control with herbicide systems containing isoxaflutole was at least 85% in most instances [84, 85].

3.1.3. Corn injury and yield

Grain yields were obtained only in 2013 at both locations and in 2015 at Taylor. Early season crop injury consisted of stunting and was never more than 3% with any herbicide treatment (data not shown). Corn recovered from the slight early season stunting and typically by harvest

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		Hophornbeam copperleaf		Common sunflower	
		2013	**2014**	**2013**	**2014**
		Days after treatment			
Treatment	Dose	95	109	95	48
	Kg ai ha^{-1}	%			
Atrazine (A)	1.1	38	80	73	77
Isoxaflutole (I)	0.05	77	98	100	79
S-metolachlor (S)	1.25	79	83	97	77
(S)+(A)	1.4 + 1.8	76	90	100	85
Alachlor+(A)	2.5 + 1.5	93	-	98	-
Mesotrione (M)	0.1	55	60	99	60
Thiencarbazone-methyl+(I)	0.02 + 0.06	100	77	98	100
Acetochlor+(A)	2.1 + 1.3	79	-	99	-
Dimethenamid–P (D)	0.8	72	82	97	79
(D)+(A)	1.7 + 3.2	80	72	97	93
Acetochlor (74.8% formulation)	6.8	-	99	-	97
Rimsulfuron (R)+(M)	0.02 + 0.2	60	67	97	93
(R)+thifensulfuron-methyl	0.02 + 0.02	98	70	87	99
(S)+(A)+(M)	1.5 + 1.5 + 0.2	98	74	100	87
Pendimethalin	1.6	69	85	95	58
Saflufenacil (Sa)	0.05	96	98	100	90
(Sa)+(D)	0.08 + 0.7	99	98	100	97
Acetochlor (33% formulation)	1.7	92	63	100	72
(S)+(M)	2.8 + 0.3	92	93	99	98
Pyroxasulfone	0.12	96	93	97	55
Untreated	-	0	0	0	0
LSD (0.05)		34	30	20	36

Table 4. Hophornbeam copperleaf and common sunflower control in corn with PRE herbicides.

no differences in corn plant growth between the untreated check and any herbicide treatments were noted (data not shown). Although no appreciable crop injury was noted in these studies, this is not always true. Instances of isoxaflutole phytotoxicity in corn have been documented [85, 86] and attributed to several factors, including application timing [87], increased use dose [37], and varied susceptibility of corn hybrids to isoxaflutole [88]. Environmental factors (cool and wet) and soil characteristics [89] can also lead to corn injury by isoxaflutole. Johnson et al. [85] reported that PPI herbicide applications resulted in greater injury than PRE applications, and this was probably due to increased amount of precipitation. Armel et al. [38] reported that acetochlor, atrazine, or mesotrione combinations did cause 11–18% corn stunting when followed by 32 mm of rainfall, but that the corn recovered quickly and by 4 weeks after treatment injury did not exceed 2%.

In 2013 at the Taylor location, atrazine, isoxaflutole, and pyroxasulfone alone, *S*-metolachlor plus atrazine and/or mesotrione produced grain yields that were greater than the untreated check (**Table 5**). Although not significant, all herbicide treatments resulted in a numerical increase in grain yield over the untreated check. At the Ganado location, grain yields from the herbicide treatments were not significantly different from the untreated check; however, all yields from the herbicide treatments were numerically greater than the untreated check with the exception of *S*-metolachlor plus mesotrione which produced a 10% decrease in yield from the untreated check. No reason for this reduction can be determined.

In 2014, no significant differences between the untreated check and any herbicide treatments were noted, although several herbicide treatments produced numerically greater yields than the untreated check (**Table 5**). Dimethenamid-P and pyroxasulfone alone, fluthiacet-methyl plus pyroxasulfone, thiencarbazone-methyl plus isoxaflutole, dimethenamid-P plus atrazine, *S*-metolachlor plus atrazine plus mesotrione, and saflufenacil plus dimethenamid-P produced grain yields that were 14–21% greater than the untreated check.

		2013		**2015**
Herbicide treatment	**Dose**	**Taylor**	**Ganado**	**Taylor**
	Kg ai ha^{-1}	**Kg ha^{-1}**		
Atrazine (A)	1.1	5586	7695	7556
Fluthiacet-methyl (FM)+pyroxasulfone (P)	0.006+0.2	-	-	9342
(F)+(P)+(A)	0.004+0.2+1.3	-	-	8092
S-metolachlor (S)	1.3	5143	7082	8806
Isoxaflutole (I)	0.05	5434	6980	7669
(S)+(A)	1.4+1.8	5396	7627	8582
Alachlor+(A)	2.5+1.5	4940	7466	-
Mesotrione (M)	0.1	4851	7727	8970
Thiencarbazone-methyl+(I)	0.02+0.06	5256	7318	9494
Acetochlor+(A)	2.1+1.3	4915	7031	8899
Dimethenamid-P (D)	0.8	5275	7172	9447
(D)+(A)	1.6+3.2	5294	8350	9611
Acetochlor (74.8%)	6.9	-	-	8738
Rimsulfuron (R)+(M)	0.02+0.2	4972	8295	-
(R)+thifensulfuron-methyl	0.02+0.02	5168	7991	7934

		2013		2015
Herbicide treatment	**Dose**	**Taylor**	**Ganado**	**Taylor**
	Kg ai ha^{-1}	**Kg ha^{-1}**		
(S)+(A)+(M)	1.5+1.5+0.2	5589	8556	9962
Pendimethalin	1.6	5264	7881	8958
Saflufenacil	0.05	4524	8311	7477
Saflufenacil+dimethenamid-P	0.08+0.7	4906	7495	9377
Acetochlor (33%)	1.7	5099	8310	8691
(S)+(M)	2.8+0.3	5501	6160	8695
Pyroxasulfone	0.1	5346	7548	9691
Untreated	-	4506	6816	8218
LSD (0.05)		796	1800	1969

Table 5. Corn yield as influenced by PRE herbicides.

With glyphosate-resistant pigweed becoming more widespread throughout the state, the use of soil-applied herbicides can not only control resistant weed species in glyphosate-resistant corn production systems but can also reduce the risk of new herbicide-resistant weed species occurring. In general, many treatments with two or three herbicide modes of action provided better weed control than one herbicide alone, and the chance of corn injury appears to be minimal with any herbicide combinations under normal growing conditions. Our results indicate that in a year with little or no rainfall within 7–14 days after PRE herbicide application, any combination of PRE herbicides may need to be followed by POST herbicides for control of escaped weeds.

3.2. Corn POST Studies

3.2.1. Annual grass control

Limited control of browntop panicum was noted when using POST herbicides. Glyphosate and tembotrione alone provided 99% browntop panicum control, while the combinations of atrazine plus *S*-metolachlor plus glyphosate, mesotrione plus *S*-metolachlor plus glyphosate, and thiencarbazone-methyl plus tembotrione provided 96–98% control (**Table 6**). Mesotrione and topramezone alone and the combination of primisulfuron-methyl plus pyroxasulfone controlled this weed 77–83%; however, no other herbicides provide better than 68% control. Stephenson et al. [13] noted that thiencarbazone plus tembotrione controlled browntop millet (*Urochloa ramose* L.) 93% which was greater than tembotrione, atrazine, or glufosinate alone. They also noted that the co-application of atrazine, glufosinate, or glyphosate with thiencarbazone plus tembotrione did not increase browntop millet control.

In 2014 at Beasley only nicosulfuron, primisulfuron-methyl, and topramezone alone or the combination of pyroxasulfone plus glyphosate provided acceptable Texas millet control (>84%), while at Beyersville only the combinations of mesotrione plus *S*-metolachlor plus glyphosate and fluthiacet-methyl plus pyroxasulfone plus atrazine controlled this weed at least 81% (**Table 6**). Prostko et al. [88] found that glyphosate applied sequentially was more effective at controlling Texas millet than either nicosulfuron or foramsulfuron. Again, the added control noted with pyroxasulfone can be attributed to the extended residual activity of this herbicide [81].

The combinations of atrazine plus *S*-metolachlor plus mesotrione plus bicyclopyrone, atrazine plus *S*-metolachlor plus glyphosate, dimethenamid plus glyphosate, fluthiacet-methyl plus pyroxasulfone plus glyphosate, mesotrione plus *S*-metolachlor plus glyphosate, pyroxasulfone plus glyphosate, and thiencarbazone-methyl plus tembotrione controlled barnyardgrass at least 93% (**Table 6**). Lamore et al. [89] reported that tembotrione at 92 g ha^{-1} provided greater than 90% control, which is similar to the results in this study. Stephenson et al. [13] reported that thiencarbazone plus tembotrione or tembotrione alone provided equivalent control of barnyardgrass to atrazine plus either glufosinate or glyphosate.

		2013	**2014**		**2015**
	Dose	**Browntop panicum**	**Texas millet[g]**		**Barnyardgrass**
Herbicide treatment	**Kg ai or ae ha^{-1}**	**Taylor**	**Bea**	**Beyers[h]**	**Taylor**
		Days after treatment			
		98	69	93	53
		%			
Atrazine (A)[c]	1.1	45	-	58	70
Carfentrazone-ethyl[a, d]	0.02	66	-	-	60
Fluroxypyr[a, c]	0.3	64	-	68	40
Fluthiacet-methyl (FM)[a, c]	0.07	43	-	53	39
Glufosinate ammonium[a]	0.7	-	-	-	85
Glyphosate (G)	1.5 ae	99	25	63	85
Halosulfuron-methyl (HM) [a, c]	0.07	49	-	72	20
Mesotrione (M)[a, c]	0.1	79	-	57	58
Nicosulfuron[b, d]	0.04	-	84	-	-
Primisulfuron-methyl (PM)[b, d]	0.04	68	89	-	-
Prosulfuron[c]	0.04	65	-	40	20
Tembotrione[a, e]	0.09	99	37	73	87
Topramezone[a, c]	0.15	77	88	77	-
(A)+*S*-metolachlor (S)+(M)+ bicyclopyrone[a, c]	0.7+1.5+ 0.17+0.04	-	-	-	93
(A)+(S)+(G)[a, c]	1.8+1.5+0.8 ae	98	56	73	99
Diflufenzopyr+dicamba (D)[a, c]	0.06+0.1 ae	59	-	-	50
Dimethenamid+(G)	0.8+1.54 ae	-	-	73	99

		2013	2014		2015
	Dose	Browntop panicum	Texas millet[g]		Barnyardgrass
Herbicide treatment	Kg ai or ae ha^{-1}	Taylor	Bea	Beyers[h]	Taylor
(FM)+(M)[a, c]	0.09+0.09	-	-	-	55
(FM)+pyroxasulfone (P)+(A)[d]	0.004+0.2+1.3	-	-	96	62
(FM)+(P)+(G)[d]	0.004+0.2+1.5 ae	-	-	-	100
(HM)+(D)[a, c]	0.07+0.1 ae	52	-	72	40
(M)+(S)+(G)[a, c]	0.1+1.1+1.1 ae	96	55	81	98
(PM)+(P)[a, c]	0.03 + 0.01	83	74	70	43
Pyroxasulfone+(G)	0.1+1.5 ae	-	96	53	96
Thiencarbazone-methyl+tembotrione[a, c]	0.02+0.07	98	53	53	98
Untreated	-	0	0	0	0
LSD (0.05)		34	18	20	28

[a] AMS (ammonium sulfate) at 3.86 kg/378.4 L.
[b] UAN (urea-ammonium nitrate) added at 2.2 L.
[c] Crop oil concentrate (Agridex) added at 1.0% v/v.
[d] Non-ionic surfactant (Induce) added at 0.25% v/v.
[e] Methylated seed oil (Phase) added at 1.1 L.
[f] Grass height at application: Taylor, ≤ 15 cm; Besley, ≤ 10 cm; Coupland, ≤ 5 cm; Taylor, ≤ 15 cm.
[g] Texas millet locations: Bea, Beasley; Beyers, Beyersville.
[h] Glyphosate at 1.54 kg ae ha^{-1} added to all treatments with the exception of glufosinate ammonium and glyphosate alone.

Table 6. Annual grass control in corn with POST herbicides[f].

3.2.2. Broadleaf weed control

In 2014 at Yoakum, under dense Palmer amaranth populations, atrazine, prosulfuron, and topramezone alone or the combinations of atrazine plus *S*-metolachlor plus glyphosate, diflufenzopyr plus dicamba, dimethenamid plus glyphosate, halosulfuron-methyl plus dicamba, mesotrione plus *S*-metolachlor plus glyphosate, pyroxasulfone plus glyphosate, and thiencarbazone-methyl plus tembotrione provided at least 91% control (**Table 7**). Armel et al. [38] reported improved weed control with mixtures of mesotrione plus acetochlor or atrazine.

At the Taylor location in 2015, under low populations, only carfentrazone-ethyl, fluroxypyr, fluthiacet-methyl, and primisulfuron-methyl plus pyroxasulfone failed to provide at least 85% Palmer amaranth control. At the Ganado location, only pyroxasulfone plus glyphosate controlled this weed at least 80%, and this general lack of control was probably due to weed height (40–60 cm) at the time of herbicide application. Herbicide application to weeds 10–15 cm tall can result in corn grain yields equal to those in weed-free plots [90], but POST applications when weeds are greater than 15 cm tall provided inconsistent season-long weed control when compared with applications when weeds are less than 15 cm tall [91]. Stephenson et al. [13] reported that atrazine alone provided 96% control of this weed, while thiencarbazone plus tembotrione or tembotrione, glufosinate, and glyphosate alone provided 92% or less control.

Glyphosate alone provided 100% pitted morningglory control, while mesotrione plus *S*- meto-lachlor plus glyphosate controlled this weed 82% (**Table 8**). Typically, glyphosate provides inadequate control of pitted morningglory when applied alone at normal label use doses [92–94]. However, greater than 90% late season control of tall morningglory (*Ipomoea purpurea* L.), ivyleaf morningglory (*I. hederacea* L.), and entireleaf morningglory (*I. hederacea* var. *integriuscula* Gray) in the field has been documented with 1.12 kg ha^{-1} of glyphosate applied to plants with six true leaves or less [95]. However, sequential in-season glyphosate applications are often required to provide similar levels of pitted morningglory control [96, 97]. No other herbicides provided better than 68% control. Bararpour et al. [98] observed 90–100% control of entireleaf and pitted morningglory with the combination of thiencarbazone plus tembotrione plus either atrazine, glufosinate, or glyphosate, while Stephenson et al. [13] observed 85–88% control with thiencarbazone plus tembotrione alone.

	Dose	**2014**	**2015**	
Herbicide treatment	**Kg ai or ae ha^{-1}**	**Yoakum**	**Taylor**	**Ganado**[g]
		Days after treatment		
		40	53	32
		%		
Atrazine (A)[c]	1.1	100	100	43
Carfentrazone-ethyl[a, d]	0.02	67	20	25
Fluroxypyr[a, c]	0.3	48	70	10
Fluthiacet-methyl (FM)[a, c]	0.07	58	54	33
Glufosinate ammonium[a]	0.7	63	100	58
Glyphosate (G)	1.5 ae	68	100	59
Halosulfuron-methyl (HM)[a, c]	0.07	53	85	13
Mesotrione (M)[a, c]	0.1	83	100	55
Prosulfuron[c]	0.04	91	98	33
Tembotrione[a, e]	0.1	83	100	63
Topremazone[a, c]	0.15	97	100	63
(A)+*S*-metolachlor(S)+(M) +bicyclopyrone[a, c]	0.8+1.5+0.2+0.04	-	99	75
(A)+(S)+(G)[a, c]	1.8+1.5+0.8 ae	100	99	73
Diflufenzopyr+dicamba (D)[a, c]	0.06+0.14 ae	91	99	65
Dimethenamid-P+(G)	0.8+1.5 ae	100	100	67
(FM)+(M)[a, c]	0.09+0.09	-	100	47

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	Dose	2014	2015	
Herbicide treatment	Kg ai or ae ha^{-1}	Yoakum	Taylor	Ganado[g]
(FM)+pyroxasulfone (P)+(G)[d]	0.004+0.15+1.3 ae	-	100	69
(FM)+(P)+(A)[d]	0.004+0.15+1.5	-	99	43
(HM)+(D)[a, c]	0.07+0.3 ae	99	100	60
(M)+(S)+(G)[a, c]	0.1+1.1+1.1 ae	100	100	60
Primisulfuron-methyl+(P)[b, c]	0.03+0.01	67	78	7
Pyroxasulfone+(G)	0.1+1.5 ae	99	100	80
Thiencarbazone-methyl+tembotrione[a, c]	0.02 + 0.07	100	100	58
Untreated	-	0	0	0
LSD (0.05)		16	22	25

[a] AMS (ammonium sulfate) added at 3.86 kg/378.4 L.
[b] UAN (urea-ammonium nitrate) added at 2.2 L.
[c] Crop oil concentrate (Agridex) added at 1.0% v/v.
[d] Non-ionic surfactant (Induce) added at 0.25% v/v.
[e] Methylated seed oil (Phase) added at 1.1 L.
[f] *A. palmeri* height at application: Yoakum, ≤ 7.6 cm; Taylor, ≤ 10 cm; Ganado, ≤ 61 cm.
[g] Glyphosate at 1.54 kg ae ha^{-1} added to all treatments with the exception of glyphosate and glufosinate ammonium alone.

Table 7. Palmer amaranth control in corn with POST herbicides[f].

		2013		2015
Herbicide treatment	Dose	Pitted morningglory	Hophornbeam copperleaf	Asiatic dayflower
	Kg ai or ae ha^{-1}	Days after treatment		
		60	60	31
		%		
Atrazine (A)[c]	1.1	12	85	45
Carfentrazone-ethyl[a, d]	0.02	15	84	-
Dicamba (D)[c]	0.56	20	54	-
Fluroxypyr[a, c]	0.3	20	40	-
Fluthiacet-methyl (FM)[a, c]	0.07	7	91	55
Glufosinate ammonium[a]	0.7	-	-	90
Glyphosate (G)	1.5 ae	100	79	62
Halosulfuron-methyl (HM) [a, c]	0.07	13	73	-
Mesotrione (M)[a, c]	0.1	47	64	84

		2013		2015
Herbicide treatment	**Dose**	**Pitted morningglory**	**Hophornbeam copperleaf**	**Asiatic dayflower**
	Kg ai or ae ha^{-1}	**Days after treatment**		
Primisulfuron-methyl (PM)[b, d]	0.04	50	65	-
Prosulfuron[c]	0.04	25	86	-
Tembotrione[a, e]	0.1	53	90	65
Topramezone[a, c]	0.15	36	74	82
A + *S*-metolachlor (S)+(M)+ bicyclopyrone[a, c]	0.8+1.5+0.2+0.04	-	-	93
(A)+(S)+(G)[a, c]	1.8+1.5+0.8 ae	63	99	93
Diflufenzopyr+(D)[a, c]	0.06+0.14 ae	30	62	79
(FM)+(M)[a, c]	0.09+0.09	-	-	78
(FM)+pyroxasulfone (P)+ (A)[d]	0.004+0.15+1.3	-	-	70
(HM)+(D)[a, c]	0.07+0.3 ae	20	40	83
(M)+(S)+(G)[a, c]	0.1+1.1+1.1 ae	82	92	81
Primisulfuron-methyl+(P)[b, c]	0.03+0.01	3	76	-
Thiencarbazone-methyl+tembotrione[a, c]	0.02+0.07	68	81	72
Untreated	-	0	0	0
LSD (0.05)		30	25	18

[a] AMS (ammonium sulfate) added at 3.86 kg/378.4 L.
[b] UAN (urea-ammonium nitrate) added at 2.2 L.
[c] Crop oil concentrate (Agridex) added at 1.0% v/v.
[d] Non-ionic surfactant (Induce) added at 0.25% v/v.
[e] Methylated seed oil (Phase) added at 1.1 L.
[f] Pitted morningglory height at application, ≤ 20 cm; hophornbeam copperleaf, ≤ 15 cm;Asiatic dayflower ≤ 7.6 cm.

Table 8. Broadleaf weed control in corn with POST herbicides[f].

Fluthiacet-methyl and tembotrione alone and the combinations of atrazine plus *S*-metolachlor plus glyphosate and mesotrione plus *S*-metolachlor plus glyphosate provided at least 90% hophornbeam copperleaf control, while atrazine, carfentrazone-ethyl, and prosulfuron alone and the combination of thiencarbazone-methyl plus tembotrione provided 81–86% control (**Table 8**).

Glufosinate ammonium alone controlled Asiatic dayflower 90%, while the combinations of atrazine plus *S*-metolachlor plus mesotrione plus bicyclopyrone and atrazine plus *S*-metolachlor plus glyphosate provided 93% control (**Table 8**).

3.2.3. Corn injury and yield

Crop injury consisted of stunting with some leaf chlorosis and necrosis and was never more than 8% with any herbicide treatment (data not shown). Corn recovered from the slight early season stunting and typically by harvest no differences in corn plant growth between the untreated check and any herbicide treatments were noted (data not shown). Although no appreciable crop injury was noted in these studies this is not always true. Other studies have reported corn injury more than 50% with isoxaflutole, imazethapyr, imazapic, and prosulfuron in field or sweet corn [99–101]. In addition, herbicides such as halosulfuron and dicamba plus diflufenzopyr have been reported to cause as much as 25 and 15% injury, respectively [102, 103]. Corn phytotoxicity has been attributed to several factors, including application timing [104], increased use doses [93], and varied susceptibility of corn hybrids to different herbicides [105].

Corn yield was combined over locations due to a lack of treatment by location interaction. Yields were likely affected more by weed control than any other factor (rainfall, etc.) in any year. Pyroxasulfone plus glyphosate produced the greatest yield while halosulfuron alone and the untreated check produced the least yield (**Table 9**). Treatments that contained the combination of atrazine plus glyphosate resulted in yields that were greater than 5200 kg ha^{-1}.

Some research suggests that timely POST control can be an effective alternative to soil-applied herbicides in corn [45, 105, 106]. The use of POST herbicides only is generally considered a greater risk and requires careful management [45, 105, 106]. Also, weed density and application timing are factors in weed efficacy with POST herbicides. Halford et al. [107] reported a reduction in yield when weeds remained beyond V6 corn. In addition, Gower et al. [106] found that subsequent emergence and competition after early glyphosate applications was likely responsible for corn yield reductions. Also, late POST applications can reduce corn grain yields, although weed control was nearly perfect [105, 108].

Herbicide treatment	**Dose**	**Yield**
	Kg ai or ae ha^{-1}	**Kg ha^{-1}**
Atrazine (A)[c]	1.1	2887
Carfentrazone-ethyl[a, d]	0.02	2253
Fluroxypyr[a, c]	0.3	1375
Fluthiacet-methyl (FM)[a, c]	0.07	3270
Glufosinate ammonium[a]	0.7	2724
Glyphosate (G)	1.5 ae	4413
Halosulfuron-methyl (HM) [a, c]	0.07	942
Mesotrione (M)[a, c]	0.1	5568
Prosulfuron[c]	0.04	2266
Tembotrione[a, e]	0.1	4199
Topramezone[a, c]	0.15	3164
(A) + S-metolachlor + (M) + bicyclopyrone[a, c]	0.8+1.5+0.2+ 0.04	5248
(A) + (S) + (G)[a, c]	1.8+1.5+ 0.8 ae	5587
Diflufenzopyr + (D)[a, c]	0.06+0.14	1601
Dimethenamid-P + (G)	0.8+1.5 ae	4425

Herbicide treatment	Dose	Yield
	Kg ai or ae ha^{-1}	Kg ha^{-1}
(FM) + (M)[a, c]	0.09+0.09	4909
(FM) + pyroxasulfone (P) + (A)[d]	0.004+0.15+1.3	2178
(HM) + (D)[a, c]	0.07+0.3 ae	3490
(M) + (S) + (G)[a, c]	0.1+1.1+1.1 ae	4149
(PM) + (P)[a, c]	0.03 + 0.01	1506
(P) + (G)	0.1+1.5 ae	5781
Thiencarbazone-methyl + tembotrione[a, c]	0.02+0.07	4281
Untreated	-	395
LSD (0.05)		2988

[a] AMS (ammonium sulfate) added at 3.86 kg/378.4 L.
[b] UAN (urea-ammonium nitrate) added at 2.2 L.
[c] Crop oil concentrate (Agridex) added at 1.0% v/v.
[d] Non-ionic surfactant (Induce) added at 0.25% v/v.
[e] Methylated seed oil (Phase) added at 1.1 L.

Table 9. Corn yield as influenced by POST herbicides.

With glyphosate-resistant pigweed becoming more widespread throughout the state, the use of POST herbicide combinations, which may or may not contain glyphosate, can not only control resistant weed species in glyphosate-resistant corn production systems but can also reduce the risk of new herbicide-resistant weed species occurring. In general, many treatments with two or three herbicides with different modes of action provided better weed control than one herbicide alone, and the chance of corn injury appears to be minimal with any herbicide combination under normal growing conditions.

3.3. Cotton studies

3.3.1. South-central Texas

A significant year-by-treatment interaction existed for all weed control and cotton yield data, thus data were analyzed separately by year. Weed control data required arcsine transformation in order to meet the assumption of homogeneity of variances for ANOVA; however, the non-transformed means are reported in the (**Table 10–13**).

In 2012, control of Palmer amaranth ranged from 29 to 97% while common waterhemp control ranged from 55 to 100% prior to EPOST applications (**Table 10**). At that timing, control of Palmer amaranth was lowest with pyrithiobac applied PRE. Similar results were seen for common waterhemp control, where pyrithiobac applied PRE provided only 55% control. After EPOST and MPOST applications, no differences in Palmer amaranth control were detected among treatments, with means ranging from 93 to 100%. After the EPOST application timing, control of common waterhemp with *S*-metolachlor plus fomesafen applied PRE was lower than control provided by trifluralin applied PPI followed by either glyphosate plus dicamba- or glufosinate plus dicamba applied EPOST, and all treatments that included glyphosate plus dicamba plus acetochlor applied EPOST. After MPOST applications, no differences in common waterhemp control among herbicide treatments were observed. Seed cotton yields of treated plots ranged from 3581 to 4002 kg ha^{-1}, which were all greater than the non-treated check (1823 kg ha^{-1}).

In 2013, Palmer amaranth control prior to EPOST application ranged from 63 to 100%, while control of common waterhemp ranged from 60 to 100% (**Table 11**). Similar to 2012, pyrithiobac applied PRE resulted in the lowest control of both Palmer amaranth and common waterhemp (63 and 60%, respectively). Treatments that included pendimethalin-applied PRE provided reduced control of Palmer amaranth (88–90%) when compared with many other treatments at the early rating. A similar pattern was observed with common waterhemp, where control was numerically lower from treatments of pendimethalin-applied PRE than many other treatments,

Herbicide and application timing[a]				**Palmer amaranth**			**Common waterhemp**			**Seed cotton**
PPI	**PRE**	**EPOST**	**MPOST**	**Early**	**Mid**	**Late**	**Early**	**Mid**	**Late**	**Yield**
				%						**Kg ha**$^{-1}$
	P	[A]		83	99	99	73	99	98	3779
	P	[A]+D+Ace		83	100	100	95	100	100	3966
	P	Pyr	Gluf	84	95	99	79	89	100	3647
	Pyr	[A]+D+Ace		29	99	100	55	100	100	3728
	S		[B]+Trif	96	99	100	95	97	100	3955
	F		[B]+Trif	88	93	100	92	89	100	3721
	S+F		[B]+Trif	85	99	100	91	85	100	3680
	S+Pr		[B]+Trif	81	99	100	89	91	100	3673
T		Gluf	Gluf	86	100	100	98	99	100	3581
T		[A]+D	[A]	97	100	100	100	100	100	3859
T		Gluf+D	[A]+D	99	100	100	100	100	100	3779
T		[A]+D+Ace		96	100	100	100	100	100	4002
-	-	-	None	0	0	0	0	0	0	1823
LSD (0.05)				15	7	1	13	11	1	559

[a]Herbicide abbreviations, product name and doses: acetochlor, Warrant (Ace) at 1.26 kg ai ha^{-1}; dicamba, Clarity (D) at 0.56 kg ae ha^{-1}; glufosinate, Liberty (Gluf) at 0.59 kg ai ha^{-1}; fomesafen, Reflex (F) at 0.28 kg ai ha^{-1};glyphosate (A), Roundup PowerMAX (Glyp [A]) at 1.26 kg ae ha^{-1}; glyphosate (B), Touchdown Total (Glyp [B]) at 0.88 kg ae ha^{-1}; pendimethalin, Prowl H_20 (P) at 1.6 kg ai ha^{-1}; prometryn, Caparol (Pr) at 0.56 kg ai ha^{-1}; pyrithiobac, Staple LX (Pyr) at 58.84 g ai ha^{-1} PRE, 72.86 g ai ha^{-1} POST; *S*-metolachlor, Dual Magnum (*S*) at 1.07 kg ai ha^{-1}; trifloxysulfuron, Envoke (Trif) at 5.25 g ai ha^{-1}; and trifluralin, Treflan (T) at 1.12 kg ai ha^{-1}.

Table 10. Palmer amaranth and common waterhemp control and seed cotton yield in 2012.

Herbicide and application timing[a]				Palmer amaranth			Common waterhemp			Seed cotton
PPI	PRE	EPOST	MPOST	Early	Mid	Late	Early	Mid	Late	Yield
				%						Kg ha^{-1}
	P	[A]		88	100	100	88	100	99	4084
	P	[A]+D+Ace		88	99	100	79	100	100	3838
	P	Pyr	Gluf	90	86	92	92	86	93	3526
	Pyr	[A] + D+Ace		63	99	100	60	99	100	4034
	S		[B]+Trif	93	82	99	91	81	98	3773
	F		[B]+Trif	100	98	99	100	100	100	3986
	S+F		[B]+Trif	100	100	100	100	100	100	4003
	S+Pr		[B]+Trif	99	93	100	97	96	99	3881
T		Gluf	Gluf	99	99	100	99	100	100	3983
T		[A]+D	[A]	99	99	99	99	100	100	4122
T		Gluf + D	[A]+D	99	100	100	98	100	100	4207
T		[A]+D+Ace		98	100	100	96	100	100	4209
-	-	-	-	0	0	0	0	0	0	254
LSD (0.05)				8	4	2	8	6	5	530

[a]Herbicide abbreviations, product name and doses: acetochlor, Warrant (Ace) at 1.26 kg ai ha^{-1}; dicamba, Clarity (D) at 0.56 kg ae ha^{-1}; fomesafen, Reflex (F) at 0.28 kg ai ha^{-1}; glufosinate, Liberty (Gluf) at 0.59 kg ai ha^{-1}; glyphosate (A), Roundup PowerMAX (Glyp [A]) at 1.26 kg ae ha^{-1}; glyphosate (B), Touchdown Total (Glyp [B]) at 0.88 kg ae ha^{-1}; pendimethalin, Prowl H_20 (P) at 1.6 kg ai ha^{-1}; prometryn, Caparol (Pr) at 0.56 kg ai ha^{-1}; pyrithiobac, Staple LX (Pyr) at 58.84 g ai ha^{-1} PRE, 72.86 g ai ha^{-1} POST; S-metolachlor, Dual Magnum (*S*) at 1.07 kg ai ha^{-1}; trifloxysulfuron, Envoke (Trif) at 5.25 g ai ha^{-1}; and trifluralin, Treflan (T) at 1.12 kg ai ha^{-1}.

Table 11. Palmer amaranth and common waterhemp control and seed cotton yield in 2013.

though this was not always significant. Prior to the MPOST application, control of Palmer amaranth with *S*-metolachlor applied PRE was less than that of all other treatments except for pendimethalin applied PRE followed by pyrithiobac applied EPOST, which itself was lower than treatments other than *S*-metolachlor plus prometryn applied PRE. Control of common waterhemp prior to the MPOST application was lowest with *S*-metolachlor applied PRE (81%) and pendimethalin applied PRE followed by pyrithiobac applied EPOST (86%). At the last rating, control of Palmer amaranth and common waterhemp was reduced with pendimethalin applied PRE followed by pyrithiobac applied EPOST followed by glufosinate applied MPOST (92 and 93%, respectively) when compared to all other herbicide treatments. Mean yield of the non-treated control was 254 kg ha^{-1}, which was lower than that of all herbicide treatments (3526–4209 kg ha^{-1}).

Pyrithiobac applied PRE has been shown to provide satisfactory control of Amaranthus weeds [109, 110]; however, the opposite was observed in this experiment, where pyrithiobac applied PRE resulted in decreased levels of control of both Palmer amaranth and common waterhemp. The reasons for this lack of control are unknown, as the treatment was applied at the recommended rate and timing [111]. Pendimethalin applied PRE provided varied levels of control of common waterhemp, particularly in 2012. This may be due to the utilization of furrow irrigation for herbicide incorporation rather than overhead irrigation, which is recommended on the product label [112]. Trifluralin applied PPI consistently provided the best levels of control of both species. This is likely due in large part to the thorough mechanical incorporation of herbicide into the soil, which has been observed to affect the efficacy of trifluralin [113, 114].

In 2013, a decreased level of control of both Palmer amaranth and common waterhemp later in the season was observed with pendimethalin applied PRE followed by pyrithiobac-applied EPOST followed by glufosinate applied MPOST. This is attributed to a failure of glufosinate to control weeds that survived pyrithiobac EPOST and grew to a size larger than that recommended for control with glufosinate [115]. This weed size effect on glufosinate performance was observed by Craigmyle et al. [116], where control of common waterhemp was found to decrease with increasing plant height. Pendimethalin applied PRE followed by glyphosate EPOST provided excellent control of both species; however, in the presence of a glyphosate-resistant population, this treatment would likely not provide acceptable levels of control. In addition, this reliance on glyphosate as the single POST herbicide mechanism of action is not recommended due to the potential for selection of glyphosate-resistant plants [117]. Excellent control of both Palmer amaranth and common waterhemp was achieved in both years in treatments that included glyphosate plus dicamba plus acetochlor-applied EPOST. In addition to providing successful levels of weed control, this tank-mix would likely be very resilient against selecting resistant biotypes as suggested by Evans et al. [118], who found that the presence of glyphosate-resistant biotypes of common waterhemp was much less common in fields that received applications of mixed herbicide mechanisms of action.

3.3.2. High Plains studies

In the glyphosate plus 2,4-D choline study, trifluralin alone failed to control Palmer amaranth with only 20% control early season and no control late season, while systems which include POST applications of either glyphosate or glufosinate alone controlled this weed 23–53% (**Table 12**). Systems which included an EPOST and MPOST application of glyphosate plus 2,4-D choline provided at least 94% season-long control of this weed. Chahal and Johnson [119] reported that the addition of 2,4-D to glyphosate provided 99% control of glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronq.] compared to only 12% with glyphosate alone. In a similar study, 2,4-D added to glufosinate provided an increased level of common waterhemp control compared to herbicide treatments consisting of glufosinate only [116]. Miller and Norsworthy [120] reported that the addition of a residual herbicide, such as trifluralin, would provide an additional effective herbicide mode of action for managing resistant Palmer amaranth. Applications of 2,4-D, glyphosate, and glufosinate alone or tank-mixed represent broad-spectrum POST herbicides that have the potential to control 9 of the 10 most problematic weeds in the southern cotton and soybean production [121].

Herbicide and application[a]			Palmer amaranth control		Cotton injury	Lint yield
PPI[a]	EPOST	MPOST	Early	Late	Early	
			%			Kg ha^{-1}
Trif	None	None	20	0	0	0
Trif	Gly	Gly	46	23	0	0
Trif	Glu	Glu	53	24	5	0
Trif	Gly+D	Gly+D	96	98	9	959
Trif	Gly+D+S	Gly+D	97	99	8	947
Trif	Gly+D	Glu	73	68	9	0
Trif	Gly+D	Glu+D	94	94	3	728
Trif	Gly+D	Glu+D+S	96	97	3	1086
Trif	S	Glu+D	99	100	0	953
Trif	Glu+D	Gly+D	97	99	4	976
Trif	Glu+D+S	Gly+D	98	100	0	830
Trif	Glu+D	Glu+D	96	95	3	850
Trif	S+Glu	Gly+Glu	64	35	3	196
Trif	S+Glu	Gly+D	83	89	19	776
None	None	None	0	0	0	0
LSD (0.05)			7	10	7	325

[a]Herbicides abbreviations and doses: Trif, trifluralin at 1.12 kg ha^{-1}; Gly, glyphosate at 1.36 kg ae ha^{-1}; Glu, glufosinate at 0.59 kg ai ha^{-1}; Gly + D, glyphosate at 0.48 kg ha^{-1} + 2,4-D choline at 0.45 kg ae ha^{-1}; S, *S*-metolachlor at 1.08 kg ai ha^{-1}; D, 2,4-D choline at 1.06 kg ae ha^{-1}.

Table 12. Palmer amaranth control with herbicide systems using glyphosate plus 2,4-D choline.

Cotton injury was greatest (19%) with trifluralin-applied PPI followed by *S*-metochlor plus glufosinate-applied EPOST followed by glyphosate plus 2,4-D choline applied MPOST (**Table 12**). Cotton lint yields were greatest with herbicide treatments which provided greater than 90% Palmer amaranth control with the exception of trifluralin applied PPI followed by glyphosate plus 2,4-D choline applied EPOST and MPOST.

In the glyphosate herbicide systems study, a late season rating suggests that the herbicide system which included glyphosate plus the pre-mix of rimsulfuron plus thifensulfuron-methyl applied preplant controlled Palmer amaranth less than 70%, while all other systems which included glyphosate plus either flumioxazin, fomesafen, or diruron applied preplant provided 89–99% control (**Table 13**). Diverse herbicide programs for controlling resistant Palmer amaranth and common waterhemp is an important herbicide-resistant management strategy [122]. Additionally, full labeled-use doses should always be used to achieve the greatest level

Herbicide and application timing[a]						
PPI	**PRE**	**EPOST**	**MPOST**	**LPOST**	**Control[b]**	**Yield**
					%	Kg ha^{-1}
Gly+Flumi	Flume+Par	Gly + Ace	Gly+Ace	D+MSMA	89	506
Gly+Ace	Flume+Par	Gly + S	Gly+S	D+MSMA	93	794
Gly+Ace	Ace+Flume+Par	Glu + Pyr	Gly	D+MSMA	99	801
Gly+Rim+Thi	Pyr+Par	Gly + Dim	Gly+Dim	D+MSMA	68	609
Gly+D	Ace+Par	Gly + Pyr	Gly+S	D+MSMA	91	770
Gly+Flumi	Ace+Flume+Par	Gly + Ace	Gly	D+MSMA	89	753
None	None	None	None	None	0	0
LSD (0.05)					16	274

[a]Herbicide abbreviations and doses: Ace, acetochlor at 1.27 kg ai ha^{-1}; Dim, dimethenamid-P at 0.63 kg ai ha^{-1}; D, direx at 1.12 kg ai ha^{-1}; Flumi, flumioxazin at 0.07 kg ai ha^{-1}; Flume, flumeturon at 1.12 kg ai ha^{-1}; Fome, fomesafen at 0.28 kg ai $ha^{-}1$; Gly, glyphosate at 1.3 kg ae ha^{-1}; Gly + S, a premix of glyphosate at 0.95 kg ae ha^{-1} + *S*-metochlor at 1.26 kg ha^{-1}; MSMA at 2.11 kg ai ha^{-1}; Par, paraquat at 0.56 kg ai ha^{-1}; Pyr, pyrithiobac at 0.06 kg ai ha^{-1}; Rim + Thi, a premix of rimsulfuron at 0.02 kg ha^{-1} + thifensulfuron-methyl at 0.04 kg ha^{-1}; MSMA, MSMA at 2.11 kg ai ha^{-1}.

[b]Palmer amaranth control and cotton yield combined over years (2015, 2016) due to lack of year by treatment interaction.

Table 13. Palmer amaranth control and cotton response to herbicide systems.

of possible control and reduce the likelihood for the evolution of resistance. These results further displayed the high level of weed control this new technology is capable of providing. Also, emphasis should be placed on a zero-tolerance weed threshold [17], herbicides should also be applied at or less than the recommended weed height, and programs should not begin with an EPOST or MPOST application but rather start prior to planting with the application of residual herbicides.

While a few late emerging Palmer amaranth plants may be considered as being harmless, previous research has reported that late season Palmer amaranth seedlings are capable of seed production within 30 days after emergence [123]. Previous research also has shown that weeds left in the field at the time of harvest have the potential to enter harvesting machinery and be distributed across the field [124]. Thus, leaving weeds in the field prior to harvest can result in spreading viable weed seeds across the field. This practice will not only lead to increasing weed populations in that field but will also negatively impact sustainable weed management [125].

Also, a major challenge in managing weeds is minimizing the return of weed seed to the soil seed bank [126]. Menges [127] reported that maintaining fields weed free for 6 years reduced the soil seed bank of Palmer amaranth by 98%; however, 18 million seeds ha^{-1} remained in the soil. Palmer amaranth seed viability decreased when buried below the depth of optimal germination for at least 36 months [128]. Given that Palmer amaranth has become the most challenging weed to manage in corn and cotton [129], understanding population dynamics of this weed may help lead to strategies that more effectively manage this weed.

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References

[1] Wiggins MS, McClure MA, Hayes R, Steckel LE. Integrating cover crops and POST herbicides for glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) control in corn. Weed Technology. 2015;**29**:412-418

[2] Anonymous, Monsanto Biotechnology Trait Acres: Fiscal Years 1996-2009 [Internet]. 2009. Available from: http://www.monsanto.com/investors/documents/2009/q4.biotech.acres

[3] Culpepper AS. Glyphosate-induced weed shifts. Weed Technology. 2006;**20**:277-281

[4] Owen MDK. Weed species shifts in glyphosate-resistant crops. Pest Management Science. 2008;**64**:377-387

[5] Culpepper AS, York AC. Weed management in glyphosate tolerant cotton. Journal of Cotton Science. 1998;**2**:174-185

[6] Johnson WG, Bradley PR, Hart SE, Buesinger ML, Massey RE. Efficacy and economics of weed management in glyphosate-resistant corn (*Zea mays*). Weed Technology. 2000;**14**:578-585

[7] Burke IC, Thomas WE, Allen JR, Collins J, Wilcut JW. A comparison of weed control in herbicide-resistant, herbicide-tolerant, and conventional corn. Weed Technology. 2008;**22**:571-579

[8] Bradley PR, Johnson WG, Hart SE, Buesinger ML, Massey RE. Economics of weed management in glufosinate-resistant corn (*Zea mays* L.). Weed Technology. 2000;**14**:495-501

[9] Ritter RL, Menbere H. Weed management systems utilizing glufosinate-resistant corn (*Zea mays*) and soybean (*Glycine max*). Weed Technology. 2001;**15**:89-94

[10] Heap I. The international survey of herbicide resistant weeds [Internet]. 2014. Available from: http://www.weedscience.com.pdf [Accessed: December 8, 2016]

[11] Morgan G, Baumann P, Chandler J. Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technology. 2001;**15**:408-412

[12] Smith D, Baker R, Steele D. Palmer amaranth (*Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technology. 2000;**14**:122-126

[13] Stephenson DO, Bond IV JA, Landry RL, Edwards HM. Weed management in corn with postemergence applications of tembotrione or thiencarbazone: Tembotrione. Weed Technology. 2015;**29**:350-358

[14] Bollman JD, Boerboom CM, Becker RL, Fritz VA. Efficacy and tolerance to HPPD-inhibiting herbicides in sweet corn. Weed Technology. 2008;**20**:267-274

[15] Stephenson DO IV, Bond JA. Evaluation of thiencarbazone-methyl- and isoxaflutole-based herbicide programs in corn. Weed Technology. 2012;**26**:37-42

[16] Walsh MJ, Stratford K, Stone K, Powles SB. Synergistic effects of atrazine and mesotrione on susceptible and resistant wild radish (*Raphanus rephanistrum*) populations and the potential for overcoming resistance to triazine herbicides. Weed Technology. 2012;**26**:341-347

[17] Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR. Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technology. 2008;**22**:108-113

[18] Hayes RM, Mueller TC, Willis JB, Montgomery RF. Glyphosate-resistant horseweed and factors influencing its control. Proceedings of the Southern Weed Science Society. 2002;**55**:119-120

[19] Yancy CH. Glyphosate Resistant Horseweed Causing Concern in North Carolina. Southeast Farm Press [Internet]. Available from: http://www.southeastfarmpress.com/glyphosate-resistant-horseweed-causing-concern-north-carolina [Accessed: January 11, 2017]

[20] Young B. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technology. 2006;**20**:301-307

[21] Legleiter T, Bradley K. Glyphosate and multiple herbicide resistance in common waterhemp (*Amaranthus rudis*) populations from Missouri. Weed Science. 2008;**56**:582-587

[22] NRCS-National Resources Conservation Service. Plants Database: Amaranthus L. [Internet]. 2011. Available from: http://plants.usda.gov/java/profile?symbol=AMARA [Accessed: December 28, 2016]

[23] Van Wychen L. 2015 baseline survey of the most common and troublesome weeds in the United States and Canada. Weed Science Society of America National Weed Survey Dataset [Internet]. 2016. Available from: http://wssa.net/wp-content/Uploads/2015_Weed_Survey_Final.xlsx [Accessed: December 12, 2017]

[24] Elmore CD, editor. Weed Identification Guide. Champaign, IL: Southern Weed Science Society; 1985. p. 225

[25] Anonymous. Palmer amaranth–weed of TWO years-2014-2015 [Internet]. 2015. Available from: https://www.ag.ndsu.edu/weeds/weed-of-the-year-files/palmer-amaranth-2 [Accessed: December 3, 2016]

[26] Correll DS, Johnston MC. Manual of the Vascular Plants of Texas. 2nd ed. Richardson, TX: University Texas at Dallas; 1979. pp. 555-556

[27] Light GG, Mohammed MY, Dotray PA, Chandler JM, Wright RJ. Glyphosate-resistant common waterhemp (*Amatanthus rudis*) confirmed in Texas. Weed Technology. 2011;**25**: 480-485

[28] Franssen AS, Skinner DZ, Al-Khatib K, Horak MJ, Kulakow PA. Interspecific hybridization and gene flow of ALS-resistance in Amaranthus species. Weed Science. 2001;**49**: 598-606

[29] Sauer JD. Recent migration and evolution of the dioecious amaranths. Evolution. 1957;**11**: 11-31

[30] Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR. Comparative growth of six Amaranthus species in Missouri. Weed Science. 2003;**51**:329-333

[31] Bond JA, Oliver LR. Comparative growth of Palmer amaranth (*Amaranthus palmeri*) accessions. Weed Science. 2006;**54**:121-126

[32] Horak MJ, Loughin TM. Growth analysis of four Amaranthus species. Weed Science. 2000;**48**:347-355

[33] Keeley PE, Carter CH, Thullen RJ. Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Science. 1987;**35**:199-204

[34] Franssen AS, Skinner DZ, Al-Khatib K, Horak MJ. Pollen morphological differences in Amaranthus species and interspecific hybrids. Weed Science. 2001;**49**:732-737

[35] Guo P, Al-Khatib K. Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Science. 2003;**51**:329-333

[36] Vyn JD, Swanton CJ, Weaver SE, Sikkema PH. Control of *Amaranthus tuberculatus* var. *rudis* (common waterhemp) with pre- and postemergence herbicides in Zea mays L. Crop Protection. 2006;**35**:1051-1056

[37] Geier PW, Stahlman PW. Efficacy of isoxaflutole alone and in combination in corn. Proceedings of the North Central Weed Science Society. 1997;**52**:81

[38] Armel GR, Wilson HP, Richardson RJ, Hines TE. Mesotrione, acetochlor, and atrazine for weed management in corn (*Zea mays*). Weed Technology. 2003;**17**:284-290

[39] Armel GR, Wilson HP, Richardson RJ, Hines TE. Mesotrione combinations in no-till corn (*Zea mays*). Weed Technology. 2003;**17**:111-116

[40] Wilcut JW, Jordan DL, Vencill WK, Richburg III JS. Weed management in cotton (*Gossypium hirsutum*) with soil-applied and post-directed herbicides. Weed Technology. 1997;**11**:221-226

[41] Welch AK, Rahn PR, Voth RD, Mills JA, Shumway CR. Evaluation of preplant and preemergence herbicides in Roundup Ready® cotton. Proceedings of the Beltwide Cotton Conferences. 1997;**21**:784

[42] Gullickson G. 6 Points to Remember about Atrazine [Internet]. 2012. Available from: Agriculture.com [Accessed: January 10, 2017]

[43] Sutton P, Richards C, Buren L, Glasgow L. Activity of mesotrione on resistant weeds in maize. Pest Management Science. 2002;**58**:981-984

[44] Swanton CJ, Gulden RH, Chandler K. A rationale for atrazine stewardship in corn. Weed Science. 2007;**55**:75-81

[45] Tapia LS, Bauman TT, Harvey RG, Kells JJ, Kapusta G, Loux MM, et al. Postemergence herbicide application timing effects on annual grass control and corn (*Zea mays*) grain yield. Weed Science. 1997;**45**:138-143

[46] Baker JL, Johnson HP. The effects of tillage systems on pesticides in runoff from small watersheds. Transactions of the American Society of Agricultural Engineers. 1979;**22**:554-559

[47] Pantone DJ, Young RA, Buhler DD, Eberlein CV, Koskinen WC, Forcella F. Water quality impacts associated with pre- and postemergence applications of atrazine in maize. Journal of Environmental Quality. 1992;**21**:567-573

[48] Shaner D, editor. Herbicide Handbook. 10th ed. Lawrence, KS: Weed Science Society of America; 2014. p. 513

[49] Behrens M, Mutlu N, Chakraborty S, Dumitru R, Jiang W, LaVallee B, et al. Dicamba resistance: Enlarging and preserving biotechnology-based weed management strategies. Science. 2007;**316**:1185-1188

[50] USDA-APHIS. Determination of Nonregulated Status for Monsanto Company MON 88701 cotton. United States Department of Agriculture. Animal and Plant Health Inspection Service. APHIS-2013-0043-4809 [Internet]. Available from: https://www.aphis.usda.gov/brs/aphisdocs/12_18501p_det.pdf [Accessed: January 15, 2017].

[51] USDA-AMS. Cotton Varieties Planted 2016 Crop. Memphis, TN: United States Department of Agriculture. Agricultural Marketing Service – Cotton and Tobacco Program. 2016. p. 10

[52] Richburg JS, Wright JR, Braxton LB, Robinson AE. Inventors; Dow AgroSciences, Assignee. Increased Tolerance of DHT-Enabled Plants to Auxinic Herbicides Resulting from Moiety Differences in Auxinic Molecule Structures. US patent 13,345,236

[53] Peterson GE. The discovery and development of 2,4-D. Agricultural History. 1967;**41**:243-254

[54] Kruger GR, Davis VM, Weller SC, Johnson WG. Response and survival of rosette-stage horseweed (*Conyza canadensis*) after exposure to 2,4-D. Weed Science. 2008;**56**:748-752

[55] Robinson AP, Simpson DM, Johnson WG. Summer annual weed control with 2,4-D and glyphosate. Weed Technology. 2012;**26**:657-660

[56] Siebert JD, Griffin JL, Jones CA. Red morningglory (*Ipomoea coccinea*) control with 2,4-D and alternative herbicides. Weed Technology. 2004;**18**:38-44

[57] White RH, Worsham AD. Control of legume cover crops in no-till corn (*Zea mays*) and cotton (*Gossypium hirsutum*). Weed Technology. 1990;**4**:57-62

[58] Egan JF, Barlow KM, Mortensen DA. A meta-analysis on the effects of 2,4-D and dicamba drift on soybean and cotton. Weed Science. 2014;**62**:193-206

[59] Mortensen DA, Egan JF, Maxwell BD, Ryan MR, Smith RG. Navigating a critical juncture for sustainable weed management. Bioscience. 2012;**62**:75-85

[60] Riar DS, Norsworthy JK, Steckel LE, Stepehenson IV DO, Bond JA. Consultant perspectives on weed management needs in Midsouthern United States cotton: A follow-up survey. Weed Technology. 2013;**27**:778-787

[61] Abel S. Dow AgroSciences Company Petition for Determination of Nonregulated Status of 2,4-D and Glufosinate-Resistant DAS-81910-7 Cotton. USDA Environmental Assessment 2015 [Internet]. Available from: https://www.aphis.usda.gov/brs/aphisdocs/13_26201p_fea.pdf [Accessed: January 15, 2017]

[62] Staten G. Contamination of cotton fields by 2,4-D or hormone-type weed sprays. Agronomy Journal. 1946;**38**:536-544

[63] Everitt JD, Keeling JW. Cotton growth and yield response to simulated 2,4-D and dicamba drift. Weed Technology. 2009;**23**:503-506

[64] Johnson VA, Fisher LR, Jordan DL, Edminsten KE, Stewart AM, York AC. Cotton, peanut, and soybean response to sublethal rates of dicamba, glufosinate, and 2,4-D. Weed Technology. 2012;**26**:195-206

[65] Sciumbato AS, Chandler JM, Senseman SA, Bovey RW, Smith KL. Determining exposure to auxin-like herbicides. I. Quantifying injury to cotton and soybean. Weed Technology. 2004;**18**:1125-1134

[66] Beckie HJ. Herbicide-resistant weeds: Management tactics and practices. Weed Technology. 2006;**20**:793-814

[67] Putwain PD. Herbicide resistance in weeds-an inevitable consequence of herbicide use? Proceedings Brighton Crop Protection Conference—Weeds. Farnham, UK: British Crop Protection Council. 1982. pp. 719-728

[68] Wrubel RP, Gressel J. Are herbicide mixtures useful for delaying the rapid evolution of resistance? A case study. Weed Technology. 1994;**8**:635-648

[69] Beckie HJ, Hall LM, Tardif FJ. Impact and management of herbicide-resistant weeds in Canada. Proceedings Brighton Crop Protection Conference—Weeds. Farnham, UK: British Crop Protection Council; 2001. pp. 747-754

[70] Diggle AJ, Neve PB, Smith FP. Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. Weed Research. 2003;**43**:371-382

[71] SAS Institute Incorporated. SAS/STAT User's Guide: Statistics, Version 9.1. Cary, NC, USA: SAS Institute; 2007. p. 204

[72] Anonymous. Crop Protection Reference. 29th ed. Chemical & Pharmaceutical Press, Inc. New York [Internet]. 2014. Available from: http://www.greenbook.net [Accessed: December 29, 2016]

[73] Buchanan GA, Murray DS, Hauser EW. Weeds and their control in peanuts. In: Pattee HE, Young CT, editors. Peanut Science and Technology. Yoakum, TX: American Peanut Research Education Society; 1982. pp. 209-249

[74] Chamblee RW, Thompson L Jr, Bunn TM. Management of broadleaf signalgrass (*Brachiaria platyphylla*) in peanuts (*Arachis hypogaea*). Weed Science. 1982;**30**:40-44

[75] Wilcut JW, Wehtje GR, Patterson MG. Economic assessment of weed control systems for peanuts (*Arachis hypogaea*). Weed Science. 1987;**35**:433-437

[76] Wilcut JW, York AC, Wehtje GR. The control and interaction of weeds in peanut (*Arachis hypogaea*). Reviews of Weed Science. 1994;**6**:177-205

[77] Wilcut JW, York AC, Grichar WJ, Wehtje GR. The biology and management of weeds in peanut (*Arachis hypogaea*). In: Pattee HE, Stalker HT, editors. Advances in Peanut Science. Stillwater, OK: American Peanut Research Education Society; 1995. pp. 207-244

[78] Ross MA, Childs DJ. Herbicide mode of action summary. WS-23-W [Internet]. 1996. Available from: http://www.extension.purdue.edu/extmedia/ws/ws-23-w.html [Accessed: January 14, 2017]

[79] Grichar WJ, Colburn AE, Keraney NS. Herbicides for reduced tillage production in peanut (*Arachis hypogaea*) in the Southwest. Weed Technology. 1994;**8**:212-216

[80] Steele GL, Porpiglia PJ, Chandler JM. Efficacy of KIH-485 on Texas panicum (*Panicum texanum*) and selected broadleaf weeds in corn. Weed Technology. 2005;**19**:866-869

[81] Anonymous. KIH-485 Herbicide. Technical Information. White Plains, NY: K-I Chemical USA, Inc., 2003. p. 6

[82] Ohmes GA, Kendig JA, Barham RL, Ezell PM. Efficacy of ZA1296 in corn. Proceedings of the Southern Weed Science Society. 2000;**53**:225

[83] Allen JR, Johnson WG, Smeda RJ, Kremer RJ. ALS-resistant Helianthus annuus interference in *Glycine max*. Weed Science. 2000;**48**:461-466

[84] Al-Khatib K, Peterson DE, Regehr DL. Control of imazethapyr-resistant common sunflower (*Helianthus annuus*) in soybean (*Glycine max*) and corn (*Zea mays*). Weed Technology. 2000;**14**:133-139

[85] Johnson WG, Chahal GS, Regehr DL. Efficacy of various corn herbicides applied preplant incorporated and preemergence. Weed Technology. 2012;**26**:220-229

[86] Taylor-Lovell S, Wax LM. Weed control in field corn (*Zea mays*) with RPA 201772 combinations with atrazine and S-metolachlor. Weed Technology. 2011;**15**:249-256

[87] Sprague CL, Kells JJ, Penner D. Effect of application timing on corn tolerance and weed control with isoxaflutole. Weed Science Society of America Abstracts. 1997;**37**:13

[88] Prostko EP, Grey TL, Davis JW. Texas panicum (*Panicum texanum*) control in irrigated field corn (*Zea mays*) with foramsulfuron, glyphosate, nicosulfuron, and pendimethalin. Weed Technology. 2006;**20**:961-964

[89] Lamore D, Simkins G, Watteyne K, Allen J. Weed control programs with tembotrione in corn. Proceedings of the North Central Weed Science Society. 2006;**61**:119

[90] Dalley CD, Bernards ML, Kells JJ. Effect of weed removal and row spacing on soil moisture in corn (*Zea mays*). Weed Technology. 2006;**20**:399-409

[91] Gower SA, Loux MM, Cardina J, Harrison SK, Sprankle PL, Probst NJ, et al. Effect of postemergence glyphosate application timing on weed control and grain yield in glyphosate-resistant corn: Results of a 2-yr multistate study. Weed Technology. 2003;**17**:821-828

[92] Norsworthy JK, Burgos NR, Oliver LR. Differences in weed tolerance to glyphosate involve different mechanisms. Weed Technology. 2001;**15**:725-731

[93] Shaw DR, Arnold JC. Weed control from herbicide combinations with glyphosate. Weed Technology. 2002;**16**:1-6

[94] Starke RJ, Oliver LR. Interaction of glyphosate with chlorimuron, fomesafen, imazethapyr, and sulfentrazone. Weed Science. 1998;**46**:652-660

[95] Culpepper AS, Gimenez AE, York AC, Batts RB, Wilcut JW. Morningglory (*Ipomoea* spp.) and large crabgrass (*Digitaria sanguinalis*) control with glyphosate and 2,4-DB mixtures in glyphosate resistant soybean (*Glycine max*). Weed Technology. 2001;**15**:56-61

[96] Norsworthy JK, Oliver LR. Effect of irrigation, soybean (*Glycine max*) density, and glyphosate on hemp sesbania (*Sesbania exaltata*) and pitted morningglory (*Ipomoea lacunosa*) interference with soybean. Weed Technology. 2002;**16**:7-17

[97] Reedy KN, Whiting K. Weed control and economic comparisons of glyphosate-resistant, sulfonylurea-tolerant, and conventional soybean (*Glycine max*) systems. Weed Technology. 2000;**14**:204-211

[98] Bararpour MT, Oliver LR, Bell CG. Comparison of HPPD inhibitors for weed control programs in corn. Proceedings of the Southern Weed Science Society. 2011;**64**:16

[99] Grier PW, Stahlman PW. EXP 31130A efficacy and corn (*Zea mays*) response in western Kansas. Weed Technology. 1999;**13**:404-410

[100] Knezevic SZ, Sikkema PH, Tardif F, Hamill AS, Chandler K, Swanton CJ. Biologically effective dose and selectivity of isoxaflutole for preemergence weed control in corn (*Zea mays* L.). Weed Technology. 1998;**12**:670-676

[101] O'Sullivan J, Thomas RJ, Sikkema PH. Sweet corn (*Zea mays*) cultivar sensitivity to RPA 201772. Weed Technology. 2001;**15**:332-336

[102] Sikkema PH, Knezevic SZ, Hamil AS, Tardif F, Swanton CJ. Biologically effective dose and selectivity for SAN 1269H for weed control in corn (*Zea mays* L.). Weed Technology. 1999;**13**:283-289

[103] Sprague CL, Kells JJ, Penner D. Weed control and corn (*Zea mays*) tolerance from soil-applied RPA 201772. Weed Technology. 1999;**13**:713-725

[104] Sprague CL, Stoller EW, Hart SE. Preemergence broadleaf weed control and crop tolerance to imidazolinone-resistant and -susceptible corn (*Zea mays*). Weed Technology. 1997;**11**:118-122

[105] Sprague CL, Penner D. Basis for different corn tolerance of four corn hybrids to isoxaflutole. Proceedings of the North Central Weed Science Society. 1998;**53**:94

[106] Gower SA, Loux MM, Cardina J, Harrison SK. Effect of planting date, residual herbicide, and postemergence application timing on weed corn and grain yield in glyphosate-tolerant corn (*Zea mays*). Weed Technology. 2002;**16**:488-494

[107] Halford C, Hamill AS, Zhang J, Doucet C. Critical period of weed control in no-till soybean (*Glycine max*) and corn (*Zea mays*). Weed Technology. 2001;**15**:737-744

[108] Myers MW, Curran WS, Vangessel MJ, Majek BA, Scott BA, Mortensen DA, et al. The effect of weed density and application timing on weed control and corn grain yield. Weed Technology. 2005;**19**:102-107

[109] Dotray P, Keeling W, Henniger G, Abernathy J. Palmer amaranth (*Amaranthus palmeri*) and devil's claw (*Proboscidea louisianica*) control in cotton with pyrithiobac. Weed Technology. 1996;**10**:7-12

[110] Branson J, Smith K, Barrentine J. Comparison of trifloxysulfuron and pyrithiobac in glyphosate-resistant and bromoxynil-resistant cotton. Weed Technology. 2005;**19**:404-410

[111] Anonymous. Staple LX Herbicide Product Label [Internet]. 2011. Available from: http://www.cdms.net/LDat/Id7DD009.pdf [Accessed: January 12, 2017]

[112] Anonymous. Prowl H_2O Herbicide Product Label [Internet]. 2016. Available from: http://www.cdms.net/Idat/Id6CT004.pdf [Accessed: January 12, 2017]

[113] Robison L, Fenster C. Residual effects of EPTC and trifluralin incorporated with different implements. Weed Science. 1968;**16**:415-417

[114] Wiese A, Chenault W, Hudspeth E. Incorporation of preplant herbicides for cotton. Weed Science. 1969;**17**:481-483

[115] Anonymous. Liberty 280 SL Herbicide Product Label [Internet]. Available from: https://www.cropscience.bayer.us/Products/herbicides/liberty/label-msds [Accessed: January 12, 2017]

[116] Craigmyle B, Ellis J, Bradley K. Influence of weed height and glufosinate plus 2,4-D combinations on weed control in soybean with resistance to 2,4-D. Weed Technology. 2013;**27**:271-280

[117] Powles S. Evolved glyphosate-resistant weeds around the world: Lessons to be learnt. Pest Management Science. 2008;**64**:360-365

[118] Evans J, Tranel P, Hager A, Schutte B, Wu C, Chatham L, Davis A. Managing the evolution of herbicide resistance. Pest Management Science. 2015;**72**:74-80

[119] Chahal GS, Johnson WG. Influence of glyphosate or glufosinate combinations with growth regulator herbicides and other agrochemicals in controlling glyphosate-resistant weeds. Weed Technology. 2012;**26**:638-643

[120] Miller MR, Norsworthy JK. Evaluation of herbicide programs for use in a 2,4-D- resistant soybean technology for control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Technology. 2016;**30**:366-376

[121] Riar DS, Norsworthy JK, Steckel LE, Stephenson DO, Eubank TW, Scott RC. Assessment of weed management practices and problematic weeds in the Midsouth United States-soybean: A consultant's perspective. Weed Technology. 2013;**27**:612-622

[122] Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, et al. Reducing the risks of herbicide resistance: Best management practices and recommendations. Weed Science (Special Issue). 2012;**60**:31-62

[123] Jha P, Norsworthy JK. Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Science. 2009;**57**:644-651

[124] Walsh MJ, Powles SB. High seed retention at maturity of annual weeds infesting field crops highlights the potential for harvest weed seed control. Weed Technology. 2014;**28**:486-493

[125] Norsworthy JK, Walsh MJ, Bagavathiannan MV, Bradley KW, Steckel L, Kruger G, et al. Harvest weed seed control: Testing Australian seedbank management tactics in USA. Proceedings of the Weed Science Society of America. 2014;**250**

[126] Swanton CJ, Booth BD. Management of weed seedbanks in the context of populations and communities. Weed Technology. 2004;**18**:1496-1502

[127] Menges RM. Weed seed population dynamics during six years of weed management systems in crop rotations on irrigated soil. Weed Science. 1987;**35**:328-332

[128] Sosnoskie LM, Webster TM, Culpepper AS. Glyphosate resistance does not affect Palmer amaranth (*Amaranthus palmeri*) seedbank longevity. Weed Science. 2013;**61**:283-288

[129] Webster TM. Weed survey-southern states: Broadleaf crop subsection. Houston: Proceedings of the Southern Weed Science Society; 2013. pp. 275-287