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Palmer Amaranth (*Amaranthus palmeri*) Management in GlyTol® LibertyLink® Cotton

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Field trials were conducted in Lubbock, TX in 2010 and 2011 to evaluate tank-mix combinations of glyphosate and glufosinate in GlyTol® LibertyLink® cotton for control of Palmer amaranth. Herbicide treatments included glyphosate and glufosinate applied at various tank-mix rate combinations (1X:1X, 1X:0.75X, 1X:0.5X, 1X:0.25X and 1X:0X of glyphosate plus glufosinate), proportional tank-mix rate combinations (1X:0X, 0.75X:0.25X, 0.5X:0.5X, 0.25X:0.75X, and 0X:1X of glyphosate plus glufosinate, where X is 0.84 kg ae ha^{-1} of glyphosate or 0.58 kg ai ha^{-1} of glufosinate ammonium), and in sequential (1X followed by 1X) applications of both herbicides in an overall weed management system. Greenhouse studies were conducted to quantify antagonistic or synergistic effects. Treatments included a nontreated control; glyphosate at 0.84, 0.63, 0.42, and 0.21 kg ha^{-1}; glufosinate at 0.58, 0.44, 0.29, and 0.15 kg ha^{-1}; and all tank-mix combinations of each herbicide rate. Dry weights were converted to percent growth values for each rate of the two herbicides alone, and these values were used to calculate expected responses of tank-mix combinations with the use of Colby's method. Expected values were compared to observed percent growth values using an augmented mixed-model method. Results of field studies indicated that tank mixes of glyphosate and glufosinate were less effective at controlling Palmer amaranth than glyphosate applied alone. The addition of any rate of glufosinate to a 1X rate of glyphosate reduced Palmer amaranth control compared to glyphosate alone. Greenhouse studies confirmed antagonism seen in the field. These results indicate that sequential applications of these two herbicides are a better option for Palmer amaranth weed management.

Nomenclature: Glufosinate; glyphosate; Palmer amaranth, *Amaranthus palmeri* S. Wats.; cotton, *Gossypium hirsutum* L. 'FiberMax 9250GL'.

Key words: Antagonism, glufosinate, glyphosate, weed control.

Se realizaron experimentos de campo en Lubbock, TX en 2010 y 2011 para evaluar combinaciones de mezclas en tanque de glyphosate y glufosinate en algodón GlyTol® LibertyLink® para el control de *Amaranthus palmeri.* Los tratamientos de herbicidas incluyeron glyphosate y glufosinate aplicados en varias combinaciones de dosis de mezclas en tanque (1X:1X, 1X:0.75X, 1X:0.25, y 1X:0X de glyphosate más glufosinate), combinaciones de dosis de mezclas en tanque proporcionales (1X:0X, 0.75X:0.25X, 0.5X:0.5X, 0.25X:0.75X, y 0X:1X de glyphosate más glufosinate, donde X es 0.84 kg ae ha^{-1} de glyphosate o 0.58 kg ai ha^{-1} de glufosinate ammonium), y en aplicaciones secuenciales (1X seguido de 1X) de ambos herbicidas en un sistema de manejo de malezas general. Se realizaron estudios de invernadero para cuantificar los efectos sinérgicos y antagónicos. Los tratamientos incluyeron un testigo no-tratado; glyphosate a 0.84, 0.63, 0.42, y 0.21 kg ha^{-1}; glufosinate a 0.58, 0.44, 0.29, y 0.15 kg ha^{-1}; y todas las combinaciones de mezcla en tanque de cada herbicida. Los pesos secos fueron convertidos a porcentaje de valores de crecimiento para cada dosis de los dos herbicidas solos, y estos valores fueron usados para calcular las respuestas esperadas de combinaciones de mezclas en tanque con el uso del método Colby. Los valores esperados fueron comparados a los porcentajes de crecimiento observados usando un método de modelo mixto. Los resultados de los experimentos de campo indicaron que las mezclas en tanque de glyphosate y glufosinate fueron menos efectivas para el control de *A. palmeri* que glyphosate aplicado solo. La adición de cualquier dosis de glufosinate a una dosis 1X de glyphosate redujo el control de *A. palmeri* al compararse con glyphosate solo. Los estudios de invernadero confirmaron el antagonismo visto en el campo. Estos resultados indican que las aplicaciones secuenciales de estos herbicidas son una mejor opción para el manejo de *A. palmeri.*

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Cotton is an economically important crop in the United States. In 2010, over 4.3 million ha of cotton were harvested, which produced over 18.1 million bales (3.9 billion kg) of cotton lint. This was slightly less than record production in 2005 (National Agricultural Statistics Service [NASS] 2012a). In 2010, Texas produced 43% of all the cotton in the United States with a value of over $3 billion (NASS 2012b).

Weeds are a major constraint to profitable cotton production. They compete for nutrients, water, and light and can reduce lint yields (Stuart et al. 1984). *Amaranthus* species are particularly troublesome weeds for cotton producers because of their ability to cause significant yield loss and profit reduction if not properly managed. In 2002, Palmer amaranth was estimated to have reduced cotton yields by 12% nationwide as well as in Texas (Byrd 2003). This weed competes with cotton throughout the growing season. Competitive infestations may reduce available soil water and nutrients for the developing cotton plant and decrease light availability due to shading, which may lead to decreased lint production and quality. In addition to the yield losses caused by this weed, losses from delayed or complicated harvest also can be significant (Smith et al. 2000). Large Palmer amaranth plants can clog harvest equipment, which increases clean-out time and reduces harvest efficiency. Managing Palmer amaranth can also impact profitability. In a 2008 Georgia survey, Culpepper et al. (2010) reported that growers spent an average of $82 ha^{-1} for control measures aimed at preventing the development of glyphosate-resistant Palmer amaranth populations.

Current management strategies for *Amaranthus* species control in cotton depend on cultivation and chemical methods. Herbicides are typically preferred due to their partial or complete selectivity and usefulness in conservation tillage systems. A number of herbicides have been used in cotton to control weeds, but several genetic transformations in cotton have allowed for the POST use of nonselective herbicides in cotton. Since 2006, enhanced glyphosate-resistant (Roundup Ready® Flex) cotton has been available to producers as a tool for controlling weeds in cotton. Roundup Ready® Flex technology allows producers to apply glyphosate POST any time during the growing season to control most herbaceous weeds effectively while leaving the crop unaffected.

Roundup Ready® cotton technology has found widespread acceptance and almost every commercial cotton seed company has incorporated this technology into most of their current commercial lines. In 2013, Roundup Ready® cotton cultivars were planted on over 98% of the hectares in Texas and almost 99% of cotton hectares in the United States (US Department of Agriculture–Agricultural Marketing Service [USDA-AMS] 2013). Postemergence in-crop applications of glyphosate have been effective and economical for controlling weeds for many producers, as evidenced by current seed-use trends. Several weed species, including johnsongrass [*Sorghum halepense* (L.) Pers.], woollyleaf bursage [*Ambrosia grayi* (A. Nels.) Shinners], and field bindweed (*Convolvulus arvensis* L.) have declined since this technology has been introduced (Anonymous 2002).

Glufosinate-resistant (LibertyLink®) cotton was commercialized in 2004. This technology allowed producers to apply glufosinate (a nonselective herbicide) POST to manage a variety of annual weeds. This herbicide is effective at controlling a number of annual weeds if applied at the proper weed stage. However, control of certain weeds such as *Amaranthus* species with glufosinate has been inconsistent, especially under poor growing conditions (Steckel et al. 1997). Glufosinate effectively controls morningglory (*Ipomoea* spp.), which is not consistently controlled with glyphosate (Culpepper et al. 2000).

New proprietary glyphosate-resistant cotton cultivars carrying the trade name GlyTol® were commercialized in 2010. Cotton cultivars containing both GlyTol® and LibertyLink® traits were developed and commercialized as GlyTol® LibertyLink® (GL) cotton in 2011. GlyTol® LibertyLink® technology offers producers the potential to manage weeds in cotton with over-the-top applications of two herbicides with distinctly different mechanisms of action. This application flexibility may allow producers to manage weeds better than with either herbicide alone, and may minimize the risk of herbicide-resistant weed populations evolving. However, the benefits of such added weed management flexibility are not well understood. Therefore, the objectives of this study were (1) to identify potential synergistic or antagonistic effects on

Palmer amaranth in the Texas High Plains following application of tank-mix combinations of glyphosate and glufosinate in GlyTol® LibertyLink® cotton, (2) to determine the most effective sequential applications for glyphosate and glufosinate in GlyTol® LibertyLink® cotton to manage Palmer amaranth, and (3) to quantify synergistic or antagonistic effects observed in field trials in controlled greenhouse studies.

Materials and Methods

Field Studies. Three field experiments were conducted in 2010 and 2011 at the Texas A&M AgriLife Research and Extension Center near Lubbock, TX (33.69°N, −101.83°W) to evaluate Palmer amaranth control with tank mixes and sequential applications of glyphosate and glufosinate-ammonium in Glytol® LibertyLink® cotton. The first study (Tank Mixes) evaluated tank mixes of glyphosate and glufosinate, a second study (Proportional Tank Mixes) evaluated proportional tank mixes, and a third study (Sequential Applications) assessed weed control systems following both herbicides used in sequence. Soils were an Acuff clay loam (fine–loamy, mixed, thermic Aridic Paleustolls) with less than 1% organic matter and a pH of 7.9. For all experiments, FM 9250GL (FiberMax® 9250GL cotton seed, Bayer CropScience LP, P.O. Box 12014, 2 T.W. Alexander Drive, Research Triangle Park, NC 27709) was planted on 102-cm rows at a depth of 3.8 cm and a seeding rate of 13.1 seeds m^{-1} of row and treated with aldicarb [2-methyl-2(methylthio)propionaldehyde 0-(methylcarbamoyl)oxime] (Temik 15G®, 0.54 kg ha^{-1}, Bayer CropScience) for insect and nematode control. Planting dates were May 19, 2010 and May 23, 2011. Plots, four rows by 9.1 m in length, were arranged in a randomized complete block design with three replications. Rainfall totaled 695 mm in 2010 and 172 mm in 2011. Tank-mix and proportional tank-mix trial plots received no supplemental furrow irrigation in 2010, whereas supplemental irrigation totaled 152 mm in 2011. Sequential application trials received an additional 76 mm of furrow irrigation in 2010 and 229 mm in 2011.

Tank Mixes. Palmer amaranth treatments included an nontreated check, glyphosate (Roundup PowerMax™, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167) at 0.84 kg ha^{-1}, glufosinate-ammonium (Liberty®, Bayer CropScience LP) at 0.58 kg ha^{-1}, and tank-mix combinations of glyphosate plus glufosinate at the following rates: 0.84 + 0.58, 0.84 + 0.44, 0.84 + 0.29, 0.84 + 0.15, 0.63 + 0.58, 0.42 + 0.44, and 0.21 + 0.58 kg ha^{-1}, respectively. Treatments were applied when Palmer amaranth was 5 to 10 cm in height or 15 to 20 cm in height. Average initial Palmer amaranth density in nontreated checks was 6 plants m^{-2} in 2010 and 365 plants m^{-2} in 2011.

Proportional Tank Mixes. Proportional tank-mix treatments included an nontreated check, glyphosate at 0.84 kg ha^{-1}, glufosinate at 0.58 kg ha^{-1}, and glyphosate + glufosinate at 0.63 + 0.15 (0.75X + 0.25X), 0.42 + 0.29 (0.5X + 0.5X), and 0.21 + 0.44 (0.25X + 0.75X) kg ha^{-1}. These tank-mix combinations kept the overall herbicide rate in the tank no greater than 1X the recommended label rate. Treatments were applied when weeds were 5 to 10 cm in height and or 15 to 20 cm in height. Average initial Palmer amaranth density in nontreated checks was 8 plants m^{-2} in 2010 and 500 plants m^{-2} in 2011.

Sequential Applications. Weed control systems were evaluated with the use of three sequential applications of glyphosate or glufosinate in all possible sequence configurations. Sequences included the following: glyphosate followed by (fb) glyphosate fb glyphosate, glyphosate fb glyphosate fb glufosinate, glyphosate fb glufosinate fb glyphosate, glufosinate fb glyphosate fb glyphosate, glufosinate fb glufosinate fb glyphosate, glufosinate fb glyphosate fb glufosinate, glyphosate fb glufosinate fb glufosinate, and glufosinate fb glufosinate fb glufosinate. Glyphosate was applied at a rate of 0.84 kg ha^{-1} and glufosinate was applied at a rate of 0.58 kg ha^{-1} at each timing. All treatments were applied when flushes of weeds were 5 to 10 cm in height. Average initial Palmer amaranth density in nontreated checks was 8 plants m^{-2} in 2010 and 282 plants m^{-2} in 2011. In 2010, late-POST (LPOST) timings were not applied becauase of canopy closure. All plots received a preplant-incorporated (PPI) application of trifluralin (Treflan™ EC, 0.84 kg ai ha^{-1}, Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268), which was incorporated 5 to 10 cm into the soil immediately after application with the use of a spring-tooth harrow.

Percent weed control was estimated 14 d after treatment (DAT) following each application. Control was estimated on a scale of 0 to 100, with 0 meaning no control and 100 meaning complete control, as indicated by plant death. At the end of the growing season, the middle two rows of each plot in the sequential applications trials were harvested mechanically with a cotton stripper and nonginned, bur-extracted seed cotton weights recorded. Cotton was harvested on October 19, 2010 and October 10, 2011. All plot weights were standardized to 33% turnout based on the nontreated check turnouts.

For all experiments, data were subjected to ANOVA with the use of the PROC MIXED (PROC MIXED, PROC IML, Statistical Analysis Systems [SAS] software, Version 9.2. Statistical Analysis Systems Institute, Inc., P.O. Box 8000, Cary, NC 25712) procedure of SAS 9.2 (SAS Institute). Year and replication were considered random variables in each experiment. Visually estimated percentage data were normalized by arcsine–square root transformation before analysis. For clarity, untransformed means are presented with interpretation based on transformed data. Transformed least-squared treatment means were separated with the use of the PDIFF option in PROC MIXED at an alpha level of $P = 0.05$. Letter groupings for means were derived with the use of the PDMIX800 macro developed by Saxton (1998).

Greenhouse Studies. Greenhouse studies were conducted in July of 2010 and 2011 to quantify synergistic or antagonistic effects of tank-mix combinations of glyphosate and glufosinate on Palmer amaranth. Seeds of a known population of glyphosate- and glufosinate-susceptible Palmer amaranth were collected from fields at Texas A&M AgriLife Research near Lubbock, TX in 2010 for use in greenhouse studies. Palmer amaranth seeds were planted at a depth of 2 mm in 9×9–cm pots with the use of SunGro Sunshine (SunGro Horticulture, 770 Silver Street, Agawam, MA 01001) SB 300 universal professional growing mix and grown at 30 $\pm$ 5 C. Pots were placed in trays, watered to saturation, and covered with clear plastic domes to maintain high relative humidity. Palmer amaranth day-length dormancy was discouraged by supplementing natural daylight with 400-W high-pressure sodium lamps providing 24 μmol m^{-2} s^{-1} and 16 h day length.

When plants reached 5 to 10 cm in height, treatments of glyphosate at 0.84, 0.63, 0.42, and 0.21 kg ha^{-1}; glufosinate at 0.58, 0.44, 0.29, and 0.15 kg ha^{-1}; and every possible tank-mix combination along with an nontreated check were assigned to pots in a randomized complete block design with three replications. Treatments were sprayed with the use of a stationary laboratory spray chamber equipped with a Turbo TeeJet® 110015 nozzle (TeeJet, Spraying Systems Co., North Avenue and Schmale Road, Wheaton, IL 60188) calibrated to deliver 93 L ha^{-1} at a pressure of 270 kPa. Fourteen DAT, plants were clipped at the soil surface and placed in separate paper bags by treatment and replication. Clipped plants were air dried and weighed.

To quantify antagonistic or synergistic effects, dry-weight data were subjected to an augmented mixed-model analysis. Dry weights were converted to a percent inhibition (control) based on the nontreated check. Percent inhibition values were converted to percent-of-nontreated check values, 100-*Y*.

Expected means for percent of control were calculated within SAS for each tank mix by Equation 1, according to Colby's method (Colby 1967):

$$E = X + Y - (XY/100), \qquad [1]$$

where E is the expected percent inhibition of growth, X is the calculated percent inhibition by herbicide A alone at the 1X rate and Y is the percent inhibition by herbicide B alone at the 1X rate. Tests of significance were based on the null hypothesis (Equation 2)

$$J_{AB} = \mu_{AB} - E_{AB} = 0, \qquad [2]$$

where J is the joint-action effect of herbicides A and B together in tank mix, μ is the observed mean for percent growth of the treatment for A and B together, and E is the expected response of A and B in tank mix based on Colby's calculated value. Negative J_{AB} effects indicate synergism, whereas positive J_{AB} effects indicate antagonism.

All data were subjected to ANOVA with the use of the augmented mixed-model methodology outlined by Blouin et al. (2010). Observed percent growth means and their variances were calculated with the use of PROC MIXED in SAS, and joint-action effects were calculated with the use of PROC

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Table 1. Palmer amaranth control 14 days after treatment with glyphosate and glufosinate tank mixes.[a,b,c]

Treatment	Rate	Palmer amaranth 2010 5–10 cm	Palmer amaranth 2010 15–20 cm	Palmer amaranth 2011 5–10 cm	Palmer amaranth 2011 15–20 cm
	(kg ha^{-1})	% control			
Untreated		0 d	0 d	0 g	0 e
Glyphosate	0.84	99 a	98 a	98 a	95 a
Glufosinate	0.58	90 b*	60 bc	52 f	73 d
Glyphosate + glufosinate	0.84 + 0.58	85 b*	65 b	93 b*	85 b
Glyphosate + glufosinate	0.84 + 0.44	90 b*	55 bc	88 bc*	80 bcd
Glyphosate + glufosinate	0.84 + 0.29	88 b*	52 c	87 bc	75 cd
Glyphosate + glufosinate	0.84 + 0.15	92 b*	58 bc	91 b	80 bcd
Glufosinate + glyphosate	0.58 + 0.63	67 c	62 bc	78 cd*	72 d
Glufosinate + glyphosate	0.58 + 0.42	70 c	60 bc	62 ef*	80 bcd
Glufosinate + glyphosate	0.58 + 0.21	65 c	57 bc	73 de*	83 bc
SE		3.7	3.1	3.9	2.9

[a] Abbreviations: DAT, days after treatment; SE, standard error.

[b] Means within columns followed by the same letter are not significantly different according to differences of transformed least-squared means with the use of the PDIFF option in SAS at P = 0.05.

[c] Asterisks denote significant differences in transformed least-squared means between weed sizes within a year with the use of the PDIFF option in SAS at P = 0.05.

IML. The Delta method for tests of significance for nonlinear functions of the means (Casella and Berger 2002; Littell et al. 2002) was implemented in PROC IML to compute variances and covariances with test statistics for each joint-action effect at $P \leq 0.05$.

Results and Discussion

A significant year-by-treatment interaction was observed in all field trials; therefore, data were analyzed separately by year.

Field Studies. *Tank Mixes.* In 2010, tank-mix combinations of glyphosate at 0.84 kg ha^{-1} plus glufosinate at 0.58, 0.44, 0.29, and 0.15 kg ha^{-1} resulted in 85 to 92% control of 5 to 10–cm Palmer amaranth 14 DAT, which was similar to glufosinate at 0.58 kg ha^{-1} (90%) (Table 1). Glyphosate at 0.84 kg ha^{-1} resulted in greater control (99%) than all other treatments.

Tank-mix combinations of glufosinate at 0.58 kg ha^{-1} plus glyphosate at 0.63, 0.42, and 0.21 kg ha^{-1} resulted in reduced Palmer amaranth control compared to glufosinate alone 14 DAT (Table 1). The addition of glufosinate to glyphosate appeared to antagonize glyphosate activity, resulting in reduced control. These results are similar to Chuah (2008) who reported moderate but reduced goosegrass (*Eleusine indica* Gaertn.) control following the addition of glufosinate to glyphosate compared to glyphosate alone.

Glyphosate alone controlled 15- to 20-cm Palmer amaranth 98% (Table 1). All other tank-mix treatments controlled this weed < 70%, which was less than the control following glyphosate alone but similar to the control following glufosinate alone (60%).

In 2011, glyphosate and glufosinate alone controlled Palmer amaranth 98 and 52%, respectively, 14 DAT (Table 1). Applications of glyphosate plus glufosinate controlled Palmer amaranth less effectively (87 to 93%) than control observed with glyphosate alone.

Mid-POST control of 15- to 20-cm Palmer amaranth by glyphosate alone and glufosinate alone was 95 and 73%, respectively, 14 DAT (Table 1). Tank mixes of glyphosate + glufosinate provided less control than the control observed from glyphosate alone (95%).

No tank mix combination controlled 5- to 10- or 15- to 20-cm weeds as well as glyphosate alone in 2010. Similarly, adding glyphosate to a 1X rate of glufosinate did not improve control compared to glufosinate alone. Weed size did affect control levels for several tank mixes. This effect was very pronounced in 2010, where control with glyphosate

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Table 2. Palmer amaranth control 14 days after treatment with glyphosate and glufosinate proportional tank mixes.[a,b,c]

		Palmer amaranth			
		2010		2011	
Treatment	Rate	5–10 cm	15–20 cm	5–10 cm	15–20 cm
	(kg ha^{-1})[d]	% control			
Untreated		0 d	0 c	0 e	0 e
Glyphosate	0.84	100 a	100 a	99 a	99 a
Glyphosate + glufosinate	0.63 + 0.15	90 c*	63 b	92 b*	55 b
Glyphosate + glufosinate	0.42 + 0.29	95 bc*	63 b	58 c	58 c
Glyphosate + glufosinate	0.21 + 0.44	96 b*	55 b	38 d*	73 d
Glufosinate	0.58	96 b*	55 b	58 c*	63 c
SE		3.3	2.4	2.6	2.6

[a] Abbreviations: DAT, days after treatment; SE, standard error.

[b] Means within columns followed by the same letter are not significantly different according to differences of transformed least-squared means using the PDIFF option in SAS at P = 0.05.

[c] Asterisks denote significant differences in transformed least-squared means between weed sizes within a year using the PDIFF option in SAS at P = 0.05.

at 0.84 kg ha^{-1} and any rate of glufosinate was greater than control with EPOST timings compared to MPOST timings. Everman et al. (2009) noted the importance of weed size at the time of application for controlling Palmer amaranth with glufosinate alone and tank mixes including glufosinate. Glufosinate appeared to be less effective in 2011, as evidenced by lower levels of control on smaller weeds for tank mixes with greater proportions of glufosinate 14 DAT (Table 1). Climatic conditions were very hot and dry in 2011, which may have contributed to the decreased glufosinate activity compared to 2010. Coetzer et al. (2001) described decreased glufosinate activity on Palmer amaranth under low relative humidity conditions. Extremely hot temperatures and low relative humidity in 2011 likely affected the contribution of glufosinate in tank mixes.

Proportional Tank Mixes. Proportional tank-mix studies aimed to maintain the total herbicide rate in the tank 1X while varying the proportions of glyphosate and glufosinate in the mix. In 2010, 5- to 10-cm Palmer amaranth control with tank mixes of glyphosate and glufosinate ranged from 90 to 96% 14 DAT, which was less than control from glyphosate alone (100%) (Table 2).

Glyphosate alone controlled 15- to 20-cm Palmer amaranth 100%, 14 DAT. Control with glyphosate plus glufosinate tank mixes ranged from 55 to 63% and was less than control achieved with glyphosate alone (100%) (Table 2). For all proportional tank-mix applications in 2010, weed size affected levels of control. Control of 5- to 10-cm weeds was greater than control of 15- to 20-cm weeds for all tank-mix combinations. Additionally, applications of glufosinate alone controlled 5- to 10-cm weeds better than 15- to 20-cm weeds.

In 2011, glyphosate at 0.84 kg ha^{-1} controlled 5- to 10-cm Palmer amaranth 99% 14 DAT (Table 2). Less control was observed with glufosinate at 0.58 kg ha^{-1} (58%). Proportional tank mixes resulted in less Palmer amaranth control (38 to 92%) than glyphosate alone. Tank-mix combinations of glyphosate plus glufosinate applied to 15- to 20-cm Palmer amaranth resulted in less control (55 to 73%) than control observed following glyphosate alone (99%). Reduced Palmer amaranth control was observed with decreasing levels of glyphosate in the tank mixes.

Tank-mix combinations of glyphosate plus glufosinate at 0.21 + 0.44 kg ha^{-1} resulted in better control of 15- to 20-cm Palmer amaranth compared to 5- to 10-cm weeds 14 DAT (Table 2). Glufosinate alone controlled 15- to 20-cm weeds better than 5- to 10-cm weeds. This improved control was likely the result of higher relative humidity and reduced plant stress at the 15- to 20-cm application timing compared to the earlier timing. The high temperature and minimum relative humidity on the day of 5- to 10-cm weed applications was 40 C and 7%, respectively. On the day of 15- to 20-cm weed applications those values were 35 C and 17%.

Table 3. Palmer amaranth control 14 days after treatment with glyphosate and glufosinate sequential treatments.[a,b]

Treatment	EPOST	MPOST	LPOST	Cotton lint yield
	% control			kg/ha
2010				
Nontreated	0 c	0 c		258 b
Gly fb gly	100 a	100 a		608 a
Gly fb glu	100 a	100 a		557 a
Glu fb gly	96 b	100 a		596 a
Glu fb glu	96 b	98 b		572 a
SE	2.3	1.8		179
2011				
Nontreated	0 c	0 d	0 g	0 e
Gly fb gly fb gly[c]	94 a	99 a	100 a	386 ab
Gly fb gly fb glu	92 a	98 a	95 b	330 b
Gly fb glu fb gly	91 a	77 bc	92 bc	217 c
Glu fb gly fb gly	60 b	98 a	99 a	395 a
Glu fb glu fb gly	62 b	68 c	87 d	46 e
Glu fb gly fb glu	60 b	95 a	90 cd	223 c
Gly fb glu fb glu	93 a	80 b	62 e	156 d
Glu fb glu fb glu	55 b	72 bc	53 f	0 e
SE	3.8	2.7	2.2	88

[a] Abbreviations: EPOST, early postemergence; fb, followed by; glu, glufosinate; gly, glyphosate; MPOST, mid-postemergence; LPOST, late-postemergence; SE, standard error.

[b] Means within columns followed by the same letter are not significantly different according to differences of transformed least-squared means with the use of the PDIFF option in SAS at P = 0.05.

Results from these trials indicate antagonism of glyphosate activity by glufosinate on Palmer amaranth control. Kudsk and Mathiassen (2004) observed antagonism of glyphosate by glufosinate when applied to wild mustard (*Sinapis arvensis* L.). These results confirmed that response levels of proportional tank mixes of these two herbicides were less than predicted by additive dose models, indicating strong antagonism between glyphosate and glufosinate. It is possible that herbicide mode of action plays a role in herbicide antagonism. In contrast, Brabham and Johnson (2010) observed synergistic effects for tank mixtures of glufosinate and fomesafen on common lambsquarters (*Chenopodium album* L.).

Sequential Applications. Palmer amaranth control in 2010 with EPOST applications of glyphosate was 100% 14 DAT, with only slightly less control observed with EPOST applications of glufosinate (96%) (Table 3). After sequential MPOST applications, at least 98% control was achieved with all treatments, and all treatments with glyphosate as part of the sequence achieved 100% Palmer amaranth control. No LPOST treatments were applied, because of canopy closure.

Cotton lint yield ranged from 258 kg ha^{-1} in the nontreated plots to 608 kg ha^{-1} in glyphosate followed by (fb) glyphosate-treated plots (Table 3). No differences in cotton lint yield were observed following any of the sequential treatments, but all treatment yields were greater than the nontreated control.

In 2011, EPOST, MPOST, and LPOST applications were made. Similar to results in 2010, EPOST applications of glyphosate were more effective at controlling Palmer amaranth than glufosinate (Table 3). Early POST control of Palmer amaranth with glyphosate ranged from 91 to 94%, whereas control following glufosinate did not exceed 62%. Mid-POST treatments of glyphosate preceded by either glyphosate or glufosinate achieved at least 95% Palmer amaranth control 14 DAT. Less Palmer amaranth control was observed in treatments in which glufosinate followed either glufosinate or glyphosate. Late-POST control of Palmer amaranth was dependent on EPOST and MPOST herbicide selection. Glyphosate applied sequentially three times resulted in 100% Palmer amaranth control. When glyphosate was applied twice in sequence following an EPOST application of glufosinate, 99% Palmer amaranth control was achieved. When glufosinate was used either second or third in sequence with two applications of glyphosate, reduced levels of Palmer amaranth control were observed (92 to 95%). Sequences with two applications of glufosinate benefited from glyphosate applied either MPOST or LPOST (87 to 90%), but EPOST applications of glyphosate fb MPOST and LPOST applications of glufosinate did not achieve greater than 62% Palmer amaranth control. Three applications of glufosinate did not effectively control Palmer amaranth (53%).

Cotton lint yields were reduced in 2011 due to hot, dry conditions. Maximum yield (386 to 395 kg ha^{-1}) was achieved with three applications of glyphosate or two applications of glyphosate following glufosinate EPOST. These two treatments also had the greatest level of weed control, whereas lower yield corresponded to reduced levels of Palmer amaranth control.

Results from these studies indicate that sequential applications of glyphosate are most effective for

Table 4. Observed means and calculated expected responses for Palmer amaranth control 14 days after treatment.[a]

Glyphosate rate	Glufosinate rate	Run 1		Run 2	
		Observed	Expected	Observed	Expected
(kg ha^{-1})	(kg ha^{-1})	% control			
0	0	0	–	0	–
0.84	0	84	–	88	–
0.63	0	74	–	83	–
0.42	0	58	–	75	–
0.21	0	46	–	69	–
0	0.58	53	–	83	–
0	0.44	35	–	75	–
0	0.29	58	–	71	–
0	0.15	41	–	56	–
0.84	0.58	58*	92	89	98
0.84	0.44	75*	89	87	97
0.84	0.29	72*	93	75*	96
0.84	0.15	57*	90	73*	95
0.63	0.58	56*	88	84*	97
0.63	0.44	44*	83	76*	96
0.63	0.29	26*	89	79*	95
0.63	0.15	66*	90	85*	95
0.42	0.58	55*	80	69*	96
0.42	0.44	69*	73	66*	94
0.42	0.29	66*	82	73*	93
0.42	0.15	37*	75	75*	89
0.21	0.58	31*	75	67*	95
0.21	0.44	34*	65	83*	92
0.21	0.29	50*	77	74*	91
0.21	0.15	46*	69	45*	86

[a] Observed means followed by an asterisk are significantly different at $P = 0.05$ from expected responses calculated with Colby's method. Observed means less than expected responses indicate antagonistic effects.

controlling Palmer amaranth in Texas High Plains Glytol® LibertyLink® cotton. Effective Palmer amaranth control was achieved even if glufosinate was used first in the sequence. Sequential applications of glyphosate effectively controlled weeds in several other crops (Norsworthy and Oliver 2002; Hutchinson et al. 2003; Thomas et al. 2004). Glyphosate may successfully control initial weed infestations as well as successive flushes of emerging weeds throughout the growing season. However, where glyphosate-resistant Palmer amaranth has infested fields, alternative modes of action or weed management strategies must be sought (Neve et al. 2011; Whitaker et al. 2010a, 2010b).

Greenhouse Studies. Significant run by treatment interactions were observed; therefore, data are presented by run. In run one, all observed treatment responses for Palmer amaranth control 14 DAT except glyphosate at 0.42 kg ha^{-1} plus glufosinate at 0.44 kg ha^{-1} were different than the calculated expected responses for those treatments (Table 4). Additionally, all different observed responses were less than expected responses, thus indicating antagonistic effects.

Most run-two observed treatment responses were also lower than expected responses. Tank-mix combinations of glyphosate plus glufosinate at 0.84 + 0.58, 0.84 + 0.44, 0.63 + 0.15, and 0.21 + 0.44 kg ha^{-1} provided similar levels of control to the expected values for these treatments. However, all other treatments resulted in antagonistic effects on Palmer amaranth control.

These greenhouse trials support the suspected high levels of antagonism observed in field studies and suggest that glyphosate and glufosinate should not be applied in a tank mixture to control Palmer amaranth. Whitaker et al. (2010a) reported antagonism of glyphosate by glufosinate on glyphosate-resistant Palmer amaranth populations in North Carolina. They suggested sequential applications of glufosinate could be used to manage this weed. Everman et al. (2007) reported that adding pyrithiobac to glufosinate provided additional control of Palmer amaranth compared to glufosinate alone. However, application and plantback restrictions for trifloxysulfuron in cotton and plantback restrictions to sorghum (*Sorghum bicolor* L.) for pyrithiobac limit tank mixes of glufosinate with these two herbicides in West Texas.

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