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Article

Integrated Palmer Amaranth Management in Glufosinate-Resistant Cotton: II. Primary, Secondary and Conservation Tillage

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Abstract: A three year field experiment was conducted to evaluate the role of soil inversion, cover crops and spring tillage methods for Palmer amaranth between-row (BR) and within-row (WR) management in glufosinate-resistant cotton. Main plots were two soil inversion treatments: fall inversion tillage (IT) and non-inversion tillage (NIT). Subplots were three cover treatments: crimson clover, cereal rye or none (*i.e.*, winter fallow); and the sub subplots were four secondary spring tillage methods: disking followed by (fb) cultivator (DCU), disking fb chisel plow (DCH), disking fb disking (DD) and no tillage (NT). Averaged over years and soil inversion, the crimson clover produced maximum cover biomass (4390 kg ha^{-1}) fb cereal rye (3698 kg ha^{-1}) and winter fallow (777 kg ha^{-1}). Two weeks after planting (WAP) and before the postemergence (POST) application, Palmer amaranth WR and BR density were two- and four-times less, respectively, in IT than NIT. Further, Palmer amaranth WR and BR density were reduced two-fold following crimson clover and cereal rye than following winter fallow at 2 WAP. Without IT, early season Palmer amaranth densities were 40% less following DCU, DCH and DD, when compared with IT. Following IT, no spring tillage method improved Palmer amaranth control. The timely application of glufosinate + *S*-metolachlor POST tank mixture greatly improved Palmer amaranth control in both IT and NIT systems. The highest cotton yields were obtained with DD following cereal rye (2251 kg ha^{-1}), DD following crimson clover (2213 kg ha^{-1}) and DD following winter fallow (2153 kg ha^{-1}). On average, IT cotton yields (2133 kg ha^{-1}) were 21% higher than NIT (1766 kg ha^{-1}). Therefore, from an integrated weed management standpoint, an occasional fall IT could greatly reduce Palmer amaranth emergence on farms highly infested with glyphosate-resistant Palmer amaranth. In addition, a cereal rye or crimson clover cover crop can effectively reduce early season Palmer amaranth emergence in both IT and NIT systems. For effective and season-long control of Palmer amaranth, one or more POST applications of glufosinate + residual herbicide as tank mixture may be needed in a glufosinate-based cotton production system.

Keywords: cover crops; glufosinate-tolerant cotton; soil inversion; spring tillage methods; specifically

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1. Introduction

Palmer amaranth [*Amaranthus palmeri* (L.) S. Wats] is one of the several pigweed species that are problematic in row crops in the southeastern United States. Compared to other pigweed species, such as common waterhemp [*Amaranthus rudis* (L.) Sauer], redroot pigweed (*Amaranthus retroflexus* L.) and tumble pigweed (*Amaranthus albus* L.), Palmer amaranth produced the highest dry weight, leaf area and height [1]. Palmer amaranth grows relatively quickly and can attain a height of 2 m or more [1]. It is a dioecious plant with tremendous seed production potential and rapid seed germination [1–3]. A single female plant can produce more than 600,000 seeds, depending upon density, which have an average diameter of 1.0 mm [2]. It has exceptional drought tolerance [4–7]. Additionally, Palmer amaranth can grow under low light conditions, such as dense crop canopies [8]. Palmer amaranth interference and subsequent yield losses have been documented in several crops, such as cotton, corn, cucurbits, grain sorghum, peanut, potato, soybean, sweet potato and several vegetable crops [9–23].

Until recently, glyphosate-resistant cotton production systems were very effective for managing a broad spectrum of weeds, including Palmer amaranth [24,25]. However, the evolution of glyphosate resistant Palmer amaranth has forced cotton producers to explore other management options and integrated approaches. These included inversion tillage and adoption of glufosinate-resistant varieties [26]. Additionally, resistance to dinitroaniline herbicides has also been reported in some Palmer amaranth populations [26,27].

The role of tillage in altering the distribution, abundance, composition of species, as well as seedling emergence patterns, has been well documented [28–36]. In conservation tillage systems, where soil incorporation is minimized, seeds accumulate near soil surface. Contrarily, the soil disturbance resulting from various tillage practices places weed seeds at different depths that vary in availability of moisture, diurnal temperature fluctuation, light exposure and activity of predators [37]. Moldboard plowing buries weed seeds deeply in the soil; however, deeper burial may lead to long-term weed problems, because of increased seedbank longevity [38].

The type of tillage implement used to till the soil greatly influences the vertical distribution and density of seeds within the soil profile [28,30,36,39–42]. Inversion tillage implements bury a large proportion of the weed seed, while non-inversion tillage implements leave more of the seed near the soil surface [28]. Previous research demonstrated that more than 60% of weed seedbank was concentrated in top 5 cm following either a no-till or chisel plow [41]. Therefore, considering the inability of small Palmer amaranth seed to emerge from depths greater than 7.5 cm and a light requirement for germination, moldboard plowing followed by a conservation system may reduce the Palmer amaranth populations to manageable levels.

Currently, an integrated weed control system utilizing high-residue cover crops as a weed management tool is gaining popularity [43–54]. Cover crops provide early season weed control by reducing light transmission and quality, altering soil temperature, physically suppressing weed emergence and allelopathy [55–58]. Cereal rye (*Secale cereale* L.) has been documented as having high biomass potential, early season weed suppression and allelopathic properties by several researchers [44,46–48,59–62]. It has also been observed that cereal rye residue alone was effective at reducing glyphosate-resistant Palmer amaranth emergence by 94% in the row middle and 50% within the cotton row [63]. Others reported that the use of high residue cover crops in conjunction with chemical and cultural weed control tactics provided effective control of established glyphosate-resistant Palmer amaranth, while helping to prevent the development of resistance in glyphosate-susceptible populations [64].

Considering the magnitude of current herbicide resistance problems, inversion tillage can likely improve control of glyphosate-resistant Palmer amaranth. However, increased input costs and potential soil erosion are significant challenges for growers. Integration of cover crops and glufosinate-resistant cotton technology may be viable alternatives in the light of these economic and environmental considerations. Therefore, with the current Palmer amaranth management challenges, a field study was conducted to evaluate the role of primary inversion tillage, cover crops and secondary tillage methods for Palmer amaranth management in glufosinate-resistant cotton.

2. Materials and Methods

2.1. Experimental Design and Establishment

A three year field experiment was conducted from fall 2008 through harvest 2011 at the E.V. Smith Research Center, Field Crops Unit near Shorter, AL, on a Compass sandy loam soil (coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults) with 1.9 to 2.1% organic matter and pH 6.2 to 6.4. The experiment occupied a site that had been in continuous strip-tillage for previous six years. The entire experimental area was infested with glyphosate-susceptible Palmer amaranth prior to experiment establishment, and the subsequent treatments remained in the same location for three years without re-randomization of treatments. Treatments consisted of a factorial arrangement of two levels of soil inversion—fall inversion tillage (IT) and non-inversion tillage (NIT)—three levels of winter cover crops—cereal rye, crimson clover (*Trifolium incarnatum* L.) and none (*i.e.*, winter fallow)—and four different spring tillage methods, resulting in a 24-treatments test. The four spring tillage methods were disk followed by (fb) chisel plow (DCH), disk fb field cultivator (DCU), disk twice (DD) and a no-tillage control (NT). The experimental design consisted of a split-split plot treatment restriction in a randomized complete block design with three replicates. Soil inversion, cover crop and spring tillage were assigned to the main plots, sub plots and sub-sub plots, respectively. The size of the main, sub and sub-sub plots were 43.9 m by 9.1 m, 14.6 by 9.1 m and 3.6 by 9.1 m, respectively. A schedule of operations performed each year is given in Table 1.

Table 1. Schedule of operations performed during the experiment.

	Experimental Years		
Operations	2008–2009	2009–2010	2010–2011
Broadcasting of Palmer amaranth seed	19 Nov 2008	–	–
Fall inversion tillage	19 Nov 2008	–	–
Planting of cover crops	20 Nov 2008	6 Jan 2010	2 Dec 2010
Rolling and termination of cover crops	22 Apr 2009	18 May 2010	19 Apr 2011
Subsoiling	23 Apr 2009	24 May 2010	26 Apr 2011
Planting of cotton	1 Jun 2009	27 May 2010	5 May 2011
Fertilization (16-16-16)	1 Jun 2009	27 May 2010	5 May 2011
POST application	16 Jun 2009	16 Jun 2010	24 May 2011
Graminicide application (Sethoxydim + COC)	13 Jul 2009	8 Jul 2010	6 Jul 2011
LAYBY application	14 Aug 2009	16 Aug 2010	19 Jul 2011
Cotton defoliation	26 Oct 2009	14 Oct 2010	13 Sep 2011
Cotton harvesting	9 Nov 2009	20 Oct 2010	30 Sep 2011

In the fall 2008, approximately 28 million native glyphosate-susceptible Palmer amaranth seeds were broadcast per hectare to ensure a sizeable seedbank of this weed. Prior to broadcasting, Palmer amaranth seed germination was tested by placing 25 seeds on commercial germination paper in four petri dishes at 35 °C. Seeds were kept moist with tap water inside closed petri dishes. Seeds were considered germinated when the radicle emerged 1 mm. Germination percentage was calculated as the number of germinated seeds divided by the total number of seeds multiplied by 100. Two weeks after initiation, 87% of the seeds germinated. One half of each block was subject to fall inversion tillage (IT) by moldboard plowing (30 cm) immediately fb one pass each of a disk and field cultivator; the other half was under non-inversion tillage (NIT) using a within-row subsoiler equipped with pneumatic tires to close the subsoiling slot. During the fall of each year, cereal rye (cv. 'Elbon' in 2009 and 2010 and 'Wrens Abruzzi' in 2011) and crimson clover (*Trifolium incarnatum* L. cv. 'Dixie') cover crops were seeded at rates of 101 and 28 kg seed ha^{-1}, respectively, in both IT and NIT. Different cereal rye cultivars had to be used due to seed availability; Wrens Abruzzi has been shown to be more allelopathic [65]. In 2009 and 2010, frequent rains delayed both the harvesting of cotton and subsequent planting of cover crops. Cereal rye cover was fertilized using 34 kg ha^{-1} of a 33-0-0 fertilizer. A winter fallow control was also included as check.

2.2. Cover Crop Management

Cover crops were rolled with a three section straight bar roller (Bigham Brothers Inc., Lubbock, TX, USA; Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA or Auburn University and does not imply endorsement of a product to the exclusion of others that may be suitable) in late April or early May using a JD 7730 equipped with an AutoSteer GPS. Cover crop rolling was immediately followed by an application of glyphosate (Roundup Weathermax®, Monsanto Company, St. Louis, MO, USA) at 0.84 kg ae ha^{-1} plus glufosinate (Ignite®, Bayer Crop Science, Research Triangle Park, NC, USA) at 0.49 kg ai ha^{-1}; the mixture was needed to enhance crimson clover termination. Cover crop biomass samples were taken prior to desiccation, and dry biomass was recorded. The entire experimental area was sub-soiled in May to 45 cm depth to break hardpans. A within-row subsoiler equipped with pneumatic tires only, to close the subsoiling slot, was used. Sub-soiling was followed by planting of glufosinate-resistant cotton (cvs. FM 1845 LLB2 in 2009 and FM 1735 LL in 2010 and 2011, Bayer Crops Science, Research Triangle Park, NC, USA). Each year, cotton was fertilized using 211 kg ha^{-1} of 16-16-16 fertilizer at the time of planting.

2.3. Secondary Tillage and Weed Management

The DCH tillage consisted of a single pass of 3 m disk fb a single pass of 1.8 m chisel plow, DD consisted of double pass of 3 m disk and DCU was a single pass of 3 m disk fb a single pass of 4.1 m field cultivator. A single postemergence (POST) application of a tank mixture of glufosinate at 0.60 kg ai ha^{-1} (Ignite®, Bayer Crops Science, Research Triangle Park, NC, USA) plus *S*-metolachlor (Dual II Magnum®, Syngenta Crop Protection, Inc., Greensboro, NC, USA) at 0.54 kg ai ha^{-1} tank mixture was made to 5 to 7.5 cm Palmer amaranth, between 15 and 20 days after planting cotton, with an ATV-mounted sprayer delivering 145 L ha^{-1} with flat-fan spray tips. In 2011, an additional POST application of glufosinate at 0.60 kg ai ha^{-1} plus *S*-metolachlor at 0.54 kg ai ha^{-1} was carried out three weeks after the first POST application. A last directed POST application (LAYBY) of prometryn (Caporal®, Syngenta Crop Protection, Inc., Greensboro, NC, USA) at 0.84 kg ai ha^{-1} plus MSMA (Drexel Chemical Company, Memphis, TN, USA) at 1.4 kg ai ha^{-1} was carried out approximately 2 months after the first POST application. Sethoxydim (Poast Plus®, Bayer Ag. Products, Research Triangle Park, NC, USA) was applied at 0.28 kg ai ha^{-1} as needed to maintain grass control.

2.4. Palmer Amaranth Sampling and Visual Control Ratings

Palmer amaranth density was determined both between (BR) and within (WR) the cotton rows before the POST application and again before the LAYBY application. BR Palmer amaranth density was recorded as number of plants in a quadrat (0.25 m^{-2}) randomly placed at four different positions between the second and third row of a four-row cotton plot. Similarly, WR Palmer amaranth density was recorded from a quadrat (0.25 m^{-2}) randomly placed at four different positions within the second and third rows. Palmer amaranth control was also assessed visually, for the entire plot, at weekly intervals on a 0 to 100 scale, where 0 and 100 indicate no control and complete control, respectively. Palmer amaranth was hand-pulled from all the plots before the LAYBY application, but following density counts and control ratings to facilitate cotton harvest. Cotton yields were determined by mechanically harvesting the two central rows within each four-row plot with a spindle picker.

2.5. Statistical Analysis

Data were analyzed using generalized linear mixed models or linear mixed models methodology as implemented in SAS® PROC GLIMMIX based on the underlying design, which was a randomized complete block design (r = 3) with a split-split-split plot in time restriction on randomization. Soil inversion, cover crop, spring tillage method, year and all their interactions were treated as fixed effects. Block and Block × treatment factors were treated as random effects. The split plot nature of the experiment requires five different residual terms: (1) block × soil inversion as the appropriate error term for soil inversion; (2) block × soil inversion × cover crop as the appropriate error term for cover crop and its interaction with soil inversion; (3) block × soil inversion × cover crop × spring tillage method as the appropriate error term for spring tillage and its interaction with soil inversion and cover crop; (4) block × year as the appropriate error term for year; and (5) the residual error term as the appropriate error term for all interactions effects of year with the remaining factors. The factor year is of a repeated measures nature that induces a covariance relationship because of the lack of re-randomization. All the standard covariance models were evaluated, but none improved the AICC fit statistic, which is a penalized -2log likelihood. However, grouping the residual variance by year using the "random _residual/group = year" option in SAS gave a slightly improved fit. Fit was improved by creating variance groups, even though the maximum F-test of residuals among the three years did not detect heterogeneous variances. Palmer amaranth density data were analyzed using a lognormal distribution function, and back transformed means along with 95% confidence intervals are reported. Palmer amaranth control rating data at three and six weeks after application were arcsine-transformed, and back transformed means along with 95% confidence intervals are reported. No transformation was required for cover crop biomass and cotton yield data. Multiple means' comparisons of significant effects were made using the "Adj = simulate" option in SAS PROC GLIMMIX at the 5% significance level.

3. Results

3.1. Cover Crop Biomass

Cover crop biomass was significantly affected by the type of cover crop. Averaged over three production years and soil inversion, crimson clover (4390 kg ha^{-1}) produced significantly higher biomass than both cereal rye (3698 kg ha^{-1}) and winter fallow (777 kg ha^{-1}).

3.2. Palmer Amaranth Density

At 2 WAP, the main effects of soil inversion, cover crop and spring tillage method were highly significant for both BR and WR density ($p < 0.0001$). Palmer amaranth density BR and WR was four and two-fold, respectively, less in IT than NIT (Table 2).

Table 2. Soil inversion, cover crop and spring tillage method means for between-row and within-row Palmer amaranth density at 2 WAP *; data combined over three production years.

Experiment variable	Palmer amaranth density			
	Between-row		Within-row	
	Mean	95% CI	Mean	95% CI
Soil inversion **	plants m^{-2}			
Non-inversion tillage	8 ***	(6,11)	5	(4,7)
Fall inversion tillage	2	(1,3)	2	(2,4)
Cover crop **				
Cereal rye	3	(2,4)	3	(2,4)
Crimson clover	3	(2,4)	3	(2,3)
Winter fallow	7	(6,8)	6	(4,7)
Spring tillage method **				
DCH	4	(3,5)	4	(3,5)
DCU	4	(3,5)	5	(3,6)
DD	3	(3,4)	3	(2,3)
NT	6	(4,7)	3	(2,4)

* Abbreviations: DCH, disking followed by (fb) chisel plow; DCU, disking fb field cultivator; DD, disking fb disking; NT, no tillage; WAP, weeks after cotton planting; ** Soil inversion means averaged over cover crops and spring tillage methods; cover crop means averaged over soil inversion and spring tillage methods; spring tillage method means averaged over soil inversion and cover crops; *** Means, UL and LL columns represent back transformed data.

Of the cover crops, both cereal rye and crimson clover resulted in a two-fold reduction in BR and WR density than winter fallow. With regard to spring tillage methods, BR density was significantly less in DD than NT. However, DCH and DCU did not result in a significant reduction in BR and WR density compared with NT. The WR density was significantly less in DD than DCH and DCU. Furthermore, the WR density in DCH, DCU and NT was similar. Previous researchers also observed two-fold higher early season pigweed density in a winter fallow conservation tillage systems compared to the similar conventional tillage systems [64]. Additionally, the effect of cover crop residue on inhibition of weed seed germination and seedling emergence has been well documented [55,62,63,65,66].

At 6WAP, a soil inversion by spring tillage method interaction revealed significant differences in BR density ($p < 0.05$). Following IT, the BR density was reduced ≥90% in DCH, DCU and DD spring tillage methods compared to NT following NIT (Table 3).

Table 3. Soil inversion by spring tillage method interaction means for between-row Palmer amaranth density at 6 WAP *; data combined over cover crops and production years.

Experiment variable		Between-row density	
Soil inversion	**Spring tillage method**	**Mean**	**95% CI**
		plants m^{-2}	
IT *	DCH *	2 **	(1,3) **
	DCU	2	(1,3)
	DD	2	(1,3)
	NT	6	(4,8)
NIT	DCH	4	(3,6)
	DCU	7	(5,10)
	DD	4	(2,5)
	NT	19	(11,27)

* Abbreviations: DCH, disking followed by (fb) chisel plow; DCU, disking fb field cultivator; DD, disking fb disking; IT, fall inversion tillage; NIT, non-inversion tillage; NT, no tillage; WAP, weeks after cotton planting; ** Means averaged over cover crops and years; means and 95% CI columns represent back transformed data.

The NT following IT resulted in a 69% reduction in BR density compared to the NT following NIT, but was similar to the DCU, DCH and DD in the NIT. Previous researchers observed a similar reduction in weed density with the comparable tillage practices [28,36,40,67–69]. With regard to WR density at 6 WAP, soil inversion and spring tillage method main effects were strongly significant ($p < 0.0001$). The Palmer amaranth WR density was two-fold less in IT (2 ± 1 plants m^{-2}) than NIT (5 ± 1 plants m^{-2}). Of spring tillage methods, DD (2 ± 1 plants m^{-2}) significantly reduced WR density compared to the NT (4 ± 1 plants m^{-2}). However, WR density was similar in DD, DCH (2 ± 2 plants m^{-2}) and DCU (2 ± 2 plants m^{-2}). Similarly, the WR density following DCH and DCU were not different from NT.

3.3. Palmer Amaranth Control

Three weeks after herbicide application (3 WAA), a soil inversion by cover crop by spring tillage method interaction was highly significant ($p < 0.05$). Following non-inversion tillage, Palmer amaranth was controlled more than 90% in both DD and DCU in crimson clover and DD in both cereal rye and winter fallow (Table 4).

With non-inversion tillage and crimson clover, Palmer amaranth control improved ≥16% in DCH, DCU and DD compared with NT. With non-inversion tillage and cereal rye, Palmer amaranth was controlled 14, 11 and 22%, more in DCH, DCU and DD, respectively, than NT. With non-inversion tillage and winter fallow, Palmer amaranth was controlled ≥74% in DCH, DCU and DD compared with NT. Furthermore, following non-inversion tillage, Palmer amaranth control was higher with all spring tillage methods in crimson clover than cereal rye and winter fallow. This may be attributed partly to the higher clover biomass, resulting in greater suppression of Palmer amaranth. Following fall inversion tillage, Palmer amaranth was controlled ≥80% in all spring tillage methods compared with NT following NIT. With fall inversion tillage, Palmer amaranth was controlled ≥91% in DCH, DCU and DD spring tillage methods regardless of type of cover crop. Furthermore, Palmer amaranth control in DCU and DD in both crimson clover and winter fallow and DD in cereal rye was significantly higher than in NT following winter fallow in IT. Previous research suggests supplementing the partial weed control obtained following different cover crops in a conservation tillage system [55]. It has been documented that cereal rye cover crop provided short-term weed control in no-till corn, but failed to provide season-long control [53]. Similarly, a 35 and 50% reduction in total weed density by wild radish and cereal rye cover crops, respectively, was recorded in sweet corn (*Zea mays* L.) at 4 WAP. However, weeds were controlled >95% when cover crops were grown in conjunction with a half or full rate of atrazine and *S*-metolachlor [70]. Several researchers have emphasized the need of conjunction of cover crops with herbicides for effective control of weeds [61,62,71].

Table 4. Soil inversion by cover crop by spring tillage method interaction means for Palmer amaranth control at 3 WAA *; data combined over production years.

		Spring tillage method							
experiment	**variable**	**DCH ***		**DCU**		**DD**		**NT**	
Soil inversion	**Cover crop**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**
					%				
IT *	Crimson clover	94 **	(85,99) **	99	(94,100)	99	(94,100)	88	(77,96)
	Cereal rye	96	(89,100)	94	(87,99)	99	(96,99)	94	(85,99)
	Winter fallow	91	(81,97)	97	(90,100)	97	(90,100)	80	(67,90)
NIT	Crimson clover	89	(78,96)	90	(84,98)	93	(83,98)	73	(59,85)
	Cereal rye	77	(63,89)	74	(60,86)	95	(87,99)	63	(49,77)
	Winter fallow	84	(72,93)	74	(60,86)	91	(81,98)	0	(0,2)

* Abbreviations: DCH, disking followed by (fb) chisel plow; DCU, disking fb field cultivator; DD, disking fb disking; NT, no tillage; IT, fall inversion tillage; NIT, non-inversion tillage; WAA, weeks after post application;
** Means averaged over years; means and 95% CI columns represent back transformed data.

Six weeks after herbicide application (6 WAA) and before LAYBY application, again, a soil inversion by cover crop by spring tillage method interaction was highly significant; results were similar to those observed at 3 WAA (data not shown). However, the Palmer amaranth control decreased four to ten percent in all spring tillage methods following cereal rye and winter fallow in NIT. Similarly, following IT, Palmer amaranth control decreased one to three percent in all spring tillage methods, regardless of the type of cover crop. Additionally, a year by spring tillage method interaction was highly significant at 6 WAA (Table 5).

In 2009, Palmer amaranth was controlled 95% in DD that was significantly higher than in DCU and NT. Palmer amaranth control in DCH (83%) was not different from DCU and NT. In 2010 and 2011, Palmer amaranth control was significantly higher in DCH, DCU and DD than observed in NT. Furthermore, Palmer amaranth control in 2011 was higher than in 2009 and 2010 due to an additional POST application.

Table 5. Year by spring tillage method interaction means for Palmer amaranth control 6 WAA *; data combined over soil inversion and cover crops.

	Spring tillage method							
	DCH *		**DCU**		**DD**		**NT**	
Year	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**	**Mean**	**95% CI**
				%				
2009	83 **	(72,92) **	69	(56,81)	95	(88,99)	65	(51,78)
2010	85	(78,90)	85	(79,91)	83	(77,89)	35	(27,42)
2011	99	(98,100)	99	(98,100)	99	(98,100)	85	(80,89)

* Abbreviations: DCH, disking followed by (fb) chisel plow; DCU, disking fb field cultivator; DD, disking fb disking; NT, no tillage; WAA, weeks after post application; ** Means averaged over soil inversion and cover crops; means and 95% CI columns represent back transformed data.

3.4. Cotton Yield

Data analysis revealed significant interaction between cover crop and spring tillage method ($p < 0.001$). The main effects of soil inversion, cover crop and spring tillage method were also highly significant ($p < 0.0001$). Cover crop by spring tillage method interaction indicated maximum cotton yields with DD, regardless of type of cover crop (Table 6).

Table 6. Interaction effect of cover crop by spring tillage method on cotton yield; data combined over cover crop and production years.

	Spring tillage method			
Experimental variable	**DCH ***	**DCU**	**DD**	**NT**
Cover crop		kg ha^{-1}		
Crimson clover	2075 abc **	2126 ab	2213 ab	1877 c
Cereal rye	1867 c	1965 bc	2251 a	1956 bc
Winter fallow	1952 bc	1867 c	2153 ab	1082 d

* Abbreviations: DCH, disking followed by (fb) chisel plow; DCU, disking fb field cultivator; DD, disking fb disking; NT, no tillage; ** Means averaged over cover crops and years; multiple mean comparisons were made using "adj = simulate" option in SAS PROC GLIMMIX; means followed by same letter are not significantly different ($p = 0.05$).

Following cereal rye, the DD tillage method produced maximum cotton (2251 kg ha^{-1}), which was similar to DD following winter fallow and DCH, DCU and DD following crimson clover. Following crimson clover, DCU and DD cotton yields were 13 and 18%, respectively, higher than NT cotton yields. However, the DCU and DCH cotton yields were similar under different cover crops. As expected, the NT following winter fallow produced the minimum cotton (1082 kg ha^{-1}), which was at least 42% less than the NT following either cereal rye or crimson clover. Averaging over cover crop and spring tillage method, the IT (2133 kg ha^{-1}) cotton yields were 21% higher than NIT (1766 kg ha^{-1}). Similar differences in cotton yields under conservation and conventional tillage systems have been reported by previous researchers [72–75].

4. Discussions and Conclusions

Our research evaluated soil inversion, cover crops and spring tillage methods as an integrated approach to managing Palmer amaranth in glufosinate-resistant cotton production. Results indicate that IT alone may result in about 60% reduction in early season Palmer amaranth density. Cover crops can also contribute to early season Palmer amaranth suppression. However, the amount of suppression likely varies with the quantity of biomass produced. Nevertheless, both crimson clover and cereal rye greatly reduced Palmer amaranth emergence compared to winter fallow. Without IT, early season Palmer amaranth densities were 40% less in DCU, DCH and DD when compared with IT. Following IT, no spring tillage method improved Palmer amaranth control. The timely application of glufosinate + *S*-metolachlor POST tank mixture greatly improved Palmer amaranth control in both IT and NIT systems. The timely application of glufosinate + *S*-metolachlor POST tank mixture greatly improved Palmer amaranth control in both IT and NIT. Therefore, from an integrated weed management standpoint, an occasional fall IT could greatly reduce Palmer amaranth emergence on farms highly infested with glyphosate-resistant Palmer amaranth. For effective and season-long control of Palmer amaranth, one or more POST applications of glufosinate + residual herbicide as tank mixture may be needed in a glufosinate-based cotton production system.

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