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Article

Integrated Palmer Amaranth Management in Glufosinate-Resistant Cotton: I. Soil-Inversion, High-Residue Cover Crops and Herbicide Regimes

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Abstract: A three year field experiment was conducted to evaluate the role of soil-inversion, cover crops and herbicide regimes for Palmer amaranth between-row (BR) and within-row (WR) management in glufosinate-resistant cotton. The main plots were two soil-inversion treatments: fall inversion tillage (IT) and non-inversion tillage (NIT). The subplots were three cover crop treatments: crimson clover, cereal rye and winter fallow; and sub subplots were four herbicide regimes: preemergence (PRE) alone, postemergence (POST) alone, PRE + POST and a no herbicide check (None). The PRE herbicide regime consisted of a single application of pendimethalin at 0.84 kg ae ha^{-1} plus fomesafen at 0.28 kg ai ha^{-1}. The POST herbicide regime consisted of a single application of glufosinate at 0.60 kg ai ha^{-1} plus *S*-metolachlor at 0.54 kg ai ha^{-1} and the PRE + POST regime combined the prior two components. At 2 weeks after planting (WAP) cotton, Palmer amaranth densities, both BR and WR, were reduced ≥90% following all cover crop treatments in the IT. In the NIT, crimson clover reduced Palmer amaranth densities >65% and 50% compared to winter fallow and cereal rye covers, respectively. At 6 WAP, the PRE and PRE + POST herbicide regimes in both IT and NIT reduced BR and WR Palmer amaranth densities >96% over the three years. Additionally, the BR density was reduced

≥59% in no-herbicide (None) following either cereal rye or crimson clover when compared to no-herbicide in the winter fallow. In IT, PRE, POST and PRE + POST herbicide regimes controlled Palmer amaranth >95% 6 WAP. In NIT, Palmer amaranth was controlled ≥79% in PRE and ≥95% in PRE + POST herbicide regimes over three years. POST herbicide regime following NIT was not very consistent. Averaged across three years, Palmer amaranth controlled ≥94% in PRE and PRE + POST herbicide regimes regardless of cover crop. Herbicide regime effect on cotton yield was highly significant; the maximum cotton yield was produced by the PRE + POST herbicide regime. Averaged over three years, the PRE, POST and PRE + POST cotton yields were about three times higher than no herbicide regime. In a conservation tillage production system, a PRE + glufosinate POST herbicide based regime coupled with a cereal rye cover crop may effectively control Palmer amaranth and maximize cotton yields.

Keywords: cover crops; glufosinate-tolerant cotton; herbicide regimes; soil-inversion

1. Introduction

Palmer amaranth (*Amaranthus palmeri* S.Wats) is a highly aggressive dioecious row crop weed in the Southeastern US [1]. It has several unique weedy characteristics including rapid growth of >5 inches a day during peak growth and can attain a final height of ≥2 m [2]. It is a prolific seed producer; a single female plant can produce more than 600,000 seeds, which have an average diameter of 1.0 mm [3]. In addition, Palmer amaranth has exceptional drought–tolerance and can endure moisture stress very well [4–7].

Palmer amaranth is highly problematic and interferes with the production of crops such as cotton, corn (*Zea mays* L.), cucurbits, grain sorghum (*Sorghum bicolor* L. Moench), peanut (*Arachis hypogea* L.), potato (*Solanum tuberosum* L.), soybean (*Glycine max* L.), sweet potato (*Ipomoea batatas* L.) and several vegetable crops [8–21].

The occurrence of glyphosate resistance in Palmer amaranth has challenged cotton-weed managers in the Southeaster US. Until 2005, glyphosate had been very efficacious on Palmer amaranth [22–24]. However, the extensive adoption of glyphosate-resistant technology virtually replaced the conventional weed control technology consisting of preplant incorporated (PPI), preemergence (PRE), postemergence (POST) and post-directed (PDS) applied herbicides [25]. The sole reliance on glyphosate has resulted in selection for resistant biotypes of Palmer amaranth. Glyphosate resistant in Palmer amaranth was first documented in Macon County Georgia, in 2006 [26,27]. As of 2010, glyphosate-resistant Palmer amaranth populations have been confirmed in 10 states [28]. Additionally, the Palmer amaranth populations resistant to dinitroaniline herbicides have been also reported [28,29].

Historically, cotton was grown in conventional tillage utilizing primary and secondary tillage including moldboard plowing, disking and cultivation. However, increasing input costs, low commodity prices, and concerns for declining soil organic quality, and in some regions subsoil compaction, necessitated the adoption of alternative tillage options such as strip-tillage production systems that utilize a within row subsoiler to disrupt soil compaction under the crop row and minimizes surface residue disturbance [30,31]. Consequently, inadequate weed control has been reported in some conservation-tillage cotton production [32]. The infestation of small-seeded annual weeds such as Palmer amaranth has often been attributed to conservation tillage systems that preclude burial of weed seed. Moldboard plowing with soil inversion to the depth of 30 cm (12 in) has been shown to reduce glyphosate-resistant Palmer amaranth emergence 46% to 60% because many of the weed seeds are placed at depths which prevent emergence [33,34]. However, the return to conventional tillage to control glyphosate-resistant Palmer amaranth threatens to reduce conservation tillage practices. Some researchers [35,36] advocate the integration of traditional and alternative weed control strategies, such as the utilization of crop and herbicide rotation and integration of high residue cereal cover crops in order to sustain conservation tillage practices.

Over the last decade, the inclusion of cover crops in conservation-tillage systems has been researched due to the ability of some cover crops to suppress early-season weed density and growth either through direct competition from cover crop biomass [37–41] or through allelopathy [42–47]. Cereal rye (*Secale cereale* L.) has been well documented for both high biomass potential and allelopathic properties by several researchers [42,43,48–52]. Several studies on cover crops have reported excellent early-season weed control that can preclude the use of preemergence herbicides in crops [39,41,52–59]. However, the success of a cover crop in early-season weed suppression is determined by the biomass production potential which varies with year, location and management practices [37,48,53,56,60]. It has been observed that cereal rye residue alone was effective in reducing the glyphosate-resistant Palmer amaranth emergence by 94% in the row middle and 50% within the row [34]. The use of high residue cover crops in conjunction with chemical and cultural weed control tactics could provide effective Palmer amaranth control in established glyphosate-resistant populations as well as help prevent the development of resistance in the remaining glyphosate-susceptible populations [61]. Thus, the inclusion of cover crops in conservation tillage system may provide weed control benefits similar to those realized from inversion tillage in conventional tillage system.

With the widespread appearance of glyphosate–resistant Palmer amaranth, cotton producers are considering other weed management options such as inversion tillage, surface tillage, and increased integration of soil active herbicides, cover crops and adoption of alternative GMO herbicide-crop systems such as glufosinate resistant cotton technology. Although inversion tillage can improve control of glyphosate-resistant Palmer amaranth, increased input costs and potential soil erosion are significant challenges. However the integration of cover crops and glufosinate-resistant cotton technology are possible viable alternatives. Therefore, a field study was conducted to evaluate the role of soil inversion, cover crops and herbicide regimes for Palmer amaranth management in glufosinate-resistant cotton.

2. Materials and Methods

A three year field experiment was conducted from fall 2008 through 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 the previous six years prior to experiment establishment, infested with a mixed population of resistant and susceptible Palmer amaranth, and subsequent treatments remained in the same location for three years without re-randomization of treatments. The experimental design consisted of a split-split plot treatment restriction in a randomized complete block design with three replicates. The main plots (43.9 by 9.1 m) were two soil-inversion treatments: fall inversion tillage (IT) and non-inversion tillage (NIT). After establishment, all IT plots reverted to NIT in future years. The subplots (14.6 by 9.1 m) were three different cover crops: crimson clover, cereal rye and winter fallow. The sub subplots (3.6 by 9.1 m) were four different herbicide regimes: preemergence (PRE) alone, postemergence (POST) alone, PRE + POST, and a no-herbicide check (None). A schedule of operations performed each year is given in Table 1.

Table 1. Schedule of operations performed during the experiment.

Operations	Experiment years		
	2008–2009	**2009–2010**	**2010–2011**
Broadcasting Palmer amaranth seed	19 Nov	–	–
Fall inversion tillage	19 Nov	–	–
Planting of cover crops	20 Nov	6 Jan	2 Dec
Rolling and termination of cover crops	22 Apr	18 May	19 Apr
Subsoiling	23 Apr	24 May	26 Apr
Cotton planting	1 Jun	27 May	5 May
Fertilization (16-16-16)	1 Jun	27 May	5 May
PRE application	3 Jun	27 May	6 May
POST application	16 Jun	16 Jun	24 May
Graminicide application (Poast Plus® + COC)	13 July	8 July	6 July
LAYBY application	14 Aug	16 Aug	19 July
Cotton defoliation	26 Oct	14 Oct	13 Sep
Cotton harvesting	9 Nov	20 Oct	30 Sep

2.1. Soil-Inversion, Cover Crops, and Cover Crop Management

In the fall 2008, approximately 28 million native glyphosate susceptible Palmer amaranth seeds were broadcast per hectare to ensure a sizeable seedbank. Half of each replicate was subjected to fall inversion tillage (IT) by moldboard plowing (30 cm) immediately fb one pass each of a disk and field cultivator, and half was under non-inversion tillage (NIT) using a within-row subsoiler equipped with pneumatic tires only to close the subsoiling slot. Subsequently each year in the fall, cereal rye (var. "Elbon" in 2009 and 2010 and "Wrens Abruzzi" in 2011) and crimson clover (*Trifolium incarnatum* L.) var. 'Dixie' cover crops were planted using 101 and 28 kg ha^{-1} seed, respectively in both the IT and NIT. Different cereal rye varieties were planted due to seed availability; Wrens Abruzzi has been shown to be more allelopathic [62]. In 2009 and 2010, frequent rain delayed both the harvesting of cotton and subsequent planting of cover crops [36]. 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.

Cover crops were rolled with a three section straight bar roller/crimper (Bigham Brothers, Inc., Lubbock, TX, USA) 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 ae ha^{-1}. The mixture was needed to enhance crimson clover termination. Cover crop biomass samples were taken prior to desiccation and oven dry biomass was recorded. The entire experimental area was sub-soiled in May using the previously described equipment to remove hardpan induced interactions; thus, no hardpans existed throughout the experimental area which could likely bias the yield results. Subsoiling was followed by planting of glufosinate-resistant cotton (FM 1845 LLB2 in 2009, and FM 1735 LL, in 2010 and 2011, Bayer Crops Science, Research Triangle Park, NC). Each year, cotton was fertilized using 211 kg·ha^{-1} of 16-16-16 fertilizer at the time of planting.

2.2. Herbicide Regimes

Four herbicide regimes constituted the sub-sub plot treatments. The PRE herbicide regime consisted of a single application of pendimethalin (Prowl®, BASF Ag. Products, Research Triangle Park, NC, USA) at 0.84 kg ae ha^{-1}plus fomesafen (Reflex®, Syngenta Crop Protection, Inc., Greensboro, NC, USA) at 0.28 kg ai ha^{-1}. The POST herbicide regime consisted of a single application of glufosinate at 0.60 kg ai ha^{-1} plus *S*-metolachlor (Dual II Magnum®, Syngenta Crop Protection, Inc., Greensboro, NC, USA) at 0.54 kg ai ha^{-1} and the PRE + POST regime consisted of both the aforementioned PRE and POST regimes. PRE herbicides were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 145 L ha^{-1} with 8002 flat-fan nozzles. POST herbicides were applied to 3 to 4 lf Palmer amaranth between 15 and 20 days after planting cotton with an ATV-mounted sprayer delivering 145 L ha^{-1} with 8002 flat-fan spray nozzles. A last application (LAYBY) directed spray consisting of a prometryn (Caporal®, Syngenta Crop Protection, Inc., Greensboro, NC, USA) at 0.84 kg ai ha^{-1} + MSMA (Drexel Chemical Company, Memphis, TN) at 1.4 kg ai ha^{-1} was applied. 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.

2.3. Palmer Amaranth Sampling and Control Ratings

Palmer amaranth density was recorded once before the application of POST and again before the LAYBY application. Between-row (BR) Palmer amaranth densities were recorded as number of plants in a quadrat (0.25 m^{-2}) randomly placed at 4 different positions between the 2nd and 3rd row of a four-row cotton plot. Similarly, the within-row (WR) Palmer densities were recorded from a quadrant (0.25 m^{-2}) randomly placed at 4 different positions within the 2nd and 3rd rows. Palmer amaranth control was assessed visually at weekly intervals, starting a week after application of PRE until LAYBY application. A 0–100 scale was used where 0 and 100 indicate no control and complete control, respectively. Each year, the Palmer amaranth was hand removed from all the plots before application of LAYBY to facilitate harvest. Therefore, Palmer amaranth was 100% controlled in each plot after LAYBY until cotton harvest. Cotton yields were recorded by mechanically harvesting two center 9 m rows within each four-row plot with a spindle picker.

2.4. Statistical Analysis

Three years data were subjected to combined ANOVA using Proc GLIMMIX in SAS (version 9.2, SAS Institute, Inc., Cary, NC, USA). Year, soil-inversion, cover crop, herbicide regime and their interactions were treated as fixed effects, while replications, replication × soil-inversion, replication × soil-inversion × cover crop were treated as random effects. When year and its interaction with other factors were significant, data were analyzed and presented by year. Palmer amaranth visual control data were arcsine-transformed and Palmer amaranth density data were square root transformed. However, the original and transformed data analyses gave similar results, thus non-transformed data are presented. Multiple mean comparisons were made using the "adj = simulate" option in the statistical analysis system at the 5% significance level.

3. Results

3.1. Cover Crop Biomass

Analysis of the three year data revealed significant effect of type of cover crop only. Averaged over three years, the maximum cover crop biomass was produced by cereal rye (4047 kg·ha^{-1}) fb crimson clover (3570 kg·ha^{-1}) that was significantly more than and winter fallow (1253 kg·ha^{-1}).

3.2. Palmer Amaranth Density

Palmer amaranth densities at 2 WAP revealed significant year by treatment interactions. Therefore data are presented by year. A soil-inversion by cover crop interaction was observed for both BR and WR densities at 2 WAP in 2008–2009 and 2010–2011 while only the IT main effect was significant in 2009–2010. The highest BR and WR densities of 49 and 35 plants m^{-2}, respectively, occurred in winter fallow following NIT in 2009–2010 (Table 2).

Table 2. Influence of soil-inversion and cover crop on Palmer amaranth density at 2 WAP over three production years.

Experimental variable		**Palmer amaranth density (plants m^{-2})**					
Soil-inversion	**Cover crop**	**2008–2009**		**2009–2010**		**2010–2011**	
		BR *	**WR**	**BR**	**WR**	**BR**	**WR**
Non-inversion (NIT)	Winter fallow	10 a **	11 a	49 a	35 a	22a	17 a
	Crimson clover	3 b	2 c	29 ab	26 a	1 c	6 c
	Cereal rye	9.0 a	7 b	18 b	31 a	10 b	12 b
	Mean	**7.3 A**	**6.7 A**	**32.0 A**	**30.7 A**	**11.0 A**	**11.7 A**
Fall-inversion (IT)	Winter fallow	1 c	0 c	2 c	2 c	2 c	1 d
	Crimson clover	0 c	0 c	2 c	0 c	0 c	0 d
	Cereal rye	1 c	1 c	3 c	2 c	0 c	1 d
	Mean	**0.7 B**	**0.3 B**	**3.7 B**	**1.3 B**	**0.7 B**	**0.7 B**

* Abbreviations: WAP, weeks after cotton planting; BR, between row; WR, within row; ** Means within a column followed by the same letter are not significant (P = 0.05).

In 2008–2009 and 2010–2011, crimson clover reduced Palmer amaranth density by as much as 96% BR and 82% WR in NIT. Similar reductions in Palmer amaranth and other weed densities by cover crop residues have been reported [63,64–66]. Both BR and WR densities were reduced >90% following all cover crops in the IT. Each year with IT both BR and WR densities of Palmer amaranth, were ≥90% lower than with NIT (Table 2). Furthermore each year at 2 WAP, Palmer amaranth was 100% controlled by the PRE and PRE + POST herbicide regimes that received a PRE application within two days of planting (data not shown).

At 6 WAP, the effect of year and its interactions with other factors were not significant. However, both the BR and WR densities demonstrated strong interaction of soil-inversion by herbicide regime. Additionally, a cover crop by herbicide regime interaction ($P < 0.0001$) was detected, for BR densities only. The BR and WR densities were markedly reduced (≤1 plant m^{-2}) under PRE, POST and PRE + POST herbicide regimes following IT and PRE and PRE + POST herbicide regimes following NIT (Table 3).

Table 3. Influence of soil–inversion and herbicide regime on Palmer amaranth density at 6 WAP * and cotton yield with cover crop and three production years' data combined.

Experimental variable		**Palmer amaranth density (plants m^{-2})**		**Cotton yield ($kg \cdot ha^{-1}$)**
Soil–inversion	**Herbicide regime**	**BR ***	**WR**	
Non-inversion (NIT)	None	26 a **	23 a	105 c
	PRE *	1 b	1 b	1520 a
	POST	4 b	3 b	1423 a
	PRE + POST	1.0 b	1 b	1716 a
	Mean	**8.0 A**	**7.0 A**	**1191 B**
Fall-inversion (IT)	None	6 b	4 b	976 b
	PRE	1 b	0 b	1544 a
	POST	1 b	1 b	1893 a
	PRE + POST	0 b	0 b	2041 a
	Mean	**2.0 B**	**1.3 B**	**1613 A**

* Abbreviations: WAP, weeks after cotton planting; BR, between row; WR, within row; PRE, only preemergence; POST, only postemergence; PRE + POST, both preemergence and postemergence; ** Means within a column followed by same letter are not significant ($P = 0.05$).

The Palmer amaranth density, both BR and WR, was reduced ≥77% in no-herbicide regime (None) following IT when compared to no–herbicide regime following NIT. The PRE and PRE + POST herbicide regimes in both IT and NIT reduced BR and WR densities ≥96%. With the cover crop by herbicide regime interaction, the BR density was reduced ≥55% in no-herbicide (None) following either cereal rye or crimson clover when compared to no-herbicide in the winter fallow (Table 4).

Table 4. Influence of cover crop and herbicide regime on BR * Palmer amaranth density at 6 WAP and cotton yield with soil-inversion and three production years' data combined.

Experimental variable		Palmer amaranth density	Cotton yield
Cover crop	**Herbicide regime**	**(plants m^{-2})**	**(kg·ha^{-1})**
Winter fallow	None	27 a **	141 b
	PRE *	1 c	1506 a
	POST	4 c	1449 a
	PRE + POST	1c	1869 a
	Mean	**11.0 A**	**1242 A**
Crimson clover	None	10 b	711 b
	PRE	1 c	1544 a
	POST	1 c	1918 a
	PRE + POST	1 c	2047 a
	Mean	**4.0 B**	**1555 A**
Cereal rye	None	11 b	768 b
	PRE	1 c	1546 a
	POST	3 c	1606 a
	PRE + POST	0 c	1720 a
	Mean	**5. 0 B**	**1410 A**

* Abbreviations: BR, between row; WAP, weeks after cotton planting; PRE, only preemergence; POST, only postemergence; PRE + POST, both preemergence and postemergence; ** Means within a column followed by same letter are not significant ($P = 0.05$).

PRE, POST and PRE + POST herbicide regimes' Palmer amaranth densities were similar but lower than the no herbicide (None) regime following any cover crop. However, the PRE and PRE + POST herbicide regimes were very consistent in reducing Palmer amaranth density (>95%) following all the cover crops. Earlier research also indicated the need of either a PRE or PRE + POST herbicide regime to supplement partial weed control obtained following different cover crops in a conservation tillage system [63]. Previous researchers also reported similar cover crop by herbicide interaction effect [67]. Excellent control of Palmer amaranth with a combination of pendimethalin and fomesafen has been reported [68].

3.3. Palmer Amaranth Visual Control

Palmer amaranth visual percent control at 6 WAP reflected significant year by treatment interactions. Analysis by year also indicated significant two way interactions between soil-inversion and herbicide regime and cover crop by herbicide regime each year. Additionally, a soil-inversion by cover crop interaction was highly significant in 2010–2011 ($P = 0.0007$). All main effects were also highly significant each year ($P < 0.0001$). In 2008–2009, Palmer amaranth was controlled 38%, 79% and 95% in POST, PRE and PRE + POST herbicide regimes, respectively, following NIT while all herbicide regimes following IT provided ≥91% control (Table 5).

Table 5. Influence of soil-inversion by herbicide regime on Palmer amaranth control at 6 WAP * with cover crop data combined in three production years.

Experimental variable		Year (% control)		
Soil-inversion	**Herbicide regime**	**2008–2009**	**2009–2010**	**2010–2011**
Non-inversion (NIT)	None	27 c **	15 c	9 c
	PRE *	79 b	93 a	100 a
	POST	38 c	84 b	100 a
	PRE + POST	95 a	98 a	100 a
	Mean	**60.0 B**	**72.0 B**	**77.0 B**
Fall-inversion (IT)	None	91 a	77 b	81 b
	PRE	99 a	98 a	100 a
	POST	95 a	97 a	100 a
	PRE + POST	100 a	100 a	100 a
	Mean	**96.0 A**	**93.0 A**	**95.0 A**

* Abbreviations: WAP, weeks after cotton planting; PRE, only preemergence; POST, only postemergence; PRE + POST, both preemergence and postemergence; ** Means within a column followed by same letter are not significant ($P = 0.05$).

In 2009–2010 and 2010–2011, both PRE and PRE + POST herbicide regimes controlled Palmer amaranth ≥93% regardless of the soil–inversion treatment. In 2009–2010, the POST herbicide regime controlled Palmer amaranth 84 and 97% in NIT and IT, respectively. However in 2010–2011, POST herbicide regime controlled Palmer amaranth 100% in both soil–inversion treatments. The reason for poor performance of the POST herbicide regime in NIT in 2008–2009 is likely attributed to the oversized (>10 cm) Palmer amaranth plants at the time of application.

Cover crop by herbicide regime interaction over years revealed ≥94% control of Palmer amaranth in PRE and PRE + POST herbicide regimes regardless of type of cover crop (Table 6).

The POST herbicide regime following both winter fallow and cereal rye provided 83% control of Palmer amaranth and was similar to the POST following crimson clover. However, Palmer amaranth control varied from 36% to 63% in no-herbicide (None) regime following different cover crops. Analysis revealed a soil–inversion by cover crop interaction in 2010–2011; Palmer amaranth control following different cover crops varied from 75% to 82% in NIT and 89% to 100% in IT, respectively (Figure 1).

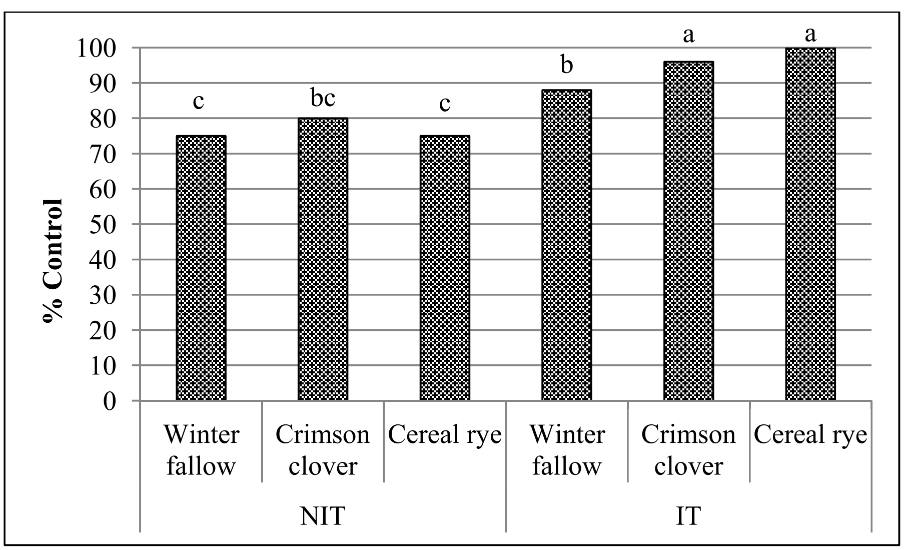
Both cereal rye and crimson clover in IT gave significantly higher Palmer amaranth control (≥97%) than winter fallow in both IT and NIT and crimson clover and cereal rye in NIT. Previous research indicates the need to utilize residual herbicides throughout the season to aid in management of glyphosate resistant Palmer amaranth [69–72].

Table 6. Cover crop by herbicide regime interaction effect on Palmer amaranth control at 6 WAP * with soil-inversion and three production years' data combined.

Experimental variable		Palmer amaranth control	Cotton yield
Cover crop	**Herbicide regime**	**(%)**	**(kg·ha^{-1})**
Winter fallow	None	36 d **	141 b
	PRE *	95 ab	1506 a
	POST	83 b	1449 a
	PRE + POST	98 ab	1869 a
	Mean	**78 B**	**1242 A**
Crimson clover	None	63 c	711 b
	PRE	96 ab	1544 a
	POST	91 ab	1918 a
	PRE + POST	99 a	2047 a
	Mean	**87 A**	**1555 A**
Cereal rye	None	52 c	768 b
	PRE	94 ab	1546 a
	POST	83 b	1606 a
	PRE + POST	99 a	1720 a
	Mean	**82 AB**	**1410 A**

* Abbreviations: WAP, weeks after cotton planting; PRE, only preemergence; POST, only postemergence; PRE + POST, both preemergence and postemergence; ** Means within a column followed by same letter are not significant ($P = 0.05$).

Figure 1. Soil-inversion by cover crop interaction on Palmer amaranth control in 2011. Different letters indicate significant differences at $P = 0.05$.



*Abbreviations: IT, fall-inversion tillage; NIT, non-inversion tillage.

3.4. Cotton Yield

Analysis of the yield data revealed significant effect of herbicide regimes only. Although the cotton yield differences were not significant between PRE, POST and PRE + POST herbicide regimes, the maximum cotton yield was produced by the PRE + POST herbicide regime (1878 kg·ha^{-1}) followed by POST (1658 kg·ha^{-1}) and PRE (1532 kg·ha^{-1}) alone regimes. PRE, POST and PRE + POST herbicide regimes' cotton yields were ≥2.7 times higher than no-herbicide (None) regime (Table 7).

Table 7. Influence of herbicide regimes on cotton yield with cover crop, soil-inversion, and three production years' data combined.

Herbicide regime	Herbicides	Cotton yield (kg·ha^{-1})
None	LAYBY consisting of prometryn + MSMA	560 b **
PRE *	Pendimethalin + fomesafen fb LAYBY	1532 a
POST	Glufosinate + *S*-metolachlor fb LAYBY	1658 a
PRE + POST	Pendimethalin + fomesafen (PRE) fb Glufosinate + *S*-metolachlor (POST) fb LAYBY	1878 a

* Abbreviations: PRE, only preemergence, POST; only postemergence; PRE + POST, both preemergence and postemergence; fb, followed by; ** Means followed by same letter are not significant (P = 0.05).

4. Discussion and Conclusions

Recent evolution of herbicide resistance in Palmer amaranth has revealed that an urgent restructuring of weed management tactics is needed. Consequently, integration of various weed management approaches such as IT, cover crops, crop rotations, competitive cultivars, herbicide rotation, soil residual chemistries and tank mixture of herbicides with different modes of action could diversify the weed control practices and thereby preclude the selection pressure for herbicide resistance. Furthermore, the longevity of herbicide resistant technology itself necessitates the inclusion of multiple tactics in weed management systems.

Fall–inversion tillage offers improved Palmer amaranth control by allowing the deep burial of seed. Considering the rapid loss of Palmer amaranth seed viability with time, IT would help reduce the amount of viable seed near the surface [73]. However, IT is well known to deplete soil quality parameters such as soil organic matter while simultaneously increasing soil erosion. An occasional rotation with IT immediately followed by a cover crop conservation-tillage system could diversify weed management systems and prevent soil erosion. There is a great need of practical weed management solutions on farms severely impacted by glyphosate resistant Palmer amaranth [74].

Our research evaluated soil–inversion, cover crops and alternative herbicide regimes as an integrated approach to managing Palmer amaranth**.** Results indicate that IT alone resulted in ≥77% control of Palmer amaranth 6 WAP due to Palmer amaranth seed burial; addition of winter cover crops further increased Palmer amaranth control. Cover crops alone in NIT provided ≤50% control of Palmer amaranth; thus indicating the need in both IT and NIT to integrate other effective weed management practices to protect cotton yields. In an IT-cereal rye cover crop situation, a PRE or POST alone herbicide regime was as effective as a PRE + POST regime due to lower Palmer amaranth densities. However, with NIT, an effective and timely PRE + POST herbicide regime was necessary to control the higher Palmer amaranth densities present in this situation. Overall, the PRE + POST herbicide regime resulted in the maximum Palmer amaranth control and higher cotton yields in both soil-inversion treatments (Table 8).

Table 8. Palmer amaranth density and visual percent control at 6 WAP * and cotton yield from selected treatments with data combined over three production years.

Experimental variable			Palmer amaranth density (plants m^{-2})		Palmer amaranth Control (%)	Cotton yield ($kg \cdot ha^{-1}$)
Soil-inversion	**Cover crop**	**Herbicide regime**	**BR ***	**WR**		
Non-inversion (NIT)	Crimson clover	PRE + POST *	1	<1	98	1931
		PRE	2	<1	92	1439
		POST	2	1	82	1652
	Cereal rye	PRE + POST	1	<1	98	1620
		PRE	2	<1	90	1433
		POST	3	1	68	1425
	Winter fallow	PRE + POST	2	1	96	1699
		PRE	1	1	90	1597
		POST	5	4	72	1185
Fall-inversion (IT)	Crimson clover	PRE + POST	0	0	100	2163
		PRE	<1	<1	99	1650
		POST	<1	<1	99	2185
	Cereal rye	PRE + POST	0	0	100	1820
		PRE	<1	0	99	1667
		POST	2	<1	97	1780
	Winter fallow	PRE + POST	0	0	100	2139
		PRE	<1	<1	99	1315
		POST	1	1	95	1713
The following treatments were the best in terms of both Palmer amaranth control and cotton yield.						
Non-inversion (NIT)	Crimson clover	PRE + POST	1	0	98	1931
	Cereal rye	PRE + POST	1	<1	98	1620
	Winter fallow	PRE + POST	2	1	96	1699
Fall-inversion (IT)	Crimson clover	PRE + POST	0	0	100	2163
	Cereal rye	PRE + POST	0	0	100	1820
	Winter fallow	PRE + POST	0	0	100	2139

* Abbreviations: WAP, weeks after cotton planting; PRE, only preemergence; POST, only postemergence; PRE + POST, both preemergence and postemergence.

The highest Palmer amaranth densities, regardless of soil-inversion treatment and herbicide regime, were consistently recorded in the winter fallow situation. Therefore, in a conservation tillage production system, a PRE + glufosinate POST herbicide based regime coupled with a cover crop may effectively control Palmer amaranth and maximize cotton yields (Table 8).

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Conflict of Interest

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA or Auburn Univ. and does not imply endorsement of a product to the exclusion of others that may be suitable.

References

1. Fernald, M.L. *Gray's Manual of Botany*, 8th ed.; American Book Co.: New York, NY, USA, 1950; p. 602.
2. Horak, M.J.; Loughin, T.M. Growth analysis of four *Amaranthus* species. *Weed Sci.* **2000**, *48*, 347–355.
3. Keeley, P.E.; Carter, C.H.; Thullen, R.M. Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). *Weed Sci.* **1987**, *35*, 199–204.
4. Ehleringer, J. Ecophysiology of *Amaranthus palmeri*, a Sonoran Desert summer annual. *Oecologia* **1983**, *57*, 107–112.
5. Jha, P.; Norsworthy, J.K.; Malik, M.S.; Bangarwa, S.K.; Oliveira, M.J. Temporal emergence of Palmer amaranth from a natural seedbank. *Proc. South. Weed Sci. Soc.* **2006**, *59*, 177.
6. Place, G.; Bowman, D.; Burton, M.; Rufty, T. Root penetration through a high bulk density soil layer: Differential response of a crop and weed species. *Plant Soil* **2008**, *307*, 179–190.
7. Wright, S.R.; Jennette, M.W.; Coble, H.D.; Rufty, T.W. Root morphology of young *Glycine max, Senna obtusifolia*, and *Amaranthus palmeri*. *Weed Sci.* **1999**, *47*, 706–711.
8. Bensch, C.N.; Horak, M.J.; Peterson, D. Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. *Weed Sci.* **2003**, *51*, 37–43.
9. Burke, I.C.; Schroeder, M.; Thomas, W.E.; Wilcut, J.W. Palmer amaranth interference and seed production in peanut. *Weed Technol.* **2007**, *21*, 367–371.
10. Klingaman, T.E.; Oliver, L.R. Palmer amaranth (*Amaranthus palmeri*) interference in soybeans (*Glycine max*). *Weed Sci.* **1994**, *42*, 523–527.
11. Massinga, R.A.; Currie, R.S.; Horak, M.J.; Boyer, J. Interference of Palmer amaranth in corn. *Weed Sci.* **2001**, *49*, 202–208.

12. Menges, R.M. Allelopathic effects of Palmer amaranth (*Amaranthus palmeri*) and other plant residues in soil. *Weed Sci.* **1987**, *35*, 339–347.
13. Meyers, S.L.; Jennings, K.M.; Schultheis, J.R.; Monks, D.W. Evaluation of Flumioxazin and *S*-metolachlor rate and timing for Palmer amaranth (*Amaranthus palmeri*) control in Sweet potato. Weed Technol. **2010**, *24*, 495–503.
14. Monks, D.M.; Oliver, L.R. Interactions between soybean (*Glycine max*) cultivars and selected weeds. *Weed Sci.* **1988**, *36*, 770–774.
15. Moore, J.W.; Murray, D.S.; Westerman, R.B. Palmer amaranth (*Amaranthus palmeri*) effects on the harvest and yield of grain sorghum (*Sorghum biclor*). *Weed Technol.* **2004**, *18*, 23–29.
16. Morgan, G.D.; Baumann, P.A.; Chandler, J.M. Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. *Weed Technol.* **2001**, *15*, 408–412.
17. Norsworthy, J.K.; Griffith, G.M.; Scott, R.C.; Smith, K.L.; Oliver, L.R. Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. *Weed Technol.* **2008**, *21*, 108–113.
18. Norsworthy, J.K.; Smith, K.L.; Scott, R.C.; Gbur, E.E. Consultant perspectives on weed management needs in Arkansas cotton. *Weed Technol.* **2007**, *21*, 825–831.
19. Rowland, M.W.; Murry, D.S.; Verhalen, L.M. Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). *Weed Sci.* **1999**, *47*, 305–309.
20. Smith, D.T.; Baker, R.V.; Steele, G.L. Palmer amaranth (Amaranthus palmeri) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). *Weed Technol.* **2000**, *14*, 122–126.
21. Webster, T.M. Weed survey—Southern states. *Proc. South. Weed Sci. Soc.* **2005**, *58*, 291–306.
22. Corbett, J.L.; Askew, S.D.; Thomas, W.E.; Wilcut, J.W. Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. *Weed Technol.* **2004**, *18*, 443–453.
23. Culpepper, A.S.; York, A.C. Weed management in glyphosate-tolerant cotton. *J. Cotton Sci.* **1998**, *2*, 174–185.
24. Parker, R.G.; York, A.C.; Jordan, D.L. Comparison of glyphosate products in glyphosate-resistant cotton (*Gossypium hirsutum*) and corn (*Zea mays*). *Weed Technol.* **2005**, *19*, 796–802.
25. Young, B.G. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. *Weed Technol.* **2006**, *20*, 301–307.
26. Culpepper, A.S.; Grey, T.L.; Vencill, W.K.; Kichler, J.M.; Webster, T.M.; Brown, S.M.; York, A.C.; Davis, J.W.; Hanna, W.W. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. *Weed Sci.* **2006**, *54*, 620–626.
27. Culpepper, A.S.; Whitaker, J.R.; MacRae, A.W.; York, A.C. Distribution of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. *J. Cotton Sci.* **2008**, *12*, 306–310.
28. Heap, I. The international survey of herbicide resistant weeds. Available online: www.weedscience.org (accessed on 11 March 2012).
29. Gosset, B.J.; Murdock, E.C.; Toler, J.E. Resistance of Palmer amaranth (*Amaranthus palmeri*) to the dinitroaniline herbicides. *Weed Technol.* **1992**, *6*, 587–591.

30. Troeh, F.R.; Hobbs, J.A.; Donahue, R.L. *Soil and Water Conservation*; Prentice Hall: Englewood Cliffs, NJ, USA, 1991; p. 232.
31. Wauchope, R.D.; McDowell, L.L.; Hagen, L.J. Environmental effects of limited tillage. In *Weed Control in Limited Tillage Systems*, Proceedings of Weed Science Society of America, Champaign, IL, USA, 14–16 January 1985; pp. 266–281.
32. McWhorter, C.G.; Jordan, T.N. Limited tillage in cotton production. In *Weed Control in Limited-Tillage Systems*; Wiese, A.F., Ed.; Weed Science Society of America: Champaign, IL, USA, 1985; pp. 61–75.
33. Culpepper, A.S.; York, A.C.; Marshall, M.W. Glyphosate-resistant Palmer amaranth in the Southeast. *Proc. South. Weed Sci. Soc. 2009*, **62**, 371.
34. Culpepper, A.S.; Kichler, J.; Sosnoskie, L.; York, A.; Sammons, D.; Nichols, R. Integrating cover crop residue and moldboard plowing into glyphosate-resistant Palmer amaranth management programs. In *Proceedings of Beltwide Cotton Conference*, New Orleans, LA, USA, 4–7 January 2010.
35. Price, A.J.; Balkcom, K.B.; Culpepper, A.S.; Kelton, J.A.; Nichols, R.L.; Schomberg, H.H. Glyphosate-resistant Palmer amaranth: A threat to conservation tillage. *J. Soil Water Conserv.* **2011**, *66*, 265–275.
36. Price, A.J.; Balkcom, K.S.; Duzy, L.M.; Kelton, J.A. Herbicide and cover cop residue integration for *Amaranth* control in conservation agriculture cotton. *Weed Technol.* **2012**, *26*, 490–498.
37. Brennan, E.B.; Smith, R.F. Winter cover crop growth and weed suppression on the central coast of California. *Weed Technol.* **2005**, *19*, 1017–1024.
38. Collins, H.P.; Delgado, J.A.; Alva, A.K.; Follett, R.F. Use of nitrogen-15 isotopic techniques to estimate nitrogen cycling from a mustard cover crop to potatoes. *Agron. J.* **2007**, *99*, 27–35.
39. Reddy, K.N. Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). *Weed Technol.* **2001**, *15*, 660–668.
40. Teasdale, J.R.; Mohler, C.L. The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Sci.* **2000**, *48*, 385–392.
41. Yenish, J.P.; Worsham, A.D.; York, A.C. Cover crops for herbicide replacement in no-tillage corn (*Zea mays*). *Weed Technol.* **1996**, *10*, 815–821.
42. Barnes, J.P.; Putnam, A.R. Evidence for allelopathy by residues and aqueous extracts of rye (*Secale cereale*). *Weed Sci.* **1986**, *34*, 384–390.
43. Barnes, J.P.; Putnam, A.R.; Burke, B.A.; Aasen, A.J. Isolation and characterization of allelochemicals in rye herbage. *Phytochemistry* **1987**, *26*, 1385–1390.
44. Burgos, N.R.; Talbert, R.E. Differential activity of allelochemicals from *Secale cereale* in seedling bioassays. *Weed Sci.* **2000**, *48*, 302–310.
45. Dhima, K.V.; Vasilakoglou, I.B.; Eleftherohorinos, I.G.; Lithourgidis, A.S. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. *Crop Sci.* **2006**, *46*, 345–352.
46. Vasilakoglou, I.; Dhima, K.; Eleftherohorinos, I.; Lithourgidis, A. Winter cereal cover crop mulches and inter-row cultivation effects on cotton development and grass weed suppression. *Agron. J.* **2006**, *98*, 1290–1297.

47. White, R.H.; Worsham, A.D.; Blum, U. 1989. Allelopathic potential of legume debris. *Weed Sci.* **1989**, *37*, 674–679.
48. Mohler, C.L.; Teasdale, J.R. Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. *Weed Res.* **1993**, *33*, 487–499.
49. Nagabhushana, G.G.; Worsham, A.D.; Yenish, J.P. Allelopathic cover crops to reduce herbicide use in sustainable agricultural systems. *Allelopathy J.* **2001**, *8*, 133–146.
50. Price, A.J.; Balkcom, K.S.; Arriaga, F.J. Rye biomass amount affects weed suppression levels in conversation-tillage cotton. In *Proceedings of the Beltwide Cotton Conference*, New Orleans, LA, USA, 4–7 January 2005; pp. 2921–2923.
51. Price, A.J.; Arriaga, F.J.; Raper, R.L.; Balkcom, K.S.; Kornecki, T.S.; Reeves, D.W. Comparison of mechanical and chemical winter cereal cover crop termination systems and cotton yield in conservation agriculture. *Cotton Sci.* **2009**, *13*, 238–245.
52. Reeves, D.W.; Price, A.J.; Patterson, M.G. Evaluation of three winter cereals for weed control in conservation-tillage non-transgenic cotton. *Weed Technol.* **2005**, *19*, 731–736.
53. Ateh, C.M.; Doll, J.D. Spring-planted winter rye as a living mulch to control weeds in soybean. *Weed Technol.* **1996**, *10*, 347–353.
54. Fisk, J.W.; Hesterman, O.B.; Shrestha, A.; Kells, J.J.; Harwood, R.R.; Squire, J.M.; Sheaffer, C.C. Weed suppression by annual legume cover crops in no tillage corn. *Agron. J.* **2001**, *93*, 319–325.
55. Isik, D.; Kaya, E.; Ngouajio, M.; Mennan, H. Weed suppression in organic pepper (*Capsicum annuum* L.) with winter cover crops. *Crop Prot.* **2009**, *28*, 356–363.
56. Teasdale, J.R. Contribution of cover crops to weed management in sustainable agricultural systems. *J. Prod. Agric.* **1996**, *9*, 475–479.
57. Teasdale, J.R.; Beste, C.E.; Potts, W.E. Response of weeds to tillage and cover crop residue. *Weed Sci.* **1991**, *39*, 195–199.
58. Teasdale, J.R.; Pillai, P.; Collins, R.T. Synergism between cover crop residue and herbicide activity on emergence and early growth of weeds. *Weed Sci.* **2005**, *53*, 521–527.
59. Zasada, I.A.; Linker, H.M.; Coble, H.D. Initial weed densities affect no-tillage weed management with a rye (*Secale cereale*) cover crop. *Weed Technol.* **1997**, *11*, 473–477.
60. Schomberg, H.H.; Endale, D.M.; Calegari, A.; Peixoto, R.; Miyazawa, M.; Cabrera, M.L. Influence of cover crops on potential nitrogen availability to succeeding crops in a Southern Piedmont soil. *Biol. Fertil. Soil* **2006**, *42*, 299–307.
61. Price, A.J.; Stoll, M.E.; Bergtold, J.S.; Arriaga, F.J.; Balkcom, K.S.; Kornecki, T.S.; Raper, R.L. Effect of cover crop extracts on cotton and radish radicle elongation. *Comm. Biometry Crop Sci.* **2008**, *3*, 60–66.
62. Reberg-Horton, S.; Burton, J.; Danehower, D.; Ma, G.; Monks, D.; Murphy, J.; Ranells, N.; Williamson, J.; Creamer, N. Changes over time in the allelochemical content of ten cultivars of rye (*Secale cereale* L.). *J. Chem. Ecol.* **2005**, *31*, 179–193.
63. Price, A.J.; Reeves, D.W.; Patterson, M.G. Evaluation of weed control provided by three winter cereals in conservation-tillage soybean. *Renew. Agric. Food Syst*. **2006**, *21*, 159–164.
64. Price, A.J.; Reeves, D.W.; Patterson, M.G.; Gamble, B.E.; Balkcom, K.S.; Arriaga, F.J.; Monks, C.D. Weed control in peanut grown in a high-residue conservation-tillage system. *Peanut Sci.* **2007**, *34*, 59–64.

65. Reddy, K.N. Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean (*Glycine max*). *Weed Technol.* **2003**, *17*, 28–35.
66. Saini, M.; Price, A.J.; van Santen, E. Cover crop residue effects on early-season weed establishment in a conservation-tillage corn-cotton rotation. In *Proceedings of the 28th Southern Conservation Systems Conference*, Amarillo, TX, USA, 26–28 June 2006.
67. Weston, L. Cover crop and herbicide influence on row crop seedling establishment in no-tillage culture. *Weed Sci.* **1990**, *38*, 166–171.
68. Timothy, L.G.; Sosnoskie, L.; Webster, T.M. Palmer amaranth control as affected by herbicide, method of application, and winter cover crop. Available online: http://commodities.caes.uga.edu/fieldcrops/cotton/rerpubs/2009/p049RER2009.pdf (accessed on 22 July 2012).
69. Steckel, L. Cotton Weed Control. In *Weed Control Manual for Tennessee*; Technical Report PB 1580-6M-12/08 for University of Tennessee Agriculture Extension Service: Knoxville, TN, USA, 2008; pp. 9–83.
70. Stephenson, D.; Stewart, S.; Vidrine, R. *Herbicide Resistance Management in Roundup Ready Cotton*; Technical Report for Louisiana State University Agricultural Center: Baton Rouge, LA, USA, 2008.
71. Whitaker, J.R.; York, A.C.; Jordan, D.L.; Culpepper, A.S.; Sosnoskie, L.M. Residual herbicides for Palmer amaranth control. *Cotton Sci.* **2011**, *15*, 89–99.
72. York, A.C.; Culpepper, A.S. Weed Management in Cotton. In *2009 Cotton Information*; North Carolina Cooperative Extension Service: Raleigh, NC, USA, 2009; pp. 68–125.
73. Sosnoski, L.M.; Webster, T.M.; Culpepper, A.S. Reductions in Palmer amaranth seed viability over time. Available online: http://commodities.caes.uga.edu/fieldcrops/cotton/rerpubs/2009/p055RER2009.pdf (accessed on 11 March 2012).
74. Shaw, D.R.; Culpepper, A.S.; Owen, M.; Price, A.J.; Wilson, R. Herbicide-resistant weeds threaten soil conservation gains: Finding a balance for soil and farm sustainability, 2012. Available online: http://www.cast-science.org (accessed on 11 March 2012).