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Evaluating Cover Crops and Herbicides for Glyphosate-Resistant Palmer Amaranth (*Amaranthus palmeri*) Control in Cotton

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Glyphosate-resistant (GR) weeds, especially GR Palmer amaranth, are very problematic in cotton-producing areas of the midsouthern region of the United States. Growers rely heavily on PRE residual herbicides to control Palmer amaranth since few effective POST options exist. Interest in integrating high-residue cover crops with existing herbicide programs to combat GR weeds has increased. Research was conducted in 2013 and 2014 in Tennessee to evaluate GR Palmer amaranth control when integrating cover crops and PRE residual herbicides. Cereal rye, crimson clover, hairy vetch, winter wheat, and combinations of one grass plus one legume were compared with winter weeds without a cover crop followed by fluometuron or acetochlor applied PRE. Biomass of cover crops was determined prior to termination 3 wk before planting. Combinations of grass and legume cover crops accumulated the most biomass (> 3,500 kg ha^{-1}) but by 28 d after application (DAA) the cereal rye and wheat provided the best Palmer amaranth control. Crimson clover and hairy vetch treatments had the greatest number of Palmer amaranth. These cereal and legume blends reduced Palmer amaranth emergence by half compared to non–cover-treated areas. Fluometuron and acetochlor controlled Palmer amaranth 95 and 89%, respectively, at 14 DAA and 54 and 62%, respectively, at 28 DAA. Cover crops in combination with a PRE herbicide did not adequately control Palmer amaranth.

Nomenclature: Acetochlor; fluometuron; Palmer amaranth, *Amaranthus palmeri* S. Wats.; cereal rye, *Secale cereal* L.; cotton, *Gossypium hirsutum* L.; crimson clover, *Trifolium incarnatum* L.; hairy vetch, *Vicia villosa* Roth; winter wheat, *Triticum aestivum* L.

Key words: Conservation agriculture, cultural weed control, resistance management.

Malezas resistentes a glyphosate (GR), especialmente *Amaranthus palmeri* GR, son muy problemáticas en áreas productoras de algodón en el la región sur-media de Estados Unidos. Los productores dependen altamente de herbicidas PRE residuales para el control de *A. palmeri*, ya que existen pocas opciones POST efectivas. El interés en integrar cultivos de cobertura con alta producción de residuos con programas existentes de herbicidas para combatir malezas GR ha incrementado. Se realizó una investigación en 2013 y 2014 en Tennessee para evaluar el control de *A. palmeri* GR al integrar cultivos de cobertura y herbicidas PRE residuales. El centeno, *Trifolium incarnatum*, *Vicia villosa*, trigo de invierno, y combinaciones de una gramínea con una leguminosa fueron comparados con malezas de invierno sin ningún cultivo de cobertura seguido por fluometuron o acetochlor aplicados PRE. La biomasa de los cultivos de cobertura fue determinada antes de la terminación de estos 3 semanas antes de la siembra. Las combinaciones de gramíneas y cultivos de cobertura de leguminosas acumularon la mayoría de la biomasa (> 3,500 kg ha^{-1}), pero a 28 d después de la aplicación (DAA), el centeno y el trigo brindaron el mejor control de *A. palmeri*. Los tratamientos de *T. incarnatum* y *V. villosa* tuvieron el mayor número de *A. palmeri*. Las mezclas de estos cereales y leguminosas redujeron la emergencia de *A. palmeri* a la mitad en comparación con las áreas sin cultivos de cobertura. Fluometuron y acetochlor controlaron *A. palmeri* 95 y 89%, respectivamente, a 14 DAA, y 54 y 62%, respectivamente, a 28 DAA. Los cultivos de cobertura con un herbicida PRE no controlaron adecuadamente *A. palmeri*.

Winter-annual cover crops have been used to prevent soil erosion, reduce water runoff, and improve soil structure, soil quality, organic carbon, and organic nitrogen (Krutz et al. 2009; Teasdale 1996). Recent interest in winter-annual cover crops in the midsouthern United States is primarily attributed to the potential for early-season weed control (Norsworthy et al. 2011; Price et al. 2012). Currently, the primary method of weed control in cotton is almost exclusively herbicidal and includes PRE herbicides, applying POST herbicides, and overlaying residual herbicides for season-long weed control as described by Culpepper et al. (2009). Introducing a cultural practice, such as cover crops, is a way for producers to be more integrated and

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sustainable in their weed management practices (Mortensen et al. 2012).

Cover crops have demonstrated early-season weed suppression in several crops, including cotton, corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.] (Reddy 2001; White and Worsham 1990). Winter-annual cover crops produce residue that creates an unfavorable environment for weeds (Teasdale 1996). This residue can reduce available light and moisture to germinating weeds. Thus, they are in direct competition for resources and weeds often will not survive (Teasdale and Mohler 1993). Winter-annual cover crops accumulate aboveground biomass from emergence in the autumn of the year until terminated in the spring of the subsequent year (Fisk et al. 2001). The accumulation of plant biomass is a strong determination of early-season weed control (Ateh and Doll 1996; Teasdale 1996; Teasdale and Mohler 1993). Although cover crops suppress many winter-annual weed species during the early spring, residues typically do not provide season-long weed control for summer crops (Teasdale 1996). Herbicides are commonly needed to achieve adequate weed control.

GR weeds are dominating management decisions across the United States (Johnson et al. 2009; Webster and Sosnoskie 2010). Palmer amaranth is the most difficult GR weed to manage, due to its biological characteristics and herbicide resistance (Culpepper and York 1998; Klingaman and Oliver 1994). It has shown the ability to greatly impact cotton yield (MacRae et al. 2013; Morgan et al. 2001). Palmer amaranth is a summer-annual weed with a lengthy germination window, robust growth habit, and prolific seed production (Bond and Oliver 2006; Horak and Loughin 2000; Keeley et al. 1987; Sellers et al. 2003). Additionally, Sosnoskie et al. (2011) documented Palmer amaranth to be resistant to many POST-applied acetolactate synthase–inhibiting herbicides and glyphosate, making POST control difficult (Bond et al. 2006; Culpepper and York 1998; Wise et al. 2009). Therefore, PRE residual herbicides are a key component in managing this weed (Norsworthy et al. 2014).

There are effective PRE herbicide options for controlling small-seeded dicotyledonous weeds in cotton. Fluometuron is a substituted urea herbicide commonly used to control many annual monocot and dicot weeds. Fluometuron can be used preplant-incorporated, PRE, POST, and POST-directed in cotton with minimal crop injury (Anonymous 2014a; Senseman 2007a; Snipes and Byrd 1994). The encapsulated formulation of acetochlor registered for PRE application in cotton is a chloroacetimide herbicide that controls annual monocot grasses and certain small-seeded dicot weeds (Senseman 2007b). Acetochlor can be used PRE, POST, and POST-directed in cotton with minimal crop injury (Anonymous 2014b; Cahoon et al. 2014).

Research is limited in the area of cover crop residue and PRE herbicide integration for controlling GR Palmer amaranth in cotton. Therefore, a study was conducted to evaluate the effectiveness of integrating high-residue cover crops with PRE fluometuron and encapsulated acetochlor. The objective of this research was to identify which integrated herbicide and cover crop system offers cotton producers the greatest amount of early-season Palmer amaranth control.

Materials and Methods

The experiments were conducted in 2013 and 2014 at the West Tennessee Research and Education Center in Jackson, TN (35.63°N, 88.86°W) (Table 1). This location was infested with nearly a 100% GR Palmer amaranth population (L. Steckel, unpublished data). Cereal rye, winter wheat, crimson clover, and hairy vetch were sowed at seeding rates of 67, 67, 17, and 22 kg ha^{-1}, respectively. Additionally, combinations of either grass species plus either legume species were sowed at rates referenced above. The cover crops were sowed in the autumn using a no-till drill and allowed to overwinter. All cover crop treatments were compared with areas of native winter vegetation consisting of henbit (*Lamium amplexicaule* L.), annual bluegrass (*Poa annua* L.), and horseweed [*Conyza canadensis* (L.) Cronquist]. These non–cover crop treated plots that consist of native winter vegetation are typical of most current production practices in Tennessee (Anonymous 2015) and will be referred to from here on as the check treatment. Plots were four rows by 9.1 m, with a row spacing of 97 cm. All other production practices followed University of Tennessee Extension recommendations.

Table 1. Location, environmental conditions, cotton planting dates and harvest dates, cover crop planting dates and termination dates.

Location	Year	Soil series/texture	Cotton planting date	Cotton harvest date	Cover crop planting date	Cover crop termination date	Total precipitation[a]	Heat accumulation[a]	Average precipitation[b]
							cm	DD60s[c]	cm
WTREC[c]	2013	Lexington silt loam[d]	May 9, 2013	October 5, 2013	September 28, 2012	April 19, 2013	57	2,174	64
WTREC	2014	Lexington silt loam	May 5, 2014	October 6, 2014	October 10, 2013	April 15, 2014	83	2,130	

[a] Climate information recorded from cotton planting to cotton harvest.
[b] Historical average rainfall from May through October from 1980–2009 recorded at WTREC.
[c] Abbreviations: DD60s, cotton growing degree units; WTREC, West Tennessee Research and Education Center, Jackson, TN.
[d] Fine-silty, mixed, active, Thermic Ultic Hapludalfs.

A 25-cm band of paraquat plus nonionic surfactant (Table 2) was applied over each row 90 d before anticipated cotton planting using a shielded sprayer and a tractor with real-time kinematic (RTK) technology (John Deere Greenstar 2, John Deere, Moline, IL). Shortly before chemical desiccation of cover crops, biomass yields were obtained from the nontreated area between the desiccated strips by clipping a 0.1-m^2 quadrat at ground level. Measurements were adjusted to address missing biomass from the banded herbicide application. These cover crop samples were dried in a forced-air oven at 60 C for 48 h. The experiment was sprayed with a burndown application of glyphosate (Table 2) 30 d before planting. It was determined that a sequential burn-down application was needed, as glyphosate did not control the hairy vetch or crimson clover effectively (Fisk et al. 2001). A sequential application of paraquat plus nonionic surfactant adequately controlled all vegetation in the trial area. The desiccated bands were then planted into utilizing the RTK technology. Cotton cultivar 'FM 1944GLB2′ (Bayer CropScience, Research Triangle Park, NC), was planted into the desiccated bands utilizing the RTK technology at depth of 2 cm with a seed population of 10 to 12 seed m^{-1} of row into an existing cover crop residue. Cover planting dates, cover termination dates, cotton planting dates, and environmental data can be found in Table 1.

The PRE herbicides were applied immediately after planting. Herbicide treatments were fluometuron, acetochlor, and a nontreated check (Table 2). Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} and equipped with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

A randomized complete block design was used with a factorial arrangement of treatments and four replications. Treatment factors included a main treatment effect of cover crop species and a secondary treatment of herbicide regime.

Palmer amaranth control was visually estimated weekly for 4 wk, starting 7 d after application (DAA) using a scale of 0 (no control) to 100 (complete control). Palmer amaranth density was recorded with three 0.25-m^{-2} quadrants per plot following visual rating of control. A broadcast application of

Table 2. Herbicides and adjuvants used in experiments in Tennessee, 2013–2015.[a]

Herbicides and adjuvants	Trade names	Formulation concentration	Application time	Application rate	Manufacturer
Acetochlor, microencapsulated	Warrant	359 g ai L^{-1}	PRE	1260 g ai ha^{-1}	Monsanto Co.
Fluometuron	Cotoran 4L	480 g ai L^{-1}	PRE	1120 g ai ha^{-1}	ADAMA Agriculture Soulutions, Ltd.
Glufosinate-ammonium[c]	Liberty	280 g ai L^{-1}	POST	590 g ai ha^{-1}	Bayer CropScience
Glyphosate potassium salt	Roundup PowerMAX	540 g ae L^{-1}	Cover crop termination	1260 g ai ha^{-1}	Monsanto Co.
Nonionic surfactant	Activator 90	90%	Cover crop termination	0.25% (V/V)	Loveland Products, Inc.
Paraquat dichloride	Gramoxone SL	240 g ai L^{-1}	Cover crop termination	840 g ai ha^{-1}	Syngenta Crop Protection

[a] Speciman labels for each product and mailing addresses and website addresses of each manufacturer can be found at http://www.cdms.net.

glufosinate-ammonium (Bayer Crop Science, 2 T.W. Alexander Dr., Research Park, NC 27709) (602 g ai ha^{-1}) was applied to all plots after these assessments to ensure harvestable plots. The center two rows of cotton were harvested using a spindle picker adapted for small-plot harvesting. Lint yields were calculated using a 35.5% gin turnout.

Data were subjected to ANOVA using the PROC MIXED procedure of SAS (version 9.3, SAS Institute, Cary, NC). ANOVA was used to test for significant main effects and interactions. Main effects and all possible interactions were tested using the appropriate expected mean square values as recommended by McIntosh (1983). Each year was considered an environment sampled at random from a population as suggested by Carmer et al. (1989). Environments, replications (nested within environments), and all interactions containing these effects were considered random effects in the model; cover crop species and herbicide regime were considered fixed effects. Means were separated using Fisher's protected LSD test at $P \leq 0.05$.

Results and Discussion

Cover Crop Biomass. Cover crop biomass varied by cover crop treatment ($P \leq 0.0001$) (Table 3).

Table 3. Cover crop dry biomass and Palmer amaranth control and density 28 DAA[a] as affected by cover crop species.

		Palmer amaranth				
		Control				Density
Cover crop	Biomass	7 DAA	14 DAA	21 DAA	28 DAA	28 DAA
	kg ha^{-1}	%				no. m^{-2}
Cereal rye	2,440 e[b]	81 ab	80 a	64 a	57 a	17 abc
Cereal rye + crimson clover	3,900 b	80 ab	76 a	54 abc	45 bc	15 bc
Cereal rye + hairy vetch	4,690 a	85 a	75 a	59 ab	48 abc	14 bc
Crimson clover	2,450 e	72 c	59 b	35 e	32 d	24 ab
Hairy vetch	3,150 cd	76 bc	64 b	39 de	27 d	27 a
Winter wheat	3,080 d	82 ab	78 a	59 ab	54 ab	17 abc
Winter wheat + crimson clover	3,530 bc	80 ab	74 a	52 bc	45 bc	11 c
Winter wheat + hairy vetch	3,620 b	85 a	78 a	55 abc	48 abc	10 c
Nontreated check[c]	990 f	68 c	62 b	48 cd	44 c	22 ab
Pr > F	< 0.0001	0.0003	< 0.0001	< 0.0001	< 0.0001	0.0146

[a] Abbreviations: DAA, days after application.
[b] Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).
[c] Areas included in the nontreated check consisted of henbit, annual bluegrass, and horseweed.

Table 4. In-season Palmer amaranth control and density 28 DAA[a] as affected by PRE herbicide treatments.

Herbicide treatments[b]	Palmer amaranth					Cotton lint yield
	Control				Density	
	7 DAA	14 DAA[c]	21 DAA	28 DAA	28 DAA	
	%				no. m^2	kg ha^{-1}
Acetochlor	97 a[d]	89 b	70 a	62 a	6 b	890 a
Fluometuron	93 a	95 a	66 a	54 b	11 a	900 a
Nontreated check	47 b	31 c	19 b	17 c	35 a	650 b
Pr > F	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001

[a] Abbreviation: DAA, days after application.

[b] Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD ($P \leq 0.05$).

Dry biomass ranged from 990 to 4,960 kg ha^{-1}. Cover crop combinations of grass and legume species had the greatest biomass. The cereal rye plus hairy vetch combination accumulated more biomass (4,960 kg ha^{-1}) than any other treatment. There were no differences in biomass of the other combination treatments and all accumulated residue greater than 3,500 kg ha^{-1}, which was more than any single species. Biomass of single cover crop species ranged from 2,440 to 3,150 kg ha^{-1}. Cereal rye accumulated biomass similar to that of crimson clover. These findings are different than results of Daniel et al. (1999), who found that cereal rye and combinations of cereal rye and hairy vetch yielded similar amounts of biomass. The contrast between this study's results and Daniel et al. (1999) suggests that biomass accumulation with blends can better establish stands when winter temperatures are more moderate. Days below 0 C for December through February in the Daniel et al. (1999) study was 49 to 62 d compared to 34 to 52 d in this study. The authors suggest the two covers combined were able to get established more quickly when winter temperatures were more moderate compared to a single species. All cover crops had greater amounts of biomass than control treatments where only native winter vegetation was present.

In-Season Palmer Amaranth Control. In-season Palmer amaranth control varied by cover crop treatment and herbicide treatment (Tables 3 and 4). The interaction of cover crop by herbicide was significant at 7 DAA ($P = 0.0025$). Palmer amaranth control at 7 DAA ranged from 19 to 99%. No differences were detected among any cover crop treatment that received a herbicide application. All treatments of cover crops and herbicides had greater than 87% Palmer amaranth control. However, cover crop treatments receiving no herbicide had less than 65% control of those that received herbicides.

No interaction effects were significant at 14 DAA ($P = 0.1677$), 21 DAA ($P = 0.4767$), or 28 DAA ($P = 0.2914$). Therefore, sequential evaluation timings from 14 to 28 DAA will be discussed by main effects, as no interaction was observed. Cover crop affected Palmer amaranth control 14 DAA, and ranged from 59 to 80% control. There were no differences between the winter-annual grass species and combinations of legume and grass species. The additional accumulation of biomass by the combination treatments improved Palmer amaranth suppression. There were no differences among the single-legume cover crops and areas of native winter vegetation. Earlier biomass results indicated that hairy vetch accumulated more biomass than cereal rye. However, the cereal rye had more in-season Palmer amaranth suppression than hairy vetch. These results suggest that the crop residue of cereal rye is more persistent than that of hairy vetch and is adding more in-season weed control. Palmer amaranth control 21 and 28 DAA showed that only cereal rye, cereal rye plus hairy vetch, and wheat were still providing better suppression of Palmer amaranth than the no-cover crop check.

The grass cover crops and combination treatments of grass and legume species provided the most Palmer amaranth control; however, it was only 45 to 57% at 28 DAA. This indicates the need for additional weed control measures to ensure a harvestable crop. As in previous research, this accumulation of biomass correlated to early-season weed control (Ateh and Doll 1996; Fisk et al. 2001; Teasdale 1996).

Herbicide treatments also impacted Palmer amaranth control, ranging from 31 to 95%, with fluometuron providing the most control by 14 DAA (Table 4). Encapsulated acetochlor also provided greater Palmer amaranth control (89%) compared with the non–cover crop treated native vegetation checks (31%). Palmer amaranth control did not differ at 21 DAA among herbicide treatments. Acetochlor controlled Palmer amaranth 62% at 28 DAA, which is not adequate where this pest pressure is high (Norsworthy et al. 2014). In this study, like cover crops, PRE herbicides add to early-season weed control, but additional measures were required to adequately manage GR Palmer amaranth.

Palmer Amaranth Density. Palmer amaranth densities differed by cover crop treatment and herbicide treatment (Tables 3 and 4). There was no interaction between main effects ($P = 0.3435$), therefore only the main effects will be discussed. Palmer amaranth density was directly affected by the amount of biomass produced and persistence of the residue on the soil surface. Crimson clover and hairy vetch treatments had the greatest number of Palmer amaranth. These cereal and legume species blends essentially cut the number of Palmer amaranth that emerged in half (10 and 11 compared to 22 Palmer amaranth m^{-1}). There were no differences observed in the single-species treatments and areas of native winter vegetation. These results suggest that selecting a cereal plus a legume cover crop mixture will add to early-season Palmer amaranth suppression when compared with a single cover crop species. This reduction in Palmer amaranth emergence could have a very positive effect in reducing selection pressure for herbicide resistance. Research has found that cover crops may reduce weed biomass, thereby reducing seed production and limiting the number of plants that emerge, which lowers the probability of selecting for new herbicide resistance development (Owen et al. 2014; Riar et al. 2013).

Palmer amaranth density at 28 DAA differed by herbicide treatment and ranged from 6 to 35 weeds m^{-2}. Fluometuron and acetochlor performed similarly and better than the nontreated.

Cotton Yield. Cotton lint yield differed by herbicide treatment. However, cover crop species ($P = 0.2453$) and the interaction of main effects ($P = 0.6075$) had no effect on yield. Lint yield ranged from 650 to 900 kg ha^{-1} (Table 4). The use of PRE herbicides resulted in more lint than the no-herbicide treated check. There were no differences in yield between PRE herbicides. Consequently, residual herbicides are recommended in cotton production. However, additional control measures will be needed in addition to cover crops and PRE herbicides to ensure optimum lint yield (Norsworthy et al. 2011).

Winter-annual cover crops and PRE residual herbicides increased control and proved to be essential for good GR Palmer amaranth control the first 2 wk in this study. Weed control by cover crops is related to accumulation and persistence of the residue. Heavier residues of winter-annual cereals alone or in combination with legume dicots aided in preventing Palmer amaranth germination and establishment. However, the single species and mixtures of cover crops failed to provide adequate GR Palmer amaranth control. The PRE herbicide treatments provided adequate early-season control of Palmer amaranth; however, control diminished to unacceptable levels as the growing season progressed. The use of a cereal and legume cover crop mixture reduced Palmer amaranth emergence by half compared to non–cover crop check. These findings show that cover crops could be a component in a herbicide resistance mitigation strategy for glufosinate-ammonium (Kichler et al. 2013; Owen et al. 2014), which is used on most Tennessee cotton acres and is often applied at that 14 to 28 d after cotton planting (author's personal experience). Multiple tactics employed together also construct an effective herbicide-resistance management program (Riar et al. 2013). Moreover, this study would suggest that a combination of high-residue cover crop and PRE herbicides can be part of an effective GR Palmer amaranth management strategy, but additional means of control are necessary for consistent control later in the cotton growing season.

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