

## Research Article

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# Influence of a Cereal Rye Cover Crop and Conservation Tillage on the Critical Period for Weed Control in Cotton

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**Abstract**

Cover crops are being increasingly recommended as an integrated approach to controlling glyphosate-resistant Palmer amaranth and other troublesome weeds. Thus, a field experiment was conducted in 2010 through 2012 to evaluate the critical period for weed control (CPWC) in cotton as affected by a cereal rye cover crop and tillage. The management systems evaluated included conventional tillage following winter fallow, conservation tillage (CT) following winter fallow, and CT following a cereal rye cover crop managed for maximum biomass. Throughout most of the growing season, weed biomass in cereal rye cover crop plots was less than the CT winter-fallow system in both years and less than both CT winter fallow and conventional tillage in 2012. The CPWC was shortest in 2010 following conventional tillage; however, in 2012, production system influences on CPWC were less. The presence of the rye cover crop delayed the critical timing for weed removal (CTWR) approximately 8 d compared with fallow treatment both years, while conventional tillage delayed CTWR about 2 wk compared with winter fallow. Relative yield losses in both years did not reach the 5% threshold limit until about 2 wk after planting (WAP) for CT following winter fallow, 3 WAP for CT following a cover crop, and 3.5 WAP following conventional tillage. Thus, CT following winter fallow should be avoided to minimize cotton yield loss.

**Introduction**

In the Midsouth and southeastern United States cotton-producing states, amaranth (*Amaranthus* spp.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], morningglory (*Ipomoea* spp.), nutsedges (*Cyperus* spp.), goosegrass [*Eleusine indica* (L.) Gaertn.], and sicklepod [*Senna obtusifolia* (L.) H. S. Irwin & Barneby] are the highest-ranked troublesome weeds (Van Wychen 2016). Widespread glyphosate-resistant horseweed (*Erigeron canadensis* L.) (Davis et al. 2007; Nichols et al. 2009; Owen and Zelaya 2005) and acetolactate synthase (ALS) inhibitor- and/or glyphosate-resistant Palmer amaranth in this area has reemphasized the need for integrated herbicide-resistant weed control strategies (Culpepper et al. 2006; Norsworthy et al. 2008; Price et al. 2009, 2011b). The urgent need for integrated weed management strategies was highlighted in a *Weed Science* journal special issue “Herbicide Resistant Weeds” containing a brief best management practice (BMP) section entitled “Cover Crops and Synthetic Mulches” (Norsworthy et al. 2012). In this section, authors described the need to understand diverse BMPs, including “cultural management techniques that suppress weeds by using crop competitiveness” and “using mechanical and biological management practices where appropriate.” Recent academic and U.S. Department of Agriculture–Agriculture Research Service (USDA–ARS) *Amaranthus* species research and state Cooperative Extension System (CES) efforts have focused on integrated cultural and chemical weed management strategies to provide effective control and reduce selection pressure for ALS-inhibitor and glyphosate resistance (Gustafson 2008; Neve et al. 2011; Norsworthy et al. 2011; Price et al. 2016). BMPs for use in integrated weed management approaches include: intensified crop rotation to disrupt reoccurring weed life cycles, conservation tillage (CT) systems that maximize cover crop residue biomass, delayed cotton planting to optimize increased soil temperatures and growing degree days advantaging cotton growth, increased scouting to identify weed emergence or management problems early, timely herbicide applications to maximize efficacy, use of diversified herbicide chemistries (including PRE herbicides) to reduce herbicide selection pressure, and intermittent inversion tillage (strategic tillage) to bury weed seed beyond successful emergence depth (Norsworthy et al. 2012; Price et al. 2011a, 2016). The implementation of these integrated approaches and practices; however, has yet to

be fully developed and subsequently adopted by producers. In addition, the increased use of tillage and subsequent decrease in CT hectareage is a major USDA–Natural Resource Conservation Service (USDA–NRCS) land resource concern due to soil-quality degradation and erosion concerns (Duzy et al. 2015; Price et al. 2011a).

The Brazilian CT system, which maximizes cover crop residue biomass, is increasingly being adopted by producers in the United States. This CT system is characterized by terminating reproductively mature cover crops using glyphosate and mechanical flattening with a roller/crimper. This practice aims to form a dense residue biomass mat ( $>4,500 \text{ kg ha}^{-1}$  to attain soil-quality benefits) on the soil surface, through which crop seeds are planted (Derpsch et al. 1991; Reeves 2003). However, research has shown that biomass  $>4,500 \text{ kg ha}^{-1}$  is needed to provide substantial weed suppression (Norsworthy et al. 2011; Price et al. 2005; Teasdale and Mohler 2000). In the Midsouth and southeastern United States, winter cereal cover crops can reach anthesis and be terminated using similar practices in a timely fashion before recommended planting windows for CT cotton and other crops (Aulakh et al. 2011, 2012, 2013; Korres and Norsworthy 2015; Mirsky et al. 2011; Price et al. 2009; Reeves et al. 2005). CT high-biomass cereal rye systems can reduce weed emergence and growth over conventional or CT winter-fallow systems (Aulakh et al. 2011; Korres and Norsworthy 2015; Mirsky et al. 2011; Price et al. 2005, 2006, 2012; Reeves et al. 2005; Ryan et al. 2011; Shilling et al. 1996; Smith et al. 2011; Teasdale and Mohler 2000).

Cotton, due to its slow emergence and initial growth, experiences increased weed interference compared with other row crops (Buchanan and Burns 1970). Because of this slow growth attribute, yield losses may be significant when problematic weeds are not controlled or suppressed in a timely manner. Currently, cotton weed management decisions are driven by the need to control resistant and troublesome weeds, as previously discussed. The critical period for weed control (CPWC) is the time interval in crop growth when a weed-free state must be maintained to prevent substantial ( $\geq 5\%$ ) yield loss (Knezevic et al. 2002). The CPWC has two separately measured weed–crop competition components: (1) the critical timing for weed removal (CTWR; i.e., the maximum time duration the crop can tolerate early-season weed competition before incurring increasingly substantial yield loss) and (2) the critical weed-free period (CWFP; i.e., the minimum time duration from time of planting onward when a crop needs to be kept weed free to prevent substantial yield losses above a predetermined level) (Knezevic et al. 2002; Korres and Norsworthy 2015; Williams et al. 2007). The CTWR determines the beginning of CPWC, while the CWFP determines its end; the combination of both components determines the duration of CWFP. Weeds that are present before or emerge after this period do not cause significant ( $>5\%$ ) yield loss (Knezevic et al. 2002). The use of cover crops managed for maximum biomass could decrease or delay weed emergence, effectively reducing the CPWC (Korres and Norsworthy 2015). Thus, a field experiment was conducted to compare how CT following high-biomass cereal rye cover crop affects CPWC and its components compared with CT following winter-fallow or conventional tillage systems.

## Materials and Methods

### Experimental Design

A field experiment was initiated during the fall of 2010 at the E. V. Smith Research Center Field Crops Unit (32.4417° N, 85.8974° W)

near Shorter, AL, on a Compass sandy loam (coarse-loamy, siliceous, subactive, thermic Paleudults). The experimental design consisted of a split-plot treatment restriction in a randomized complete block design with four replicates. The main plots consisted of agronomic system: (1) conventional tillage without a cover crop (CVT), (2) CT following winter fallow (CT + WF), or (3) CT following a cereal rye cover crop (CT + CC) managed for maximum biomass, and subplots were various durations of naturally occurring weed interference and weed-free periods. These periods consisted of 10 durations of 0 to 70 d after planting (DAP) in 1-wk increments. Season-long weed-free and season-long weed interference were also included and started at 0 DAP. Weed control after each weed interference duration or for maintaining weed-free periods consisted of glyphosate applied at  $1.12 \text{ kg ae ha}^{-1}$  as needed throughout the experiment using a  $\text{CO}_2$ -pressurized backpack sprayer equipped with 11102 XR nozzles calibrated to deliver  $187 \text{ L ha}^{-1}$ . There were no glyphosate-resistant weeds in the experimental area during this experiment.

### Crop Establishment and Management

Cereal rye ‘Wrens Abbuzi’ in the CT + CC plots was established with a no-till drill each fall at a seeding rate of  $101 \text{ kg ha}^{-1}$ . In early spring,  $34 \text{ kg N ha}^{-1}$  (as  $\text{NH}_4\text{NO}_3$ ) was applied to the cover crop to enhance biomass production. In the spring before termination, cover crop biomass samples were collected by clipping all aboveground plant parts close to the soil surface from one randomly selected  $0.25\text{-m}^2$  section in each plot. Plant material was dried at  $60 \text{ C}$  for 72 h and weighed. All plots were then rolled with a mechanical roller-crimper before glyphosate application, as described by Ashford and Reeves (2003), to aid in cover crop termination and to provide a uniform mat of residue on the soil surface in CT + CC plots, while desiccating emerged winter weeds in CT + WF plots.

Because the experimental site had a well-developed hardpan, the entire experimental area (including the CVT treatments, to eliminate the chance of a deep-tillage interaction) was in-row subsoiled before cotton planting with a narrow-shank parabolic subsoiler (Parabolic subsoiler, KMC, Tifton, GA) equipped with pneumatic tires to close the subsoil channel. This equipment minimally disturbed residue and soil in a 5-cm-wide planting zone. Two disking passes and multiple field cultivator passes were then performed in the CVT plots.

Cotton ‘Stoneville 4427 B2RF’ (Stoneville Pedigreed Seed Company, Inc., MO, US/Bayer CropScience) was planted on May 17, 2010, and May 17, 2012, respectively. All plots received  $47 \text{ kg N ha}^{-1}$  as a starter in the form of  $\text{NH}_4\text{NO}_3$ , before planting. An additional  $67 \text{ kg N ha}^{-1}$  was side-dressed as urea-ammonium nitrate.

### CPWC Estimation

CPWC is a time period that is inferred rather than verified from two independently and distinctly different competition components, the CTWR and the critical weed-free period (CWFP) that determine the beginning and the end of CPWC, respectively (Knezevic et al. 2002; Weaver 1984). It is evaluated by typically fitting a logistic model to CTWR data and a Gompertz model to CWFP data. The first step is the choice of an acceptable level of yield potential (i.e., relative yield for both CTWR and CWFP in relation to season-long weed-free treatment) for both the

beginning and end of the CPWC. Usually, an acceptable yield response is 95% (Blankenship et al. 2003; Knezevic et al. 2002). Relative yield was then regressed as a function of timing of weed removal/interference. Once the nonlinear regression models corresponding to CTWR and CWFP are fit, the CPWC is estimated.

Therefore, CPWC for each of the CVT, CT + WF, and CT + CC treatments was evaluated as described by Knezevic et al. (2002), Williams et al. (2007), and Korres and Norsworthy (2015). More specifically, a logistic model with three parameters was fit to relative cotton yield (expressed as percentage of season-long weed-free treatment) for the evaluation of the CTWR (weedy) treatments (Equation 1).

$$y = \frac{a}{1 + e^{-b(x-x_0)}} \quad [1]$$

In addition, a Gompertz model with three parameters (Equation 2) was employed to describe the effects of the CWFP (weed-free) on cotton relative yield.

$$y = ae^{e^{-b(x-x_0)}} \quad [2]$$

where  $y$  is the relative yield,  $a$  is the asymptote,  $b$  is the slope of the curve,  $x_0$  is the point of inflection, and  $x$  is time (i.e., weeks after planting). The combination of these two components represents the duration of CPWC based on yield losses of 5% for each of the experimental treatments.

As mentioned earlier, weed removal studies evaluate the relationship between time of weed removal and relative yield crop yield, and then infer the optimum interval of weed control. Typically, these studies are designed as split plots that result in multiple error terms or other error structures (Blankenship et al. 2003). To strengthen the outcome of the results described in this work, an inverse prediction for 95% relative yield was performed to estimate both CTWR and CWFP for CVT, CT + WF, and CT + CC treatments.

### Weed Biomass

Weed biomass production was also examined as a function of the weed removal timing and the weed-free period for each experimental treatment as it was described previously using Equations 1 and 2 (i.e.,  $y$  in this instance represents weed biomass).

### Data Analysis

Cotton yield data were subjected to ANOVA and means were separated using Fisher's LSD at  $\alpha = 0.05$  to evaluate treatment effects on actual and relative (expressed as percentage of weed-free period) cotton yield. Because there was a treatment by year interaction, subsequent statistical analysis for estimating CPWC was done and is presented separately for each experiment.

SigmaPlot v. 13.0 (Systat Software, San Jose, CA) and JMP Pro v. 13 (SAS Institute, Cary, NC) were used for ANOVAs, curve-fitting regressions, and inverse predictions and for the evaluation of the significance of model parameters. Model parameters, particularly curve asymptotes, are used for corroboration (i.e., the estimation of inverse predictions) when the value of an explanatory variable, in our case time period of CTWR and CWFP, is predicted given a value of a response variable, in this case relative yield. Coefficient of determination ( $r^2$ ) was used to assess the fit of each model, whereas comparisons between model parameters were conducted to examine the influence of experimental treatments on weed biomass production.

## Results and Discussion

### Rye Biomass and Cotton Yield

At time of termination, rye biomass was 4,100 and 7,900 kg ha<sup>-1</sup> in 2010 and 2012, respectively. The crop establishment treatments affected the cotton yield differently in the two years. Weed-free seed cotton yield in 2010 following rye was similar to winter fallow and conventional tillage (1,564, 1,547, and 1,523 kg ha<sup>-1</sup>, respectively). In 2012, weed-free seed cotton yield following rye was significantly less (1,543 kg ha<sup>-1</sup>) than winter fallow (2,484 kg ha<sup>-1</sup>) and conventional tillage (2,623 kg ha<sup>-1</sup>). Variability in yields following different cover crop and tillage regimes is well documented (Aulakh et al. 2011; Price et al. 2006, 2012).

### Critical Period for Weed Control

The presence of rye cover crop (i.e., CT + CC) delayed the CTWR and shortened CWFP in both experimental years. When relative yield in relation to season-long weed-free control is 95%, the predicted value of CTWR in 2010 equals 1.7, 3.2, and 3.7 WAP for CT + WF, CT + CC, and CVT, respectively. Additionally, the predicted value of CWFP at the same experimental year equals 7.7, 8.1, and 4.8 for CT, CT + CC, and CVT, respectively (Table 1). The predicted value of CTWR equals 1.6, 2.6, and 3.5 WAP, while that of CWFP for 2012 equals 8.4, 7.4, and 8.3 WAP for CT + WF, CT + CC, and CVT respectively (Table 2). In general, CTWR under CT + CC was approximately 7 to 10 d delayed compared with CT + WF, while CVT delayed CTWR about 2 wk compared with CT + WF for 2010 and 2012 (Figure 1; Tables 1 and 2), likely due to delayed weed seedling emergence (Haramoto and Gallandt 2004; Korres and Norsworthy 2015; Teasdale 1996). In 2010, seed yield loss reached 5% in less than 2 wk in the winter-fallow system in the presence of competition, while CT + CC reached 5% in 3.2 wk and CVT reached 5% in 3.7 wk. Thus, comparing CT + WF and CT + CC systems, the presence of rye delayed the beginning of CWFP about 1 wk, but did not change the duration. Similarly, in 2012, the relative order of CTWR and CWFP did not change, although there was less system influence (Figure 1; Tables 1 and 2). In 2012, CT + CC and

**Table 1.** Point estimates (inverse predictions), standard errors (SE) of inverse predictions, and confidence intervals (CI<sub>95</sub>) corresponding to a 5% acceptable yield loss level for the logistic and Gompertz models used to determine the beginning and end of the critical period in 2010 for weed control in cotton under three agronomic tillage systems.

Model <sup>a</sup>	Tillage system <sup>b</sup>	Inverse prediction	SE	CI <sub>95</sub> lower	CI <sub>95</sub> upper
Logistic (CTWR)	CT + WF	1.7	1.41	-0.41	13.21
	CT + CC	3.2	1.01	1.25	5.21
	CVT	3.7	0.69	2.32	5.10
Gompertz (CWFP)	CT + WF	7.7	1.97	2.88	10.61
	CT + CC	8.1	6.04	-0.27	14.98
	CVT	4.8	0.68	3.29	6.01

<sup>a</sup>CWFP, critical weed-free period; CTWR, critical timing for weed removal.

<sup>b</sup>CT + CC, conservation tillage following a cereal rye cover crop; CT + WF, conservation tillage following winter fallow; CVT, conventional tillage without a cover crop.

**Table 2.** Point estimates (inverse predictions), standard errors (SE) of inverse predictions, and confidence intervals (CI<sub>95</sub>) corresponding to a 5% acceptable yield loss level for the logistic and Gompertz models used to determine the beginning and end of the critical period in 2012 for weed control in cotton under three agronomic tillage systems.

Model <sup>a</sup>	Tillage system <sup>b</sup>	Inverse prediction	SE	CI <sub>95</sub> lower	CI <sub>95</sub> upper
Logistic (CTWR)	CT + WF	1.6	0.96	-0.24	3.50
	CT + CC	2.6	1.16	0.31	4.87
	CVT	3.5	3.56	-1.9	13.7
Gompertz (CWFP)	CT + WF	8.4	0.71	6.96	9.78
	CT + CC	7.4	1.61	5.19	11.67
	CVT	8.3	0.75	6.89	9.83

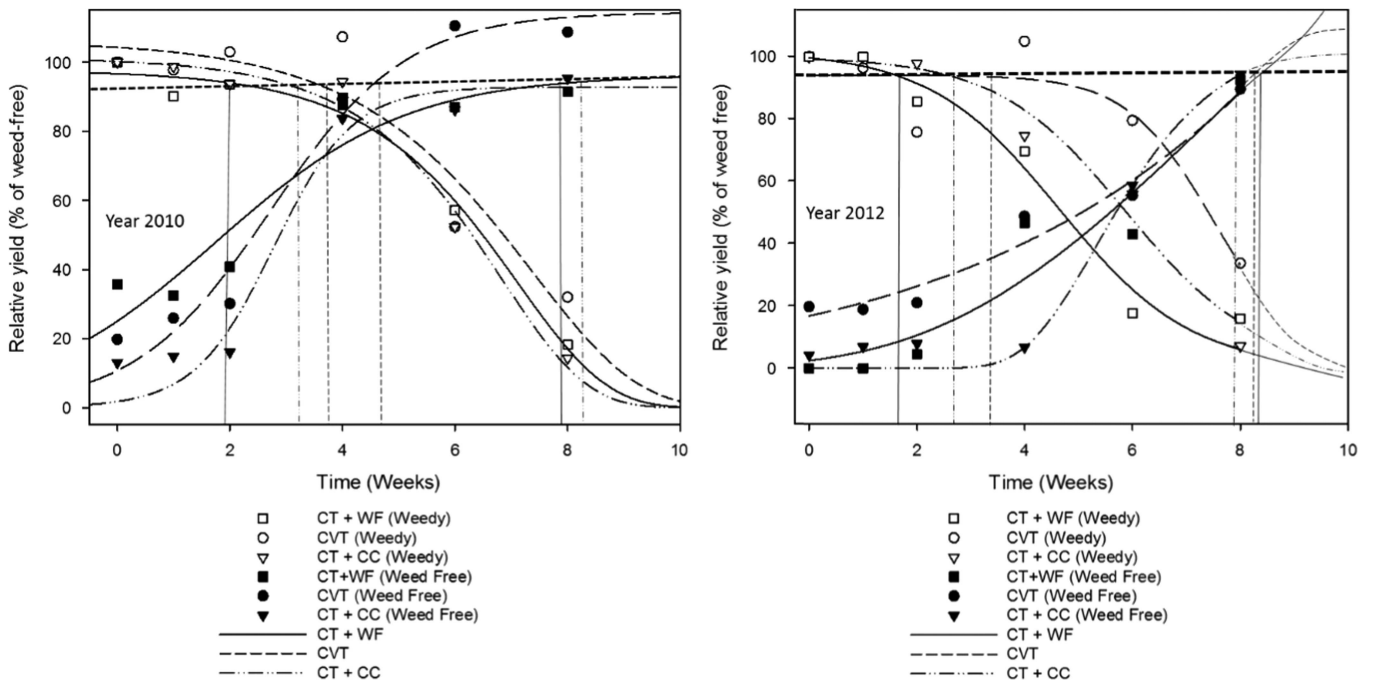
<sup>a</sup>CTWR, critical time for weed removal; CWFP, critical weed-free period.  
<sup>b</sup>CT + CC, conservation tillage following a cereal rye cover crop; CT + WF, conservation tillage following winter fallow; CVT, conventional tillage without a cover crop.

CVT both shortened the CPWC by approximately 1.5 wk compared with CT + WF (Figure 1; Tables 1 and 2). This could offer a significant competitive advantage for cotton against weeds.

The results, as presented in Figure 1 and Tables 1 and 2, revealed the influence of CVT treatment on relative yield by extending the CTWR compared with CT + WF and CT + CC treatments (i.e., inflection point under CVT treatment equals 2.7 and 7.5 WAP, compared with 1.8 and 5.7 WAP for CT + WF and 2.8 and 6.1 WAP for CT + CC in 2010 and 2012, respectively; Table 3). The inflection point for CWFP under CVT treatment recorded at 7.4 and 8.0 wk was compared with those of CT + WF (7.1 and 6.8 wk) and rye cover crop (CT + CC; 6.8 and 5.2 wk) for 2010 and 2012, respectively (Table 4). Analysis of means for asymptote, inflection, and growth rate estimates

**Table 3.** Statistics of the three-parameter logistic regression model (critical timing for weed removal, CTWR) used for each of the conservation tillage following winter fallow (CT + WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT + CC) treatments for the evaluation of the critical period of weed control.

Experiment	Treatment	Coefficients	SE	t-value	r <sup>2</sup>	
Experiment 2010	CT + WF	α	96.4	12.13	7.08	0.951
		b	0.6	0.25	2.07	
		x <sub>0</sub>	1.8	0.71	2.23	
CVT	CVT	α	114.4	10.05	12.81	0.987
		b	0.8	0.23	3.99	
		x <sub>0</sub>	2.7	0.46	6.63	
CT + CC	CT + CC	α	95.8	7.73	12.31	0.982
		b	1.4	0.51	2.83	
		x <sub>0</sub>	2.8	0.41	6.96	
<b>Experiment 2012</b>						
CT + WF	CT + WF	α	98.5	13.27	13.93	0.963
		b	1.4	0.68	-1.25	
		x <sub>0</sub>	5.7	0.35	16.71	
CVT	CVT	α	94.2	6.99	13.46	0.921
		b	0.2	0.17	-1.70	
		x <sub>0</sub>	7.5	0.48	15.52	
CT + CC	CT + CC	α	101.8	8.63	11.79	0.971
		b	0.5	0.22	-3.18	
		x <sub>0</sub>	6.1	1.8	10.15	



**Figure 1.** Critical period for weed control and its components (critical timing for weed control [CTWR; i.e., weedy] and critical weed-free period [CWFP; i.e., weed free]) for each of the conservation tillage following winter fallow (CT + WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT + CC) experimental treatments for 2010 and 2012. Point estimates for CTWR and CWFP for CT + WF, CT + CC, and CVT treatments are presented in Tables 1 and 2.



**Table 4.** Statistics of the three-parameter Gompertz regression model (critical weed-free period, CWFP) used for each of the conservation tillage following winter fallow (CT+WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT+CC) treatments for the evaluation of the critical period of weed control.

Experiment 2010		Coefficients	SE	t-value	r <sup>2</sup>
CT+WF	$\alpha$	97.7	6.76	25.55	0.998
	$b$	-0.6	0.21	-5.62	
	$x_0$	7.1	0.36	35.87	
CVT	$\alpha$	106.2	7.95	8.79	0.943
	$b$	-0.5	0.18	-1.92	
	$x_0$	7.4	0.37	12.81	
CT+CC	$\alpha$	101.3	6.73	23.93	0.992
	$b$	-0.6	0.21	-5.1	
	$x_0$	6.8	0.034	31.73	
Experiment 2012					
CT+WF	$\alpha$	94.8	7.41	6.31	0.991
	$b$	-0.9	0.46	12.76	
	$x_0$	6.8	0.48	15.5	
CVT	$\alpha$	94.2	6.80	0.033	0.982
	$b$	-1.1	0.64	0.245	
	$x_0$	8.0	0.35	0.17	
CT+CC	$\alpha$	102.4	13.67	1.15	0.948
	$b$	-0.7	0.34	1.21	
	$x_0$	5.2	0.50	1.57	

revealed no significant differences between parameter estimates for each of the CTWR curves fit for fallow, CT, and rye cover treatments (unpublished data). Similar results were obtained for CWFP curve parameters of CT+WF, CT+CC, and CVT for 2010 and 2012.

Curve parallelism tests revealed no significant differences between CTWR or CWFP treatment curves in both years 2010 and 2012 (unpublished data), indicating a similar impact of CT+WF, CVT, and CT+CC treatment on CPWC. Previous research has reported that cover crop use in CT causes weed seedling emergence and establishment delays due to allelopathic compound releases, decreased environmental cues weed seed may require for germination initiation, or physical interference with emergence (Akemo et al. 2000; Haramoto and Gallandt 2004; Korres and Norsworthy 2015; Peachy et al. 1999; Teasdale 1996; Teasdale and Mohler 1993). CPWC was found to equal 6, 4.9, and 1.1 wk in 2010 and 6.8, 4.8, and 4.8 wk in 2012 for CT+WF, CT+CC, and CVT, respectively (Figure 1; Tables 1 and 2).

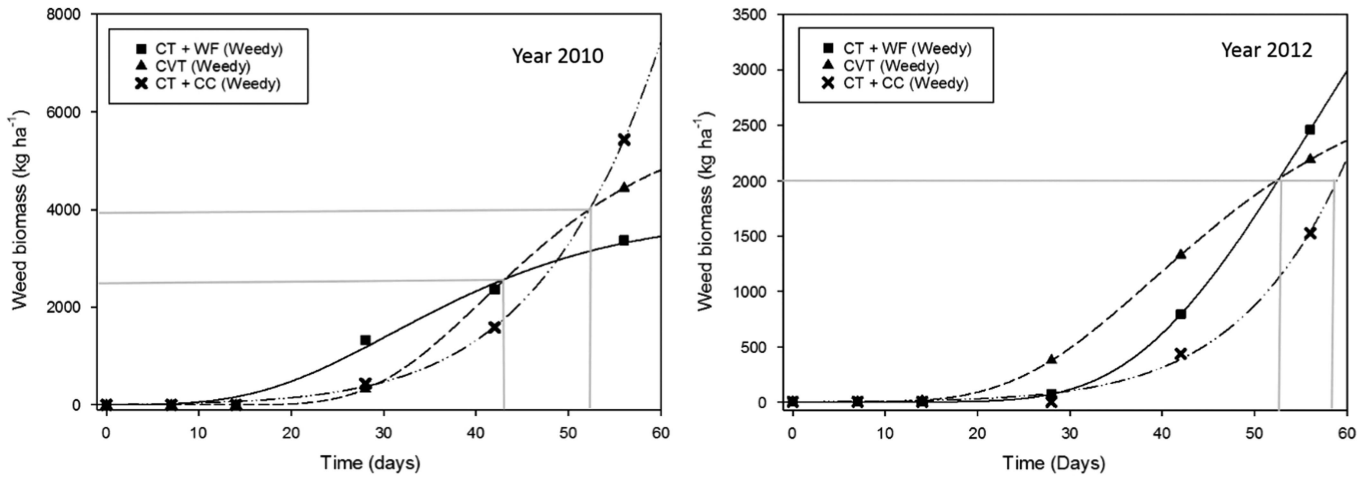
#### Effects of Treatments on Weed Biomass Production

Grasses (large crabgrass and goosegrass), nutsedges (yellow nutsedge [*Cyperus esculentus* L.] and purple nutsedge [*Cyperus rotundus* L.]

**Table 5.** Statistics for the three-parameter Gompertz model used for fitting weed biomass production under various weedy periods for each of the conservation tillage following winter fallow (CT+WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT+CC) treatments.

Experiment 2010		Coefficient	SE	t-value	r <sup>2</sup>
CT+WF	$\alpha$	3,949.3	330.52	7.31	0.996
	$b$	0.069	0.011	11.12	
	$x_0$	30.7	1.69	3.78	
CVT	$\alpha$	5,914.7	555.09	3,152.23	0.997
	$b$	0.08	0.01	8,267.61	
	$x_0$	40.9	1.46	1,967.49	
CT+CC	$\alpha$	5,652	813.73	0.23	0.998
	$b$	0.01	0.01	1.51	
	$x_0$	86.3	48.42	1.78	
Experiment 2012					
CT+WF	$\alpha$	6,761.5	105.79	339.83	0.998
	$b$	0.05	0.0005	1,034.19	
	$x_0$	56.2	0.28	506.2	
CVT	$\alpha$	3,046.5	9.13	193.71	0.998
	$b$	0.06	0.0002	398.28	
	$x_0$	39.2	0.057	137.27	
CT+CC	$\alpha$	1,657.5	29.71	1.40	0.997
	$b$	0.2	3.94	11.46	
	$x_0$	43.4	7.33	13.51	

sicklepod, and Palmer amaranth were the dominant weed species present during both years. In 2010, to prevent a yield loss greater than 5%, CTWR was initiated at approximately 2 WAP, and it was maintained up to 6 to 8 wk for all treatments in which weed biomass was recorded between 200 and 400 g m<sup>-2</sup> (2,000 to 4,000 kg ha<sup>-1</sup>) (Figure 2). A similar trend was observed for 2012, although the production of the weed biomass was recorded at approximately 200 g m<sup>-2</sup> (2,000 kg ha<sup>-1</sup>) (Figure 2). The presence of the rye cover crop (CT+CC) suppressed the production of weed biomass up to approximately 7 WAP in 2010 and 2012 compared with CT+WF and CVT treatments, a result with direct implications on weed soil seedbank. Of note is the extended period, based on inflection point evaluations, for weed removal under the rye cover crop compared with fallow and, to lesser extent, CVT treatments (Table 5). This result is particularly notable in 2010 and contributes greatly to differences between curve parallelism tests. This is an indication of whether the fitted curves between experimental treatments exhibit the same shape and/or are shifted along the x-axis. Differences between growth rate and inflection point estimates of CT+CC and CVT in comparison with CT+WF treatment (Table 6) resulted in differences of curve shape between treatments. Increased CWFP resulted in decreased weed biomass



**Figure 2.** Weed biomass as a function of critical timing for weed removal (duration of weed interference with crop) under conservation tillage following winter fallow (CT + WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT + CC) for 2010 and 2012 treatments. Parameters of the models are presented in Table 4.

**Table 6.** Analysis of means for inflection point and slope of the curve estimates for the evaluation of the parallelism of fitted curves between experimental treatments in 2010.

Experiment 2010 <sup>a</sup>	Inflection point	Lower limit	Upper limit	Exceeded
CT + WF	30.7	32.76	40.33	Lower limit
CVT	40.9	33.27	39.82	Upper limit
CT + CC	86.3	0.000	619.11	
	Slope	Lower limit	Upper limit	Exceeded
CT + WF	0.06	0.026	0.078	
CVT	0.08	0.023	0.079	Upper limit
CT + CC	0.01	0.026	0.079	Lower limit

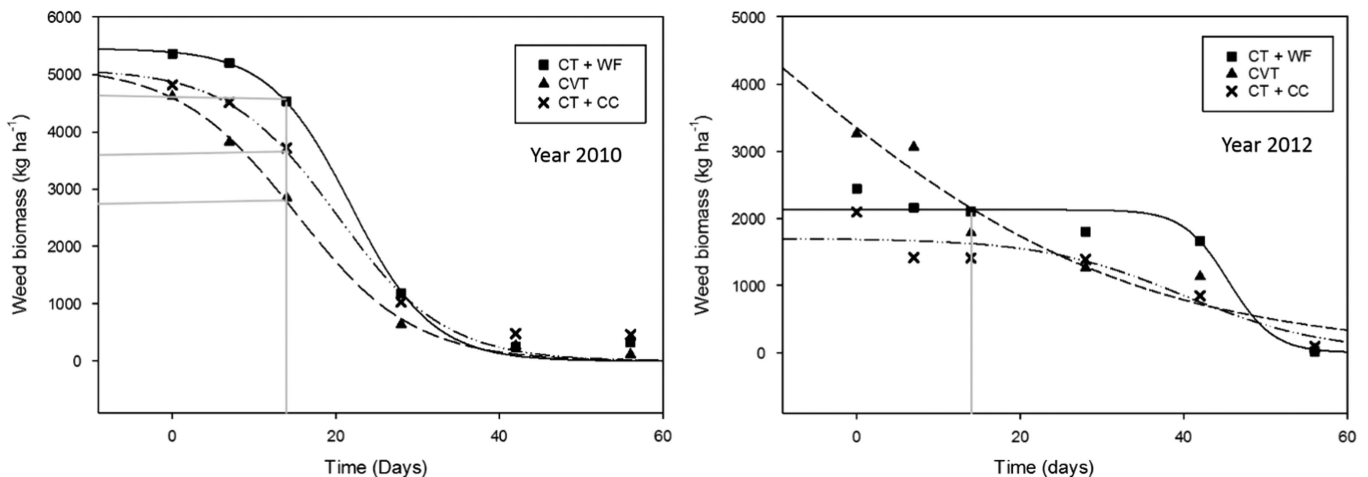
<sup>a</sup>CT + CC, conservation tillage following a cereal rye cover crop; CT + WF, conservation tillage following winter fallow; CVT, conventional tillage without a cover crop.

production between 2 and 5 WAP for maintaining yield losses below 5% (Figure 3). None of the model parameters evaluated for CWFP (Table 7) was significantly different between experimental treatments in both years (unpublished data),

indicating the importance of CTWR for selecting the most effective treatment for yield loss prevention below the acceptable 5% level.

**Practical Application**

Understanding how different cultural practices affect CWFP can be valuable when making decisions about integrated weed management systems and resistant weed management (Korres and Norsworthy 2015). In this study, rye biomass suppressed early-season weed biomass and extended the CPWC, thus delaying the start of the CPWC. CPWC was found to be 6, 4.9, and 1.1 wk in 2010 and 6.8, 4.8, and 4.8 wk in 2012 for CT + WF, CT + CC, and CVT, respectively. Integrating weed-suppressive high-biomass cover crops in cotton could decrease troublesome weed interference and subsequently decrease reliance on herbicides or tillage (Price et al. 2011a). Results also indicate that systems using CT practices following winter fallow are risking greater yield loss if herbicides alone are not effective at controlling problematic weeds, compared with CT systems that include high-biomass cover crops. These results concerning CT winter fallow are similar to previous research results (Aulakh et al. 2012, 2013; Price et al. 2005, 2012).



**Figure 3.** Weed biomass as a function of critical weed-free period under conservation tillage following winter fallow (CT + WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT + CC) for 2010 and 2012 treatments. Parameters of the model are presented in Table 6.

**Table 7.** Statistics for the three-parameter logistic model used for fitting weed biomass production under various weed-free periods for each of the conservation tillage following winter fallow (CT+WF), conventional tillage without a cover crop (CVT), and conservation tillage following a cereal rye cover crop (CT+CC) treatments.

Experiment 2010	Coefficient	SE	t-value	r <sup>2</sup>	
CT+WF	$\alpha$	5,451.1	213.49	25.53	0.998
	$b$	-4.97	0.74	-6.76	
	$x_0$	21.79	1.13	19.27	
CVT	$\alpha$	5,151.9	319.41	16.13	0.998
	$b$	-7.19	0.87	-8.26	
	$x_0$	15.12	1.29	11.69	
CT+CC	$\alpha$	5,099.7	482.5	10.6	0.993
	$b$	-6.6	1.66	-3.96	
	$x_0$	20.1	2.43	8.28	
Experiment 2012					
CT+WF	$\alpha$	2,127.43	130.98	16.24	0.972
	$b$	-2.75	3.209	0.857	
	$x_0$	45.46	4.28	10.608	
CVT	$\alpha$	8,748.29	20,751.34	0.42	0.963
	$b$	-21.76	16.66	-1.354	
	$x_0$	-10.37	88.65	-0.117	
CT+CC	$\alpha$	1,704.36	250.82	6.79	0.931
	$b$	-8.686	5.84	-1.48	
	$x_0$	39.95	6.39	6.25	

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