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Influence of a cereal rye cover crop on the critical period for weed control in soybean

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Abstract

Soybean is the world's most widely grown leguminous crop and is an important source of oil and protein for food and feed in addition to other industrial uses. However, herbicide-resistant and troublesome weed control challenges limit yield potential and threaten conservation tillage (CT) systems. Cover crops have been widely adopted as an integrated pest management component in CT systems to suppress weeds and maintain soybean yield potential. A 3-yr field experiment was conducted to estimate the influence of a cereal rye cover crop following CT on the critical period for weed control (CPWC) in soybean. The experiment was implemented in a split-plot design in which main plots as CT following cover crop (CT + CC), CT following winter fallow (CT + WF), and conventional tillage (CVT), and subplots were multiple durations of weed-free and weed interference. Results showed that the estimated CPWC of CT + CC and CT + WF treatments was 0 wk and >7 wk, respectively, in 2018. In 2019, the estimated CPWC was 0 wk, 5.0 wk, and 1.3 wk under CT + CC, CT + WF, and CVT treatments, respectively. In 2020, the estimated CPWC was 3.5 wk, >6.2 wk, and 0 wk under CT + CC, CT + WF, and CVT treatments, respectively. The presence of a cover crop delayed the CTWR and caused an early beginning of the CWFP compared with CT + WF treatment, and hence shortened the CPWC in 2018 and 2019. In conclusion, the CT + WF system did not reduce the weed competition and subsequent yield loss in soybean compared to the CT + CC system.

Introduction

Food and feed production must continue to increase globally to meet the nutrition requirements and dietary choices of the human population. Soybean is a protein-rich food source and nutritionally beneficial for both human consumption and use in animal feed; thus, it is important to maintain or enhance soybean yield production. In addition, soybean-derived products are used in manufacturing of numerous industrial applications such as paints, plastics, and cleaning materials. However, herbicide-resistant or hard-to-control weeds increasingly threaten soybean production and conservation systems due to the subsequent increased use of tillage to control escaped weeds (Price et al. 2016). Because of this, integrated weed management (IWM) practices are needed. Large crabgrass [*Digitaria sanguinalis* (L.) Scop.], morningglory (*Ipomoea* spp.), nutsedges (*Cyperus* spp.), sicklepod [*Senna obtusifolia* (L.)], and herbicide-resistant Palmer amaranth [*Amaranthus palmeri* (S.) Watson] were identified as the predominant troublesome weed species in soybean production areas in mid-south, southeastern, and mid-Atlantic states (Price et al. 2006; Van Wychen 2016).

Conservation systems were initially used to prevent soil erosion and rainfall run-off losses to maintain soil quality and moisture availability (Kaspar et al. 2001). With the development of herbicide-resistant crop cultivars, a combination of conservation tillage (CT) with a diversity of herbicide modes of action was used successfully (Vencill et al. 2012). But with time, herbicide-resistant weeds, small-seeded weeds, and perennial weeds have become the major challenge in retention and adoption of CT systems (Bajwa 2014; Price et al. 2011; Shaw et al. 2012). Therefore, integrated strategies must be used to disrupt herbicide-resistant and troublesome weed establishment and growth while maintaining potential crop yield. IWM practices in CT systems include the use of cover crops, timely herbicide applications, crop rotation to disrupt the weed complex reproductive cycle, scouting to assess weed populations, and use of various chemical herbicide modes of action (Norsworthy et al. 2012; Price et al. 2011, 2016). High residue cover crops combined with CT systems have been increasingly adopted by row crop producers to maintain crop yield potential due to weed suppressive and allelopathic qualities of cover crops (Creamer et al. 1997; Nagabhushana et al. 2001; Norsworthy et al. 2011; Price et al. 2006; Teasdale and Mohler 2000; Vann et al. 2019).

Cereal rye is the most used winter cover crop in soybean cultivation throughout the southeastern United States due to its capacity for rapid growth, potential high biomass residue, and subsequent weed suppression (Clark 2007). Moreover, CT following a cereal rye cover crop (CC) could be more effective in decreasing weed germination and growth than conventional tillage (CVT) or CT winter-fallow (WF) systems (Aulakh et al. 2011; Korres and Norsworthy 2015; Mirsky et al. 2011; Price et al. 2012; Shilling et al. 1996; Smith et al. 2011). Price et al. (2006) described that CT following the planting of a cereal rye cover crop provided >70% control of weed species including annual grasses, Palmer amaranth, and sicklepod in soybean. In CT systems, termination of a matured cereal cover crop has been accomplished through chemical treatment with glyphosate and sometimes the additional use of a mechanical roller/crimper (Kornecki 2020). Combined, these practices result in a high residue biomass mat over the ground, through which seeds are planted (Norsworthy et al. 2011; Price et al. 2005; Reeves et al. 2005; Teasdale and Mohler 2000; Vann et al. 2018). After planting soybean, due to the cooler soil temperature typically found in CT systems, soybeans emerge and grow slower than they do in conventional systems (Philbrook et al. 1991). However, both root and vegetative development are positively influenced by good soil environmental conditions such as reduced soil compaction, improved soil moisture retention after cover crop termination, and reduced weed competition during initial soybean vegetative growth stages (Krausz et al. 2001; Unger and Kaspar 1994; Vollmann et al. 2010).

The critical period for weed control (CPWC) is the time window of the crop growing cycle when weed interference must be restricted to prevent ≥5% relative yield losses, 5% being the academically acceptable standard (Knezevic et al. 2002). The CPWC includes two different components of weed-crop competition: 1) the critical timing for weed removal (CTWR): the extent of time up to which a crop can compete and tolerate early-emerging weeds before causing yield loss; and 2) the critical weed-free period (CWFP): the minimum time that a crop requires weed-free conditions from planting forward to maintain yield (Knezevic et al. 2002; Korres and Norsworthy 2015; Williams et al. 2007). The CTWR defines the starting time from when a weed should be controlled, whereas the CWFP defines the end time of weed control. Moreover, the difference between CWFP and CTWR defines the CPWC. Weed interference before and after the CPWC does not result in substantial yield loss (Knezevic et al. 2002). The use of cover crops to attain high biomass residue might decrease or delay weed emergence and thus decrease the CPWC (Korres and Norsworthy 2015). Little research determining the influences of a high residue winter cover crop on soybean production and CPWC has been published. The objective of this field study was to estimate the influence of CT following high-biomass cereal rye cover crop (CT + CC) on CPWC in soybean and its comparison to CT following winter-fallow (CT + WF) or conventional tillage (CVT).

Materials and Methods

A 3-yr field experiment was conducted from 2018 to 2020 at E.V. Smith Auburn University Research and Extension Center (Field Crops Unit; 32.4417°N, 85.8974°W) near Shorter, Alabama. The soil characteristics at the research site were sandy loam (coarse-loamy, siliceous, subactive, thermic Paleudults), pH 6.2, and 0.8% organic matter.

Cover Crop Management

The cereal rye cover crop was managed to maximize biomass production. Cereal rye ('Elbon') was planted with a no-till 3.7-m End Wheel Drill (Great Plains, Salina, KS) at a seeding rate of 101 kg ha^{-1} with a no-till grain drill in the CT + CC plots on November 16, 2017, October 31, 2018, and October 28, 2019, respectively. To enhance biomass production, 34 kg N ha^{-1} (as NH_4NO_3) was applied to cereal rye plots in February each spring. After sampling of cover crop, all plots were mechanically rolled by using a three-section straight bar roller-crimper (I & J Mfg., Gordonville, PA) to flatten the biomass residue on the soil surface of CT plots on April 18, 2018, May 20, 2019, and June 6, 2020, respectively (Kornecki 2020). Immediately after rolling, termination of cover crop in CT + CC and weeds in CT + WF plots was attained with an application of glyphosate (Roundup Powermax®; Monsanto Company, St. Louis, MO) applied at 1.12 kg ae ha^{-1}. The experimental site had the soil hardpan that restricts the penetration of crop root into soil; hence, all plots were in-row subsoiled with a narrow-shank parabolic subsoiler equipped with pneumatic tires (Kelly Manufacturing Co., Tifton, GA) before soybean planting. The narrow-shank parabolic subsoiler equipment minimally disturbed the residue and soil in a 5-cm-wide planting zone. Two passes with a field cultivator following disking were accomplished for CVT plots. Soybean 'P55A49X', 'P52A43L', and 'P48A99L' was planted on May 1, 2018, May 29, 2019, and May 21, 2020, respectively, using a precision planter Green Star GPS (John Deere, Moline, IL) with population set at 286,915 seeds per ha^{-1}.

Experimental Design

The split-plot design was used within a randomized complete block design with four replications of treatment. Within the split-plot design, main plots were considered agronomic practice systems: (a) (CVT), (CT + WF), and (CT + CC), whereas subplots (b) were various durations of naturally occurring weed interference and weed-free periods. Weedy and weed-free periods comprised of weekly durations from 0 wk after planting (WAP) to 8 WAP of soybean. The weed interference and weed-free durations were initiated at 0 WAP. Weed control was needed after each weed interference duration and maintaining weed-free periods using labeled herbicides based on herbicide-resistant soybean technology. In 2018, glyphosate (Roundup Powermax®) at 1.12 kg ae ha^{-1} tank-mixed with dicamba (Engenia; BASF Crop Protection, Durham, NC) at 560 g ae ha^{-1} was used for weed control. In 2019 and 2020, the weed control program consisted of glufosinate (Liberty 280SL; Bayer, St. Louis, MO) applied at 882 g ai ha^{-1}. In all years, applications of clethodim (Select 2EC; Sumitomo Chemical Co., Tokyo, Japan) at 0.28 g ai/ha plus 1% crop oil concentrate applied over the top were used to manage grass species as needed following interference duration or weed-free period timings. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with 11102 XR nozzles (TeeJet, Glendale Heights, IL) calibrated to deliver 187 L ha^{-1}. Any weed escapes were then hand-pulled biweekly following herbicide treatment. Soybeans was harvested from the center two rows for yield with a small-plot combine.

Data Collection

Immediately prior to termination of the cover crop, biomass samples were taken by clipping all aboveground plant parts near the soil surface from each cover crop plot using a randomly selected 0.25-m^2 quadrat per plot. The cover crop samples were placed into a drier at 65 C for 72 h, and then dry weight was recorded. Weed biomass was collected based on randomly selected 0.25-m^2 quadrats from each subplot in the weedy plots immediately before applying glyphosate or glufosinate. For example, W2 timing (i.e., 2 wk weedy); plots were kept weedy for 2 wk, then weed biomass samples were taken immediately before applying an herbicide. Moreover, weed biomass was collected once at the 8 WAP in the weed-free plots. In total, there were five different timings, including 0 WAP, 2 WAP, 4 WAP, 6 WAP, and 8 WAP.

Evaluation of Critical Period for Weed Control

CPWC is the time interval that is derived from two independent components of crop-weed interaction, the CTWR, and CWFP (Knezevic et al. 2002). The CTWR is the maximum length of time during which a crop can tolerate the early-season weed competition without resulting in significant crop yield loss. The CWFP is the minimum length of time during which a crop must be weed-free to prevent unacceptable yield loss after which weed competition has little effect on yield (Knezevic et al. 2003; Weaver and Tan 1983; Williams et al. 2007). Weed interference before and after the CPWC does not cause significant yield reduction (Knezevic et al. 2003; Mahammadi and Amiri 2011). As previously stated, the CTWR component defines the beginning and CWFP defines the end of the CPWC, whereas the combination of both components determines the length of the CPWC. In general, the weed interference period in weedy plots represented the CTWR, and the weed-free period in weed-free plots represented the CWFP.

Thus, the duration between beginning and end determines the CPWC by using a functional approach dependent on a 5% acceptable yield loss (AYL) and a relative yield of 95% (Blankenship et al. 2003; Knezevic et al. 2002). Yield loss of 5% (traditionally acceptable yield loss level relative to the weed-free yield) was chosen to calculate the beginning and end of the critical period. In addition, AYL is not fixed; it can be adjusted based on the prices of inputs such as fertilizer, herbicides, cover crop seed, and expected net monetary gain.

The CPWC was evaluated after fitting the best nonlinear regression models as proposed by Korres and Norsworthy (2015) and Williams et al. (2007). A better fit to the model was determined through the calculation of the coefficient of determination (R^2) for each regression (Schabenberger et al. 1999). The logistic model with three parameters was fit to relative soybean yield (expressed as a percentage of season-long weed-free treatment) for the estimation of the CTWR (i.e., weedy) under each agronomic tillage system:

$$\mathrm{Y} = \frac{\alpha}{1 + \mathrm{e}^{-\left(\frac{x - x_0}{b}\right)}} \quad [1]$$

Furthermore, the Gompertz equation was used to estimate the CWFP (i.e., weed-free) and the effect of increasing the duration of a weed-free period on soybean yield under each agronomic tillage system:

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

where y is the relative soybean yield, x_0 is depicted as the point of inflection, b is the slope of the curve, α is the asymptote, and x represents the duration (weeks after planting). The duration of CPWC was estimated using the above-mentioned two components depending on a 5% acceptable yield loss and inverse prediction of 95% relative yield for each treatment. Additionally, weed biomass was also examined as a function of the CTWR and CWFP using Equations 1 and 2; y in this instance represents weed biomass. Both CPWC component models (Logistic and Gompertz) are used to fit weed biomass obtained across growing period, to determine whether the treatments influenced either relative seed cotton yield or weed biomass production to the same extent.

Data Analysis

Soybean yield data were analyzed using the MIXED procedure with SAS software (SAS Institute, Cary, NC). ANOVA was applied to check the significance level of treatment, year, and interaction. Means were separated using Fisher's LSD at $\alpha = 0.05$ to check the treatment effects on soybean yield for both actual and relative (percentage of the season-long weed-free period). There was a significant year*treatment interaction; hence CPWC was estimated differently for all treatments by year.

Figures, curve fitting regressions, significance model parameters, and inverse predictions were estimated using Sigma Plot software (version 13.0; Systat Software, San Jose, CA) and JMP Pro software (version 13; SAS Institute). Coefficient of determination R^2 was used to observe the fitness for each model, while comparisons between model parameters were performed such as standard errors and t-values were used to check the effect of experimental field treatments on weed biomass production. The three-parameter Gompertz model was used to describe the effect of increasing duration of weed-free period on seed cotton yield. This model provides the best fit to crop yield because it is influenced by increasing length of the weed-free period. A logistic model was used for the CTWR for both cover treatments to describe the effect of weed interference period increases on the relative seed cotton yield (Korres and Norsworthy, 2015).

Results and Discussion

Rye Biomass

Cereal rye biomass was collected in CT + CC plots just before termination, and dry weight was recorded. The collected averaged cover crop biomass was 4,315 kg ha^{-1}, 6,708 kg ha^{-1}, and 3,782 kg ha^{-1} in 2018, 2019, and 2020, respectively. In the weedy plots, the collected rye biomass was approximately 3,924 kg ha^{-1} in 2018. Although the averaged rye biomass was 4,707 kg ha^{-1} in weed-free plots. In 2019, the recorded averaged dry weight of rye was 6,319 kg ha^{-1} from weedy plots. Additionally, the collected averaged cover crop biomass was 7,099 kg ha^{-1} from weed-free plots. In 2020, the recorded averaged rye biomass was 4,627 kg ha^{-1} from weedy plots. The collected averaged rye biomass was 2,936 kg ha^{-1} from weed-free plots. Some plot variations along with cover crop biomass were observed in weed-free plots in 2020. Also, weather conditions and the effects of annual climate on cover crop biomass production should be considered. According to a report by Palhano et al. (2019), the cereal rye was planted at the seeding rate of 56, 112, and 168 kg ha^{-1} at the Arkansas Research and Extension Center in Fayetteville, AR. The observed cover crop biomass at 56 kg ha^{-1} of seed rate was 3,060 and 2,460 kg ha^{-1} in 2014 and 2015, respectively. At 112 kg ha^{-1} of cereale rye seed rate, 4,000 and 3,310 kg ha^{-1} biomass production in 2014 and 2015, respectively. At 168 kg ha^{-1} of cereale rye seed rate, 4,460 and 3,620 kg ha^{-1}

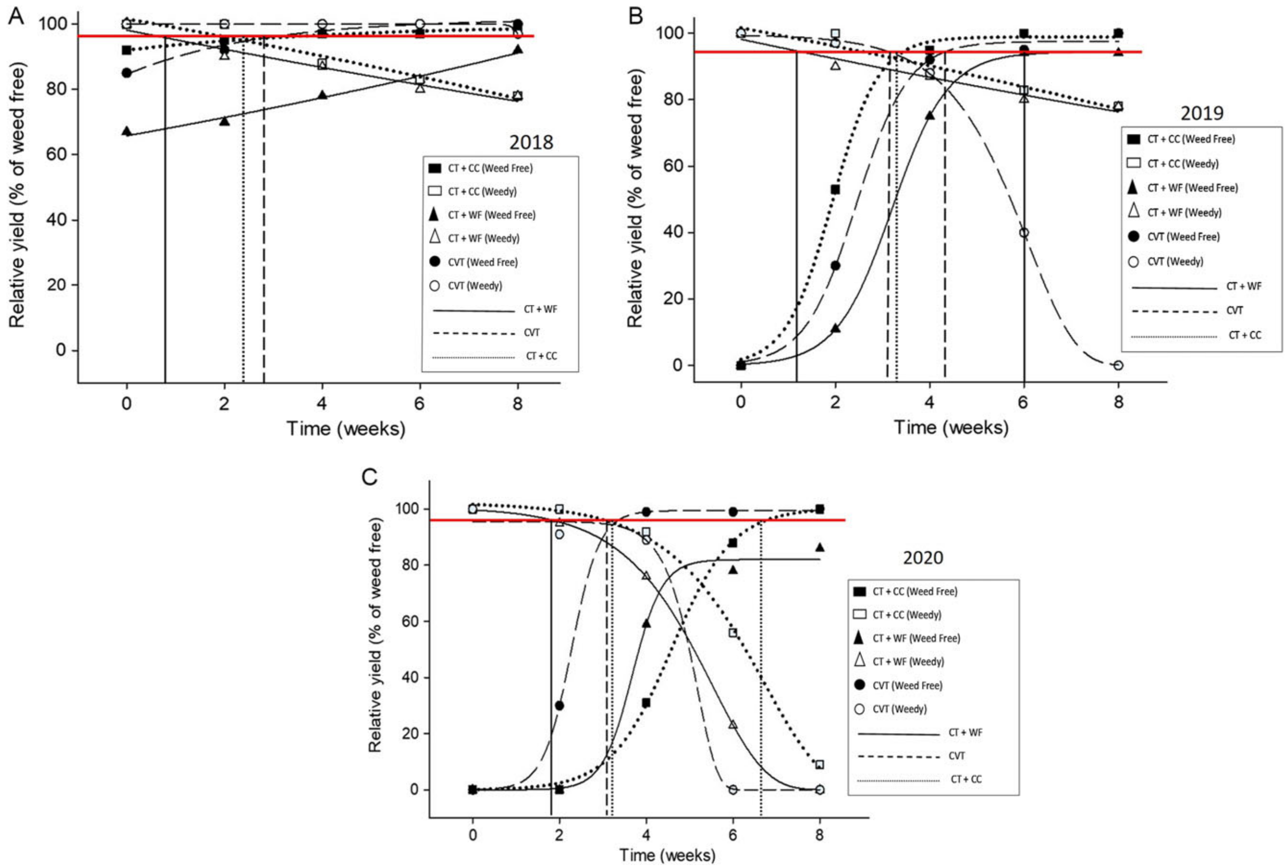

Figure 1. Critical period for weed control and its components (critical timing for weed control [CTWR, i.e., weedy] and critical weed-free period [CWFP, i.e., weed free]) for each of the conservation tillage following a cereal rye cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2018 (A), 2019 (B), and 2020 (C). Point estimates for CTWR and CWFP for CT + CC, CT + WF, and CVT treatments are presented in Tables 1 and 2.

biomass production in 2014 and 2015, respectively. According to Price et al. (2012), the cereal rye 'Elbon' was planted at a seeding rate of 100 kg ha^{-1} at the T.N. Valley Research Station, in Belle Mina, AL. The collected biomass of cover crop cereal rye was 7,397 to 8,807 kg ha^{-1}. At the E.V. Smith Research Station, in Shorter, AL, the recorded biomass of cereal rye was 6,059 to 9,160 kg ha^{-1} with the same seeding rate.

Soybean Yield

In 2018, the average yield of CVT, CT + CC, and CT + WF treatments were 2,089 kg ha^{-1}, 2,971 kg ha^{-1}, and 2,805 kg ha^{-1}, respectively. Greater yield was recorded following CT + CC than CVT treatment, likely due to cover crop residue providing moisture conservation after termination. In addition, the greatest difference between cover crops and winter fallow treatments in terms of soil moisture contents can be expected in shorter dry periods approximately 7 to 14 d (Smith et al. 1987). However, in 2019, the soybean yield following the CVT system was greater (1,188 kg ha^{-1}) than that of CT + CC and CT + WF (946 kg ha^{-1} and 945 kg ha^{-1}). Similarly in 2020, soybean yield under the CT + CC system was less (1,230 kg ha^{-1}) than that of the CVT and CT + WF treatments (1,872 kg ha^{-1} and 1,477 kg ha^{-1}, respectively), likely due to the cover crop depleting soil moisture before termination. Aulakh et al. (2011) and Price et al. (2006) also described variability at this site in crop yield following different cover crops and tillage practices.

Critical Period for Weed Control

When considering 95% relative soybean yield in comparison to season-long weed-free control, soybean yield loss did not reach a 5% threshold limit until 2.4 and 1.0 WAP under CT + CC and CT + WF systems, respectively, in 2018. However, yield loss increased when weed removal was delayed after these time durations (Figure 1A; Table 1). At the same time, the model did not predict the CTWR value of CVT treatment due to a greater than 95% relative yield of weedy plots during most of the growing season. In 2018, CTWR following CT + CC was delayed by approximately 1.4 wk compared to CT + WF. The CWFP for the same experimental year ended at 2.4 WAP and 2.8 WAP under CT + CC and CVT systems (Figure 1A; Table 2). For the CT + WF treatment, the relative yield did not reach the 95% level during 8 wk, hence, there was no prediction of CWFP. Moreover, the early beginning of CTWR in CT + WF plots compared to other systems because of a higher infestation of early-season weed species in 2018. Additionally, the estimated value of CWFP (i.e., weed-free plots) and CTWR (i.e., weedy plots) in the CT + CC system was the same (i.e., 2.4 WAP in 2018). Hence, the estimated CPWC was 0 wk, with the beginning at 2.4 WAP and ended at 2.4 WAP in the CT + CC system.

In 2019, the predicted value of CTWR was 3.4, 1.0, and 3.2 WAP, and the CWFP ended at 3.4, 6.0, 4.5 WAP following CT + CC, CT + WF, and CVT systems, respectively (Figure 1B; Tables 1 and 2). In the same year, CTWR following CT + CC and CVT systems was delayed approximately 2.4 wk and 2.2 wk

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Table 1. Statistics of the three-parameter logistic regression model fitted to relative soybean yield to estimate the critical timing for weed removal for each of conservation tillage following a cereal rye cover crop, conservation tillage following winter fallow, and conventional tillage without a cover crop treatment for estimation of the critical period for weed control.[a]

	2018			
CT + CC	Parameter	Std error	t value	R^2
α	99.75	2.029	49.145	0.964
b	4.162	2.311	1.801	
x_o	−10.340	4.918	−2.103	
CT + WF				
α	3,434.15	2,483.75	0.014	0.986
b	23.959	40.58	0.590	
x_o	94.29	192.593	0.049	
CVT				
α	101.46	2.334	43.466	0.979
b	2.32	0.965	2.403	
x_o	−3.746	1.463	−2.559	
2019				
CT + CC				
α	98.86	1.549	63.821	0.989
b	0.49	0.137	3.559	
x_o	1.93	0.052	36.835	
CT + WF				
α	94.402	0.367	257.011	0.991
b	0.59	0.011	53.744	
x_o	3.20	0.018	174.027	
CVT				
α	97.54	1.841	52.691	0.996
b	0.55	0.089	6.173	
x_o	2.45	0.099	25.267	
2020				
CT + CC				
α	100.3	2.099	47.775	0.998
b	0.69	0.062	11.336	
x_o	4.581	0.079	57.719	
CT + WF				
α	82.064	2.840	28.891	0.991
b	0.343	0.383	0.896	
x_o	3.68	0.363	10.193	
CVT				
α	99.49	0.354	281.109	0.998
b	0.324	0.066	4.897	
x_o	2.272	0.057	39.905	

[a]Abbreviations: α, asymptote of the model; b, slope of the curve; x_o, point of inflection; CT + CC, conservation tillage following a cereal rye cover crop; CPWC, critical period for weed control; CTWF, conservation tillage following winter fallow; CTWR, critical timing for weed removal; CVT, conventional tillage without a cover crop.

Table 2. Statistics of the three-parameter Gompertz regression model fitted to relative soybean yield to estimate the critical weed-free period for each of the conservation tillage practices following a cereal rye cover crop, conservation tillage practices following winter fallow, and conventional tillage without a cover crop treatment to evaluate the CPWC.[a]

	2018			
CT + CC	Coefficient	Std error	t value	R^2
α	151.07	180.801	0.836	0.939
b	−15.199	35.299	−0.431	
x_o	14.059	12.696	1.107	
CT + WF				
α	995.24	906.970	0.011	0.956
b	−150.95	290.355	−0.052	
x_o	−230.983	742.073	−0.031	
CVT				
α	99.8	134.218	0.951	0.981
b	−0.104	1.456	−0.089	
x_o	8.362	4.975	3.785	
2019				
CT + CC				
α	151.07	180.800	0.836	0.879
b	−15.19	35.299	−0.431	
x_o	14.059	12.696	1.107	
CT + WF				
α	9,952.4	6,970.335	0.011	0.913
b	−150.95	209.557	−0.052	
x_o	-230.98	742.737	-0.031	
CVT				
α	99.57	0.675	147.406	0.988
b	−1.01	0.048	−20.954	
x_o	6.09	0.023	262.098	
2020				
CT + CC				
α	102.33	1.935	52.890	0.996
b	−1.337	0.114	−11.738	
x_o	6.735	0.088	76.137	
CT + WF				
α	100.77	0.366	275.11	0.999
b	−1.21	0.018	−65.876	
x_o	5.528	0.013	428.816	
CVT				
α	95.599	3.199	29.879	0.992
b	−0.454	0.322	−1.413	
x_o	5.190	0.818	6.343	

[a]Abbreviations: α, asymptote of the model; b, slope of the curve; x_o, point of inflection; CT + CC, conservation tillage following a cereal rye cover crop; CPWC, critical period for weed control; CT + WF, conservation tillage following winter fallow; CTWR, critical timing for weed removal; CVT, conventional tillage without a cover crop.

respectively, compared to the CT + WF treatment. While CWFP was early following CT + CC and CVT treatment by approximately by 2.6 wk and 1.5 wk compared with the CT + WF system (Figure 1B; Tables 1 and 2). Thus, the estimated CPWC was 5 wk and 1.3 wk under the CT + WF and CVT treatments, respectively (Table 3). The estimated value of CWFP and CTWR in the CT + CC system was the same (i.e., 3.4 WAP in 2019). Hence, the estimated CPWC was 0 wk with the beginning at 3.4 WAP, and ended at 3.4 WAP in the CT + CC system.

In 2020, soybean yield loss began to increase greater than the threshold (5%) when weed removal was delayed beyond the CTWR of 3.2, 1.8, and 3.0 WAP following CT + CC, CT + WF, and CVT systems, respectively (Figure 1C; Table 1). In 2020, CTWR following CT + CC and CVT was delayed approximately 1.4 wk and 1.2 wk, respectively, compared to the CT + WF treatment. Moreover, the predicted CWFP was 6.7 WAP for the CT + CC treatment (Figure 1C; Table 2). Again, the model did not predict the CWFP for the CT + WF treatment because the relative yield of soybean did not reach 95% during the 8 wk of duration due to competitive early-season weed species in CT + WF plots and reflects higher weed biomass collected from winter fallow plots. In the same experimental year, there was one estimated value (3.0 WAP) of CWFP and CTWR in the CVT system (Figure 1C; Tables 1 and 2). Hence, the estimated CPWC was 3.5 wk following the CT + CC system and 6.2 wk following the CT + WF system (Table 5). Remarkably, the estimated value of CWFP and CTWR in the CVT system was the same (i.e., 3.0 WAP). The longer duration of CPWC in cereal rye plots than the CVT system in 2020 is likely due to poor cover crop growth and low cover crop biomass in weed-free plots at the time of termination due to dryer soil conditions; hence, there was a lower yield than that from other treatments as described above in the soybean yield discussion. Although some of the treatments had only one CPWC because the model did not predict the value of either CTWR and CWFP due to greater than or less than 95% of relative yield within 8 wk of time.

In all 3 yr, the CTWR was delayed in cereal rye cover crop treatment. Halford et al. (2001) described that the beginning of the

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Table 3. Estimated value of the CTWR, CWFP, weed-free plots, and duration of CPWC for each of conservation tillage practices following a cereal rye cover crop, conservation tillage following winter fallow, and conventional tillage without a cover crop treatment.[a]

	CTWR	CWFP	CPWC
	WAP	WAP	week
2018			
CT + CC	2.4	2.4	0
CT + WF	1.0	>8	>7
CVT	–	2.8	–
2019			
CT + CC	3.4	3.4	0
CT + WF	1.0	6.0	5
CVT	3.2	4.5	1.3
2020			
CT + CC	3.2	6.7	3.5
CT + WF	1.8	>8	>6.2
CVT	3.0	3.0	0

[a]Abbreviations: α, asymptote of the model; b, slope of the curve; x_o, point of inflection; CT+CC, conservation tillage following a cereal rye cover crop; CTWR, critical time for weed removal; CT + WF, conservation tillage following winter fallow; CWFP, critical weed-free period; CPWC, critical period for weed control; CVT, conventional tillage without a cover crop; WAP, week after planting.

Table 4. Statistics for the three parameters Gompertz model used for fitting weed biomass production under various weedy periods for each of the conservation tillage practices following a cereal rye cover crop, conservation tillage following winter fallow, and conventional tillage without a cover crop treatment.[a]

2018				
CT + CC	Coefficient	Std error	*t* value	R^2
α	719.87	0.003	260.247	0.998
b	1.62	0.008	177.155	
x_o	6.67	0.007	138.700	
CT + WF				
α	967.79	84.574	11.443	0.916
b	0.98	0.398	2.469	
x_o	3.10	0.372	8.353	
CVT				
α	2,162.54	44.087	49.051	0.981
b	1.37	0.085	16.146	
x_o	4.31	0.047	90.9-3	
2019				
CT + CC				
α	2,850.03	10.871	262.159	0.996
b	1.26	0.013	95.117	
x_o	4.60	0.009	492.128	
CT + WF				
α	5,352.92	143.789	37.228	0.998
b	2.82	0.109	25.866	
x_o	4.59	0.095	48.33	
CVT				
α	7,257.93	117.52	61.761	0.993
b	0.92	0.053	17.406	
x_o	4.50	0.042	106.060	
2020				
CT + CC				
α	2,153.54	9.522	226.16	0.998
b	1.665	0.013	132.649	
x_o	5.692	0.009	578.490	
CT + WF				
α	1,824.76	304.04	6.002	0.952
b	1.646	0.766	2.149	
x_o	3.589	0.500	7.177	
CVT				
α	16,610.39	12,167.968	1.365	0.988
b	4.432	2.140	2.071	
x_o	8.028	3.172	2.531	

[a]Abbreviations: α, asymptote of the model; b, slope of the curve; x_o, point of inflection; CT+CC, conservation tillage following a cereal rye cover crop; CTWR, critical time for weed removal; CW + FP, critical weed-free period; CPWC, critical period for weed control; CVT, conventional tillage without a cover crop; WAP, week after planting.

Table 5. Statistics for the three parameters sigmoidal model used for fitting weed biomass production under various weed-free periods for each of the conservation tillage practices following a cereal rye cover crop, conservation tillage following winter fallow, and conventional tillage without a cover crop treatment.[a]

2018				
CT + CC	Coefficient	Std error	t value	R^2
	621.12	25.764	24.108	0.998
b	−1.06	0.088	−12.015	
x_o	2.094	0.132	15.907	
CT + WF				
α	2,546.30	1,373.754	1.853	0.974
b	−3.47	1.129	−3.072	
x_o	0.867	3.799	0.228	
CVT				
α	3,605.22	3,744.11	0.963	0.956
b	−7.59	5.419	−1.399	
x_o	0.62	15.655	0.039	
2019				
CT + CC				
α	2,511.87	98.762	25.434	0.979
b	−1.06	0.091	−11.671	
x_o	2.42	0.133	18.223	
CT + WF				
α	19,653.77	8,837.391	0.003	0.986
b	−1.795	0.881	−2.037	
x_o	−10.375	544.057	−0.019	
CVT				
α	21,090.48	15,084.754	0.139	0.991
b	−1.11	0.099	−11.164	
x_o	−3.981	8.539	−0.466	
2020				
CT + CC				
α	1,340.52	7.472	179.41	0.998
b	−0.692	0.011	−65.388	
x_o	1.512	0.014	107.429	
CT + WF				
α	2,175.39	27.516	79.059	0.998
b	0.707	0.025	−27.783	
x_o	1.573	0.032	49.479	
CVT				
α	45,093.01	39,657.618	0.114	0.980
b	−1.980	0.985	−2.009	
x_o	−4.441	21.394	−0.207	

[a]Abbreviations: α, asymptote of the model; b, slope of the curve; x_o, point of inflection; CT + CC, conservation tillage following a cereal rye cover crop; CW + FP, critical weed-free period; CVT, conventional tillage without a cover crop.

critical period for weed control in soybean was comparatively more stable than the end period. Our results showed that CTWR and CWFP following CT + CC and CVT treatments was around 3 WAP to 4 WAP in soybean, respectively. While CT + WF treatment resulted in an early start of the CTWR, 1 WAP, again due to higher early-season weed competition in winter fallow plots.

In conclusion, the presence of a cereal rye cover crop delayed the CTWR and caused the early beginning of CWFP, and hence, a shortened CPWC in the 2018 and 2019 by delaying weed emergence and growth of weeds (Table 3). Previous research also concluded that cereal rye delayed CTWR and shortened CPWC in cotton (Korres and Norworthy 2015; Price et al. 2018). Thus, a cereal cover crop probably could provide a significant competitive benefit to soybean against problematic weed species. Comparing CT + CC with CT + WF, the presence of rye shortened the competition duration on soybean in two out of three years. Low residue biomass of cover crop rye was likely the reason for the extended CWFP and relatively longer CPWC duration under the CT + CC treatment in 2020. Hence, a significant amount of

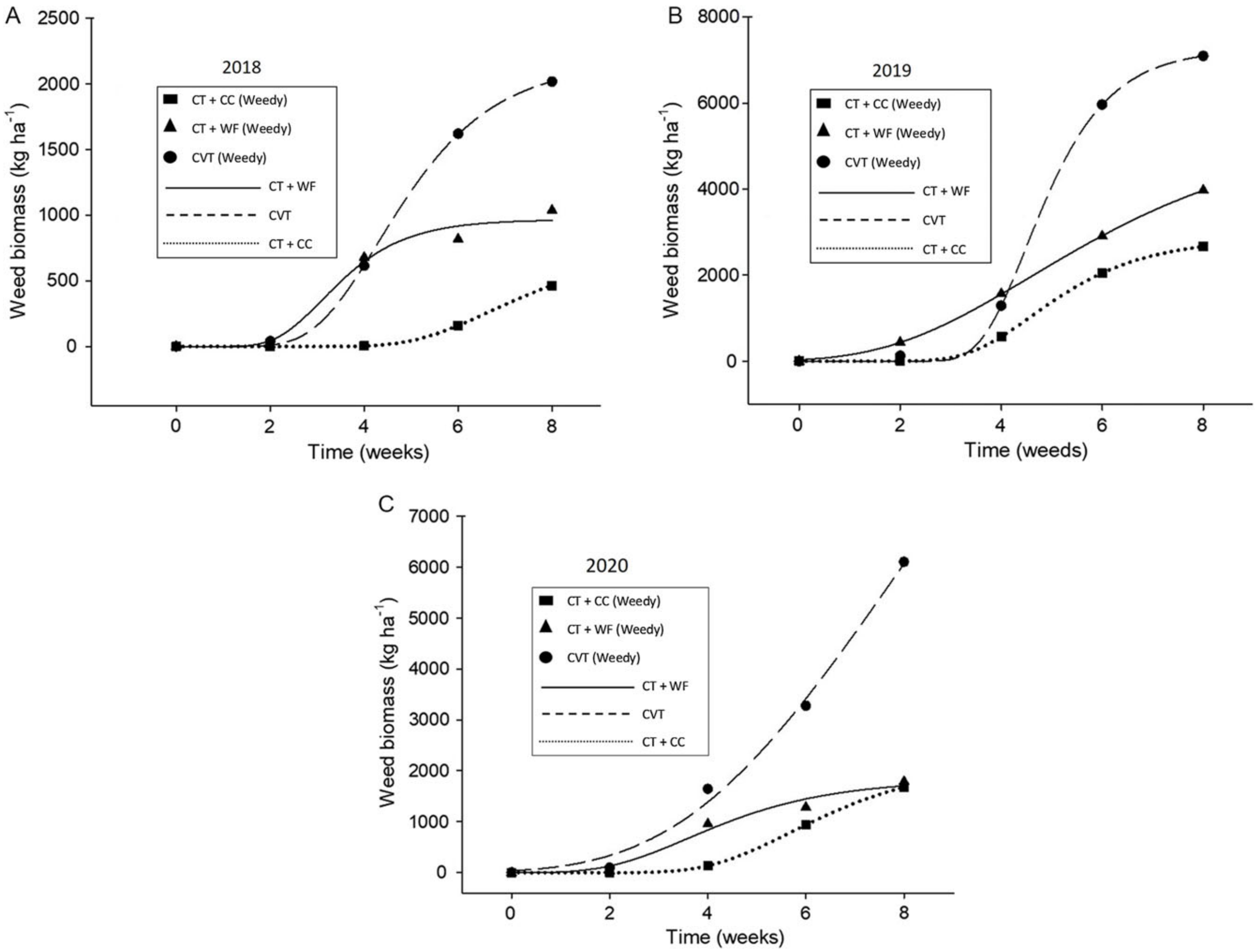

Figure 2. Weed biomass as a function of critical timing for weed removal (CTWR; duration of weed interference with soybean crop) for each of the conservation tillage following a cereal rye cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2018 (A), 2019 (B), and 2020 (C). Parameters of the models are presented in Table 4.

cover crop biomass is required to delay the CTWR and shortened the CPWC duration. Along with the benefits of the cover crop, including soil erosion control, minimizing the nutrient losses, etc., cereal rye also offers advantages to soybean by stabilizing potential crop yield.

In addition, the estimated duration of the CPWC in soybean was more extended in the CT + WF treatment compared with the CVT treatment, and similar results were also illustrated by Halford et al. (2001). Our results supported these conclusions that in all 3 yr, the CVT treatment had a shorter CPWC than the CT + WF treatments.

Effects of Treatments on Weed Biomass Production

In 2018, weed biomass 4 wk after planting was lower in the CT + CC (30 to 35 kg ha^{-1}) system than the CT + WF system (350 kg ha^{-1}; Figure 2A; Table 4). In 2019, based on the predicted value of CTWR, when weed removal started, approximately at 3.5 WAP for both CT + CC and CVT systems and 1.0 WAP for CT + WF, the recorded dry weight of weed flora was between 350 and 400 kg ha^{-1} for all treatments (Figure 2B; Table 4). In 2020, to maintain the relative yield of 95%, when CTWR was initiated, at approximately 3 WAP for CT + CC and CVT systems and 2 WAP for the CT + WF system, weed biomass was 30 to 40, 750, and 200 kg ha^{-1}, respectively (Figure 2C; Table 4). We found variation in weed biomass in weedy plots (i.e., estimation of CTWR) in each year, although the trend was the same among the 3 yr. Additionally, the weed biomass in weedy plots of the CVT treatment was lower than the CT + WF treatment up to 4 WAP, drastically increasing afterward in 2018 and 2019. Moreover, the recorded weed biomass at 2.4 and 2.8 WAP was approximately 300 and 1,700 kg ha^{-1} for CT + CC and CVT treatments, respectively, in 2018 (Figure 3A; Table 4). In 2019, the collected dry weight of weed biomass was approximately 1,500, 460, and 250 kg ha^{-1} at the ending time of critical period for CT+ CC and CT + WF, CVT systems, respectively (Figure 3B; Table 5). In 2020, the recorded weed biomass at the ending time of the critical period was 10 to 15 kg ha^{-1} for CT + CC and 1,250 kg ha^{-1} for CVT systems, respectively (Figure 3C; Table 5).

We collected lower weed biomass from CT + CC than CT + WF and CVT systems in both weedy and weed-free plots (Figures 2 and 3; Tables 4 and 5). Moreover, the presence the cereal rye cover crop rye suppressed weed competition during the growing season of soybean in all 3 yr. Palmer amaranth, sicklepod, morningglory, goosegrass, and nutsedge were the key weed species observed every year.

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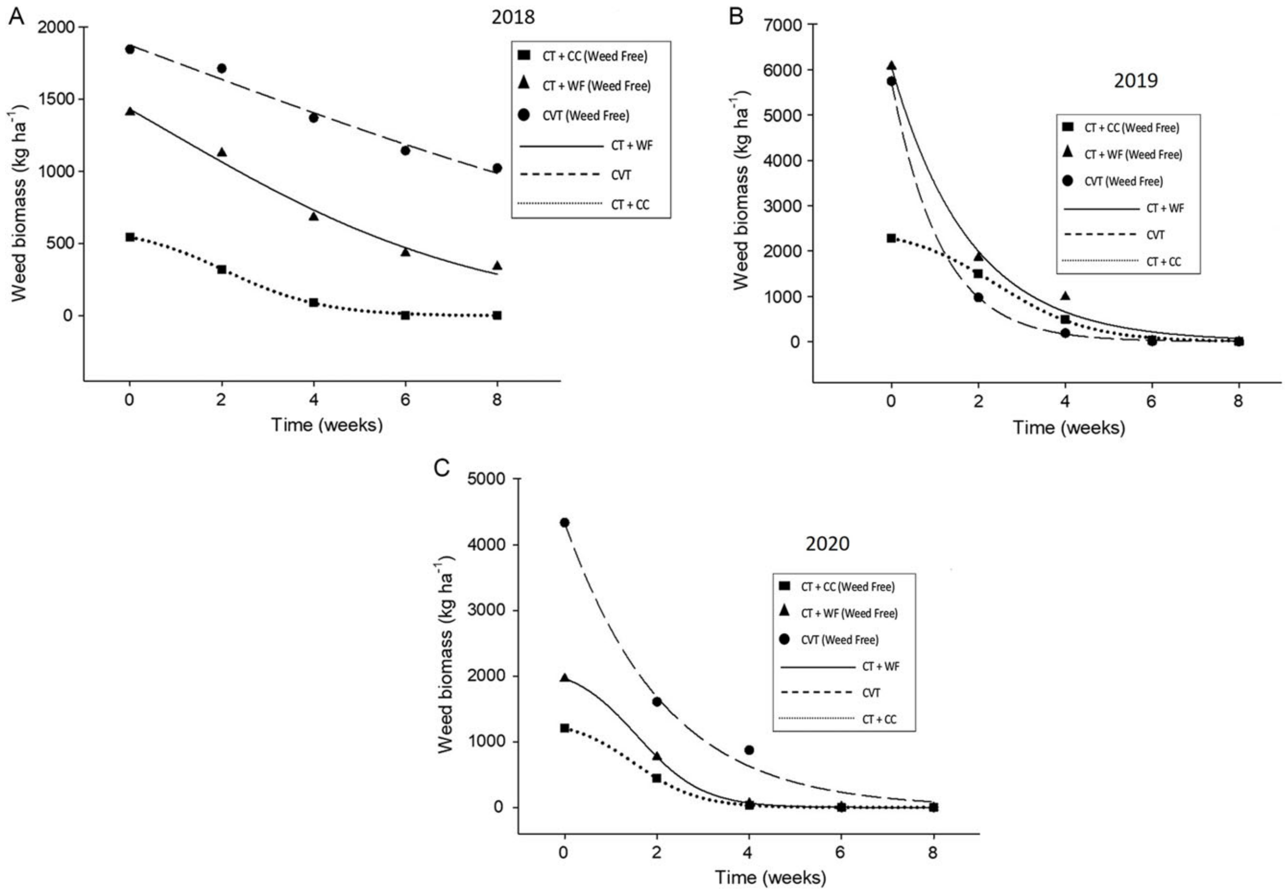

Figure 3. Weed biomass as a function of critical weed free period (CWFP) for each of the conservation tillage following a cereal rye cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2018 (A), 2019 (B), and 2020 (C). Parameters of the model are presented in Table 5.

Practical Implications

The core idea behind the estimation of CPWC is to identify the most effective application timing for nonchemical weed control options and to control troublesome weed species. Our research findings were similar to those of Price et al. (2018), and demonstrated that a conservation system following winter fallow (CT + WF) caused more reduction in yield potential compared to a cover crop system (CT + CC) if herbicides alone were not effective in weed control. A reduction in weed biomass was observed when cover crop cereal rye was planted with conservation tillage compared with winter fallow in other studies (Aulakh et al. 2012, 2013; Korres and Norsworthy 2015; Price et al. 2005, 2012).

Our results demonstrated that IWM strategies using high-residue cover crop biomass affect the CPWC, thus impacting problematic weed species and increasing conservation system adoption. When the CPWC is short (i.e., CT + CC treatment), then the use of efficacious postemergence herbicides could be more targeted (Van Acker et al. 1993). However, weed seed bank additions after CPWC should also be considered for the management of resistant weed species (Norsworthy et al. 2012, 2014).

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