Effect of Cover Crops on the Critical Period for Weed Control in Soybean and Corn

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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.

An increasing number of herbicide-resistant weeds, in addition to troublesome weeds, pose a significant challenge for chemical weed control in corn. Simultaneously, high-biomass cover crop adoption has gained popularity among farmers as an efficient weed control strategy. While the critical period of weed control (CPWC) following conventional tillage has been well documented, there is little knowledge of CPWC following high residue cover crops in corn. A two-year field experiment was conducted to estimate the influence of a high biomass crimson clover cover crop and conservation tillage on the critical period of weed control (CPWC) in corn. The experiment was implemented in a split-plot design in which the main plots were conventional tillage (CVT), conservation tillage following winter fallow (CT + WF), and conservation tillage following crimson clover (CT + CC), and the subplot included multiple durations of weedy plots (estimation of critical timing of weed removal (CTWR), i.e., beginning of weed control) and weed-free plots (estimation of critical weed-free period (CWFP), i.e., end of weed control). The results described that the estimated duration of CPWC in three systems, included CT + CC, CT + WF and CVT equals 2.8 weeks, 3.5 weeks, and 4.9 weeks respectively in 2019. In 2020, the predicted value of CTWR under CT + CC equals 3.8 weeks after planting and the predicted values of CWFP were 5.1 and 5.7 weeks after planting under CT + WF and CVT systems, however, the model did not predict some values within the fitted 8 weeks of time. In conclusion, the presence of a crimson clover cover crop delayed the CTWR and caused the early beginning of CWFP and hence shortened CPWC in 2019. During most of the growing season, weed biomass production was less under CT + CC plots than CVT and CT + WF systems of weedy treatment in both years. While weed biomass production fluctuated in CT + CC, CVT and CT + WF systems in weed-free treatment.

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Table of Contents

List of Tables

List of Figures

Abbreviations

CTWR Critical timing for weed control

CPWC Critical period for weed control

CWFP Critical weed-free period

IWM Integrated Weed Management

CT Conservation Tillage

CV Conventional Tillage

CC Cover crops

WF Winter fallow

Chapter 1: Literature Review

Introduction

Soybean Production and Weed Competition: Soybean (*Glycine max* L. Merr.) is one of the most widely cultivated and valuable agricultural crops in the United States. The United States contributes greater than 50% of soybean production worldwide (Zimdahl, 2004). According to a survey by USDA-NASS 2014, the United States leading in soybean production globally, with 31% in 2012 and 2013. However, troublesome, and hard to control weeds cause major yield loss in soybean production. Globally, it has been estimated that 37% of manageable soybean production is threatened by weed competition and interference, which is significantly greater than other losses such as pathogens and pests with 11% and viruses only 1%. (Oerke 2006). Weed species interfere with soybean plants and create competition for water, light, essential nutrients, and other resources which significantly decrease soybean yield and seed quality. If weeds are present during later crop growth stages and harvesting time that could stain soybean seeds and decrease seed quality with negatively impact on the efficiency of harvesting operations (Burnside 1973). Food and feed production must remain improved worldwide to meet the nutritional needs and dietary selections of the growing human population.

Soybeans provide high quality protein food source and nutritionally valuable for human consumption and animal feed; hence, it should be considered to sustain or improve soybean yield production. Moreover, soybean-derived products are used for manufacturing various industrial purposes, for example paints, plastics, oleochemicals, and cleaning materials. Soybean accounts for greater than 50% of the oilseed production worldwide.

However, increased use of tillage to control escaped herbicide-resistant and hard-to-control weeds threating the conservation tillage and soybean production (Price et al. 2016).

Similarly, other research studies indicated that continued weed intervention throughout the growing season caused a substantial soybean yield and seed quality losses. Hence, early-season weed management practices should be consider to attain economically acceptable yield which is approx. 95% (Knezevic et al., 2003; Hock et al., 2005). According Van Acker et al. (1993), weeds interference until starting of reproductive phase (R5), specifically seed filling stage can cause 8–55% decline in soybean yield. A recent study observed that yield losses by weeds exceed 50% in soybean (Datta et al., 2017).

Corn Production and Weed Competition: Corn (*Zea mays* L.) is major grain crop grown worldwide and the United States has been the top corn producer globally. There are multiple usages of corn, such as food products for both humans and livestock as well as industrial purposes like ethanol production. The United States was leading the corn production globally with 35.5% in 2011 (FAO Stat 2012). Because of weed intervention specifically herbicide-resistant and problematic weed species, significant corn yield losses were observed and have been increasing since the end of the 1990s (Chandler et al., 1984). Weeds pose the greatest threat to corn production, reducing potential yields and causing economic losses of billions of dollars. This is due to competition for resources such as nutrients, moisture, water, and light, as well as the cost of weed control, decreased harvesting efficiency, and contamination of harvested grain. Weeds are the greatest concerning threat to corn production and reduce the potential yield, causing economic losses of billions of dollars and increase cost of weed control, decrease the harvesting efficiency, and contaminate grain (Chandler et al., 1984), this is due to competition for resources such as nutrients, moisture, water, and light. According to Soltani et al. (2017), an average of seven years of data revealed that weed competition caused a 50% corn yield loss, which compares to 148 million tons of corn valued at around U.S.$26.7 billion yearly in the United States and Canada.

Increasing the number of herbicide-resistant weed species is a major issue nowadays, so it is necessary to incorporate other weed control measures to tackle these troublesome weed species and prevent a significant yield loss in corn and soybean. Integrated Weed Management using multiple strategies such as crop rotation, cover crops adoption, chemical applications during sensitive crop growth stage, scouting, and use of different modes of action of herbicide would be the most effective approach for long-term and sustainable weed management (Norsworthy et al., 2012).

To appropriately apply herbicides during a crop's sensitive growth stages, it is necessary to understand and estimate the critical period of crop. Reducing weed control efforts to only the critical growth period, rather than throughout the season, may decrease the number of herbicide applications and lower production costs for farmers.

Critical Period for Weed Control in Corn and Soybean: The critical period for weed control (CPWC) is a time of the crop growth cycle during which crops should be kept weed-free to avoid any significant yield losses (>5%) resulting from weed interference and competition for resources (Knezevic et al., 2002). The critical period is described as a 'window' of weed competition period during crop growing season in which it is essential to control weeds to maintain crop potential yield (Knezevic et al., 2002; Swanton et al., 1991).

Dillehay et al. (2011), stated that investigation of CPWC is an excellent approach to develop better weed management practices and recommendations. Additionally, CPWC describe the period of the crop growing season in which the crop is most sensitive to weed interference, likely the yield loss caused by weed competition surpasses the weed control cost (Charles et al., 2019a, 2019b; Fast et al., 2009; Korres and Norsworthy 2015; Webster et al., 2009). Weed control during the critical period can increase weed management efficiency and maintain crop yield (Hall et al., 1992; Van Acker et al., 1993).

According to Zimdahl (2004), the critical period has two corresponding concepts during the crop growth cycle. The first concept is the critical timing of weed removal (CTWR), which illustrates the interferences of weeds with the crop. CTWR defines the time when weed control should start to prevent significant yield losses. Another concept includes, the critical weed-free period (CWFP), observes the effect of weeds emerging later after crop emergence and continuing in the crop until the growing season. CWFP defines the ending time when weed control should stop, expecting that after this point, there will be no significant effect of weed interferences on crop yield. The combination of the CTWR and CWFP explains the critical period for weed control (CPWC).

Weed and crop germination and weed–crop interaction can greatly be influenced by tillage and planting practices, crop varieties, row spacing, plant population, weed density, type of weed species, other management strategies and climatic conditions (Swanton and Weise 1991; (Rajcan and Swanton 2001). A research study observed that the CPWC starting and ending period was earlier in a no-till system compared to conventional tillage systems in corn (Halford et al., 2001). In corn the beginning time of critical period (CTWR) varies greatly, starting just before the six-leaf stage and just afterward the nine-leaf stage, respectively. Although, the ending time of critical period (CWFP) was similar around 14-leaf stage across all sites excluding one regardless of fluctuations in environmental conditional, weed species, and weed densities between different sites (Hall et al., 1992).

Acker et al. (1993) observed that in a soybean study, the ending time of weed control (CWFP) was shorter in length compared to starting time (CTWR) and showed consistent results across locations in both years. Moreover, the CPWC continues up to the fourth node growth of vegetative stage which is around 30 days after soybeans emergence; to prevent an unacceptable yield loss (>2.5%). Similarly, in soybean, the presence of the cover crop cereal rye in conservation tillage delayed the beginning of weed removal (CTWR) by approximately 1.4 to 2.4 week compared to conservation tillage following winter fallow system (Kumari et al., 2023a). The presence of a cover crop delayed the beginning time of weed removal as well as early ending of critical period, and resulted in shortened the CPWC in all years except one in soybean. Kumari et al. (2023b) evaluated the duration of CPWC in cover crop, winter fallow and conventional tillage equals 2.8 weeks, 3.5 weeks, and 4.9 weeks respectively; the presence of a crimson clover cover crop shortened the CPWC in one year out of two years in conservation tillage corn. The cover crop treatments had greater weed biomass reduction than conventional tillage system via the CPWC (Yurchak et al., 2023). The use of a fall-seeded cereal rye cover crop in combination with conservation tillage delayed the beginning of weed removal by approximately 3 week after planting, thus shortening the total CPWC in cotton (Price et al., 2018).

Cover crop adoption in the southern United States has gained substantial popularity among row crop growers due to multiple advantages of cover crops. Cover crop benefits include preventing soil erosion, reducing water runoff losses, and improving water infiltration, soil moisture content, and soil organic carbon (Balanco et al., 2015; Dabney et al., 2001). Cover crops as one of the potential weed suppression management strategy due to their ability to suppress the early season weed establishment and control weed growth by blocking light and physically due a dense mat of residue on ground (Norsworthy et al., 2011; Price et al., 2016; Teasdale and Mohler 2000); also releasing allelopathic chemicals (Burgos and Talbert 2000). Cereal rye (*Secale cereale* L.) is among the most widely grown and adopted small grains, and crimson clover (*Trifolium incarnatum* L.) is among the most adopted legume cover crop in the southeastern region (Farmaha et al., 2021). A study conducted in Alabama stated that cover crop cereal rye was very effective to suppress weed species as compared to radish (Kumari et al., 2024)

Some studies have estimated the CPWC in corn and soybean, however, there are huge variability found due to weather condition, site-specific, and management practices in different crops and limited research has been conducted considering the effect of cover crop on CPWC in the southeastern United States. Therefore, we conducted a field experiment in Alabama, to estimate the critical period for weed control in conservation tillage corn and soybean. The goal of this study is to help farmers make informed decisions with respect to timely weed control measures and prevent significant crop yield losses. Moreover, an understanding of the CPWC is necessary for the development of sustainable weed management strategies to prevent unacceptable yield loss in soybean and corn.

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Chapter 2: Influence of a Cereal Rye Cover Crop on the Critical Period for Weed Control in Soybean

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 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 soybeans, 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:

$$y = \frac{\alpha}{1+e^{-b(x-x_O)}} \qquad (1)$$

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:

$$y = \alpha e^{-(e^{-b(x-x_O)})} \qquad (2)$$

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 average 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} 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 2-1A; Table 2-1). 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 2-1A; Table 2-2). 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 2-1B; Tables 2-1 and 2-2). In the same year, CTWR following CT + CC and CVT systems was delayed approximately 2.4 wk and 2.2 wk 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 2-1B; Tables 2-1 and 2-2). Thus, the estimated CPWC was 5 wk and 1.3 wk under the CT + WF and CVT treatments, respectively (Table 2-3). 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 2-1C; Table 2-1). 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 2-1C; Table 2-2). 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 2-1C; Tables 2-1 and 2-2). Hence, the estimated CPWC was 3.5 wk following the CT + CC system and 6.2 wk following the CT + WF system (Table 2-

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 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 2-3). 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 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 2-2A; Table 2-4). 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 2-2B; Table 2-4). 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 2-2C; Table 2-4). 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 2-3A; Table 2-4). 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 2-3B; Table 2-5). 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 2-3C; Table 2-5). We collected lower weed biomass from CT + CC than CT + WF and CVT systems in both weedy and weed-free plots (Figures 2-2 and 2-3; Tables 2-4 and 2-5). Moreover, the presence of 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.

Conclusions

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. 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. 2014).

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Tables:

Table 2-1. Statistics of the three-parameter logistic regression model fitted to relative soybean yield to estimate the critical timing for weed removal (CTWR i.e., weedy plots) for each of 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 for the estimation of critical period for weed control (CPWC) in 2018, 2019 and 2020.

Year 2018	Parameter	Std error	t value	R^2
CT+CC				
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	3434.15	2483.75	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	
Year 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	
Year 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	

Table 2-2. Statistics of the three-parameter Gompertz regression model fitted to relative soybean yield to estimate the critical weed-free period (CWFP i.e., weed-free plots) 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 to evaluate CPWC in 2018, 2019 and 2020.

Year 2018	Coefficient	Std error	t value	R^2
CT+CC				
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	
Year 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	9952.4	6970.335	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	
Year 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	

Table 2-3: 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 (CT+CC), conservation tillage following winter fallow (CT+WF), and conventional tillage without a cover crop treatment (CVT).

	CTWR WAP	CWFP WAP	CPWC 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	
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

Abbreviations: CTWR, critical time for weed removal; CWFP, critical weed-free period; CPWC, critical period for weed control; WAP, week after planting.

Table 2-4: Statistics for the three parameters gompertz model used for fitting weed biomass production under various weedy (W) periods 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, 2019 and 2020.

Year 2018	Coefficient	Std error	t value	R^2
CT+CC				
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	2162.54	44.087	49.051	0.981
b	1.37	0.085	16.146	
x_o	4.31	0.047	90.9-3	
Year 2019				
CT+CC				
α	2850.03	10.871	262.159	0.996
b	1.26	0.013	95;117	
x_o	4.60	0.009	492.128	
CT+WF				
a	5352.92	143.789	37.228	0.998
b	2.82	0.109	25.866	
x_o	4.59	0.095	48.33	
CVT				
α	7257.93	117.52	61.761	0.993
b	0.92	0.053	17.406	
x_o	4.50	0.042	106.060	
Year 2020				
CT+CC				
α	2153.54	9.522	226.16	0.998
b	1.665	0.013	132.649	
x_o	5.692	0.009	578.490	
CT+WF				

α	1824.76	304.04	6.002	0.952
b	1.646	0.766	2.149	
x_o	3.589	0.500	7.177	
CVT				
α	16610.39	12167.968	1.365	0.988
b	4.432	2.140	2.071	
x_o	8.028	3.172	2.531	

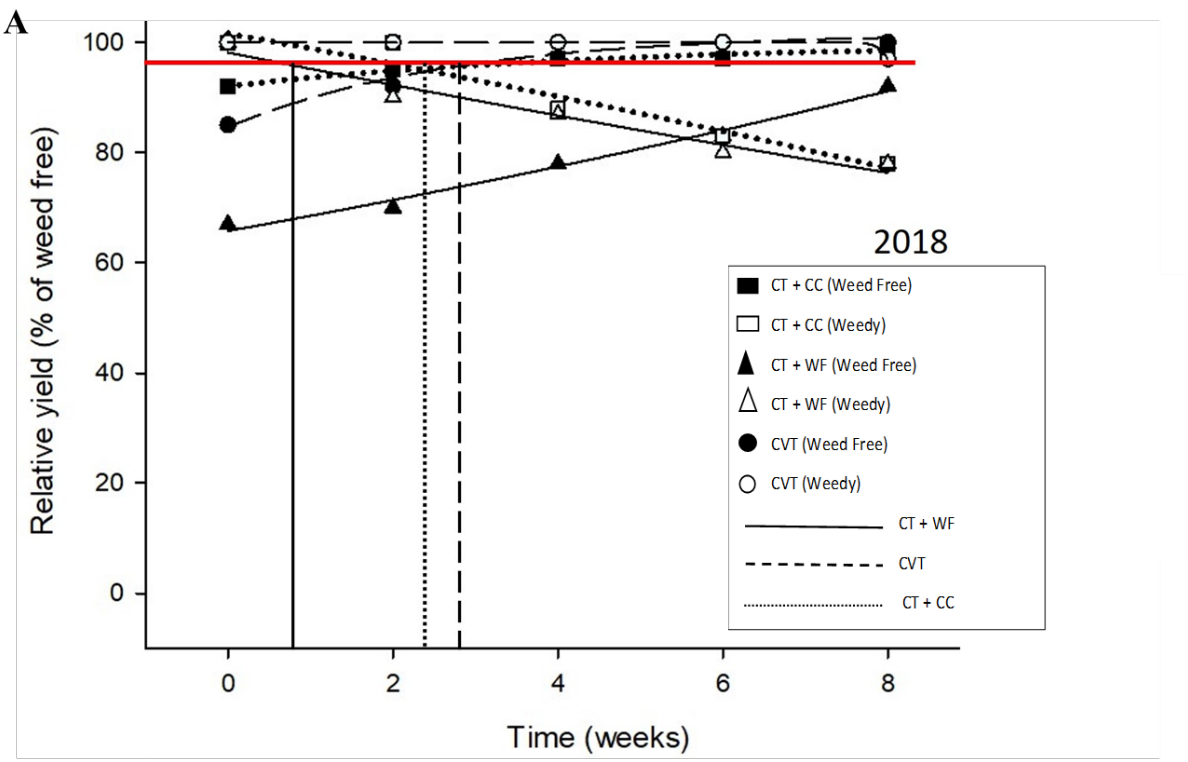
Table 2-5. Statistics for the three parameters sigmoidal model used for fitting weed biomass production under various weed-free (WF) periods for each of the conservation tillage following a cereal rye cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2018, 2019 and 2020.

Year 2018	Coefficient	Std error	t value	R^2
CT+CC				
α	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	2546.30	1373.754	1.853	0.974
b	-3.47	1.129	-3.072	
x_o	0.867	3.799	0.228	
CVT				
α	3605.22	3744.11	0.963	0.956
b	-7.59	5.419	-1.399	
x_o	0.62	15.655	0.039	
Year 2019				
CT+CC				
α	2511.87	98.762	25.434	0.979
b	-1.06	0.091	-11.671	
x_o	2.42	0.133	18.223	
CT+WF				
α	19653.77	8837.391	0.003	0.986
b	-1.795	0.881	-2.037	
x_o	-10.375	544.057	-0.019	
CVT				
α	21090.48	15084.754	0.139	0.991
b	-1.11	0.099	-11.164	
x_o	-3.981	8.539	-0.466	
Year 2020				
CT+CC				
α	1340.52	7.472	179.41	0.998
b	-0.692	0.011	-65.388	
x_o	1.512	0.014	107.429	
CT+WF				
α	2175.39	27.516	79.059	0.998
b	0.707	0.025	-27.783	
x_o	1.573	0.032	49.479	

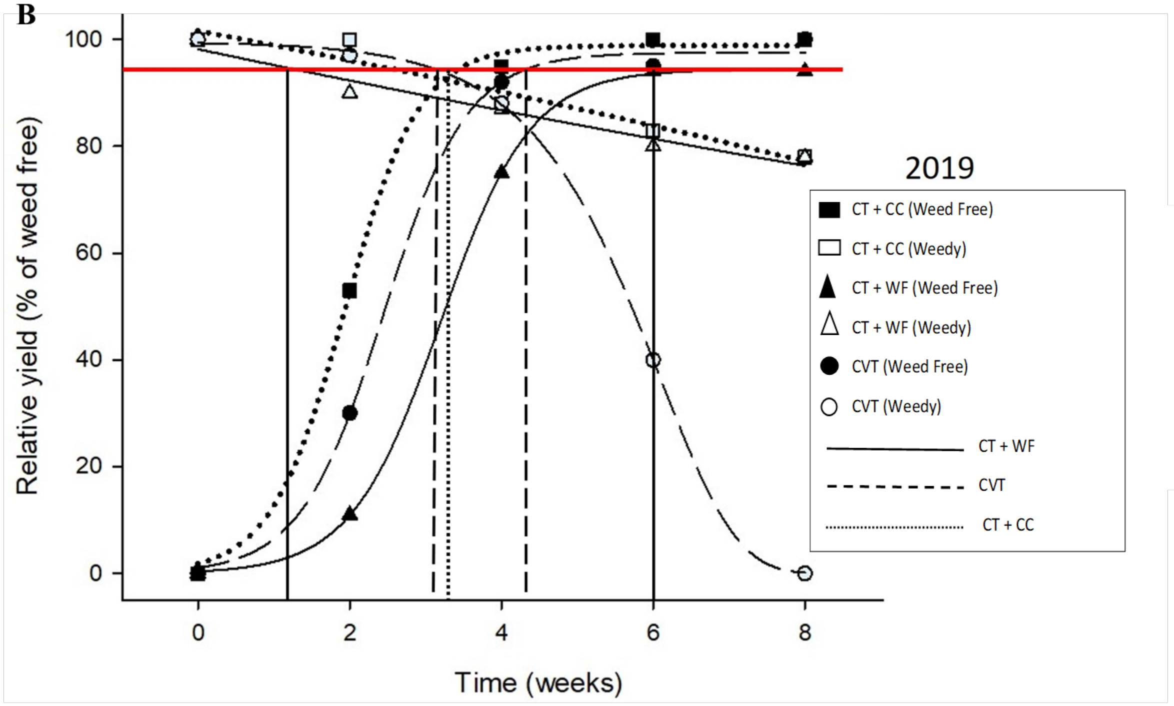
CVT				
α	45093.01	39657.618	0.114	0.980
b	-1.980	0.985	-2.009	
x_o	-4.441	21.394	-0.207	

Figures:

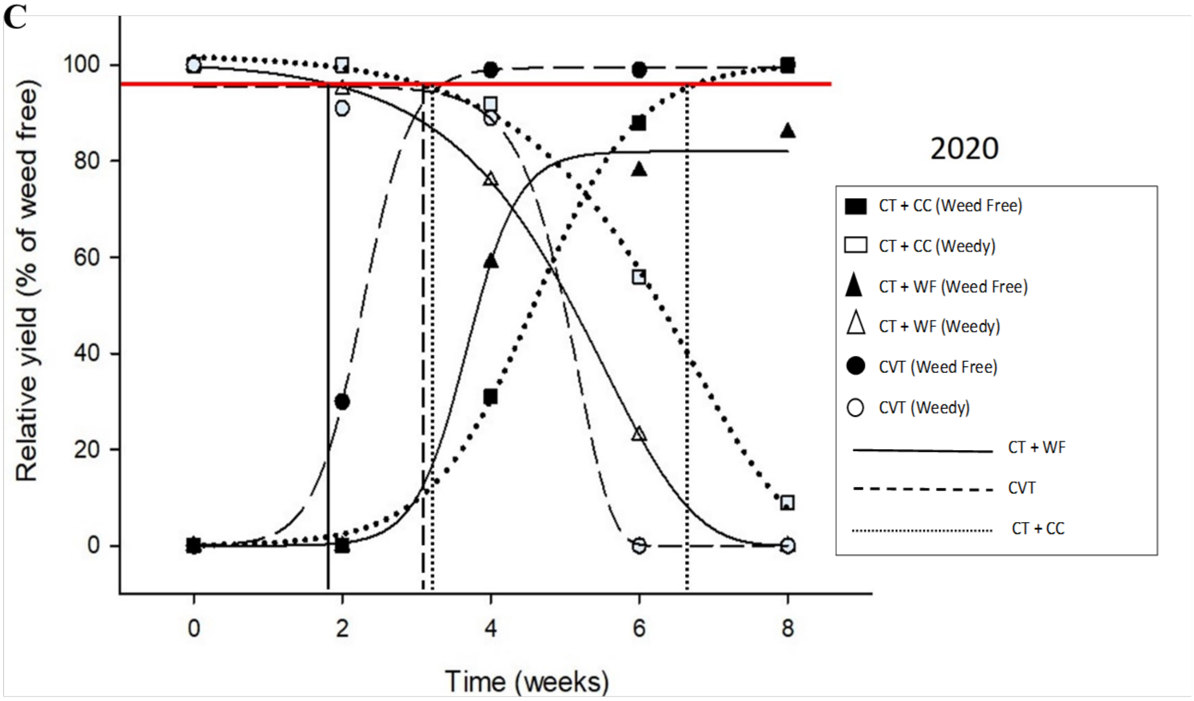
Figures 2-1:



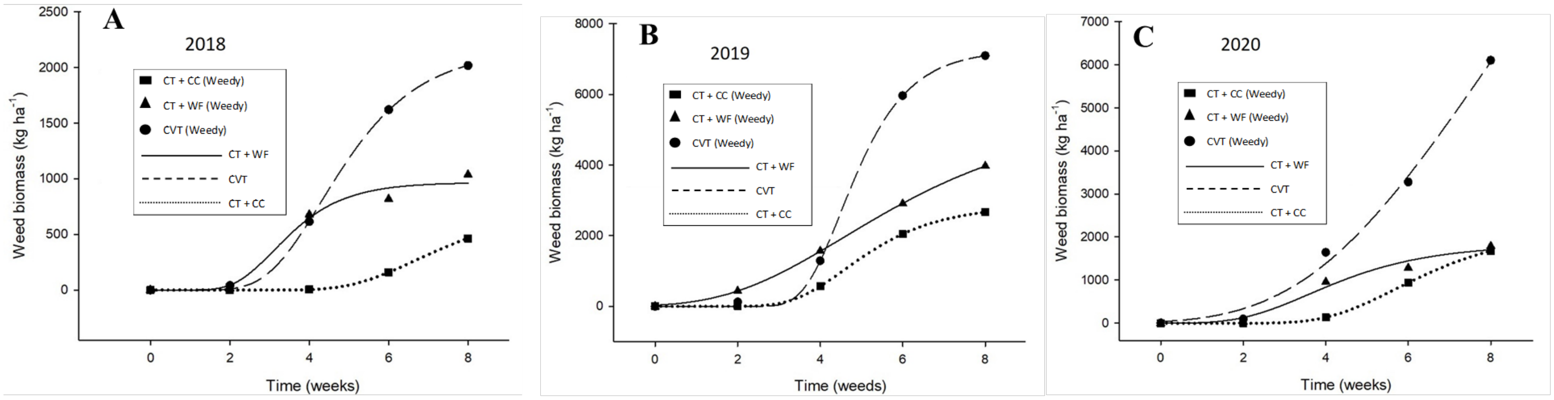
B



C



Figures 2-1: 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).



Figures 2-2: 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).

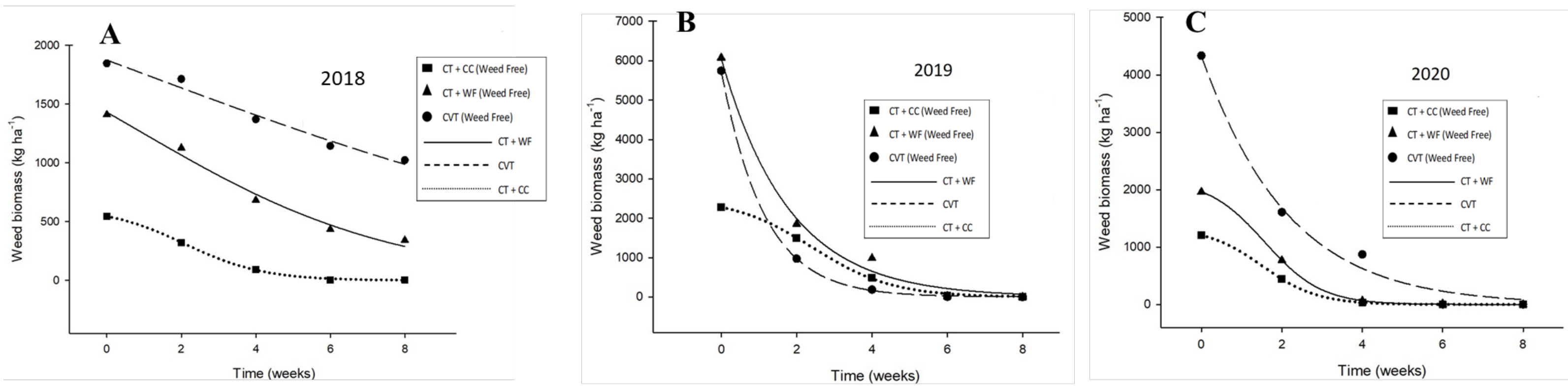


Figure 2-3. Weed biomass as a function of critical weed free period (CWFP) for each of the conservation tillage following a cereal rye cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2018 (A), 2019 (B), and 2020 (C).

Chapter 3: Effect of Crimson Clover on the Critical Period of Weed Control in Conservation Tillage Corn

Introduction

Corn (*Zea mays* L.) is one of the major grain crops cultivated worldwide, with the U.S. leading production globally. Corn has extensive uses, including food products and cooking oil, animal feed, industrial purposes, and ethanol production. Since the late 90s, potential corn yield losses have been increasing due to weed competition from herbicide-resistant and troublesome weed species (Chandler et al., 1984; Vissoh et al., 2004). Integrated weed management approach included the utilization of diverse herbicide modes of action and cover crops to decrease the selection pressure of herbicide resistance and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in corn (Wiggins et al., 2015). Therefore, the understanding of innovative strategies that reduce growers' reliance on herbicide should be adopted for increased weed control continues to be important. Best management practices to sustain or increase weed control included cultural, mechanical, and biological practices illustrated in the "Herbicide Resistant Weeds" section (Norsworthy et al., 2012). In the southeastern U.S., the adoption of conservation tillage utilizing high residue cover crops is increasing in corn and cotton (*Gossypium hirsutum* L.) production systems due to numerous advantages (Price et al., 2006; Price and Kelton, 2013; Reeves et al., 2005). Among other benefits, cover crops improve soil organic matter, nutrient cycling, and soil water conservation (Holderbaum et al., 1990; Sainju and Singh, 1997; Kaspar et al., 2001). Cover crops, including legumes, inhibit weed seed germination and seedling growth due to physical suppression and through allelopathic properties (Barnes and Putnam, 1983; Chase et al., 1991; Akemo et al., 2000; Teasdale and Mohler, 2000; Price et al., 2006; Price et al., 2008). Moreover, cover crops can also improve the soil's physical, chemical, and biological properties by increasing the soil organic matter content in case of grass cover crops with a higher C:N ratio and, nitrogen availability in case of leguminous cover crop species (Hubbard et al., 2013; Romdhane et al., 2019). The crimson clover (*Trifolium incarnatum*) contained N is an essential source of nitrogen for the succeeding crops. However, the rate of N disappearance was more rapid in conventional tillage than no-tillage system (Wilson and Hargrove, 1986). A study in Alabama suggested that conservation tillage with the utilization of crimson clover decreased the weed biomass and suppress the germination of early season weed species in corn. Further, lowest weed biomass recorded was 36 kg ha^{-1} corresponding to crimson clover biomass of 2453 kg ha^{-1} and the highest was 158 kg ha^{-1} corresponding to crimson clover biomass of 373 kg ha^{-1} (Saini et al., 2006). Hence, with the utilization of crimson clover in conservation tillage, it is necessary to establish the critical period of weed control (CPWC) parameters in an integrated weed management system to further understand cover crop weed suppressive attributes and efficient utilization of chemical herbicides (Swanton and Weise, 1991). Moreover, CPWC information is necessary and can be valuable in making decisions based on the need and timing of weed management (Hall et al., 1992; Van Acker et al., 1993). Also, cover crop seeding, and cultivation timing could be improved based upon CPWC knowledge.

The critical period of weed control (CPWC) is described as a 'window' of weed competition period during the crop growing season in which it is essential to control weeds to maintain crop potential yield (Swanton and Weise, 1991). CPWC has two independent components, including critical timing of weed removal (CTWR), which defines the beginning of the critical period from which weeds must be controlled and the maximum tolerance of the crop to the early emerging weeds without causing any unacceptable yield loss (>5%). While the critical weed-free period

(CWFP) describes the end of weed control, to prevent considerable potential yield losses by late-emerging weeds (Knezevic et al., 2002; Williams et al., 2007; Korres and Norsworthy, 2015; Price et al., 2018). Thus, the weed interference duration in weedy plots represented CTWR and the weed-free duration in weed-free plots represented CWFP, with both parameters' length defined by 5% yield loss. Ultimately, weedy plots represented CTWR (beginning of weed control) and weed-free plots represented CWFP (end of weed control) and difference of CWFP and CTWR described the duration of CPWC.

The objective of this research was to evaluate the effect of a high residue crimson clover (*Trifolium incarnatum*) on the critical period of weed control in corn. Therefore, a field study was performed comparing a conservation tillage system with a clover cover crop (CT + CC) managed for maximum biomass, a conservation tillage system with winter fallow (CT + WF), and a conventional tillage (CVT) system on the CPWC.

Materials and Methods

Location site

Field experiments were conducted in 2019 and 2020 at the E.V. Smith Research Center Field Crops Unit (32.4417° N, 85.8974° W) Shorter, Alabama. The soil characteristics at the research site were sandy loam, (coarse-loamy, siliceous, sub-active, thermic Paleudults) with pH 6.2 and 0.8% organic matter. The average temperature ranged from 18.1°C to 27.6°C and precipitation was 8.26 mm to 1.25 mm from April to August 2019. In 2020, the average temperature ranged from 17.27°C to 26.98°C and precipitation was 2.03 mm to 3.37 mm from April to August.

Experimental design

The study was conducted in a split-plot design with four replications. As previously stated, the three systems i.e., conservation tillage with a crimson clover cover crop (CT + CC), conservation tillage with winter fallow (CT + WF), and conventional tillage (CVT), were considered in the main plots. The durations of weedy plots described the beginning of weed removal (CTWR), and the durations of weed-free plots illustrated the end of weed control (CWFP). Hence, these durations in weedy and weed-free plots from 0 to 8 weeks after planting were considered in subplots.

Cover crop management and corn establishment

Crimson clover cultivar "Dixie" was seeded at a rate of 22.4 kg ha^{-1} using a grain drill. Termination of crimson clover was accomplished using a roller-crimper (Ashford and Reeves, 2003) followed by an application of glyphosate (Roundup Powermax®, Monsanto Company, St. Louis, MO) plus glufosinate (Liberty®, Bayer Crop Science, Research Triangle Park, NC) herbicides sprayed at the rate of 841 g ae ha^{-1} and 492 g ae ha^{-1} respectively. Within all plots, a KMC 4-row parabolic subsoiler (Kelly Manufacturing Company, Tifton, GA) was used to disrupt naturally occurring hard pans found at this location before planting corn in all treatments to prevent deep-tillage interaction. Subsequently, CVT plots were cultivated using three disks, and two field cultivator passes. Corn (Pioneer® 1197 YHR) was planted using a precision planter with the population set at 12950 seeds ha^{-1} on April 16, 2019, and April 27, 2020, respectively. A starter application of nitrogen, phosphorus, and potassium (NPK) fertilizer was applied at a rate of 45 kg ha^{-1} after planting corn. A tank mixture of glyphosate plus acetochlor (Warrant, Monsanto Company, St. Louis, MO) herbicide sprayed at the rate of 841 g ae ha^{-1} and 1682 g ae ha^{-1}, respectively, followed by hand hoeing, was utilized for weed control in a weed-free period and after weedy intervals using TDI 11004 nozzles. The corn was harvested on August 19, 2019, and August 27, 2019.

Data collection

Crimson clover biomass samples were collected randomly from a 0.25 m^2 area per plot before termination. The collected samples were placed in a forced air drier for 72 h at 65°C, and then the weight was recorded. Weed biomass was collected from a randomly selected 0.25 m^2 quadrat from weedy plots (CTWR) immediately before applying herbicides. For example, W2, i.e., two weeks weedy; herbicides sprayed at two weeks after planting and weed biomass collected just before application. Additionally, weed biomass collected once at the end of the growing season in the weed-free duration plots. Weed species inside the randomly selected area were cut at the soil surface, placed in a forced air drier for 72 h at 65°C, and then weighed.

Critical period for weed control estimation

A sigmoidal logistic model was fitted for the weedy periods (i.e., CTWR), while the Gompertz model was fitted for the weed-free periods (i.e., CWFP) in each winter fallow (CT + WF), conventional tillage (CVT), and cover crop treatments (CT + CC). The inverse prediction method applied at 95% relative yield to estimate the CTWR and CWFP (i.e., weeks on the x-axis). The estimation of CPWC components were the next steps under which there were not a relative yield reduction greater than 5%, as the acceptable yield losses (AYL) were considered at 5% for both curves Gompertz and logistic as described by Knezevic et al. (2002); Blankenship et al. (2003), and Price et al. (2018). Regression of relative yield was performed as a function of time for both CTWR and CWFP, and then nonlinear regression models were fitted to assess the CPWC, as illustrated by Knezevic et al. (2002); Williams et al. (2007) and Korres and Norsworthy (2015). For the weedy periods to estimate CTWR, a logistic model with three parameters was fitted to relative corn yield under all three treatments.

$y = \frac{\alpha}{1+e^{-b(x-x_o)}}$ Equation (1)

Moreover, for the weed-free periods to evaluate CWFP, a Gompertz model with three parameters was fitted to relative corn yield under all three treatments.

$y = \alpha e^{-(e^{-b(x-x_O)})}$ Equation (2)

Where y is the relative corn yield, α 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).

Hence, the difference between CWFP and CTWR components described the CPWC estimation with a 5% acceptable corn yield loss in CT + CC, CT + WF, and CVT systems. As described previously, weed control experiments estimate the relation between weed interference timings and relative crop yield and then determine the CPWC.

The collected weed biomass was quantified as a function of critical timing of weed removal (CTWR) and the critical weed-free period (CWFP) for each CT + CC, CT + WF, and CVT system using equations 1 and 2 mentioned above, in which y represents weed biomass. A sigmoidal logistic model was fitted for various weed-free periods, while the Gompertz model was fitted for the weedy periods in CT + CC, CT + WF, and CVT systems to assess weed biomass.

Statistical data analysis

The ANOVA was applied to estimate treatment effects on actual and relative (percentage of long season weed-free period) corn yield data, and means were separated through Fisher's LSD at α=0.05. The CPWC was estimated separately for each year due to significant treatments × year interaction. Sigma Plot 14.0 (Systat Software, San Jose, CA) and JMP Pro v. 13 (SAS Institute, Cary, NC) was used for the estimation of ANOVAs, inverse predictions, curve fitting regressions, and significance model parameters. The model parameters were utilized to support the predicted values of an explanatory variable (i.e., type of independent variable) CTWR and CWFP based on the response variable of relative corn yield. Coefficient of determination (R^2) was used to check the fitness of the regression model to the observed data. The comparisons between model parameters were used to evaluate the effect of experimental treatments, including CT + CC, CT + WF, and CVT, on weed biomass production.

Results and discussion

Crimson clover biomass and corn yield

At clover termination, the cover crop biomass was 4,204 kg ha^{-1} and 3,890 kg ha^{-1} in 2019 and 2020, respectively. The average yield following crimson clover was 7,575 kg ha^{-1}, winter fallow 6,478 kg ha^{-1}, and conventional tillage 7,400 kg ha^{-1} in 2019. The average yield following crimson clover was 8,253 kg ha^{-1}, winter fallow 7,224 kg ha^{-1}, and conventional tillage 7,280 kg ha^{-1} in 2020.

Critical period of weed control

Again, 5% acceptable yield loss (AYL) was considered to estimate the values of CTWR and CWFP as described by Blankenship et al. (2003) and Knezevic et al. (2002). In 2019, the predicted value of CTWR equals 2.5, 2.8, and 1.5 weeks after planting (WAP) for CT + CC, CT + WF and CVT systems, respectively (Figure 3-1 and Tables 3-1, 3-2). In addition, the predicted value of CWFP equals 5.3, 6.3, and 6.4 weeks after planting for CT + CC, CT + WF, and CVT, respectively (Figure 3-1 and Tables 3-1, 3-3). In 2019, based on the predicted values of CTWR for each system individually, the CTWR following the CT + CC system was delayed approximately 1.0 weeks compared with CVT system, while the beginning of CTWR under both CT + WF and CT + WF systems was in between second to third weeks (Figure 3-1 and Tables 3-1, 3-2). Additionally, comparing CT + CC system with CT + WF and CVT systems, the presence of crimson clover caused the early ending of CWFP at about 1.0 and 1.1 weeks respectively.

However, the ending of CWFP under CT + WF and CVT systems were almost same during the weeks of 6 WAP.

In 2020, the predicted value of CTWR equals 3.8 WAP for CT + CC system. While the relative yield was above the threshold level of 95% for 8 weeks, so the model did not predict the CTWR value for CT + WF and CVT systems because curves were fitted only for 8 weeks (Figure 3-1 and Tables 3-1, 3-2). Moreover, the predicted values of CWFP equals 5.1, and 5.7 WAP for CT + WF and CVT, respectively, whereas for CT + CC system, the model did not predict the value due to greater than 95% relative yield during most of growing season (Figure 3-1 and Tables 3-1, 3-3). Hence, comparing the CVT system with CT + WF system, conventional tillage and winter fallow had almost same ending period during 5th weeks of timing (Figure 3-1 and Tables 3-1, 3-3).

We observed yield loss increased with the extent in time of weed infestation, and Gantoli et al. (2013) reported the same in the estimation of corn CPWC. Although our points of estimated critical period were not exact same among two years because of different weed pressure in two years (Figure 3-2). Some previous publications indicated that the CPWC differed remarkably when estimated in respect of days after planting or days after germination (Gantoli et al., 2013). Moreover, several corn studies have estimated the critical period of weed control, and there was great variability in the CPWC. The starting of the corn CPWC was more variable (3-14 leaf stage) than the end (14-leaf stage) in Canada (Hall et al., 1992). In contrast, Halford et al. (2001) illustrated that starting of the CPWC was more stable (around 6-leaf stage) than the end period (9-13 leaf stage or 24 to 46 DAE) in corn. Results reported by Evans et al. (2003) described that the starting of CPWC was estimated from germination up to the seven-leaf stage, while the end of the CPWC was estimated from seven-leaf stage up to anthesis in corn crop. A field experiment was conducted in Canada to compare the CPWC between conventional and no-till corn and summarized that the CPWC starting and ending period was earlier under a no-till system than in conventional tillage systems (Halford et al., 2001). In addition, the previous study concluded that the estimated value of CPWC in narrow-row spacing was different than wide rows spacing in corn due to higher competition for late-germinating weeds (Murphy et al., 1996). Thus, high-density corn planted in narrow row spacing would most likely decrease the end of the CPWC (Teasdale, 1998). However, Norsworthy and Oliveira (2004) concluded that there was no significant difference between light interception in narrow and wide row spacing of corn; hence CPWC and competition of late germination weeds were almost the same in these two systems.

Treatment effects on weed biomass production

The most common and troublesome weed species found in the southeastern United States cropping systems are Palmer amaranth (*Amaranthus* spp.), sicklepod [*Senna obtusifolia* (L.)], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], morning glory (*Ipomoea* spp.), and nutsedges (*Cyperus* spp.) (Van Wychen, 2016). In 2019, weed removal needed to start before 150-200 kg ha^{-1} of weed biomass for all systems (Figure 3-2), based on the predicted values CTWR that started at approx. 3 WAP under CT + CC and CT + WF systems while approx. 1.5 WAP following the CVT system to prevent a yield loss greater than 5% in each system (Figure 3-2 and Table 3-4). In 2020 the recorded dry weight of weed biomass based on prediction value of CTWR (3.8 WAP) for CT + CC treatment was 30 kg ha^{-1} approximately. Although weed biomass of CT + WF and CVT systems were approx. 60 and 400 kg ha^{-1} respectively (Figure 3-2 and Table 3-4) in between 3 to 4 WAP in 2019. In both years, the weed biomass increased as the critical timing of weed removal (CTWR) increased. However, results showed differences in point estimates between slope and inflection points under each system for both years due to difference in weed pressure among both years. It has been observed that weed density was lower in 2020 than in 2019 (Figures 3-2, 3-3 and Tables 3-4, 3-5).

The same strategy was followed in the case of the critical weed-free period (i.e., CWFP) following CT + CC, CT + WF, and CVT systems in both years (Figure 3-3 and Table 3-5). In 2019 the weed biomass was recorded during the predicted value of CWFP (5.3 WAP) following CT + CC treatment was approx. 100 kg ha^{-1}. However, in case of CT + WF and CVT systems, the recorded dry weight was approx. 50-60 kg ha^{-1} at 6 WAP (Figure 3-3 and Table 3-5). In 2020, the recorded weed biomass level at predicted value of CWFP following CT + WF treatment (i.e., 5.1 WAP) and CVT treatment (i.e., 5.7 WAP) was 50 kg ha^{-1} approximately.

Moreover, the recorded maximum production of weed biomass level in both weedy and weed-free plots following CT + CC (cover crop) treatment was lower as compared to CT + WF and CVT systems under both years (Figures 3-2 and 3-3, Tables 3-4 and 3-5). This is likely due to the cover crop inhibiting weed seed (mainly small, seeded weeds) germination and decreased growth through physical suppression and allelopathy in the conservation tillage system (Akemo et al., 2000; Haramoto and Gallandt, 2004; Korres and Norsworthy, 2015). The practical application for this research is to understand the critical period of weed control (CPWC) in row crops to maintain crop yield potential is a key point in the cropping system. In addition, it is very important to have knowledge about how different cultural practices, including cover crops among others, can influence the critical period for weed removal (CPWC) and weed biomass production. Estimation of critical period of weed control (CPWC) indicated that use of residual herbicides for weed control is required (Korres and Norsworthy, 2015). The use of effective POST herbicides could effectively control the problematic weed species, especially when the critical weed-free period is short Van Acker et al. (1993). A better understanding of the CPWC in different systems, including a high residue cover crop in corn, should help farmers to maintain yield and schedule appropriate weed control timing.

Conclusions:

In general, a difference of CWFP (i.e., end of weed control) and CTWR (i.e., beginning of weed removal) estimated the CPWC (critical period of weed control, i.e., duration) as we discussed previously. In 2019, the cover crop system had a predicted value of critical timing of weed removal (i.e., starting time) equal 2.5 weeks after planting, and critical weed-free period (i.e., ending time) equal 5.3 weeks after planting, hence the estimated duration of critical period of weed control based on two components was 2.8 weeks. While for the winter fallow system the predicted values of critical timing of weed removal equal 2.8 weeks after planting and critical weed-free period equal 6.3 weeks after planting, hence the estimated duration of critical period of weed control based on two components was 3.5 weeks in 2019. For the conventional tillage system, we found that the estimated values of critical timing of weed removal equal 1.5 weeks after planting and critical weed-free period equal 6.4 weeks after planting, hence the determined duration of critical period of weed control based on two components was 4.9 weeks in the same experimental year. Therefore, the evaluated duration of critical period of weed control in three systems, including cover crop, winter fallow and conventional tillage had 2.8, 3.5, and 4.9 weeks respectively in 2019. The presence of crimson clover cover crop delayed the critical timing of weed removal and caused the early beginning of critical weed-free period and hence shortened critical period of weed control in the 2019 experimental year likely because of later weed emergence and suppression of growth thus a crimson clover cover crop will likely provide a significant competitive advantage to corn against troublesome weed species. In 2020, as we discussed above the model did not predict the critical timing of weed removal values for winter fallow and conventional tillage system since the relative corn yield is above the 95% threshold during most of the growing season. For the critical weed-free period the estimated values were 5.1 and 5.7 weeks after planting following winter fallow and conventional tillage systems, but no prediction following the cover crop system due to the same reason of a greater 95% relative yield in 2020. In conclusion, conservation tillage following crimson clover cover crop shortened the length of critical period of weed control in corn. Moreover, the end of weed control was almost similar (in between 5 to 6 weeks after planting) under winter fallow and conventional tillage systems depending on the weed pressure during the growing season. Also, the beginning of weed removal under cover crop treatment was quite stable from the 2.5 to 3.5 weeks after planting depending on weed density during growing season. Weed control during critical periods offered a significant benefit to corn against troublesome weeds and maintained relative corn yield.

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Tables:

Table 3-1: The estimation of points (i.e., inverse predictions), standard errors (SE) of inverse predictions, and confidence intervals (CI_{95}) corresponding to a 5% acceptable yield loss for the Logistic and Gompertz models used to estimate the beginning and end of the critical period in 2019 and 2020 for weed control in corn under three different tillage systems.

Model[a]	Tillage system[b]	Inverse prediction	SE	CI_{95} lower	CI_{95} upper
Year 2019					
Logistic (CTWR)	CT + CC	2.5	0.27	1.97	3.04
	CT+ WF	2.8	0.76	1.29	4.27
	CVT	1.5	0.27	0.97	2.03
Gompertz (CWFP)	CT + CC	5.3	0.81	3.68	6.89
	CT+ WF	6.3	0.21	5.93	6.75
	CVT	6.4	0.24	5.94	6.89
Year 2020					
Logistic (CTWR)	CT + CC	3.8	0.19	3.47	4.21
	CT+ WF	-	-	-	-
	CVT	-	-	-	-
Gompertz (CWFP)	CT + CC	-	-	-	
	CT+ WF	5.1	0.54	4.06	6.17
	CVT	5.7	0.43	4.87	6.55

[a]CWFP, critical weed-free period; CTWR, critical timing for weed removal.
[b]CT + CC, conservation tillage following a crimson clover cover crop; CT + WF, conservation tillage following winter fallow; CVT, conventional tillage without a cover crop

Table 3-2: Statistics of the three-parameter logistic regression model fitted to relative corn yield to estimate the critical weedy period (CTWR) for each of the conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020.

Year 2019	Coefficient	Std error	t value	R^2
Clover				
α	90.89	0.195	61.732	0.997
b	-0.95	-12.339	-12.339	
x_o	5.34	6.732	34.492	
Fallow				
α	90.43	0.450	37.358	0.973
b	-1.317	0.197	-6.689	
x_o	6.438	0.172	16.729	
Conventional				
α	100.00	1.294	17.986	0.992
b	0.65	1.321	2.965	
x_o	6.03	1.956	12.836	

Year 2020	Coefficient	Std error	t value	R^2
Clover				
α	100.25	0.365	274.928	0.986
b	-2.31	0.845	-2.736	
x_o	15.85	2.748	5.768	
Fallow				
α	108.32	13.428	8.067	0.982
b	-9.91	9.305	-0.958	
x_o	23.22	10.219	2.272	
Conventional				
α	101.12	1.606	62.982	0.988
b	-2.12	0.678	-3.128	
x_o	11.59	1.097	10.564	

Table 3-3: Statistics of the three-parameter Gompertz regression model fitted to relative corn yield to estimate the critical weed-free periods (CWFP) for each conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020.

Year 2019	Parameter	Std error	t value	R^2
Clover				
α	101.07	0.961	105.190	0.992
b	2.24	0.402	5.584	
x_o	-3.66	0.620	-5.906	
Fallow				
α	105.83	12.366	8.558	0.9324
b	6.97	8.206	0.850	
x_o	-12.35	9.533	-1.295	
Conventional				
α	102.08	1.944	52.504	0.983
b	4.52	1.792	2.522	
x_o	-10.23	3.347	-3.055	

Year 2020	Parameter	Std error	t value	R^2
Clover				
α	101.51	0.861	117.873	0.997
b	2.10	0.179	11.704	
x_o	-1,83	0.165	-11.099	
Fallow				
α	100.00	0.00	98.345	0.996
b	0.045	0.045	9.876	
x_o	-3.156	0.00	-2.118	
Conventional				
α	100.00	0.00	99.877	0.998
b	0.087	0.001	10.036	
x_o	-2.165	0.00	-1.291	

Table 3-4: Statistics for the three parameters Gompertz model used for fitting weed biomass production under various weedy periods for each of the conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020.

Year 2019	Coefficient	Std error	t value	R^2
Clover				
α	1716.68	4.856	353.498	0.998
b	2.38	0.008	279.455	
x_o	5.79	0.007	709.749	
Fallow				
α	2238.08	7.223	309.858	0.996
b	0.90	0.011	83.470	
x_o	5.13	0.009	531.994	
Conventional				
α	1603.97	155.229	10.333	0.997
b	2.02	0.381	5.312	
x_o	4.52	0.268	16.873	

Year 2020	Coefficient	Std error	t value	R^2
Clover				
α	1896.51	186.449	0.044	0.999
b	4.92	19.046	0.258	
x_o	15.73	53.124	0.296	
Fallow				
α	2008.49	41.324	48.603	0.999
b	2.58	0.045	57.201	
x_o	7.23	0.057	126.277	
Conventional				
α	2118.25	3142.11	0.674	0.965
b	4.22	5.304	0.795	
x_o	6.47	6.703	0.966	

Table 3-5: Statistics for the three parameters logistic model used for fitting weed biomass production under various weed-free periods for each of the conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020.

Year 2019	Coefficient	Std error	t value	R^2
Clover				
α	2553.16	744.482	3.429	0.966
b	-1.73	0.153	-11.298	
x_o	-0.84	0.882	-0.949	
Fallow				
α	719.58	2.049	351.235	0.953
b	-0.38	0.007	-58.140	
x_o	2.73	0.014	19.275	
Conventional				
α	4569.27	1432.115	0.003	0.924
b	-1.49	0.677	-2.197	
x_o	-8.702	4.496	-0.018	

Year 2020	Coefficient	Std error	t value	R^2
Clover				
α	810.28	3.291	246.195	0.997
b	-0.60	0.008	-72.534	
x_o	2.77	0.014	196.926	
Fallow				
α	1161.62	0.606	1917.307	0.995
b	-0.51	0.002	-272.223	
x_o	1.72	0.002	1175.335	
Conventional				
α	903.41	0.261	3467.218	0.998
b	-0.45	0.009	-509.481	
x_o	1.55	0;001	1454.769	

Figure 3-1:

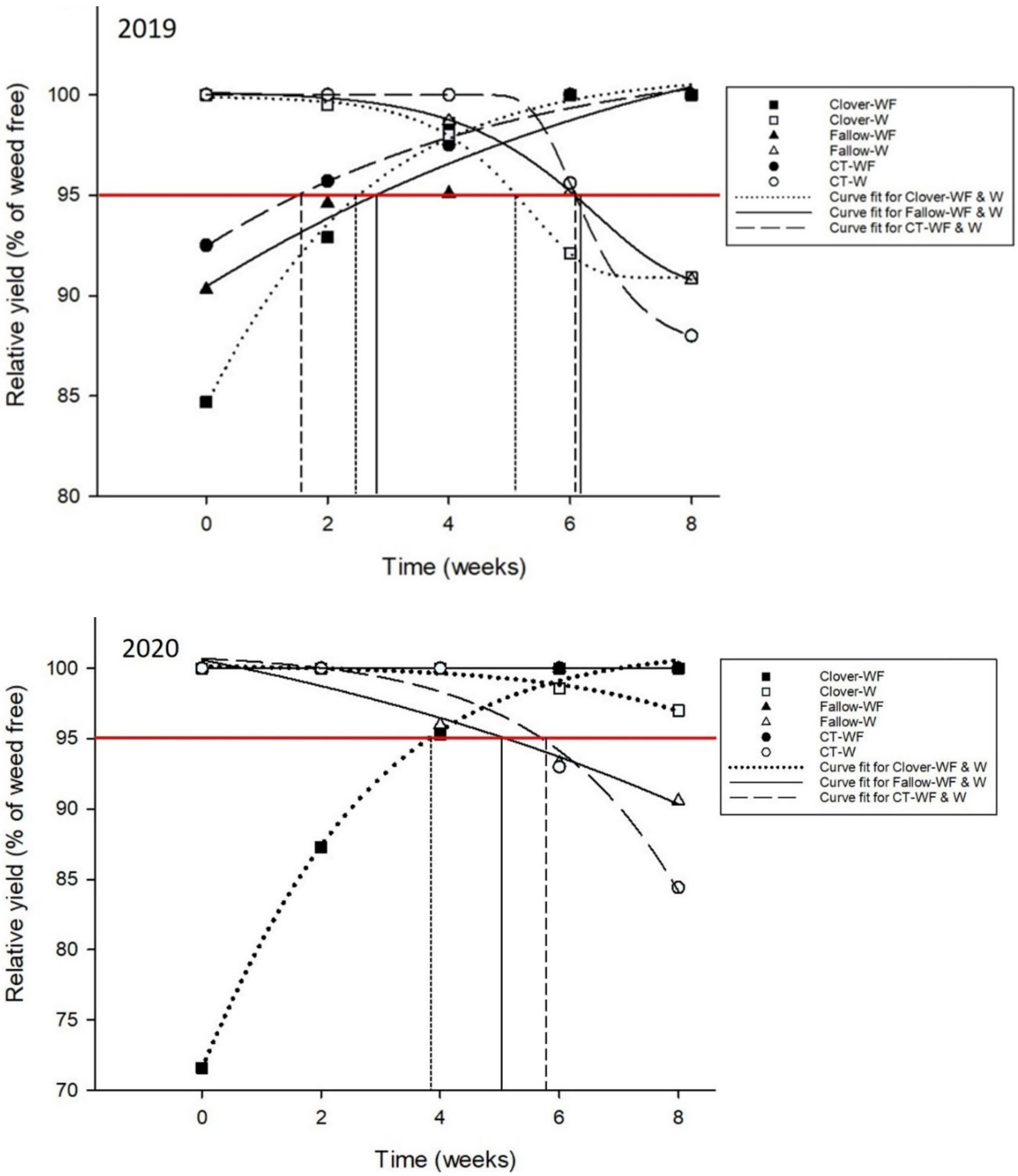
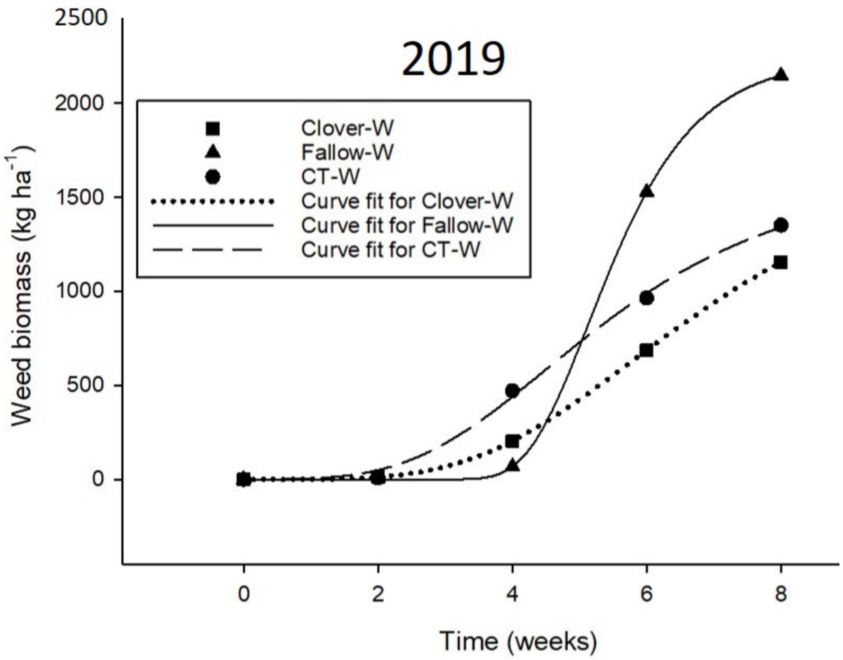


Figure 3-1: The critical period for weed control and its components (critical timing for weed control [CTWR, i.e., weedy] and critical weed-free period [CWFP, i.e., weed free]) for each of the conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020.

Figure 3-2:



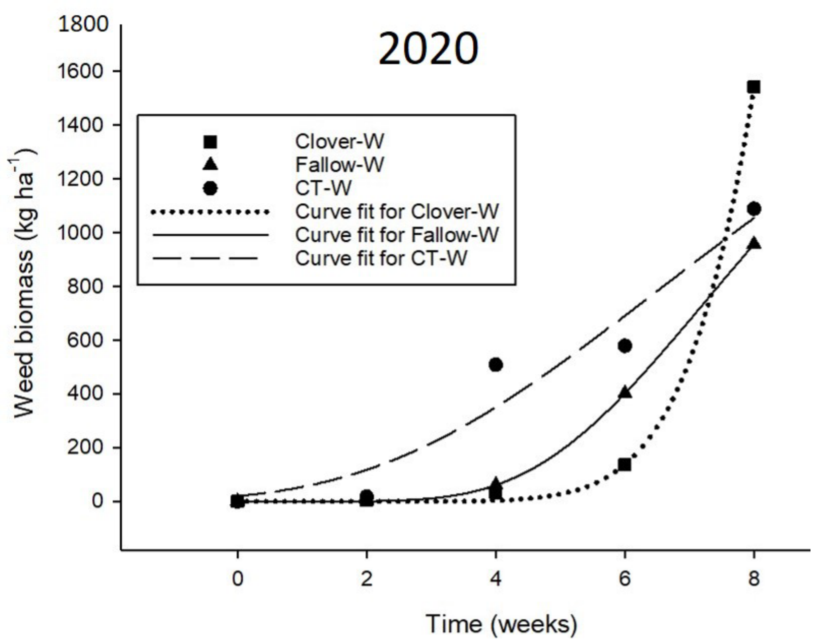


Figure 3-2: Weed biomass as a function of critical timing for weed removal CTWR (duration of weed interference with corn) for each of the conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020.

Figure 3-3.

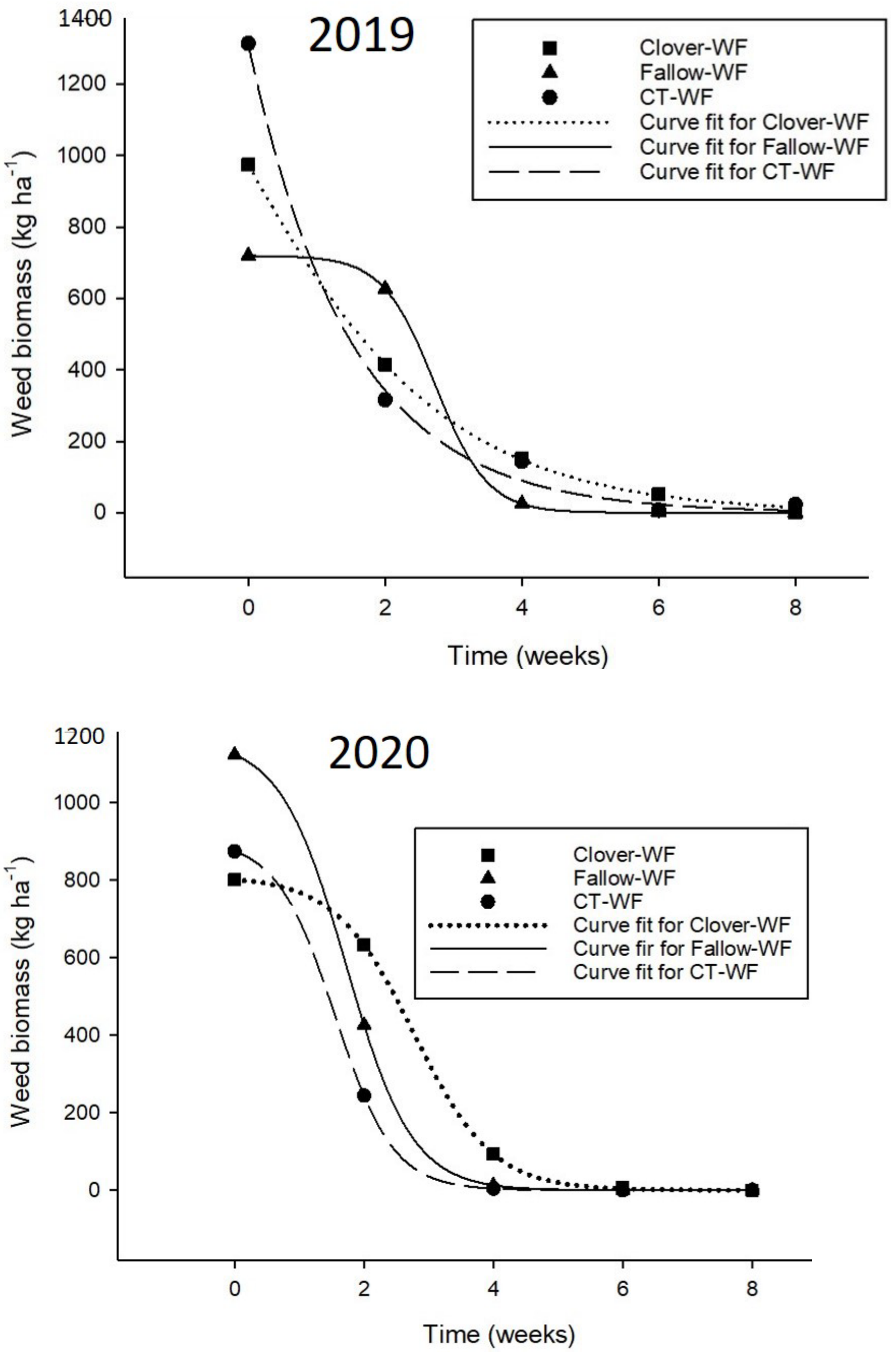


Figure 3-3: Weed biomass as a function of critical weed-free period CWFP for each of the conservation tillage following a crimson clover cover crop (CT + CC), conservation tillage following winter fallow (CT + WF), and conventional tillage without a cover crop (CVT) treatment in 2019 and 2020 experimental treatments.