Utilizing Cover Crops to Improve Sustainability of Conventional Weed Management Programs

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Garret Brown Montgomery

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DEDICATION

I would like to dedicate this work to my son, Clayton Montgomery, my sisters, Hope and Megan Montgomery, and my parents, Amy and Bob Montgomery. I will never be able to thank you enough for your support and encouragement through the good times and the tough situations. Without the love and support of these people, I would not be where I am today.

ABSTRACT

Research was conducted from the fall of 2014 to the fall of 2016 to evaluate the optimal utilization of cover crops for weed control in no-till environments. Studies included a corn (*Zea mays* L.) termination timing study to evaluation different termination intervals of cereal rye (*Cereal rye* L.), hairy vetch (*Vicia villosa* Roth.), and a combination of cereal rye and hairy vetch cover crops on corn growth and development, an evaluation of a roller crimper for cover crop termination prior to corn study, an evaluation of a roller crimper for cover crop termination prior to soybeans [*Glycine max* (L.) Merr.], an evaluation of glyphosate + dicamba tolerant (GDT) soybean utilization in a cover cropping system, and a study to evaluate the effects of fall applied herbicides on four cover crop species from controlling Italian ryegrass (*Lolium perenne* ssp. *multiflorum*).

Results from this research indicate that a cover crop termination interval prior to corn planting can influence corn growth, development, and yield, a roller crimper is not currently a viable tool for cover crop termination prior to planting corn, a roller crimper can be effectively used for cover crop termination prior to soybeans, GDT soybeans can be readily utilized into a cover cropping system, and that fall applied herbicides can be used with cover crops and aid in controlling Italian ryegrass.

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Introduction

Herbicides are the foundation for weed control in commercial agricultural production systems of the United States (Norsworthy et al. 2012). However, overreliance on a small number of these herbicides and extreme selection pressure has led to an increase in the number of herbicide-resistant weed species (Heap 2016). These species have become the forefront of weed control research programs and cause for increasing concern around protecting current herbicide modes of action. Previous research has indicated that incorporating cultural management practices such as crop row spacing, tillage, and/or cover crops can greatly reduce selective pressure on herbicides for resistance (Cavan et al. 2001; Esbenshade et al. 2001; Beckie 2006; Moss et al. 2007; Wilson et al. 2007; Norsworthy et al. 2012). Although tillage and row spacing are being implemented where they are feasible, the knowledge base around other management practices such as cover cropping systems among agronomic producers in Tennessee is comparatively low. This has indicated a need for research on how cover crops can be implemented into minimal and no-tillage weed control systems that are commonly utilized in this geography.

Glyphosate Resistant Palmer Amaranth

Amaranthus, or pigweed, species are common broadleaf weeds infesting crops in the United States and throughout the world (Gossett and Toler 1999). The *Amaranthus* genus is notable as a group due to the success of many members as weeds in agronomic scenarios (Steckel et al. 2004). Although Palmer amaranth is native to the Sonoran Desert, in recent decades it has spread eastward and proliferated in the Southeast and Midsouth regions of the United States (Ehleringer 1983; Bond and Oliver 2006; Culpepper et al. 2006; Steckel 2007; Barnett et al. 2013). This trend can, in part, be associated with the adoption of reduced tillage systems in combination with an overall reduction in the amount of residual herbicides being utilized (Culpepper 2006; Young 2006). Palmer amaranth is one of ten dioecious (male and female flowers on separate plants) *Amaranthus* spp. native to North America (Bond and Oliver 2006; Steckel 2007). It is one of the most prevalent and troublesome of the *Amaranthus* species (Horak and Loughin 2000; Guo and Al-Khatib 2003; Norsworthy et al. 2008; Main et al. 2012). Palmer amaranth exhibits an extremely rapid growth habit and can grow 24 to 62% more per growing degree day than any other *Amaranthus* species (Culpepper et al. 2006). The aggressive growth rate and stature of this weed make it extremely competitive with agronomic crops (Klingaman and Oliver 1994; Bond and Oliver 2006; Culpepper et al. 2006).

Until the mid to late 1990s, weedy vegetation was traditionally controlled with an initial burndown herbicide application or tillage measure and then producers predominantly relied on sequential preemergence herbicide applications (Culpepper 2006; Givens et al. 2009; Price et al. 2011). These herbicides forced producers to be timely with applications to achieve optimal weed control (Powles and Preston 2006). Glyphosate is a non-selective, post-emerge herbicide that controls many different weed species across a wide spectrum of growth stages. Since the introduction of glyphosate-resistant (GR) soybean, cotton, and corn in 1996, 1997, and 1998, respectively, the approach to herbicide weed control has changed drastically (Culpepper and York 1998; Corbet et al. 2004; Burke et al. 2005; Young 2006). The ability to use glyphosate during the growing season allowed producers to reduce the amount of total herbicides being used in their crops and reduce the need for tillage to control weeds prior to planting (Culpepper 2006; Young 2006). Over-reliance on glyphosate caused a shift in the overall weed spectrum through extreme selection pressure and GR biotypes of key weed species, such as horseweed and Palmer amaranth, have become common in the major agronomic areas of the U.S. (VanGessel 2001; Koger et al. 2004b; Culpepper et al. 2006; Norsworthy et al. 2008). Palmer amaranth was first confirmed glyphosate-resistant (GR) in Georgia in 2004, and is currently documented as GR in most of the major U.S. agronomic states in the U.S. (Culpepper et al. 2006; Heap 2016). Since that time, Palmer amaranth has become one of the most economically damaging weeds in the U.S. (Beckie 2011). Multiple mechanisms of GR have been documented and resistance being spread long distances to other *Amaranthus* spp. through pollen dispersed from GR Palmer amaranth has been recorded (Ward et al. 2013). Postemergence control options for Palmer amaranth are limited in some of the major agronomic crops. There has been an increase in the use of residual herbicides and transgenic crops exhibiting tolerance to glufosinate in recent years. Efficacious herbicide programs for controlling Palmer amaranth must contain multiple modes of action combined with overlapping residual herbicides (DeVore et al. 2013; Riar et al. 2013). These programs can become very costly and time consuming (Price et al. 2011). These factors have driven researchers to examine alternative options to aid in controlling Palmer amaranth.

Cover Crops

A cover crop is any living ground cover that is planted into or after a cash crop and then commonly terminated before or shortly after the next main crop is planted (Hartwig and Ammon 2002). Along with weed suppression, cover crops offer many advantages over standard cropping systems, including: reduced soil erosion and water runoff, improved soil moisture retention, water infiltration, organic matter in the soil, soil tilth, soil nitrogen, and reducing tillage needs (Teasdale 1996; Yenish et al. 1996; Mallory et al. 1998; Varco et al. 1999; Reddy et al. 2003). Cereal rye (*Secale cereal*), hairy vetch (*Vicia villosa*), oats (*Avena sativa*), ryegrass species (*Lolium* spp.), winter wheat (*Triticum aestivum*), and clover species (*Trifolium* spp.) are commonly used as cover crops (Koger et al. 2004a; Mirsky et al. 2011; Reddy 2001). The intent of a winter-annual cover crop for weed suppression is to produce unfavorable growing conditions through production of above ground mulch from plant residue creating competition for resources and sunlight between the cover crop and weeds (Teasdale 1996). Cover crops interfere with weed species more than they do most agronomic crop species. This is largely due to cash crop species having larger seeds with greater energy, nutrient resources, and having precise placement into the soil (Mirsky et al. 2013).

Cover crops provide many benefits in agronomic situations, however, some difficulties can be associated with them. Inclement conditions could allow for weed species to germinate and become problematic in cover cropping systems. Very little research has been conducted on weed control for cover crops. Competitive winter weeds such as horseweed or Italian ryegrass can cause negative impacts on agronomic crops (Bond et al. 2005; Nandula et al. 2007; Eubank et al. 2008; Owen et al. 2011). These negative impacts could be translated to cover crops, compromising the integrity and possibly reducing the amount of early season, summer-annual weed suppression from a winter cover crop. Bond et al. (2014) reported that fall applications of residual herbicides provided acceptable control of Italian ryegrass and other winter weed species in Mississippi. Little research has been conducted around the concept of combining fall-applied herbicides and cover crops to increase control of both winter and summer weed species.

Weed control in conventional agronomic areas of the United States is commonly achieved through the use of herbicides; however, over reliance on herbicidal weed control has led to a continuous increase of the number of herbicide resistant weeds since the mid 1990’s (Heap 2016). With the advent of new herbicide modes of action being unlikely, the need for mechanical or biological weed control measures is ever increasing (Norsworthy et al. 2012). Weed suppression from cover crops has been widely documented (Barnes and Putnam 1986; Reddy 2001; Mirsky et al. 2011; DeVore et al. 2013). In some cases cover cropping systems can provide similar weed control to herbicide control programs (Liebel et al. 1992). Weed suppression due to cover crop interference can be species specific, thus the soil seed bank and weed species present in the area factor in to the efficacy of cover crop for weed control.

Cover Crop Termination

Cover crop termination is one of the most influential factors in determining the amount of weed suppression (Mirsky et al. 2013). The quantity of biomass present at a given time by a cover crop directly contributes to the amount of weed suppression that can be achieved (Norsworthy et al. 2011; Ryan et al. 2011; Mirsky et al. 2013). Non-selective herbicides, such as glyphosate, glufosinate, or paraquat, or mechanical control measures such as tillage, mowing, or a roller crimper are commonly utilized for cover crop termination. Regardless of termination method, complete cover crop control is necessary for producing a successful cash crop. Insufficient control of a cover crop has been reported to cause similar problems to that of early season weed pressure and can ultimately lead to a yield reduction in the following cash crop (Fisk et al. 2001; Tharp and Kells 2001; Mirsky 2008).

Although weed suppression from cover crops has been widely documented (Peterson et al. 2001; Reddy 2001; Hartwig and Ammon 2002;

Reddy et al. 2003), inconsistencies in weed suppression have also been recorded (Reddy et al. 2003; Mischler et al. 2010; Mirsky et al. 2013). These inconsistencies possibly could have been explained by termination timings and methods of the different studies. In all of the experiments previously described, cover crops were terminated two- to three-weeks prior to planting the crop. Research surrounding mechanical tools for cover crops has been increasing in recent decades. One of these tools is the cover crop roller crimper which is a cylinder with protruding fins that rotates on a lengthwise axis as is it drawn over the cover crop. The weight of the roller crimper is concentrated onto a finite area with the protruding fins, which creates a 'crimp' in plant stems, breaks essential vascular tissues, and can lead to plant death. In addition to cover crop termination, a roller crimper also compacts residue from the existing cover crop into a horizontal mat on the soil surface. Mischler et al. 2010 reported that using a roller crimper in addition to a herbicide for termination of cereal rye provided similar weed control to that of a herbicide program in some instances. Delaying termination of cover crop species could allow cover crops greater time to increase biomass and let cash crops utilize weed suppression from the cover crop later in the growing season (Coulter and Nafzinger 2007); however, more research is needed to determine the most efficacious termination timing and method for each crop in Tennessee to maximize weed suppression while still protecting crop yield.

Winter-Annual Grass Cover Crops

Cereal rye and winter wheat are the two most common winter annual grass species used for cover cropping systems in the southeastern United States. Winter wheat is an appealing cover crop for many producers because it is economical and most producers already have experience growing winter wheat as a cash crop. Although winter wheat can be grown as a cash crop, it should be managed differently if it is being grown as a cover crop (SARE 2007). Cereal rye is the hardiest of the cereals (Daniel et al. 1999), and has the ability to produce extreme amounts of biomass (Reddy 2003; Norsworthy et al. 2011; Mirsky et al. 2013). Many studies have indicated that cereal rye can provide greater weed suppression than other cover crops (Price et al. 2007; Norsworthy et al. 2011). Cereal rye provides a wide planting window that will still allow it to produce considerable amounts of biomass, extensive root systems, and weed suppression. Because it could immobilize nitrogen in the soil, it is recommended to be seeded in combination with a legume cover crop species (SARE 2007). Daniel et al. (1999) observed that both rye and winter wheat improved soil characteristics. Because of the high amounts of biomass produced both above and below ground, termination of winter annual grass cover crops is essential. If adequate control of the cover crop is not obtained at termination, the cover crop can compete with the intended crop for moisture, nutrients and sunlight (Fisk et al. 2001). Glyphosate provides inconsistent control of these species, especially rye, making paraquat a more effective option for termination (White and Worsham 1990).

Legume Winter-Annual Cover Crops

Crimson clover (*Trifolium incarnatum*) and hairy vetch are two winter-annual legume species that have been researched extensively as cover crops (White and Worsham 1990; Reddy 2001; Norsworthy et al. 2010). Annual legumes have been shown to reduce pressure on some winter- and summer-annual weeds similarly to winter-annual grass species (Fisk et al. 2001; Isik et al. 2009). Although these species do not generate large amounts of biomass like winter-annual grass species, they provide other benefits to the subsequent crop. Leguminous species have the ability to fixate atmospheric nitrogen and significantly increase the amount of nitrogen in the soil (Duck and Tyler 1996). As with cereals, termination of winter-annual legume cover crop species is essential. Glyphosate provides inadequate control of these species, especially hairy vetch. This can cause early-season competition between the cover crop and the intended crop (Fisk et al. 2001). As with cereals, paraquat provides adequate control of these species, but auxinic herbicides such as 2,4-D or dicamba are also effective (White and Worsham 1990; McCurdy et al. 2013).

Conclusion

Over reliance on glyphosate caused a shift in the weed spectrum and caused several important weed species to develop GR (Culpeppper et al. 2006; Young

2006; Norsworthy et al. 2008; Heap 2016). This evolution of GR weeds has eliminated the viability of glyphosate-only weed control systems (Whitaker et al. 2010). Although glyphosate-tolerant crop technology initially caused a declined interest and research in non-herbicide weed control measures, the increase of GR biotypes of key weed species caused a renewed interest in alternative weed control systems. In areas such as west Tennessee, the focus of these alternative weed control measures has been based around systems that can be implemented into no-till or reduced tillage practices that complement what is currently being utilized. Winter-annual cover crops allow producers to maintain their current no-till systems and have the ability to suppress Palmer amaranth, which has become an extensive problem in Tennessee and throughout the Midsouthern U.S. (Price et al. 2007; Norsworthy et al. 2011; Webster 2012; Webster 2013). Although weed suppression has been recorded, inconsistencies in weed suppression have also been recorded. These inconsistencies have revealed a need for additional research to determine the most efficacious time and method of cover crop termination and for weed control measures in cover crops to provide consistent weed suppression of all problematic species.

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CHAPTER I:
EFFECTS OF CEREAL RYE, HAIRY VETCH, AND CEREAL RYE + HAIRY VETCH COVER CROP COMBINATIONS ON CORN GROWTH, DEVELOPMENT, AND YIELD

Abstract

Field experiments were conducted at the University of Tennessee's West Tennessee Research and Education Center in Jackson, TN in 2015 and 2016 to evaluate corn response to different termination timings of cereal rye, hairy vetch, and cereal rye + hairy vetch. Additionally a standard no cover crop, no-till treatment (NC) was included as a standard comparison. Termination intervals for each cover crop treatment were 0, 14, or 28 d prior to planting (DPP). NC treatment was terminated 28 DPP. Corn stand was similar when hairy vetch or cereal rye + hairy vetch was terminated 14 and 28 DPP, but was significantly lower if cover crop termination was delayed to 0 DPP. Corn vigor was greater when planted into hairy vetch or cereal rye + hairy vetch compared to cereal rye alone regardless of termination interval. Terminating hairy vetch or cereal rye + hairy vetch 14 or 28 DPP resulted in greater vigor than that of the NC. Similarly, corn height in hairy vetch or cereal rye + hairy vetch cover crop terminated prior to 0 DPP was greater than the NC and cereal rye alone. When cereal rye or hairy vetch were terminated 28 DPP corn yielded significantly below the NC. Other treatments were similar to the NC. A hairy vetch or cereal rye + hairy vetch cover crop in corn should be terminated 14 DPP to maximize cover crop biomass, and minimize impact on corn growth, development, or yield.

Introduction

Corn is the number one cereal crop in the United States, and the third most cultivated cereal crop in the world (Anonymous 2016; Fageria et al. 2011). Tennessee producers planted over 360 thousand ha in 2014, making it a major cash crop in Tennessee (Anonymous 2016). No-till crop production is prevalent in Tennessee, where 71% of the corn, cotton (*Gossipium hirisutum* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) hectarage were produced in a no-tillage production system in 2014 (Kenerson 2014). As herbicide-resistant (HR) weeds have become more numerous and prevalent, integrating winter-annual cover crops into no-tillage cropping systems as a means of weed suppression has become more common in Tennessee and indeed throughout the MidSouth and Southeastern regions of the United States.

Cover crops can be an important component of ecological weed management (Teasdale and Mohler 1993; Teasdale et al. 2007), and offer a variety of benefits that can enhance environmental quality and cropping sustainability (Mallory et al. 1998; Reddy et al. 2003; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996). Winter-annual cover crops that are utilized for weed suppression produce large amounts of biomass and can reduce available light and moisture for emerging weeds (Teasdale and Mohler 1993). The quantity of biomass present at a given time by a cover crop directly contributes to the amount of weed suppression that can be achieved (Mirsky et al. 2013; Norsworthy et al. 2011; Ryan et al. 2011). Cover crop termination is one of the most influential factors in determining the amount of weed suppression (Mirsky et al. 2013).

Some cover crop species that are commonly utilized for weed control include cereal rye, winter wheat, crimson clover, and hairy vetch (Wiggins et al. 2016). Producers often plant a combination of grass and legume cover crop species to provide increased biomass over that of either planted alone (Clark et al. 1993; Decker et al. 1994; Johnson et al. 1993; Mitchel and Tell 1977; Wiggins et al. 2016). Mirsky et al. (2011) found that delaying a cereal rye or cereal rye + hairy vetch cover crop termination from May 1 to May 30 increased biomass by 6015 kg ha^{-1} in Pennsylvania. This delay in termination ultimately led to greater weed suppression.

Although cover crop termination is often delayed to maximize weed suppression, cash crops such as corn can be negatively affected when existing vegetation is not terminated prior to planting (Hellwig et al. 2002). Tharp and Kells (2001) reported that when wheat cover crop termination was delayed to corn spike or 3-leaf stage, early season heights were decreased 28% and 42%, respectively, compared to when wheat was terminated PRE. Additionally, Munawar et al. (1990) reported a 14% and 9% reduction in corn yields in 1986 and 1987, respectively, when cereal rye was terminated at planting vs. 3 weeks prior to planting. Teasdale and Shirley (2013) reported that terminating a hairy vetch cover crop 1 to 3 weeks prior to planting produced higher corn yields than when the cover crop was terminated at corn planting or after corn emergence.

However, Johnson et al. (1993) concluded that a cereal rye cover reduced corn yield when terminated 3 d prior to planting while corn planted into a hairy vetch cover crop yielded similarly to corn planted into soybean residue.

The critical weed-free period of corn can be manipulated with nitrogen (N). Evans et al. (2003) found that 120 kg ha^{-1} N delayed the onset of the critical period for weed control in corn when compared to the 0 kg ha^{-1} in all site years, and also delayed the critical period for weed control in 3 of 4 site years when compared to 60 kg ha^{-1}. It was noted in this study that corn yield is sensitive to both N level and weed interference. Many producers utilize grass/legume cover crop combinations for their synergistic effects on cover crop biomass, however, little is known about how the combination of these cover crop species' interact with corn growth, development, and ultimately yield when termination is being delayed until at or near planting for maximum weed control.

Producers utilizing cover crops for weed control delay termination until near or at planting to maximize cover crop biomass for weed control (Larry Steckel, personal communication). Research evaluating corn growth, development, and yield interactions with grass, legume, and grass and legume combinations of cover crops at different termination timings is limited. The objective of this research is to identify the optimal termination interval for cereal rye, hairy vetch, or a combination of cereal rye and hairy vetch cover crop combinations that will maximize corn growth, development, and yield.

Materials and Methods

A study to evaluate corn response to different cover crop species and termination timings was conducted during the 2015 and 2016 growing seasons at the University of Tennessee's West Tennessee Research and Education Center in Jackson, TN (35.633, -88.856). The experimental site was planted to corn in each of the previous cropping season. In each year, corn stalks from the previous year were mowed immediately after harvest to facilitate corn residue decomposition and cover crop planting.

Covers were drilled in September and October of 2014 and 2015, respectively, using a no-till drill and allowed to over winter. The corn hybrid P1319-YHR (Pioneer Hi-Bred, Johnston, IA) was planted on April 22, 2015 and April 25, 2016. Corn was planted 7 cm deep at a population of 89,000 seed ha^{-1} into the existing cover crop residue with a no-tillage planter. Each plot consisted of 4 rows spaced 76 cm that were 9.1 m in length. All data were collected from the center two rows minimize border effects and maintain the integrity of the plot. The current University of Tennessee N recommendation for following a legume cover crop that has reached early bloom stage is to reduce total N rate by 67 to 90 kg ha^{-1} (Savoy and Joines 2009). However, in this trial 32-0-0 liquid N was applied at a rate of 202 kg ha^{-1} to the entire plot area at the V4 growth stage using a side-dressing implement. N rate was not reduced for the legume cover crop plots so that cover crop effects would not be confounded by N rates.

Treatments were replicated four times in a two-factor factorial within a randomized complete block design. The first factor was cover crop and consisted of cereal rye, hairy vetch, or a cereal rye/hairy vetch mix. Planting rates for cereal rye and hairy vetch were 67 and 22 kg ha^{-1}, respectively, whether planted alone or in combination. The second factor was termination timing and consisted of 28 d prior to planting (DPP), 14 DPP, and 0 DPP. Additionally, a no-cover, no-till (NC) was included as a standard for comparison. At each prescribed termination interval, designated plots were treated with paraquat at 851 g ai ha^{-1} plus 0.25% non-ionic surfactant. After termination, cover crop control was maintained thereafter. The existing vegetation in the NC plots consisted of henbit (*Lamium amplexicaule*) and annual bluegrass (*Poa annua*) was terminated 28 DPP and maintained weed free thereafter. Termination treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL). Blanket applications of paraquat at 851 g ai ha^{-1}, atrazine 454 g ai ha^{-1}, pyroxasulfone 48 g ai ha^{-1} plus 0.25% non-ionic surfactant 1 d after planting and a premix of glyphosate + s-metolachlor + mesotrione (1048 + 1048 + 105 g ai ha^{-1}) when corn reached the V3 growth stage provided season long weed control.

Corn vigor was visually estimated 14, 21, 28, and 35 d after planting (DAP) using a scale of 1-9, where 1=poor vigor and 9=exceptional vigor. Vigor was assessed as an overall measure of crop height, stand, and visual plant health (Tekrony and Egli 1991; Zhao et al. 2006). Data was also collected on corn stand 28 DAP and height was measured when corn reached the V3 and V6 growth stages. Corn stand was counted for the entire plot in the two data collection rows and then converted to plants per ha^{-1}. Crop heights were collected from 5 randomly selected plants and averaged for data analysis. Corn was harvested from this trial during both years of the study from rows one and two using a combine adapted for small-plot harvesting. Grain weights were recorded from each plot and later adjusted for moisture content to 15%.

All data were subjected to an analysis of variance using PROC GLIMMIX in SAS (ver. 9.4; SAS Institute; Cary, NC). Random effects were years, locations, and replications nested within years by location (Blouin et al. 2011). Considering year and location an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Evaluation interval was considered a repeated-measures variable for corn vigor and height data, which allows for comparisons across intervals and the changes in corn vigor and height over time (Blouin et al. 2004). Corn height data were $\log_{10}$ transformed. The transformation improved the homogeneity of variance based on visual inspection of the plotted residuals. Transformed data were used to determine mean separation; however, for ease of interpretation, actual means are presented based on the $\log_{10}$ transformed data analysis. Nontransformed data were used for corn vigor ratings, stand counts, and yield. Type III statistics were used to test the fixed effect of cover.

Termination timing and cover type were combined and analyzed as separate treatments to allow cover crop treatments to be compared to the NC treatment as a standard. Least square means were calculated based on $\alpha = 0.05$ and used for mean separation. Additionally, crop vigor, height, and stand and all combinations of these factors were regressed against yield to determine if any predictable relationships were present. This was done with a variable selection model in the PROC REG procedure in SAS. The DANDA.sas design and analysis macro collection (Saxton 2013) was utilized to build all PROC GLIMMIX (MMAOV) and PROC REG (REG) procedures, examine normality, perform necessary data transformations, and convert mean separation to letter groupings when appropriate.

Results and Discussion

A significant treatment effect was detected for corn stand (Tables 1 and 2). Corn stand was greatest in treatments with a cereal rye cover, terminated 14 DPP. Corn stand following cereal rye terminated 14 DPP was greater than the NC treatment, but not different than that of cereal rye alone treatments terminated at 0 or 28 DPP. Stand in hairy vetch treatments was similar when terminated 14 and 28 DPP, however, stand in hairy vetch terminated 0 DPP was lower than that of 14 or 28 DPP. Similarly, in cereal rye + hairy vetch treatments, stand was significantly lower at the 0 DPP termination timing than that of the 14 or 28 DPP intervals. Differences in stand were not detected when cereal rye + hairy vetch was terminated 14 or 28 DPP. Stand was similar for the NC, cereal rye terminated 0 or 28 DPP, hairy vetch terminated 14 or 28 DPP, and cereal rye + hairy vetch terminated 14 or 28 DPP. Hairy vetch or cereal rye + hairy vetch terminated 0 DPP were the only treatments that resulted in a stand significantly lower than that of the NC. Although there were significant differences among the treatments in corn stand, the stand in this study ranged from 76900 to 88600 plants per ha^{-1}, which is above the minimum 49400 plants per ha^{-1} which are needed to maintain yield according to University of Tennessee recommendations (Flinchum 2001).

Significant effects of cover treatment and rating interval were detected for corn vigor. However, there was no interaction among the main effects (Tables 1 and 3). Corn vigor, pooled across all treatments, was greatest 21 and 35 DAP. These intervals were significantly greater than 14 or 28 DAP intervals. Pooled across all rating intervals, corn vigor was greatest with hairy vetch terminated 14 DPP. Corn vigor in hairy vetch terminated 14 DPP was significantly greater than that of hairy vetch terminated 28 DPP, and cereal rye + hair vetch terminated 14 or 28 DPP; however, all of these treatments were more vigorous than that of the NC standard. Vigor from cereal rye treatments, at all termination intervals, was significantly lower than that of the NC. There were no significant differences between the NC and hairy vetch or cereal rye + hairy vetch treatments terminated 0 DPP.

Corn height followed a similar pattern to that of corn vigor. Significant main effects of treatment and growth stage were detected for corn height;

however, no interaction among the main effects was present (Tables 1 and 4). Pooled across each growth stage, corn height was greatest for treatments containing hairy vetch terminated 0 or 14 DPP. Corn heights for hairy vetch terminated 14 DPP was similar to hairy vetch terminated 28 DPP and cereal rye + hairy vetch terminated 28 DPP. Height from treatments containing cereal rye + hair vetch terminated 14 DPP were similar to cereal rye + hairy vetch terminated 0 and 28 DPP. All cereal rye alone treatments and cereal rye + hairy vetch terminated 0 DPP were similar to that of the NC. Additionally, all hairy vetch alone treatments and cereal rye + hairy vetch terminated 14 or 28 DPP had greater heights than that of the NC treatment.

Corn height and vigor were greater for vetch than cereal rye at all termination timings. Similarly, Yenish et al. (1996) found that corn height was greater when legume cover crops were utilized versus cereal rye in North Carolina. Also, Wiggins et al. (2016a) found that corn heights in hairy vetch cover crop were greater than that of the nontreated control at the V5 growth stage in Tennessee. Enhanced corn height and vigor can be largely be attributed to N supplied from the legume cover crop in the soil, whereas a cereal rye cover crop is a nitrogen scavenger (Ruffo et al. 2003). Additionally, Hydrick et al. (2015) found that corn growth rate per day was reduced from a stand of GR Italian ryegrass if termination was not conducted at least 28 DPP. This is indicative that corn growth and development can be adversely affected by other grass species if not the termination interval prior to planting is not great enough.

There was no interaction between rating intervals or growth stage for crop vigor or height (Table 1), therefore, data from these plots were averaged across all rating intervals or growth stages before being regressed. Additionally, height data was $\log_{10}$ transformed to improve normality prior to being subjected to the regression. However, a variable selection regression model indicated that crop stand, vigor, height, or any combination of these variables did not produce an R^2 greater than 0.28 and were not good indicators of final corn yield in this study (data not presented).

The ANOVA indicated a significant main effect of cover for corn yield (Tables 1 and 5). Hairy vetch terminated 14 DPP or cereal rye + hairy vetch terminated 28 DPP produced highest yields in this experiment, which were similar to the NC. Yields from these treatments were greater than that of cereal rye at all termination timings or hairy vetch terminated at 0 or 28 DPP. The lowest yields occurred where cereal rye or hairy vetch terminated 28 DPP, and were lower than that of the NC. However, these treatments were not different from cereal rye at all other termination intervals or hairy vetch terminated 0 DPP.

These results are similar to other researcher's findings, specifically that high biomass cover crops can be utilized in corn and will produce yields that are similar to no-till programs as long as weed control is maintained (Clark et al. 1993; Decker et al. 1994; Ebelhar et al. 1984; Gallagher et al. 2003; Johnson et al. 1993; Mitchel and Tell 1977; Utomo et al. 1989; Wiggins et al. 2016a). Clark et al. (1993) reported that corn yields from a vetch or cereal rye + hairy vetch cover crop were similar to that of standard no-till and greater than that of corn yields in a cereal rye alone cover crop, when terminated 10 d prior to planting; however differences were not as great when termination was conducted ~38 d prior to planting. In this study, yields from hairy vetch or cereal rye alone cover crop were similar to that of the NC when terminated 0 or 14 DPP; however, yields from cereal rye + hairy vetch were similar to that of the NC and that of the greatest treatments at all termination timings. Utilizing cereal rye + hairy vetch cover crop can create a synergistic effect increasing cover crop biomass (Clark et al. 1993; Clark et al. 1997; Ranells and Wagger 1996; Sanju et al. 2005; Teasdale and Abdul-Baki 1998; Wiggins et al. 2016; Zotarelli et al. 2009). This research indicates that cereal rye, hairy vetch, or cereal rye + hairy vetch combinations can be terminated 0 to 14 d prior to planting without impacting yields compared to standard no-tillage systems. Delayed termination timing can allow cover crop biomass and weed suppression to be increased. However, delaying termination timing to 0 DPP can also adversely affect corn stand, vigor, and height which might impact yields in some years. Therefore, cereal rye + hairy vetch or hairy vetch alone should be terminated 14 DPP for optimal corn growth, development, and yield in a weed control cover crop system.

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Appendix

Table 1: Significance of the main effects of cover crop treatment on corn stand, vigor, height, and yield in the evaluation of different termination timings of cereal rye, hairy vetch, or cereal rye + hairy vetch in Jackson, TN, in 2015 and 2016.

Effect[a,b]	Stand[c]	Vigor[d]	Height[e]	Yield[f]
	——p-value——			
Treatment	<.0001	<.0001	<.0001	0.0217
Rating	-	<.0001	<.0001	-
Treatment*Rating	-	0.1222	0.4704	-

[a] Treatment consisted of a cereal rye, hairy vetch, or cereal rye + hairy vetch cover crop terminated 0, 14, or 28 d prior to planting and also a no cover, no-till comparison.\

[b] Rating consisted of 14, 21, 28, and 35 d after planting ratings for vigor and measurements taken at V3 and V6 corn growth stages for height.

[c] Stand consisted of corn stand (plants per ha^{-1}) and were recorded 14 d after planting.

[d] Vigor consisted of a visual rating to assess overall measure of crop height, stand, and visual plant health.

[e] Height consisted of an average of 5 randomly selected plants per plot.

[f] Yield consisted of corn grain yield (kg ha^{-1}) adjusted to 15% moisture.

Table 2: Corn stand with cereal rye, hairy vetch, and cereal rye + hairy vetch at three termination intervals compared to a standard no-tillage system in Jackson, TN, in 2015 and 2016.

Cover Type	Termination[a]	Stand[b]
	DPP	$Plants/ha^{-1}$
No Cover	-	84200bc
Cereal rye	0	84800abc
Cereal rye	14	88600a
Cereal rye	28	86300ab
Hairy vetch	0	77400d
Hairy vetch	14	85000abc
Hairy vetch	28	83400c
Cereal rye + hairy vetch	0	77500d
Cereal rye + hairy vetch	14	84200bc
Cereal rye + hairy vetch	28	85900abc

[a] Abbreviations: DPP, days prior to planting. DAP, days after planting.
[b] Means for each corn stand followed by the same letter are not significantly different at $p \leq 0.05$.

Table 3: Corn vigor, a visual measure of crop height, stand, and visual plant health, when planted into different cover crop species terminated 0, 14, or 28 d prior to planting in Jackson, TN, in 2015 and 2016.

Main Effect		Termination[a]	Vigor[b]
Cover		DPP	1-9
	No Cover	-	6.3cd
	Cereal rye	0	4.8g
	Cereal rye	14	5.7ef
	Cereal rye	28	5.4f
	Hairy vetch	0	6.6bc
	Hairy vetch	14	7.4a
	Hairy vetch	28	6.9b
	Cereal rye + hairy vetch	0	6.1de
	Cereal rye + hairy vetch	14	6.8b
	Cereal rye + hairy vetch	28	6.8b

[a] Abbreviations: DPP, days prior to planting. DAP, days after planting
[b] Means for each corn vigor followed by the same letter are not significantly different at $p \leq 0.05$.

Table 4: Corn height as affected by a cereal rye, hairy vetch or cereal rye + hairy vetch cover crop terminated at 0, 14, or 28 d prior to planting in Jackson, TN, in 2015 and 2016.

Main Effect		Termination[a]	Height[b]
Cover		DPP	cm
	No Cover	-	37e
	Cereal rye	0	37e
	Cereal rye	14	41de
	Cereal rye	28	38e
	Hairy vetch	0	49ab
	Hairy vetch	14	54a
	Hairy vetch	28	46bc
	Cereal rye + hairy vetch	0	39de
	Cereal rye + hairy vetch	14	44cd
	Cereal rye + hairy vetch	28	46bc

[a] Abbreviations: DPP, days prior to planting.
[b] Means for each corn height followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of least squared means within each main effect.

Table 5: Corn yield with cereal rye, hairy vetch, or cereal rye + hairy vetch terminated at different intervals in Tennessee in 2015 and 2016 growing seasons.

Cover Type	Termination	Yield[b]
	DPP[a]	kg ha^{-1}
No Cover	-	11700ab
Cereal rye	0	10900bc
Cereal rye	14	11100bc
Cereal rye	28	10800c
Hairy vetch	0	11100bc
Hairy vetch	14	12200a
Hairy vetch	28	10700c
Cereal rye + hairy vetch	0	11400abc
Cereal rye + hairy vetch	14	11500abc
Cereal rye + hairy vetch	28	12000a

[a] Abbreviations: DPP, days prior to planting.
[b] Means for each corn yield followed by the same letter are not significantly different at $p \leq 0.05$.

CHAPTER II:
EVALUATION OF A ROLLER CRIMPER FOR CONTROL OF COVER CROPS AND WEEDS IN CONVENTIONAL CORN PRODUCTION

Abstract

Field experiments were conducted at the University of Tennessee's West Tennessee Research and Education Center in Jackson, TN in 2015 and 2016 to evaluate and compare the efficacy of glyphosate, glyphosate followed by (fb) a roller crimper, or a roller crimper alone, for terminating cereal rye or hairy vetch 0, 7, or 14 DPP corn. For glyphosate fb roller crimper treatments, glyphosate was applied 7 d prior and treatments were rolled at the prescribed termination interval. Pooled across cover crop species, glyphosate alone or fb a roller crimper provided $\geq$97% control 14d after planting (DAP). Biomass did not differ between cereal rye and hairy vetch, but biomass of each species was significantly increased by delaying termination. Additionally, biomass from glyphosate fb a roller crimper was less than of the roller crimper alone when pooled across both cover specie and all termination intervals (2110 and 2500 kg ha^{-1}, respectively). The roller crimper alone did not provide adequate control of either cover crop specie at any termination interval ($\leq$50% 14 DAP). The lack of control decreased the harvestable number of corn ears per ha^{-1} and corn yield to below that of other termination treatments and the no cover, nontreated control. Although glyphosate fb a roller crimper can be used to effectively terminate a cereal rye or hairy vetch cover crop, it did not improve weed control or corn yields over that of glyphosate alone. Additionally, of all the treatments, maximum control of Palmer amaranth or junglerice was 87 or 79%, respectively, 28 DAP indicating that additional control measures such as in-season herbicides should

be used in tandem with cover crops to provide season-long weed control. However, a roller crimper does not provide added benefits to producers in latitudes near Tennessee producing high yield corn.

Introduction

Corn is, by hectarage, the number one cereal crop in the United States, and the third most cultivated cereal crop in the world (Anonymous 2016; Fageria et al. 2011). Tennessee producers planted over 360 thousand ha in 2014, making it a major cash crop in Tennessee agriculture (Anonymous 2016). No-till crop production is prevalent in Tennessee, with 71% of the corn, cotton (*Gossipium hirisutum* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) hectares produced in a no-till environment in 2014 (Kenerson 2014). Until the mid to late 1990s, weedy vegetation was traditionally controlled with an initial burndown herbicide application or tillage then often followed by sequential preemergence herbicide applications (Culpepper 2006; Givens et al. 2009; Price et al. 2011). Producers were forced to be timely with those herbicide applications to achieve optimal weed control (Powles and Preston 2006). Glyphosate is a non-selective, post-emerge herbicide that controls many different weed species across a wide spectrum of growth stages. Since the introduction of glyphosate-resistant (GR) soybean, cotton, and corn in 1996, 1997, and 1998, respectively, the approach to herbicide weed control has changed drastically (Culpepper and York 1998; Corbet et al. 2004; Burke et al. 2005; Young 2006).

Palmer amaranth was first confirmed glyphosate-resistant (GR) in Georgia in 2004, and is currently documented as GR in most of the major U.S. agronomic states (Culpepper et al. 2006; Heap 2016). Postemergence control options for Palmer amaranth are limited in some of the major agronomic crops. The *Amaranthus* genus is notable as a group due to the success of many members as weeds in agronomic scenarios (Steckel et al. 2004). Although Palmer amaranth is native to the Sonoran Desert, in recent decades it has spread and proliferated in the Southeast and Midsouth regions of the United States (Ehleringer 1983; Bond and Oliver 2006; Culpepper et al. 2006; Steckel 2007; Barnett et al. 2013). This trend can, in part, be associated with the adoption of reduced tillage systems in combination with an overall reduction in the amount of residual herbicides being utilized (Culpepper 2006; Young 2006). Palmer amaranth is one of ten dioecious (male and female flowers on separate plants) *Amaranthus* spp. native to North America (Bond and Oliver 2006; Steckel 2007). It is one of the most prevalent and troublesome of the *Amaranthus* species (Horak and Loughin 2000; Guo and Al-Khatib 2003; Norsworthy et al. 2008; Main et al. 2012). Palmer amaranth exhibits an extremely rapid growth habit and can grow 24 to 62% more per growing degree day than any other *Amaranthus* species (Culpepper et al. 2006). The aggressive growth rate and stature of this weed make it extremely competitive with agronomic crops (Klingaman and Oliver 1994; Bond and Oliver 2006; Culpepper et al. 2006).

A cover crop is any living ground cover that is planted into or after a cash crop and then commonly terminated before or shortly after the next main crop is planted (Hartwig and Ammon 2002). The intent of a winter-annual cover crop for weed suppression is to produce unfavorable growing conditions through production of above ground mulch from plant residue creating competition for resources and sunlight between the cover crop and weeds (Teasdale 1996; Teasdale and Mohler 1993). Cover crops can be an important component of ecological weed management (Teasdale and Mohler 1993; Teasdale et al. 2007), and offer a variety of benefits that can enhance environmental quality and cropping sustainability (Mallory et al. 1998; Reddy et al. 2003; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996).

Cereal rye is the hardiest of the cereals (Daniel et al. 1999), and has the ability to produce extreme amounts of biomass (Reddy et al. 2003; Norsworthy et al. 2011; Mirsky et al. 2013). Many studies have indicated that cereal rye can provide greater weed suppression than other cover crops (Price et al. 2007; Norsworthy et al. 2011; Wiggins et al. 2016). Cereal rye may be planted during a wide planting window that will still allow it to produce considerable amounts of biomass, extensive root systems, and weed suppression. Annual legume covers have been shown to reduce populations of some winter- and summer-annual weeds similarly to winter-annual grass species (Fisk et al. 2001; Isik et al. 2009). Although these species do not generate large amounts of biomass like winter-annual grass species, they provide other benefits to the subsequent crop.

Leguminous species have the ability to fixate atmospheric nitrogen and significantly increase the amount of nitrogen in the soil (Duck and Tyler 1996). Regardless of cover crop species, adequate termination is essential.

Cover crop termination is one of the most influential factors in determining the amount of weed suppression (Mirsky et al. 2013). The quantity of biomass present at a given time by a cover crop directly contributes to the amount of weed suppression that can be achieved (Norsworthy et al. 2011; Ryan et al. 2011; Mirsky et al. 2013). Non-selective herbicides, such as glyphosate, glufosinate, or paraquat, or mechanical control measures such as tillage, mowing, or a roller crimper are commonly utilized for cover crop termination. Regardless of termination method, complete cover crop control is necessary for producing a successful cash crop. Insufficient control of a cover crop may cause problems similar to that of early-season weed pressure and can ultimately lead to a yield reduction in the following cash crop (Fisk et al. 2001; Tharp and Kells 2001; Mirsky 2008).

Research examining mechanical tools for cover crops has been increasing in recent decades. One of these tools is the roller crimper which is a cylinder with protruding fins that rotates on a lengthwise axis as is it drawn over the cover crop. The weight of the roller crimper is concentrated onto a finite area with the protruding fins, which creates a ‘crimp’ in plant stems, breaks essential vascular tissues, and can lead to plant death. In addition to cover crop termination, a roller crimper also compacts residue from the existing cover crop into a horizontal mat on the soil surface. Mischler et al. (2010) reported that using a roller crimper in addition to a herbicide to terminate of cereal rye resulted in weed control similar to that of a herbicide program in some instances. Ashford Reeves (2003) reported that a roller crimper was an effective tool for terminating a cereal rye cover crop at the soft dough stage but that a roller crimper + a herbicide was required for termination at earlier growth stages in Alabama. Utilizing a roller crimper to terminate a hairy vetch cover crop is more variable as hairy vetch growth stage is also important in determining the amount of control that will be achieved from a roller crimper (Hoffman et al. 1993, Mischler et al. 2010).

Inquiries about mechanically terminating cover crops are increasing, while the knowledge base around how cover crops will respond in the environment found in Tennessee is limited. Therefore, a study was conducted to evaluate the effectiveness of a roller crimper versus a herbicide to terminate hairy vetch and cereal rye cover crops in Tennessee. The objective of this research is to identify which termination method is most appropriate for corn producers who want to utilize cover crops for weed control in typical corn production systems.

Materials and Methods

A study to evaluate cereal rye and hairy vetch cover crop response to different termination methods and timings prior to corn planting was conducted during the 2015 and 2016 growing seasons at the University of Tennessee's West Tennessee Research and Education Center in Jackson, TN (35.633, -88.856). Cereal rye and hairy vetch were sowed at seeding rates of 67 and 22 kg ha^{-1}, respectively, following soybeans and corn the previous cropping season in 2014 and 2015, respectively. Following the 2015 growing season, corn stalks were mowed immediately after harvest to facilitate residue decomposition and cover crop planting; however, in each year, the sites were planted into standard no-tillage environments common to west Tennessee.

Covers were drilled in September and October of 2014 and 2015, respectively, using a no-till drill and allowed to over winter. The corn hybrid P1319-YHR (Pioneer Hi-Bred, Johnston IA) was planted on April 22, 2015 and April 25, 2016. Corn was planted 7 cm deep at a population of 89,000 seed ha^{-1} into the existing cover crop residue with a no-tillage planter. Individual plots consisted of two, 76 cm rows that were 9.1 m in length. The University of Tennessee recommends reducing total nitrogen in corn by 67 to 90 kg ha^{-1} following a legume cover crop that has reached early bloom stage (Savoy and Joines 2009). However, in this 32-0-0 liquid nitrogen was applied at a rate of 202 kg ha^{-1} at the V4 growth stage using a side-dressing implement to the entire plot area. Nitrogen rate was not adjusted for the legume covers to reduce the potential for differences in nitrogen fertilizer to confound the effect of cover crop.

Treatments were replicated four times in a modified split-plot arrangement within a randomized complete block. The first factor level was termination timing and consisted of 14 d prior to planting (DPP), 7 DPP, and 0 DPP. The second factor level was termination method and consisted of glyphosate at 1260 g ae ha^{-1}, a roller crimper, or glyphosate 1260 g ae ha^{-1} 7 d prior to the roller crimper. In the herbicide + roller crimper treatments, glyphosate was applied 7 d prior to the prescribed interval and the roller crimper was utilized at the designated timing. Each termination method contained subplots of cereal rye or hairy vetch cover crop species. The roller crimper utilized in this study (I & J Manufacturing, Gap, PA) was 3 m wide and similar in design to the roller tested by Kornecki et al. (2006), with metal blades perpendicularly attached to the cylinder in a chevron pattern. The width of the roller crimper in this study necessitated the split-plot arrangement of different cover species within each termination method. Additionally, a no cover treatment (NC) was included as a nontreated comparison for all cover termination timings, termination methods, and species. The NC plot was treated with paraquat at 851 g ai ha^{-1} plus 0.25% non-ionic surfactant to terminate any existing vegetation at planting, but no other weed control measures were conducted thereafter. Termination dates and cover crop growth stage at each termination timing are presented in Table 6 for cereal rye and hairy vetch (Zadoks et al. 1974). Herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

Cover crop biomass was collected at each termination timing for each termination method and cover crop from 0.5 m^2 quadrants. These cover crop samples were then dried for 48 hours in a forced-air oven at 60°C and weighed. Cover crop control was visually estimated at 7, 14, 21, and 28 d after planting

(DAP) on a scale of 0 to 100%, where 0 no injury or control and 100 complete plant death. Control of Palmer amaranth and junglerice [*Echonichloa crus-galli* (L.) P. Beauv] was visually assessed 7 to 28 DAP in weekly increments. Lack of cover crop control in some treatments was noted and the number of harvestable ears per 3 m of row was counted and used to express the effects of incomplete cover crop control on corn growth. Corn was harvested in each year of this experiment with a small plot combine and yields were adjusted to 15% moisture.

All data were subjected to an analysis of variance using PROC GLIMMIX in SAS (ver. 9.4; SAS Institute; Cary, NC). Random effects were years, locations, and replications nested within years by location (Blouin et al. 2011). Considering year and location an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). The square roots of visual estimates for cover crop and weed control were arcsine transformed and biomass and yield data were $\log_{10}$ transformed. The transformations did not improve homogeneity of variance for Palmer amaranth or junglerice control, biomass or yield based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. The arcsine square root transformation improved the homogeneity of cover crop control data, so actual least squared means are presented for ease of interpretation, with mean separation based on that of the transformed data. Data from the nontreated control were deleted prior to analysis of visual control estimates to stabilize variance. Data for yield and harvestable ears per ha^{-1} of the nontreated control was averaged for each site year and then subtracted from each plot in that siteyear to provide a number for relative yield and harvestable ears per ha^{-1}. Type III statistics were used to test all fixed effects or interactions between the fixed effects. Least square means were calculated based on α = 0.05 and utilized for mean separation. The DANDA.sas design and analysis macro collection (Saxton 2013) was used to build all PROC GLIMMIX (MMAOV) procedures, examine normality, perform necessary data transformations, and convert mean separation to letter groupings when appropriate.

Results and Discussion

Significant main effects of DPP and termination method were detected for cover crop biomass (Tables 7 and 8). When pooled across cereal rye and hairy vetch cover crops, cover crop biomass was the greatest when termination was delayed until 0 DPP, and similar at termination intervals of 7 or 14 DPP. A glyphosate termination produced greater biomass than either the roller crimper alone or glyphosate fb the roller crimper. It is the authors' belief that differences between the roller crimper and herbicide alone sampling method influenced the amount of biomass measured. Treatments were rolled immediately prior to collecting biomass samples and a similar trend was present throughout both covers and all termination intervals. However, biomass differences between the roller crimper and glyphosate fb roller crimper indicate that utilizing glyphosate 7 d prior to the roller crimper does reduce the amount of biomass produced by the cover crop.

Cover crop control was affected by termination method*termination interval (DPP) (Tables 9 and 10) and termination method*cover crop species 7 DAP (data not presented). Pooled across termination intervals, control was greatest for glyphosate fb roller crimper treatments with 99 and 96% control of cereal rye and hairy vetch, respectively, and was followed by glyphosate alone, with 88 and 87% control. Control from glyphosate fb roller crimper was greater than that of glyphosate alone. However, control did not differ among cover species for either of these methods. Control from the roller crimper alone was lower than that of other termination methods with hairy vetch control (53%) being greater than that of cereal rye (36%) 7 DAP. Pooled across covers, control from glyphosate alone ranged from 77 to 93%, with the 0 DPP interval being lower than that of 7 or 14 DPP; however, control increased to ≥97% with glyphosate alone or glyphosate fb roller crimper 14 DAP. The roller crimper alone provided ≤54% control at all termination intervals when pooled across covers 7 or 14 DAP. Main effects of termination interval, termination method, and cover crop species were significant 21 DAP, however there was no interaction among the main effects (Tables 9 and 11). Pooled across cover species and termination methods, cover crop control was greatest when terminated 0 or 7 DPP. Control when termination was delayed to 0 DPP was greater than at 14 DPP. Utilizing glyphosate or glyphosate fb roller crimper provided more control than that of the roller crimper alone across all timings and cover species. Additionally, control of cereal rye was greater than that of hairy vetch. Although there was an interaction in the main effects of termination method and cover species 28 DAP, all treatments provided greater than 93% control at this interval.

Because of the lack of control from roller crimper alone treatments, it was decided to measure harvestable corn ears per ha^{-1}. A significant effect of termination method was detected for harvestable ears (Tables 7 and 8). Harvestable corn ears for glyphosate and glyphosate fb the roller crimper (2000 and 1500 harvestable ears ha^{-1}, respectively) were similar and greater than that of the nontreated, while that of the roller crimper alone (-1600 harvestable ears ha^{-1}) were less than that of the other termination methods and the nontreated control. Additionally, there were significant main effects of termination interval, method, and cover crop species on corn yield, but no interaction among the main effects (Tables 7 and 8). Corn yields were drastically higher in hairy vetch treatments compared to cereal rye. Corn yield was greater, pooled across covers and methods, when termination was 0 or 7 DPP compared to 14 DPP termination interval. Termination methods of glyphosate or glyphosate fb roller crimper were similar and greater than when the roller crimper was utilized alone. When the roller crimper was used alone for cover crop control, corn yields were 32 kg ha^{-1} less than that of the nontreated control. This, in combination with the reduction of harvestable ears per ha^{-1}, was indicative that the uncontrolled cover crop was more competitive with the corn than the native weed population. Because the cover crop was not terminated effectively, weed control ratings in these plots were disproportionally skewed and deleted from weed control ratings as they do not represent a viable system for use by producers.

There was a significant main effect of termination method*cover crop species for Palmer amaranth control 7 DAP; however control at this interval ranged from 96 to 99% (data not presented) and will not be discussed in depth. Significant effects of termination method and cover crop*termination interval (Tables 9 and 12) were detected for Palmer amaranth control 14 and 21 DAP. Pooled across termination intervals and cover crop species, terminating with glyphosate alone was more efficacious than termination with glyphosate fb a roller crimper at each rating. This was likely due to the reduction in biomass from utilizing glyphosate 7 d prior to rolling. Pooled over termination methods, cereal rye provided greater Palmer control than hairy vetch at the 7 and 14 DPP intervals 14 DAP, and at all termination intervals 21 DAP. However, 14 DAP hairy vetch terminated 0 DPP provided 97% control of Palmer amaranth and was similar to that of the best treatment. Termination timing and cover crop species were the only significant main effects for Palmer amaranth control 28 DAP. Pooled over methods and cover crop species, Palmer amaranth control was significantly decreased at each termination interval, with the greatest control being achieved from 0 DPP termination timing. Also, cereal rye provided greater control of Palmer amaranth than hairy vetch when pooled across all termination methods and timings.

A significant interaction of the main effects of cover crop species, termination interval, and termination method was present for junglerice control 7 DAP (Table 9). However, this was transient as the three-way interaction was not different at later evaluation timings. Moreover, all treatments except hairy vetch terminated with glyphosate fb a roller crimper 14 DPP (83%) were similar and provided ≥97% control (data not presented). Control 14 DAP, pooled over covers and termination intervals (Table 9) was greater with glyphosate alone than with glyphosate fb a roller crimper (92 and 85% control, respectively). At 14 DAP, there was an interaction of the main effects of cover crop species and termination interval. At this rating, cereal rye terminated 0 or 7 DPP and hairy vetch terminated 0 DPP provided ≥93% control and maximized control at this interval. Control with hairy vetch terminated 7 DPP was similar to that of cereal rye terminated 7 or 14 DPP (86, 93, and 87% control, respectively) but less than either cover terminated 0 DPP. Hairy vetch terminated 14 DPP was significantly lower than all other treatments at this rating (74%). Significant main effects of termination, interval, and cover crop species were present for junglerice control 21 and 28 DAP, however no interaction of the main effects was present at these intervals (Tables 9 and 13). Similar patterns were present at each rating interval for each of the main effects. Junglerice control increased as DPP decreased at each termination interval, with 0 DPP termination providing the greatest control. Glyphosate provided greater control than that of glyphosate fb a roller crimper at each rating and control from cereal rye was greater than that of hairy vetch.

Control of Palmer amaranth or junglerice from the best treatments was less than acceptable 28 DAP (87 and 79%, respectively).

Mischler et al. (2010) reported that when cereal rye termination was delayed from late-April to mid-May, resulting biomass from the cover crop nearly doubled in most instances and ultimately led to increased weed control. Also, in the aforementioned study, biomass from cereal rye, in the late-April termination ranged from 2593 to 5013 kg ha^{-1}. Biomass from either cover crop in this study ranged from 2650 to 3600 kg ha^{-1} and 2350 to 2900 kg ha^{-1} for cereal rye and hairy vetch, respectively, in glyphosate alone termination treatments. The biomass from this study is about one-third to one-half that (6,000 to 6,790 kg ha^{-1}) reported from research conducted in more southern latitudes of the U.S. (Price et al 2012; 2016). Corn in this study was planted in late April, which is common in west Tennessee. Research in Tennessee has indicated that delaying corn planting until after May 1st will likely result in lower yields (McClure 2009). Delaying cover crop termination later was not an option as it would not have allowed corn to reach its maximum yield potential.

Weed suppression was increased by delaying cover crop termination until corn planting; however, utilizing a roller crimper did not improve weed control or corn yields. Although cereal rye provided greater control of Palmer amaranth and junglerice, corn yields were greater in hairy vetch treatments. Although corn growth, development, and yield can be influenced by improper termination timing and species of cover crops, the critical weed-free period of corn can be manipulated with nitrogen. Evans et al. (2003) found that 120 kg ha^{-1} delayed the onset of the critical period for weed control in corn when compared to the 0 kg ha^{-1} in all site years, and also delayed the critical period for weed control in three of four site years when compared to 60 kg ha^{-1}. It was noted in this study that corn yield is sensitive to both nitrogen and weed interference. The effects on corn yield in this study were likely affected by the nitrogen released in the hairy vetch treatments. Although glyphosate fb a roller crimper can be used to effectively terminate a cereal rye or hairy vetch cover crop, it did not improve weed control or corn yields over that of glyphosate alone. Additionally, of all the treatments, maximum control of Palmer amaranth or junglerice was 87 or 79%, respectively, 28 DAP indicating that additional control measures such as in-season herbicides should be used in tandem with cover crops to provide season long weed control (Wiggins et al. 2016); however, a roller crimper does not provide any added benefits to producers in latitudes near Tennessee producing high yield corn.

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Appendix

Table 6. Cereal rye and hairy vetch growth stages at 0, 7, and 14 d prior to planting termination intervals at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016.

Termination Interval[a]	Cereal rye[b]		Hairy vetch		Date	
	2015	2016	2015	2016	2015	2016
0 DPP	41	43	veg	veg	April 20	April 25
7 DPP	39	41	veg	veg	April 12	April 18
14 DPP	36	39	veg	veg	April 6	April 13

[a] Abbreviations: DPP, days prior to planting; veg, vegetative growth stage.
[b] According to Zadoks growth staging.

Table 7: Analysis of variance for cover crop biomass, harvestable corn ears per ha^{-1}, and yield in a cereal rye or hairy vetch cover crop terminated with a roller crimper, glyphosate, or glyphosate fb a roller crimper at different termination intervals in Jackson, TN, in 2015 and 2016.

Main Effect[a]	Biomass	Harvestable Ears	Yield
		p value	
DPP	<.0001	0.9937	0.0057
Method	<.0001	0.0001	<.0001
Method*DPP	0.8212	0.1768	0.0650
Cover	0.1317	0.0838	0.0001
DPP*Cover	0.2432	0.7241	0.4467
Method*Cover	0.2859	0.4349	0.6067
Method*DBP*Cover	0.5918	0.3911	0.1813

[a] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}), a roller crimper, or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover, represents two cover crop species: cereal rye or hairy vetch.

Table 8: The significant effects cover crop biomass, harvestable corn ears per ha^{-1}, and corn yields from different termination timings and methods with a cereal rye or hairy vetch cover crop in Jackson, TN, in 2015 and 2016[a].

Main effect[b]	Factor Levels[c,d]	Biomass	Harvestable Ears	Yield
		kg ha^{-1}	no. ha^{-1}	kg ha^{-1}
Termination Interval				
	0 DPP	2870a	640ns	940a
	7 DPP	2320b	698ns	1200a
	14 DPP	2180b	598ns	260b
Termination Method				
	Glyphosate	2760a	2000a	1100a
	Roller Crimper	2500b	-1600b	-32b
	Glyphosate fb Roller Crimper	2110c	1500a	1300a
Cover				
	Cereal Rye	2580ns	0ns	290b
	Hairy Vetch	2330ns	1290ns	1300a

[a] Means from harvestable ears ha^{-1} and corn yield are presented in relation to the no cover crop, nontreated control. The nontreated control averaged 18,500 harvestable ears per ha^{-1} and 7300 kg ha^{-1} of grain yield. Data for each main effect are pooled each other main effect shown.

[b] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect.

[c] Abbreviation: DPP, days prior to planting.

[d] Glyphosate was applied at 1260 g ae ha^{-1} and was applied 7 d prior to the roller crimper in 'Glyphosate fb Roller Crimper' treatments..

Table 9: Significance of the main effects of termination interval, termination method, and cover crop species and the interaction of the main effects on cover crop, Palmer amaranth, and jungle rice control at 7, 14, 21, and 28 days after corn planting at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016[a].

Effects[b]	Cover Crop				Palmer amaranth				Jungle rice			
	7	14	21	28	7	14	21	28	7	14	21	28
	p-value											
DPP	0.537	0.016	0.017	0.169	0.069	<.001	<.001	<.001	0.003	<.001	<.001	<.001
Method	<.001	<.001	<.001	<.001	0.031	0.001	0.003	0.254	0.016	0.001	0.001	0.005
Method*DPP	<.001	0.022	0.232	0.133	0.069	0.429	0.952	0.612	0.006	0.208	0.674	0.828
Cover	0.521	0.037	0.001	0.042	0.086	0.014	<.001	<.001	0.004	0.077	0.034	<.001
DPP*Cover	0.309	0.865	0.845	0.823	0.069	<.001	0.018	0.112	0.001	0.001	0.255	0.155
Method*Cov	<.001	0.691	0.813	0.001	0.031	0.418	0.834	0.069	0.004	0.878	0.883	0.691
Method*DPP*Cov	0.209	0.597	0.821	0.941	0.069	0.539	0.533	0.627	0.020	0.352	0.687	0.612

[a] Column headings 7, 14, 21, and 28 designate evaluation intervals of 7, 14, 21, and 28 days after corn planting.
[b] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}), a roller crimper, or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover or Cov, represents two cover crop species: cereal rye or hairy vetch.

Table 10: Percent control of a cereal rye or hairy vetch cover crop from a roller crimper, glyphosate, or glyphosate fb a roller crimper prior to planting corn in Tennessee in 2015 and 2016[a,b,c].

Effect	Factor Levels	Control 7 DAP	Control 14 DAP
		—%—	
Method*DPP			
	Glyphosate - 0 DPP	77c	98a
	Glyphosate - 7 DPP	93ab	98a
	Glyphosate - 14 DPP	92b	98a
	Roller Crimper - 0 DPP	54d	50b
	Roller Crimper - 7 DPP	41e	42c
	Roller Crimper - 14 DPP	38e	31d
	Glyphosate fb Roller Crimper - 0 DPP	98a	99a
	Glyphosate fb Roller Crimper - 7 DPP	98a	99a
	Glyphosate fb Roller Crimper - 14 DPP	97a	97a
Cover			
	Cereal rye	75ns	81a
	Hairy vetch	79ns	77b

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$._Letters are only reflective of means within each main effect.
[b] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}), a roller crimper, or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover, represents two cover crop species: cereal rye or hairy vetch.
[c] Data from the main effect of Method*DPP are pooled over the cover crop species listed below. Data from the cover crop species are pooled over the termination methods and intervals listed above.

Table 11: Control of cereal rye and hairy vetch cover crops from glyphosate, a roller crimper, or glyphosate fb a roller crimper 21 days after planting corn at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016[a,b,c].

Effects		Cover Crop Control
	Factor levels	%
Days Prior to Planting		
	0	79a
	7	76ab
	14	73b
Method		
	Glyphosate	98a
	Roller Crimper	34b
	Glyphosate fb Roller Crimper	97a
Cover		
	Cereal rye	79a
	Hairy Vetch	73b

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect.
[b] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}), a roller crimper, or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover, represents two cover crop species: cereal rye or hairy vetch.
[c] Data for each main effect are pooled each other main effect shown.

Table 12: Control of Palmer amaranth from a cereal rye or hairy vetch cover crop terminated with glyphosate or glyphosate fb a roller crimper 0, 7, or 14 days prior to planting corn in Tennessee in 2015 and 2016[a,b,c].

Main effect	Factor Levels	Days after Planting 14	21	28
			%	
DPP				
	0	97ns	88ns	83a
	7	93ns	81ns	76b
	14	86ns	74ns	70c
Method				
	Glyphosate	94a	84a	77ns
	Glyphosate fb Roller Crimper	90b	78b	75ns
Cover				
	Cereal rye	96ns	87ns	82a
	Hairy vetch	87ns	75ns	71b
Cover*DPP				
	Cereal rye - 0 DPP	97a	91a	87ns
	Hairy vetch - 0 DPP	97a	85b	79ns
	Cereal rye - 7 DPP	97a	86ab	81ns
	Hairy vetch - 7 DPP	88b	76c	71ns
	Cereal rye - 14 DPP	95a	83b	77ns
	Hairy vetch - 14 DPP	77c	65d	62ns

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect or interaction of main effects.

[b] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}) or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover, represents two cover crop species: cereal rye or hairy vetch.

[c] Data for each main effect or interaction of main effects are pooled each other main effect shown.

Table 13: Control of junglerice 21 and 28 days after corn planting from a cereal rye or hairy vetch cover crop terminated with glyphosate or glyphosate fb a roller crimper at termination intervals of 0, 7, or 14 days prior to planting in Tennessee in 2015 and 2016[a,b,c].

Main effect	Factor Levels	Days after Planting 21	28
		—%—	
DPP			
	0	84a	79a
	7	77b	72b
	14	72c	66c
Method			
	Glyphosate	81a	75a
	Glyphosate fb Roller crimper	74b	70b
Cover			
	Cereal rye	81a	76a
	Hairy vetch	74b	69b

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect or interaction of main effects.
[b] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}) or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover, represents two cover crop species: cereal rye or hairy vetch.
[c] Data for each main effect are pooled each other main effect shown.

CHAPTER III:
EVALUATION OF A ROLLER CRIMPER FOR CEREAL RYE OR HAIRY VETCH COVER CROP TERMINATION PRIOR TO SOYBEANS IN TENNESSEE

Abstract

A study to evaluate cereal rye and hairy vetch cover crop response to different termination methods and timings prior to soybean planting was conducted during the 2015 and 2016 growing seasons at the University of Tennessee's West Tennessee Research and Education Center in Jackson, TN. Treatments were arranged in a modified split-plot design within a randomized complete block with four replications. The first factor was termination timings at 14 d prior to planting (DPP), 7 DPP, and 0 DPP. The second factor was termination methods of glyphosate at 1260 g ae ha^{-1}, a roller crimper, or glyphosate 1260 g ae ha^{-1} 7 d prior to (fb) the roller crimper. Each termination method contained subplots of cereal rye or hairy vetch. Pooled across each cover crop species, biomass increased with each delayed termination interval, and cereal rye produced greater biomass than hairy vetch when pooled over all termination intervals. Palmer amaranth control 21 DAP was not affected by termination method but was affected by termination interval. Control increased incrementally with each delay in termination. A similar trend with increasing Palmer control at each termination interval was also present 28 DAP. However, control 35 DAP at the 14 DPP termination interval was 15 to 9% less than the 0 and 7 DPP terminations, respectively. Junglerice control 28 DAP was greatest from cereal rye and hairy vetch terminated 0 DPP, with a roller crimper or glyphosate alone being the most efficacious termination methods. Soybean yields were similar and highest in cereal rye cover crop treatments that were

terminated with glyphosate fb a roller crimper or the roller crimper alone. A roller crimper provides benefits that can be utilized for terminating a cereal rye or hairy vetch cover crop 0 to 14 d prior to planting soybeans in Tennessee. However, for greatest weed control and soybean yields, producers should utilize a cereal rye cover, terminated with a roller crimper 0 to 7 d prior to planting soybeans in tandem with in-season herbicides.

Introduction

There were approximately 4.4 million ha of soybeans planted in Tennessee in the 2016 growing season making it an important crop in the state (Anonymous 2016). No-tillage is prevalent in Tennessee, with 71% of the corn (*Zea mays* L.), cotton (*Gossypium hirisutum* L.), soybean, and wheat (*Triticum aestivum* L) hectares were produced in a no-till environment in 2014 (Kenerson 2014). Palmer amaranth is native to the Sonoran Desert, and in recent decades it has spread eastward and proliferated in the Southeast and Midsouth regions of the United States (Ehleringer 1983; Bond and Oliver 2006; Culpepper et al. 2006; Steckel 2007; Barnett et al. 2013). This trend can, in part, be associated with the adoption of reduced tillage systems in combination with an overall reduction in the amount of residual herbicides being utilized (Culpepper 2006; Young 2006). The aggressive growth rate, stature, and inherent survival abilities of this weed make it extremely competitive with agronomic crops (Klingaman and Oliver 1994; Bond and Oliver 2006; Culpepper et al. 2006). For over 10 years, the majority of soybeans sown in Tennessee were glyphosate-tolerant. Glyphosate-resistant

Palmer amaranth was first confirmed in Georgia in 2004 followed by Tennessee in 2006 (Culpepper et al. 2006; Heap 2016; Steckel et al. 2008). It has since become one of the most economically damaging weeds in the United States (Beckie 2011). In the past, soybean producers in Tennessee and the Midsouth have relied heavily on protoporphyrinogen IX oxidase herbicides for control of this weed (Miller and Norsworthy 2016). However, the confirmation and spread of protoporphyrinogen IX oxidase-resistant (PR) Palmer amaranth caused a shift in management strategies among producers (Heap 2016; L. Steckel, personal communication).

Cover crops are one method for weed suppression that has been the subject of increasing interest, especially in areas where no-tillage cropping systems are prevalent. A cover crop is any living ground cover that is planted into or after a cash crop and then terminated before or shortly after the next main crop is planted (Hartwig and Ammon 2002). The intent of a winter-annual cover crop for weed suppression is to produce unfavorable growing conditions through production of above ground mulch from plant residue, creating competition for resources and sunlight between the cover crop and weeds (Teasdale 1996). Cover crops can be an important component of ecological weed management (Teasdale and Mohler 1993; Teasdale et al. 2007), and offer a variety of benefits that can enhance environmental quality and cropping sustainability (Mallory et al. 1998; Reddy et al. 2003; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996).

Cover crop termination is one of the most influential factors in determining the amount of biomass or weed suppression that will be produced from the cover crop (Mirsky et al. 2013). Cereal rye is the hardiest of the cereals (Daniel et al. 1999), and has the ability to produce large amounts of biomass (Mirsky et al. 2013; Norsworthy et al. 2011; Reddy et al. 2003). Many studies have indicated that cereal rye can provide greater weed suppression than other cover crops (Norsworthy et al. 2011; Price et al. 2007; Wiggins et al. 2016). Cereal rye can produce extensive root systems, considerable amounts of biomass, and is planted across a wide planting window before the cash crop. Annual legumes have been shown to reduce pressure on some winter- and summer-annual weeds similarly to winter-annual grass species (Fisk et al. 2001; Isik et al. 2009). The quantity of biomass present at a given time by a cover crop directly contributes to the amount of weed suppression that can be achieved (Mirsky et al. 2013; Norsworthy et al. 2011; Ryan et al. 2011). Non-selective herbicides, such as glyphosate, glufosinate, or paraquat, or mechanical control measures such as tillage, mowing, or a roller crimper are commonly utilized for cover crop termination. Regardless of termination method, complete cover crop control is essential for producing a successful cash crop. Insufficient control of a cover crop has been reported to cause similar problems to that of early season weed pressure and can ultimately lead to a yield reduction in the following cash crop (Fisk et al. 2001; Tharp and Kells 2001; Mirsky 2008).

Research surrounding mechanical tools for cover crops has been increasing in recent decades. One of these tools is the cover crop roller crimper which is a cylinder with protruding fins that rotates on a lengthwise axis as it is drawn over the cover crop. The weight of the roller crimper is concentrated onto a finite area with the protruding fins, which creates a 'crimp' in plant stems, breaks essential vascular tissues, and can lead to plant death. In addition to cover crop termination, a roller crimper also compacts residue from the existing cover crop into a horizontal mat on the soil surface. Mischler et al. 2010 reported that using a roller crimper in addition to a herbicide for termination of cereal rye provided similar weed control to that of a herbicide program in some instances. Ashford and Reeves (2003) reported that using a roller crimper was an effective tool for terminating a cereal rye cover crop at the soft dough stage but that a roller crimper + a herbicide was required for termination at earlier growth stages in Alabama. Utilizing a roller crimper for terminating a hairy vetch cover crop is more variable as hairy vetch growth stage is also important in determining the amount of control that will be achieved from a roller crimper (Hoffman et al. 1993, Mischler et al. 2010).

With increases in herbicide resistant biotypes of Palmer amaranth (Heap 2016) and inquiries from producers about how to effectively manage cover crops for control of this weed species, a niche for additional research into the use of herbicide and mechanical cover crop control methods prior to planting soybeans was identified. Therefore, a study was conducted to evaluate the effectiveness of a roller crimper versus a herbicide for terminating cereal rye and hairy vetch prior to soybean planting in Tennessee. The objective of this research is to identify and quantify the attributes or lack thereof from different cover crop termination methods in no-till soybean production.

Materials and Methods

A study to evaluate cereal rye and hairy vetch cover crop response to different termination methods and timings prior to soybean planting was conducted during the 2015 and 2016 growing seasons at the University of Tennessee's West Tennessee Research and Education Center in Jackson, TN (35.633, -88.856). The experimental site was planted to soybeans and cotton the previous cropping season in 2014 and 2015, respectively. Following the 2015 growing season, cotton stalks were mowed immediately after harvest to facilitate residue decomposition and cover crop planting. However, in each year, the sites were planted into standard no-tillage environments common to west Tennessee (Kenerson 2014).

Covers were drilled in September and October of 2014 and 2015, respectively, using a no-till drill and allowed to over winter. The soybean variety 4850LL (Bayer CropScience AG, Rhein, Germany) was planted on May 26, 2015 and May 16, 2016. Soybeans were planted 3 cm deep at a population of 346,000 seed ha^{-1} into the existing cover crop residue with a no-tillage planter. Individual plots consisted of two, 76 cm rows that were 9.1 m in length. Treatments were replicated four times in a modified split-plot arrangement within a randomized complete block. The first factor level was termination timing and consisted of 14 d prior to planting (DPP), 7 DPP, and 0 DPP. The second factor level was termination method and consisted of glyphosate at 1260 g ae ha^{-1}, a roller crimper, or glyphosate 1260 g ae ha^{-1} 7 d prior to (fb) the roller crimper. Each termination method contained subplots of cereal rye or hairy vetch. Cover crop seeding rates were 67 and 22 kg ha^{-1} for cereal rye and hairy vetch, respectively. The roller crimper utilized in this study (I & J Manufacturing, Gap, PA) was 3 m wide and similar in design to the roller tested by Kornecki et al. (2006), with metal blades perpendicularly attached to the cylinder in a chevron pattern. The width of the roller crimper in this study necessitated the split-plot arrangement of different cover species within each termination method. Additionally, a no cover treatment (NC) was included as a nontreated comparison for all cover termination timings, termination methods, and species. The NC treatments consisted of winter annual henbit (*Lamium amplexicaule* L.), horseweed (*Conyza canadensis* (L) Cronq.), chickweed (*Stellaria media* L.), and annual bluegrass (*Poa annua* L.). The NC plot was treated with paraquat at 851 g ai ha^{-1} plus 0.25% non-ionic surfactant to terminate any existing vegetation at planting. Termination dates and cover crop growth stage at each termination timing are presented in Table 1 for cereal rye and hairy vetch (Zadok et al. 1974). Herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} using AIXR11002 nozzles (AIXR TeeJet Air

Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

Cover crop biomass was collected at each termination timing for each termination method and cover crop from 0.5 m^2 quadrants. These cover crop samples were then dried in a forced-air oven at 60°C for 48 hrs. Cover crop control was visually estimated 7, 14, 21, and 28 d after planting (DAP) on a scale of 0 to 100%, where 0 represented no injury or control and 100 represented complete plant death. Cover crop growth stages and treatment application dates are presented in Table 14. Control ratings for cover crops did not begin until after planting because the authors' previous research indicated that the process of planting the cash crop with a no-till planter increases cover crop control (unpublished data). Control of Palmer amaranth and junglerice was visually assessed 7, 14, 21, 28, and 35 DAP. A sequential, broadcast application of glufosinate (602 g ai ha^{-1}) was applied to all plots after all assessment data was collected to facilitate mechanical harvest. Soybeans were harvested in each year of this experiment with a small plot combine and yields were adjusted to a moisture content of 13%.

All data were subjected to an analysis of variance using PROC GLIMMIX in SAS (ver. 9.4; SAS Institute; Cary, NC). Random effects were years, locations, and replications nested within years by location (Blouin et al. 2011). Considering year and location an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). The square roots of visual estimates for cover crop and weed control were arcsine transformed and cover crop biomass and yield data were $\log_{10}$ transformed. The transformations did not improve homogeneity of variance for biomass or cover crop, Palmer amaranth, or junglerice control, or yield based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Data for yield of the nontreated control was averaged for each site year and then subtracted from each plot in that siteyear to provide a number for relative yield.

There was an interaction of the main effects of termination timing, termination method, and cover crop species (data not shown, Pr>f=0.0252). However, upon visual inspection of the least squared means, it was determined that the differences were caused by a sampling error, as the designated treatments were rolled prior to biomass samples being collected. The initial data indicated that roller crimper and glyphosate fb roller crimper treatments produced less biomass than treatments terminated at the same time with glyphosate alone. Therefore, data from glyphosate alone treatments were analyzed separately and used as reflective biomass samples from each termination timing, and roller crimper and glyphosate fb roller crimper data were analyzed using single degree of freedom contrast statements. Contrast statements analyzed the differences in each cover crop species at each termination timing, each cover crop pooled over all termination timings, and both cover crop species pooled over all termination timings to determine if using glyphosate 7 d prior to the roller crimper reduced cover crop biomass compared to that of the roller crimper alone.

Type III statistics were used to test all fixed effects or interactions between the fixed effects. Least square means were calculated based on α = 0.05 and utilized for mean separation. The DANDA.sas design and analysis macro collection (Saxton 2013) was utilized to build all PROC GLIMMIX (MMAOV) procedures, examine normality, perform necessary data transformations, and convert mean separation to letter groupings when appropriate.

Results and Discussion

The analysis of variance, for cover crop biomass when terminated with glyphosate, detected significant main effects of termination interval and cover crop species, but there was no interaction among the main effects (Tables 15 and 16). Pooled across each cover crop species, biomass significantly increased with each delayed termination interval, and cereal rye provided greater biomass than hairy vetch when pooled over all termination intervals. Additionally, contrast statements comparing glyphosate fb a roller crimper or the roller crimper alone detected no differences in biomass for cereal rye or hairy vetch at any termination timing, covers pooled over all termination timings, or when pooled over each cover crop and all termination timings, therefore data not shown. There was a main effect of termination method for cover crop control 7 DAP (Table 14); however, this difference was considered transient as all treatments provided $\geq$97% control at this interval. Additionally, there were no significant differences in cover crop control 14 DAP and all treatments provided $\geq$98% control (data not presented). These data would agree with Ashford and Reeves (2003) and Mirsky (2008) who reported that a roller crimper, similar to the one used in this research, effectively controlled a cereal rye cover crop at the soft dough or anthesis growth stages, respectively. Research examining a roller crimper for control of hairy vetch is slightly more variable. Mischler et al. (2010) reported that control of hairy vetch with a roller crimper was variable through the flowering stages, but after early pod set, control was more consistent and acceptable. However, Davis (2010) noted that soybean performance in hairy vetch was decidedly worse when using a roller crimper in comparison to a herbicide burndown due to lack of cover crop control.

Although control of each weed species was assessed 7 DAP in each site year, no weeds were present at this timing in any cover crop treatment. However, in each year, at this rating, weeds had already begun to emerge in the no cover, nontreated control. For Palmer amaranth control there were significant main effects of termination method and cover crop species, but other main effects or interactions among the main effects were not detected 14 DAP (Tables 17 and 18). At this rating, control of Palmer amaranth, pooled over termination intervals and cover crop species, was significantly greater with the roller crimper than with glyphosate fb the roller crimper, and control from glyphosate alone was intermediate but not different from the other termination methods (Table 18). Additionally, at 14 DAP Palmer control with cereal rye was greater than that of hairy vetch, and these results were present and similar for all other rating intervals. Control 21 DAP was not affected by termination method but was affected by termination interval. Control decreased incrementally with each delay in termination. A similar trend with decreasing Palmer control at each termination interval was also present 28 DAP. However, control 35 DAP at the 14 DPP termination interval was 15 to 9% less than the 0 and 7 DPP terminations, respectively.

A similar trend was also present for the main effect of termination method 28 and 35 DAP. Control at each of the intervals was similar for glyphosate and glyphosate fb the roller crimper and less than that of the roller crimper alone. Burgos and Talbert (1996) reported that low rates of atrazine and metolachlor reduced total weed density more effectively in a no cover system than did a hairy vetch cover crop. Moreover, they found that when no herbicide was used, cereal rye significantly improved control of Palmer amaranth compared to that of hairy vetch cover crop alone. Palmer amaranth was controlled greater with a cover crop of cereal rye than hairy vetch at each rating. These differences in control between cover crops became more drastic at the later ratings. Hairy vetch residue does not persist on the soil surface as long as the residue of cereal rye (Reddy 2001). Additionally, hairy vetch is a legume species and fixes nitrogen. After the residue from hairy vetch decomposes, the increase in soil nitrogen can increase Palmer amaranth growth (Ruf 2005; Ward et al. 2013). Control of Palmer amaranth was greater from the roller crimper alone than with glyphosate fb the roller crimper 14 and 28 DAP. Weed suppression from cereal rye is predominantly due to the quantity of biomass produced and left on the soil surface (Barnes and Putnam 1985; Teasdale et al. 1991; Reeves et al. 2005; Price et al. 2006; 2007; 2011; Culpepper et al. 2009; 2010). It was noted in this study that, even though cover crop biomass was similar, cereal rye residue deteriorated faster in treatments with glyphosate 7 d prior being rolled when compared to roller crimper alone treatments (Davis 2010). This could possibly explain the difference in control from glyphosate fb the roller crimper and the roller crimper alone.

A significant interaction of the main effects of termination method and termination interval were detected for junglerice control 14 DAP (Tables 17 and 19). Junglerice was controlled best with termination methods of glyphosate or the roller crimper alone 0 DPP. Glyphosate fb the roller crimper 14 DPP provided the least control at this timing. Control 21 DAP was influenced by the main effect of termination method and the interaction of the main effects of cover crop species and termination interval. Junglerice control was similar from termination methods of glyphosate or the roller crimper alone and greater than glyphosate fb the roller crimper. Control was greatest with cereal rye terminated 0 or 7 DPP or hairy vetch terminated 0 DPP. Control incrementally decreased for hairy vetch terminated 7 DPP, cereal rye terminated 14 DPP, and hairy vetch terminated 14 DPP. A similar trend was observed 28 DAP, where junglerice control was greatest from cereal rye and hairy vetch terminated 0 DPP. The least control at this time was from hairy vetch terminated 14 DPP. An interaction of the main effects of termination timing and method was also detected at this timing for junglerice control, with control being maximized from utilizing the roller crimper or glyphosate alone when terminated 0 DPP. Interactions of the main effects of cover crop species*termination timing and cover crop species*termination method were detected for junglerice control 35 DAP. Control was greatest from cereal rye terminated 0 or 7 DPP. These treatments were greater than hairy vetch at all termination timings, but control from cereal rye terminated at 7 or 14 DPP did not differ. Also at this rating, control from cereal rye with similar for all termination methods and greater than hairy vetch for all termination methods. However, control from hairy vetch was greater from the roller crimper alone than with glyphosate or glyphosate fb the roller crimper. Similarly, Burgos and Talbert (1996) reported cereal rye improved the control of large crabgrass (*Digitari sanguinalis*) over that of the hairy vetch cover crop alone. The effects of this are thought to be similar to the mechanisms that make cereal rye a better suppressant of Palmer amaranth than hairy vetch.

There was a significant interaction in the main effects of cover crop species and termination method on soybean yield (Tables 15 and 20). Soybean yields were similar and highest in cereal rye cover crop treatments that were terminated with glyphosate fb a roller crimper or the roller crimper alone. Yields from all other treatments were similar and lower than that of the aforementioned treatments. It is the authors’ belief that yield loss in hairy vetch cover treatments can be attributed to lack of weed control as Palmer amaranth and junglerice control was significantly lower in these treatments than cereal rye treatments 35 DAP. In addition to increasing weed control, the roller can also benefit the cash crop in that it is not having to grow through the substantial amount of standing biomass that was produced by cereal rye. Although 35 DAP weed control of Palmer amaranth was less for glyphosate fb the roller crimper than the roller crimper alone and junglerice control was not significantly different, yields from these termination methods were similar in cereal rye. Although termination method, timing, and cover crop species did influence weed control in this research, the greatest control from any treatment was 67 or 56% control of Palmer amaranth or junglerice, respectively (Tables 19 and 20). This control is not acceptable on an agronomic level indicating a need for additional management strategies, such as in-season herbicides, should still be used for season long weed control for season long control (Norsworthy et al. 2014; Reddy et al. 2003; Wiggins et al. 2016; Yenish et al. 1996). A roller crimper does provide benefits and can be utilized for terminating a cereal rye or hairy vetch cover crop 0 to 14 DPP soybeans in Tennessee. However, for greatest weed control and soybean yields, producers should utilize a cereal rye cover, terminated with a roller crimper 0 to 7 d prior to planting soybeans in tandem with in-season herbicides.

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Appendix

Table 14: Cereal rye and hairy vetch growth stages and corresponding dates at 0, 7, and 14 DPP soybeans at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016.

Termination Interval[a]	Cereal rye[b]		Hairy vetch		Date	
	2015	2016	2015	2016	2015	2016
0 DPP	69	67	early pod	mid pod	May 26	May 16
7 DPP	65	62	early pod	early pod	May 19	May 10
14 DPP	61	59	late flower	early pod	May 11	May 4

[a] Abbreviations: DPP, days prior to planting.
[b] According to Zadok's growth staging.

Table 15: Main effects of termination intervals, termination methods, cover crop species, and the interaction of these effects on cover crop biomass and control and soybean yield in no-till environment in Tennessee in 2015 and 2016.

Main Effect[a]	Biomass	Cover Crop Control[b]		Soybean yield
		7	14	
	p-value			
DPP	<.0001	0.9035	0.8092	0.1597
Method	-	0.0115	0.9951	0.0945
Method*DPP	-	0.9852	0.4971	0.2460
Cover	<.0001	0.3785	0.1861	<.0001
Cover*DPP	0.2371	0.8782	0.9318	0.7790
Method*Cover	-	0.0912	0.7541	0.0086
Method*Cover*DPP	-	0.9829	0.3448	0.0579

[a] Termination intervals were 0, 7, and 14 d prior to planting soybeans. Termination methods consisted of glyphosate, glyphosate 7 d prior to a roller crimper, and a roller crimper alone. Cover crop species consisted of cereal rye or hairy vetch planted at 67 and 22 kg ha^{-1}, respectively.
[b] Column headings 7 and 14 designate termination intervals 7 and 14 d prior to planting soybeans.

Table 16: Cover crop biomass as affected by termination intervals and methods at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016[a,b].

Main effect		Biomass
	Factor Levels	kg ha^{-1}
Termination Interval		
	0 DPP	4390a
	7 DPP	3590b
	14 DPP	2210c
Cover Crop Species		
	Cereal rye	4010a
	Hairy vetch	2790b

[a] Abbreviation: DPP, refers to termination interval or days prior to planting.
[b] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect. Data for each main effect are pooled over the other main effect shown.

Table 17: The main effects of termination interval (DBP), termination method (Method), cover crop specie (Cover), and the interactions among the main effects for Palmer amaranth and junglerice control after planting soybeans in Tennessee in 2015 and 2016[a,b].

Effect	Palmer amaranth control				Junglerice control			
	14	21	28	35	14	21	28	35
	p-value							
DPP	0.318	<.001	<.001	0.001	<.001	<.001	<.001	<.001
Method	0.018	0.083	0.001	0.017	<.001	<.001	<.001	0.012
Method* DPP	0.583	0.757	0.083	0.437	0.020	0.199	0.022	0.945
Cover	0.033	<.001	<.001	<.001	0.430	<.001	0.013	<.001
Cover* DPP	0.201	0.383	0.333	0.179	0.769	0.010	<.001	0.048
Method* Cover	0.698	0.553	0.519	0.310	0.542	0.509	0.134	0.007
Method* Cov*DPP	0.721	0.103	0.186	0.261	0.064	0.774	0.079	0.719

[a] Termination intervals were 0, 7, and 14 d prior to planting soybeans. Termination methods consisted of glyphosate, glyphosate 7 d prior to a roller crimper, and a roller crimper alone. Cover crop species consisted of cereal rye or hairy vetch planted at 67 and 22 kg ha^{-1}, respectively.
[b] Column headings 14, 21, 28, and 35 designate evaluation intervals of 14, 21, 28, and 35 d after planting soybeans.

Table 18: Palmer control affected by cover crop termination interval, method, and species in soybeans at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016.

Effect[a,b]		Palmer amaranth control[c]			
	Factor Levels	14	21	28	35
		%			
DBP					
	0	ns	82a	72a	60a
	7	ns	79b	66b	56a
	14	ns	70c	58c	51b
Method					
	Glyphosate	88ab	ns	63b	53b
	Glyphosate fb Roller Crimper	86b	ns	64b	55b
	Roller Crimper	91a	ns	68a	59a
Cover					
	Cereal rye	91a	84a	74a	67a
	Hairy vetch	86b	70b	56b	45b

[a] Abbreviations: DPP, represents three termination intervals: 0, 7, or 14 days prior to planting; Method, represents three termination methods: glyphosate (1260 g ae ha^{-1}), a roller crimper, or glyphosate (1260 g ae ha^{-1}) 7 days prior to the roller crimper at the designated termination interval; Cover, represents two cover crop species: cereal rye or hairy vetch.

[b] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect.

[c] Column headings 14, 21, 28, and 35 designate evaluation intervals of 14, 21, 28, and 35 d after planting soybeans.

Table 19: Junglerice control affected by cover crop termination interval, method, and species in soybeans at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016[a,b].

Effect	Factor Levels	Junglerice control			
		14	21	28	35
		%			
Method					
	Glyphosate	ns	75a	ns	ns
	Glyphosate fb Roller Crimper	ns	70b	ns	ns
	Roller Crimper	ns	77a	ns	ns
Method* DPP					
	Glyphosate - 0	95a	ns	74ab	ns
	Glyphosate - 7	84de	ns	71b	ns
	Glyphosate - 14	82e	ns	64c	ns
	Glyphosate fb Roller Crimper - 0	87cde	ns	70b	ns
	Glyphosate fb Roller Crimper - 7	85cde	ns	60c	ns
	Glyphosate fb Roller Crimper - 14	76f	ns	51d	ns
	Roller Crimper - 0	94ab	ns	77a	ns
	Roller Crimper - 7	89bc	ns	64c	ns
	Roller Crimper - 14	88cd	ns	62c	ns
Cover* DPP					
	Cereal rye - 0	ns	82a	72ab	56a
	Hairy vetch - 0	ns	81a	75a	46c
	Cereal rye - 7	ns	79a	69bc	55ab
	Hairy vetch - 7	ns	74b	61d	38d
	Cereal rye - 14	ns	69c	65cd	49bc
	Hairy vetch - 14	ns	58d	53e	32e
Method* Cover					
	Cereal rye - Glyphosate	ns	ns	ns	53a
	Hairy vetch - Glyphosate	ns	ns	ns	38c
	Cereal rye - Glyphosate fb Roller Crimper	ns	ns	ns	54a

Table 19 Continued: Junglerice control affected by cover crop termination interval, method, and species in soybeans at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016[a,b].

Effect		Junglerice control			
	Factor Levels	14	21	28	35
Method* Cover		——	——	%	——
	Hairy vetch - Glyphosate fb Roller Crimper	ns	ns	ns	33c
	Cereal rye - Roller Crimper	ns	ns	ns	53a
	Hairy vetch - Roller Crimper	ns	ns	ns	45b

[a] Means within a column followed by the same letter are not significantly different at $p < 0.05$. Letters are only reflective of means within each main effect. Means designated as 'ns' are not significant at $p < 0.05$ or are reflected in a higher interaction of main effects.

[b] Column headings 14, 21, 28, and 35 designate evaluation intervals of 14, 21, 28, and 35 d after planting soybeans.

Table 20: Soybean yields from a cereal rye or hairy vetch cover crop terminated with glyphosate, glyphosate 7 d prior to a roller crimper, or a roller crimper at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016[a,b].

Cover*Termination Method	Soybean yield
	kg ha^{-1}
Glyphosate - Cereal rye	1160b
Glyphosate - Hairy vetch	1080b
Glyphosate fb Roller Crimper - Cereal rye	1750a
Glyphosate fb Roller Crimper - Hairy vetch	830b
Roller Crimper - Cereal rye	1690a
Roller Crimper - Hairy vetch	1130b

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.
[b] Means from soybean yield are presented in relation to the no cover crop, nontreated control.

CHAPTER IV:
UTILIZING GLYPHOSATE PLUS DICAMBA TOLERANT SOYBEANS IN A COVER CROPPING SYSTEM TO CONTROL PALMER AMARANTH

Abstract

A study to evaluate the response of glyphosate- and dicama-tolerant (GDT) soybeans and weed control from different termination intervals before and after soybean planting into a wheat + hairy vetch cover crop. The whole plot consisted of cover crop termination timings of 14 d prior to planting (DPP), 7 DPP, 0 DPP, 7 d after planting (DAP), and 14 DAP. The sub plot was POST herbicide program and consisted of a premix of glyphosate plus fomesafen (1120 and 280 g ae ha^{-1}, respectively) or a proprietary premix of glyphosate plus the diglycolamine salt of dicamba (1120 and 560 g ae ha^{-1}, respectively) applied when Palmer amaranth for that termination interval reached 10 cm in height. Cover crop biomass was highest when terminated 0 DPP, and control decreased incrementally with the 7 DPP and DAP timings and again at the 14 DPP and DAP timings. Decreased cover crop biomass after planting was a result of partial cover crop control with the planter. Glyphosate + dicamba provided total cover of cover crops by 21 DAP. Cover crop termination timing did not influence soybean population or yield. However, treatments receiving a POST application of glyphosate + dicamba yielded 100 kg ha^{-1} higher than those treated with fomesafen. Control at the 21 and 28 DAT ratings ranged from 97 to 99%, with dicamba providing the greatest control at these ratings. Significant main effects or interactions among the main effects were not detected at the final, R6 soybean stage, rating and all treatments provided $\geq$ 97% control of Palmer amaranth. Although differences in Palmer amaranth control were not apparent at the end of

the season, early season Palmer amaranth control ratings (21 and 28 DAT) followed a similar trend to that of soybean yields. When utilizing a wheat + hairy vetch cover crop in DGT soybeans, producers should delay cover crop termination until 11 to 14 DPP and make at least one POST application of glyphosate + dicamba + an additional herbicide MOA to maximize Palmer amaranth control and soybean yields.

Introduction

Glyphosate-resistant (GR) soybean, cotton (*Gossypium hirisutum* L.), and corn (*Zea mays* L.) were introduced into the United States marketplace (Roundup Ready®, Monsanto, St. Louis, MO) in 1996, 1997, and 1998, respectively, and soon thereafter drastically changed the approach to weed control (Burke et al. 2005; Corbett et al. 2004; Culpepper 2006; Culpepper and York 1998; Norsworthy et al. 2012; Young 2006). Producers shifted to total POST herbicide programs, often solely relying on glyphosate for weed control (Culpepper 2006; Norsworthy et al. 2012; Young 2006). The ability to effectively use glyphosate during the growing season for broad spectrum weed control allowed producers to apply fewer total herbicides to their crops and become less dependent on tillage to control weeds prior to planting (Culpepper 2006; Young 2006). Over-reliance on glyphosate caused a shift in the overall weed spectrum through extreme selection pressure and GR biotypes of key weed species, such as horseweed [*Conyza canadensis* (L.) Cronq.] and Palmer amaranth, have become common in the major agronomic areas of the U.S. (Culpepper 2006; Koger et al. 2004;

Norsworthy et al. 2008; VanGessel 2001). Palmer amaranth was first confirmed GR in Georgia in 2004, and is currently documented as GR in most of the major U.S. agronomic states (Culpepper 2006; Heap 2016). Since that time, Palmer amaranth has become one of the most economically damaging weeds in the U.S. and dominates in-season weed management decisions where present (Beckie 2011; Johnson et al. 2009; Price et al. 2011; Webster and Sosnoskie 2010). The aggressive growth rate, stature, and inherent survival abilities of this weed make it extremely competitive with agronomic crops (Klingaman and Oliver 1994; Bond and Oliver 2006; Culpepper et al. 2006).

There were approximately 4.4 million ha of soybeans planted in Tennessee in the 2016 growing season making it an important crop in the state (Anonymous 2016). In 2014, 94% of the soybean hectarage in the United States was planted with herbicide-resistant soybean cultivars (USDA NASS 2014). The majority of soybeans sown in Tennessee between the late 1990's and 2015 were glyphosate-tolerant (L. Steckel, personal communication). In the past, soybean producers in Tennessee and the Midsouth have heavily relied on protoporphyrinogen IX oxidase (PPO) herbicides for control of GR Palmer amaranth (Miller and Norsworthy 2016). However, the confirmation and spread of PPO-resistant Palmer amaranth resulted in growers shifting to more glufosinate-tolerant soybeans 2016 (Heap 2016; L. Steckel, personal communication). The loss of PPO herbicides removed effective POST herbicide options for controlling Palmer amaranth in GR soybeans. In response to the increased incidence of weed resistance to glyphosate and other herbicides, seed companies are now developing soybean cultivars with resistance to multiple herbicides such as glyphosate plus dicamba (GDT).

Dicamba has been widely used for over 40 yr, and is an effective herbicide for the control of most broadleaf weed species (Behrens et al. 2007; Mueller et al. 2013; Shaner 2014). Dicamba is an auxin-mimicking herbicide that controls GR Palmer amaranth and other broadleaf weeds alone or in combination with other herbicides (Cahoon et al. 2015; Green and Owen 2010; Merchant et al. 2013; Samples et al. 2013; Sanders and Marshall 2014; York et al. 2012, 2015). Inman et al. (2016) reported that glyphosate plus dicamba significantly decreased the frequency of a mix of glyphosate-resistant/susecptible population of Palmer amaranth and total Palmer amaranth density when compared to glyphosate alone. Crow et al. (2016) reported that dicamba + diflufenzopyr provided similar to or greater control of large (>20cm) Palmer amaranth when compared to other single herbicide mode of action (MOA) treatments in corn. The ability to utilize this MOA in-season in soybeans could greatly increase the sustainability and durability of weed control programs in the future if it is properly fostered (Vink et al. 2016).

Additionally, producers have begun utilizing other management practices such as cover crops to combat multiple herbicide-resistant weed species. No-till crop production is prevalent in Tennessee, where seventy one percent of the corn, cotton, soybean, and wheat hectares were produced in a no-till environment in 2014 (Kenerson 2014). No-tillage limit the cultural control methods available to producers for combating difficult herbicide-resistant weeds, such as Palmer amaranth (Price et al. 2011). However, cover crops can be implemented into no-till systems to increase the sustainability of weed control programs (Barnes and Putnam 1985; Beckie 2011; Burgos and Talbert 1996; Fisk et al 2001; Mirsky et al. 2013; Norsworthy et al. 2011; Wiggins et al. 2016; 2016a). Cereal rye and winter wheat are two common winter annual grass species used for cover cropping systems in the southeastern United States (Currie and Klocke 2005; Daniel et al. 1999; Norsworthy et al. 2011; Wiggins et al. 2016). Winter wheat is an appealing cover crop for many producers because it is economical and many producers already have experience growing it as a cash crop. However, winter wheat should be managed differently if it is being grown as a cover crop (SARE 2007). Crimson clover (*Trifolium incarnatum* L.) and hairy vetch are two winter-annual legume species that have been researched extensively as cover crops (Norsworthy et al. 2010; Reddy 2001; White and Worsham 1990). Annual legumes have been shown to reduce pressure on some winter- and summer-annual weeds similarly to winter-annual grass species (Fisk et al. 2001; Isik et al. 2009). However, utilizing a cereal + legume cover crop combination can create a synergistic effect increasing cover crop biomass (Clark et al. 1993; Clark et al. 1997; Ranells and Wagger 1996; Sanju et al. 2005; Teasdale and Abdul-Baki 1998; Wiggins et al. 2016; Zotarelli et al. 2009). The quantity of biomass present at a given time by a cover crop directly contributes to the amount of weed suppression that can be achieved (Mirsky et al. 2013; Norsworthy et al. 2011; Ryan et al. 2011a; Wiggins et al. 2016).

Cover crop termination is one of the most influential factors in determining the amount of weed suppression (Mirsky et al. 2013). Delaying cover crop termination until at or near planting of the cash crop allows the cover crop a longer growing season, thus producing more biomass (Ashford and Reeves 2003; Mischler et al. 2011; Mirksy et al. 2009; Wortman et al. 2012). Although chemical termination of cereal cover crop species such as cereal rye or wheat can easily be accomplished with glyphosate (Ashford and Reeves 2003; Currie and Klocke 2005; Price et al. 2009), termination of legume cover crops with herbicides labeled for at or near cash crop planting can be more challenging (Davis 2010; Fisk et al. 2001; Wiggins et al. 2016, 2016a; White and Worsham 1990). However, auxin herbicides such as 2,4-D or dicamba have proven to be effective herbicides to control legume cover crop species (Curran et al. 2015; McCurdy et al. 2013). White and Worsham (1990) reported that dicamba provided 97% control of hairy vetch prior to planting corn in North Carolina.

Cereal + legume cover crop mixtures are becoming more common in areas where producers are utilizing cover crops to combat difficult to control weed species. The advent of GDT soybean technologies could provide producers with an effective herbicide option for terminating such cover crop mixtures near soybean planting. The ability to delay termination of cover crop mixtures used in combination with new herbicide-tolerant crop technologies could provide producers an effective means to increase sustainability of weed control systems for soybeans in no-till environments. Therefore, research was conducted to determine the viability of using glyphosate + dicamba for terminating a wheat + hairy vetch cover crop at different timings before and after planting GDT soybeans in Tennessee.

Materials and Methods

A study to evaluate wheat + hairy vetch termination and in-crop weed control with fomesafen and dicamba in GDT soybean systems was done in the growing seasons of 2015 and 2016 at the West Tennessee Research and Education Center, in Jackson, TN (35.633, -88.856). The experimental site was planted to soybeans in each of the previous site years, and both cover crops and soybeans were sown into long term no-till environments common to west Tennessee.

Wheat and vetch cover crops (seeded at 67 and 22 kg ha^{-1}, respectively) were drilled in September and October of 2014 and 2015, respectively, using a no-till drill and allowed to over winter (Table 1). An experimental, proprietary, late-four maturity group GDT soybean variety (Monsanto Co., St. Louis, MO) was sown on May 11, 2015 and May 16, 2016. Soybeans were planted 3 cm deep at a population of 346,000 seed ha^{-1} into the existing cover crop residue with a no-tillage planter. Individual plots consisted of two, 76 cm rows that were 9.1 m in length. Treatments were replicated four times in a split-plot design within a randomized complete block. The whole plot was termination timing and consisted of 14 d prior to planting (DPP), 7 DPP, 0 DPP, 7 d after planting (DAP), and 14 DAP. The sub plot was POST herbicide and consisted of a premix of glyphosate plus fomesafen (1120 and 280 g ae ha^{-1}, respectively) or a proprietary premix of glyphosate plus the diglyocolamine salt of dicamba (1120 and 560 g ae ha^{-1}, respectively) applied when Palmer amaranth for that termination interval reached 10 cm in height. The research site was infested with nearly 100% GR Palmer amaranth (unpublished data), so these treatments are referred to as fomesafen and dicamba, respectively. Termination dates and cover crop growth stage at each termination timing are presented in Table 21 for wheat and hairy vetch (Zadok et al. 1974). POST herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} equipped with TTI110025 nozzles (TTI Turbo TeeJet Spray Tips, TeeJet Technologies, Wheaton, IL), in accordance with currently proposed nozzle requirements for using dicamba on GDT-soybeans (R. Montgomery, personal communication).

Cover crop biomass was collected from 0.5 m^2 quadrants at each termination timing for each termination method and cover crop. Cover crop samples were then dried in a forced-air oven at 60°C for 48 hrs. Soybean stand was counted and averaged over two randomly selected sections of 0.5 m per row in each plot and converted to plants per ha^{-1}. Cover crop control was visually estimated on a scale of 0 to 100%, where 0 represented no injury or control and

100 represented complete plant death at 7, 14, and 21 DAP. Control ratings for cover crops did not begin until after planting because the authors' previous experiences indicated that the no-till planter for the cash crop increases cover crop control. Palmer amaranth emergence and growth was monitored until it reach a height of 10 cm in a particular termination interval. Cover crop termination interval was regressed against the number of days after soybean planting it took for Palmer amaranth to reach a height of 10 cm (Equation 1). The logistic model was fit using SigmaPlot (ver. 8.02; SPSS, Inc; Chicago, IL) to determine the correlation of termination interval and days until Palmer amaranth triggered a POST application.

$$y = y0 + \frac{a}{1}\exp(-\frac{x - x0}{b}))$$

In this model, y0 is minimum number of days for Palmer amaranth to reach 10 cm in height, b is the slope, x0 half the number of days for Palmer amaranth to reach 10 cm, and a is the inflection point, or days before or after planting required to maximize the number of days for Palmer amaranth to reach 10 cm in height. Palmer amaranth control was visually assessed 7, 14, 21, and 28 d after the POST application was made (DAT). An additional evaluation was made when soybeans reached the R6 maturity stage as an end of season weed control rating. Days until the POST application were also recorded as DAP (Table 1). Soybeans were harvested in each year of this experiment with a small plot combine and yields were adjusted to a moisture content of 13%.

All data were subjected to an analysis of variance using PROC GLIMMIX in SAS (ver. 9.4; SAS Institute; Cary, NC). Random effects were years, replications, and replications nested within years (Blouin et al. 2011). Considering year an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Cover crop biomass, control, and soybean stands were analyzed using only termination intervals as the fixed effect, as these data were collected prior to the application of any POST treatments. Palmer amaranth control and soybean yields were analyzed using the fixed effects of termination interval, POST, and the interaction among the fixed effects. The square roots of visual estimates for cover crop and weed control were arcsine transformed and soybean population, cover crop biomass, and yield data were $\log_{10}$ transformed. The transformations did not improve homogeneity of variance for any data point based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Type III statistics were used to test all fixed effects or interactions between the fixed effects. Least square means were calculated based on $\alpha = 0.05$ and utilized for mean separation. The DANDA.sas design and analysis macro collection (Saxton 2013) was utilized to build all PROC GLIMMIX (MMAOV) procedures, examine normality, perform necessary data transformations, and convert mean separation to letter groupings when appropriate.

Results and Discussion

A significant effect of termination interval was detected for cover crop biomass (Tables 22 and 23). Biomass was highest when terminated 0 DPP, and decreased incrementally with the 7 DPP and DAP timings and again at the 14 DPP and DAP timings. Decreased biomass at the 7 and 14 DAP timings coincided with the authors previous experience of a no-till planter providing a similar, but less efficacious, effect to that of other mechanical termination methods such as a roller crimper, especially in cereal cover crops planted in a mixture with hairy vetch. The cereal + hairy vetch mixtures generally become entangled and are pressed to the ground with the planter. This effect is further explained with the cover crop control ratings. For both wheat and hairy vetch control, there was a significant main effect of termination timing 7 and 14 DAP (Tables 22 and 23). All treatments applied prior to planting provided 99% control of wheat and hairy vetch 7 DAP. Control of wheat or hairy vetch ranged from 85-87% in the 7 and 14 DAP termination timings, immediately prior to the 7 DAP termination treatment being applied. Similarly, 14 DAP control of wheat and hairy vetch was 91 and 90%, respectively, immediately prior to the 14 DAP termination treatment being applied. Data from the 21 DAP rating is not presented, as all treatments provided total control of each cover crop species. Similarly, Curran et al. (2015) reported that dicamba applied at 140 g ai ha^{-1} provided $\geq$ 90% control of hairy vetch whether applied in the fall or spring. The rate of dicamba used in the aforementioned study was much lower than the one used in this research. Many other studies have documented the efficacy of dicamba on various vetch species at lower rates than used in this study confirming the viability of this herbicide for controlling vetch species (Curran et al. 2015; McCurdy et al. 2013; Power et al. 1991; White and Worsham 1990; Wolfe et al. 2016). Also, the efficacy of glyphosate for controlling wheat is well documented (Ashford and Reeves 2003; Davis 2010; Price et al. 2009; Reddy 2001). The combination of these herbicides can control a wheat + hairy vetch cover crop before or after soybean establishment at the rates currently proposed for use in DGT soybeans.

Significant main effects were not present for crop stand (Tables 22 and 23). However, reported least squared means for crop stand are generally low. A severe early season infestation of threecornered alfalfa hoppers (*Spissistilus festinus* Say) occurred in 2015. This caused notable stand loss across all treatments. However, stand loss was uniform across all treatments and did not cause an interaction with data for stands between site years (P=0.8369, data not shown). Crop stands in 2015 and 2016 were 238,200 and 303,200 plants ha^{-1}. However, because of the aforementioned insect problem in 2015, a blanket application of a pyrethroid insecticide was made in 2016 at planting to alleviate this problem (S. Stewart, personal communication). Additionally, there was a significant main effect of POST herbicide for soybean yields (Tables 22 and 25). Pooled over all termination timings, treatments receiving a POST application of dicamba yielded 100 kg ha^{-1} higher than those treated with fomesafen. Although there were differences in yield among POST herbicide treatments, least squared means for each herbicide treatment was still above the 2015 average yield of 3300 kg ha^{-1} for Tennessee (Anonymous 2016). Similarly, Reddy et al. (2003) reported no differences in soybean stand or yield when comparing a cereal rye or crimson clover cover crop to a conventional no-till system in Mississippi.

The parameters for the logistic regression of termination interval and days to 10 cm Palmer amaranth produced a model with the parameter estimates $y = 28.3+11.3/(1+\exp(-(x-0.9)/5.5))$ with an $R^2 = 0.86$ (Figure 1). This would estimate that all termination treatments delayed Palmer amaranth growth to 10 cm in height at least 28 d. The termination interval for a wheat + vetch cover crop to maximize the number of days for Palmer amaranth to reach 10 cm in height is 11 DAP. Similarly, Ryan et al (2011) reported that increased cereal rye biomass was strongly related to decreasing weed biomass. Although biomass in this study stopped increasing at cash crop planting, the effects of delayed termination until after planting proved to be an effective way to increase the amount of time necessary for Palmer amaranth to reach 10 cm in height. Palmer amaranth control was significantly affected by termination interval 7 and 14 DAT (Tables 24 and 25). Control was lowest 7 DAT in 7 DPP and 14 DAP termination treatments. At this rating, differences in control among the other termination treatments were not significant and control among these treatments ranged from 96-97%. Additionally, 14 DAT control from all treatments except the 14 DAP (93%) termination interval was similar ($\geq$ 97%). However, these differences were transient, as differences among termination intervals were not present 21 or 28 DAT, and, pooled over POST herbicides, all treatments provided ≥ 97% control at these timings. There was a significant main effect of POST herbicide treatment 21 and 28 DAT. Control at the 21 and 28 DAT ratings ranged from 97 to 99%, with dicamba having the greatest control at these ratings. Significant main effects or interactions among the main effects were not detected at the final (R6 soybean stage) rating and all treatments provided ≥ 97% control of Palmer amaranth.

Although differences in Palmer amaranth control were not apparent at the end of the season, early season Palmer amaranth control ratings (21 and 28 DAT) followed a similar trend to that of soybean yields. Van Acker et al. (1993) reported in four of six site years, the critical period of weed removal to prevent 2.5% yield loss in soybeans was ≥27 d after emergence. However, in this same study, the critical period of weed removal to prevent a 5% yield loss was ≥ 40 d after emergence in three of six site years. POST treatments for control of Palmer amaranth were applied 29 to 39 d after planting, meaning the weed removal in this study fell in a period that could cause 2.5 to 5% yield loss. The differences in yield are thought to be attributed to early season weed control.

Glyphosate + dicamba can be an effective tool for terminating wheat + hairy vetch cover crops when used 14 DPP to 14 DAP. Additionally, in all treatments, one effective POST herbicide application + a cover crop was sufficient to provide ≥ 97% control of GR Palmer amaranth while still maintaining soybean yields above the state average (Anonymous 2016). The ability to use glyphosate + dicamba shortly before or after planting for cover crop control in DGT soybeans allows producers increased flexibility in managing high biomass cover crops for control of Palmer amaranth. However, producers should be aware of other possible pests such as insects when delaying cover crop termination until near soybean planting. Additionally, it is well documented that including at least one other effective MOA will greatly improve the sustainability and longevity of dicamba as an effective POST for Palmer amaranth (Beckie 2011; Burke et al. 2005; Culpepper 2006; Inman et al. 2016; Miller and Norsworthy 2016; Price et al. 2011; Riar et al. 2013; Young 2006). These data suggest that a wheat + hairy vetch cover crop terminated 14 DPP, Palmer amaranth growth to 10 cm in height is delayed $\geq$28 DAP. Moreover, delaying cover termination until 14 DAP can correspondently delay this interval for Palmer to 38 DAP. When utilizing a wheat + hairy vetch cover crop in DGT soybeans, producers should delay cover crop termination until 11 to 14 DPP and make at least one POST application of glyphosate + dicamba + an additional herbicide MOA to maximize Palmer amaranth control and soybean yields.

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Appendix

Table 21: Wheat and hairy vetch growth stages at 14, 7, and 0 d before and 7 and 14 d after soybean planting termination intervals at the West Tennessee Research and Education Center in Jackson, TN, in 2015 and 2016.

[a] Abbreviations: DPP, days prior to planting. DAP, days after planting.

Termination Interval[a]	Wheat[b]		Hairy vetch		Application dates		Days to POST[c]	
	2015	2016	2015	2016	2015	2016	2015	2016
-14 DPP	59	59	early pod	mid pod	27-Apr	2-May	30	29
-7 DPP	61	61	early pod	mid pod	4-May	10-May	30	29
0 DPP	64	64	mid pod	late pod	11-May	16-May	37	32
7 DAP	64	64	mid pod	late pod	19-May	24-May	37	35
14 DAP	64	64	mid pod	late pod	27-May	31-May	39	39

[b] According to Zadok's growth staging.

[c] Days to POST application is recorded as days after soybean planting until a POST application was initiated because Palmer amaranth in that termination interval had reached a height of 10 cm.

Table 22: Main effects of termination interval, POST herbicide application, and the interaction of the main effects on wheat + hairy vetch's cover crop biomass and control and soybean stand and yield[a,b].

Effect	Biomass	Cover crop control				Crop Stand	Yield
		Wheat		Vetch			
		7	14	7	14		
	——————————p-value——————————						
Termination Interval	<.001	<.001	<.001	<.001	<.001	0.169	0.375
POST	na	na	na	na	na	na	0.042
Termination Interval*POST	na	na	na	na	na	na	0.855

[a] Termination interval refers to cover crop termination intervals of 14, 7, and 0 d prior to planting, and 7 and 14 d after planting. POST stands for POST herbicide premixes of glyphosate + fomesafen (1120 and 280 g ae ha^{-1}, respectively) or glyphosate plus the diglyocolamine salt of dicamba (1120 and 560 g ae ha^{-1}, respectively) applied when Palmer amaranth for that termination interval reached 10 cm in height.

[b] Column headings of 7 and 14 designate rating intervals of 7 and 14 d after planting soybeans.

Table 23: Biomass and control of a wheat + hairy vetch cover crop, and soybean population as effected by termination intervals before and after planting soybeans in Tennessee in 2015 and 2016 [a,b,c].

Term Interval	Biomass	Cover Crop Control				Crop Stand
		Wheat		Hairy vetch		
		7	14	7	14	
	kg ha^{-1}	%				plants ha^{-1}
-14	7000c	99a	99a	99a	99a	247800
-7	11300b	99a	99a	99a	99a	275700
0	16000a	99a	99a	99a	99a	288000
7	10200b	87b	99a	87b	99a	273200
14	6100c	86b	91b	85c	90b	269100

[a] Termination intervals of -14, -7, 0, 7 and 14 designate the number of days before or after soybean planting that the termination treatment of glyphosate + dicamba (1120 and 560 g ae ha^{-1}, respectively) was applied.
[b] Column headings of 7 and 14 designate rating intervals of 7 and 14 d after planting soybeans.
[c] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$.

Table 24: The main effects of cover crop termination interval, POST herbicide treatment, and the interaction among the main effects on Palmer amaranth control in Jackson, TN, in 2015 and 2016.

Effect	Palmer amaranth				
	7	14	21	28	R6
	p-value				
Termination Interval	0.0099	0.0001	0.0861	0.1568	0.3389
POST	0.5232	0.2580	0.0026	0.0029	0.0812
Termination Interval*POST	0.1560	0.0828	0.1347	0.1568	0.5885

[a] Termination interval refers to cover crop termination intervals of 14, 7, and 0 d prior to planting, and 7 and 14 d after planting. POST stands for POST herbicide premixes of glyphosate + fomesafen (1120 and 280 g ae ha^{-1}, respectively) or glyphosate plus the diglyocolamine salt of dicamba (1120 and 560 g ae ha^{-1}, respectively) applied when Palmer amaranth for that termination interval reached 10 cm in height.

[b] Column headings of 7, 14, 21, and 28 designate rating intervals of 7, 14, 21, and 28 d after POST herbicide application. Column heading R6 refers to soybean growth stage of R6 and was taken as an end of season rating.

Table 25: Control of Palmer amaranth and dicamba-tolerant soybean yield in a wheat + hairy vetch cover crop mixture in Jackson, TN, in 2015 and 2016 [a,b,c].

Effect		Palmer amaranth control					Yield
		7	14	21	28	R6	
				%			kg ha^{-1}
POST							
	Dicamba	95	98	99a	99a	99	4300a
	Fomesafen	95	96	97b	97b	98	4200b
Term Interval							
	-14 DPP	96ab	97a	97	98	98	4200
	-7 DPP	92c	98a	97	98	99	4400
	0 DPP	97ab	97a	97	97	98	4200
	7 DAP	97a	99a	99	99	99	4200
	14 DAP	93bc	93b	99	99	98	4200
Term* POST							
	Dicamba -14 DPP	97	99	98	99	98	4300
	Fomesafen -14 DPP	96	96	96	96	97	4100
	Dicamba -7 DPP	92	99	99	99	99	4400
	Fomesafen -7 DPP	92	98	96	97	99	4400
	Dicamba - 0 DPP	98	99	99	99	99	4300
	Fomesafen - 0 DPP	95	96	95	95	97	4100
	Dicamba - 7 DAP	96	99	99	99	99	4300
	Fomesafen - 7 DAP	98	99	99	99	99	4100
	Dicamba - 14 DAP	91	92	99	99	99	4300
	Fomesafen - 14 DAP	96	95	99	99	98	4100

[a] Termination intervals of -14, -7, 0, 7 and 14 designate the number of days before or after soybean planting that the termination treatment of glyphosate + dicamba (1120 and 560 g ae ha^{-1}, respectively) was applied.
[b] Column headings of 7, 14, 21, and 28 designate rating intervals of 7, 14, 21, and 28 d after POST herbicide application. Column heading R6 refers to soybean growth stage of R6 and was taken as an end of season rating.
[c] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within a main effect. Means followed by no letter are either not significantly different at $p \leq 0.05$ or letter separation is shown in a higher interaction.

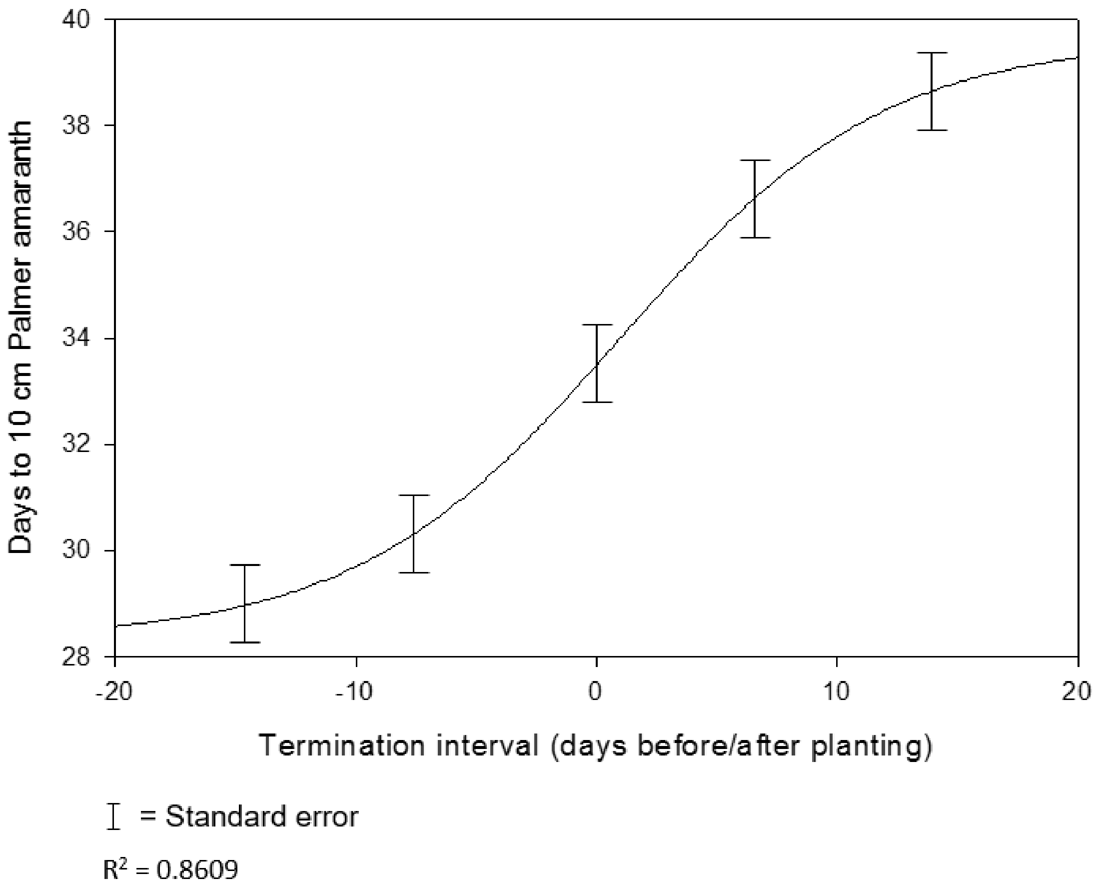

Figure 1: Termination interval of a wheat + hairy vetch cover crop effects the number of days until Palmer amaranth can reach 10 cm in height.

CHAPTER V:
EVALUATING THE USE OF FALL APPLIED HERBICIDES FOR CONTROLLING ITALIAN RYEGRASS IN COVER CROPS

Abstract

A study was conducted to evaluate Italian ryegrass and henbit control with fall applied herbicides to a cereal rye, wheat, crimson clover, or hairy vetch cover crop was conducted in Tennessee and Mississippi from the fall of 2014 to the spring of 2016. The first factor level was cover type, and consisted of cover crop or no cover crop, and each cover crop was analyzed separately. The second factor was herbicide and consisted of flumioxazin, *s*-metolachlor, an encapsulated formulation of acetochlor, pyroxasulfone, metribuzin, pendimethalin, flufenacet, saflufenacil and a no herbicide treatment. Cereal rye and wheat injury from these herbicides was 0 to 14% at all ratings. Biomass from cereal rye or wheat treated with a herbicide was not different from that of the nontreated control. Flumioxazin and metribuzin were the most injurious to hairy vetch and reduced biomass compared to the nontreated control. All herbicides severely injured crimson clover (17 to 37%) 150 DAT. Herbicides improved Italian ryegrass control over the cover crop alone but control level 150 DAT was not acceptable for any herbicide or herbicide + cover crop. Pyroxasulfone was the most effect herbicideon Italian ryegrass at 82% control 150 DAT. Cover crops did effectively suppress henbit. Herbicides did not improve henbit control in cereal rye or wheat, but acetochlor, flumioxazin, and pendimethalin improved henbit control over that of hairy vetch alone. Although herbicides proved too injurious to use on a crimson clover cover crop, several safe herbicide options were identified for use in a cereal rye, wheat, and/or hairy

vetch cover crop which could help control winter annual broadleaf weeds such as henbit. However, even a cover crop + herbicide was not effective in controlling Italian ryegrass. A single cover crop species should not be utilized in areas where this weed is problematic.

Introduction

Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) is a short, rhizomatous, annual or biennial bunchgrass commonly found throughout the United States (Dickson et al. 2011; Ellis et al. 2008; Hashem et al 1995). It can be extremely problematic in winter annual crops (Appeby and Brewster 1992; Barnes et al. 2001; Bell 1995; Davies 1928;). Glyphosate-resistant (GR) Italian ryegrass was first identified in Chile (Perez and Kogan 2003). The first documented case of GR Italian ryegrass in the United States occurred in 2003 (Perez-Jones et al. 2005). However, each of the cases were in fruit orchards where glyphosate was solely relied on for weed control for multiple successive years. The first documented case of GR Italian ryegrass in row crops was documented in 2007 in Mississippi (Nandula et al. 2007). Two separate populations survived glyphosate rates of 0.84 and 1.68 ka ae ha^{-1} of glyphosate, representing a threefold resistance compared to the susceptible population (Nandula et al. 2007). The problem has since spread to all agronomic areas of the Mississippi Delta region and into the neighboring agronomic areas of Arkansas and Tennessee (Heap 2016).

A cover crop is any living ground cover that is planted into or after a cash crop and then terminated before or shortly after the subsequent cash crop is planted (Hartwig and Ammon 2002). Along with weed suppression, cover crops offer many advantages over standard cropping systems, including: reduced soil erosion and water runoff, improved soil moisture retention, water infiltration, organic matter in the soil, soil tilth, soil nitrogen, and reducing tillage needs (Mallory et al. 1998; Reddy et al. 2003; Teasdale 1996; Varco et al. 1999; Yenish et al. 1996). Cover crops are especially advantageous to producers in areas where no-tillage management systems are common. Some cover crop species that are commonly utilized for weed control include cereal rye, winter wheat, crimson clover, and hairy vetch (Wiggins et al. 2016). These species are commonly utilized either alone or in combination because of their ability to accumulate large, consistent quantities of biomass and termination options. They allow producers additional cultural options for weed management without sacrificing soil health. Delaying cover crop termination until at or near planting of the cash crop allows the cover crop a longer growing season, thus producing more biomass (Ashford and Reeves 2003; Mischler et al. 2011; Mirksy et al. 2009; Wortman et al. 2012).

Competitive winter weeds such as horseweed or Italian ryegrass can cause negative impacts on agronomic crops (Bond et al. 2005; Eubank et al. 2008; Nandula et al. 2007; Owen et al. 2011). Italian ryegrass is highly competitive with winter cereal crops such as winter wheat (Appleby and Brewster

1992), and competition reduced yield up to 92% (Hashem et al. 1998). Studies conducted from 1981 to 1983 concluded that wheat grain yields were reduced an average of 4.2% for every 10 plants m^{-2} of Italian ryegrass, primarily because of reduced crop tillering (Liebl and Worsham 1987). These negative impacts could occur in cover crops, compromising the integrity, increasing the difficulty of termination, and possibly reducing the amount of early season, summer-annual weed suppression from a winter cover crop. Additionally, glyphosate is commonly utilized for control of cover crops at or near planting (Ashford and Reeves 2003; Currie and Klocke 2005; Price et al. 2009). Lack of GR horseweed or Italian ryegrass control at this time could have significant negative impacts on the following cash crop. Hydrick et al. (2015) reported that controlling Italian ryegrass < 28 d prior to planting can negatively impact crop yields, and control options for this weed become more limited after the cash crop emerges (Bond and Eubank 2013).

Problems from GR Italian ryegrass interference in cover crops have become more apparent in Tennessee in recent years (L. Steckel, personal communication). Additionally, preliminary data suggests that herbicide burndown applications prior to cover crop planting can significantly reduce horseweed populations within a cover crop (L. Steckel, unpublished data). Bond et al. (2014) reported that fall applications of residual herbicides provided acceptable control of Italian ryegrass and other winter weed species in Mississippi. However, to be effective, these herbicides would need to be applied near cover crop sowing and little is known about their effectiveness on cover crop species when applied at this timing. Therefore, research was conducted to determine the viability of fall applied herbicides on four cover crop species and the ensuing control of Italian ryegrass and henbit in a no-till environment.

Materials and Methods

A study was conducted to evaluate the response of fall applied herbicides on a cereal rye, wheat, crimson clover, or hairy vetch cover crop. This research was done in the fall and spring of 2014-2015 in Stoneville, MS, 2014-2015 and 2015-2016 Jackson, TN, and in 2015-2016 in Milan and Union City, TN. The experimental site in Stoneville was managed in a conventional tillage environment, and all sites in Tennessee were managed in a no- or minimum-tillage environment.

Cereal rye and wheat (seeded at 67 and 67 kg ha^{-1}, respectively) were sown in Stoneville, MS. Cereal rye, wheat, crimson clover, and hairy vetch (seeded at 67, 67, 17, and 22 kg seed ha^{-1}) were sown in Jackson, Milan, and Union City, TN. Treatments were replicated four times in a two-factor factorial within a randomized complete block design. The first factor level was cover type, and consisted of cover crop or no cover crop. Covers were sown perpendicularly to the direction of the spray application, and the cover crops were analyzed separately. The second factor was fall applied herbicide and consisted of flumioxazin, *s*-metolachlor, an encapsulated formulation of acetochlor, pyroxasulfone, metribuzin, pendimethalin, flufenacet, saflufenacil and a no herbicide treatment (Table 26). Flumioxazin, pendimethalin, and saflufenacil were applied preemergence. *S*-metolachlor, acetochlor, pyroxasulfone, metribuzin, and flufenacet were applied as postemergence treatments when cover crops reached the 1 to 2 lf growth stage. The saflufenacil treatment was only present at the Milan and Union City locations as it does not provide residual control of grass weed species. Herbicides were applied to cover and no cover plots simultaneously, and each experimental site was treated with paraquat at 851 g ai ha^{-1} plus 0.25% non-ionic surfactant to control all existing vegetation at cover crop planting. Treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} equipped with AIXR11002 nozzles (AIXR TeeJet Air Induction Extended Range Flat Fan Spray Tips, TeeJet Technologies, Wheaton, IL).

Cover crop injury, henbit (*Lamium amplexicaule* L), and Italian ryegrass control was visually assessed 10, 30, 60, 90, and 150 d after the post application (DAT) on a scale of 0 to 100%, where 0 represented no injury or control and 100 represented complete plant death. Italian ryegrass was present in Stonevillle and Jackson. Italian ryegrass was not present in Milan or Union City, however, henbit was present at these sites and control was rated. A consistent stand of crimson clover could not be established at the Union City location so data for henbit control and biomass are not presented for this cover crop. Injury data from locations were pooled and analyzed at each rating interval. Injury was analyzed in an incomplete block design to allow for comparisons between saflufenacil and all other herbicides. Italian ryegrass control was similar for all herbicides in early season ratings (10 to 60 DAT) and late season ratings (90 to 150 DAT) only data from the 30 and 150 DAT are presented and discussed for brevity. Similarly, only henbit control data from the 150 DAT rating is presented. Immediately after the 150 DAT, cover crop biomass was collected at each termination timing for each termination method and cover crop from 0.5 m^2 quadrants at the Milan and Union City locations. Samples were dried in a forced-air oven at 60°C for 48 hrs.

All data were subjected to an analysis of variance using PROC GLIMMIX in SAS (ver. 9.4; SAS Institute; Cary, NC). Random effects were years, locations, and replications nested within years by location (Blouin et al. 2011). Considering year and location an environmental or random effect permits inferences about treatments to be made over a range of environments (Blouin et al. 2011; Carmer et al. 1989). Injury data for each cover crop were analyzed using only herbicide as a fixed effect. Weed control data were analyzed using fixed effects of herbicide, cover crop, and the interaction of these fixed effects. For each cover crop, the no herbicide, cover crop treatment was deleted from the ANOVA when analyzing the fixed effects of herbicide and cover crop to allow the statistical model to maintain a factorial design. However, single degree of freedom contrast statements were used to compare the no herbicide, cover crop treatment to each cover + herbicide treatment to determine if the herbicide improved weed control over that of the cover crop alone. Additionally, 150 DAT injury and biomass from cereal rye, wheat, and hairy vetch were tested for correlations utilizing PROC CORR in SAS. The square roots of visual estimates for cover crop and weed control were arcsine transformed and cover crop biomass data were $\log_{10}$ transformed. The transformations did not improve homogeneity of variance for any data point based on visual inspection of plotted residuals; therefore, nontransformed data were used in analyses. Type III statistics were used to test all fixed effects or interactions between the fixed effects. Least square means were calculated based on $\alpha = 0.05$ and utilized for mean separation. The DANDA.sas design and analysis macro collection (Saxton 2013) was utilized to build all PROC GLIMMIX (MMAOV) and PROC CORR (REG) procedures, examine normality, perform necessary data transformations, and convert mean separation to letter groupings when appropriate.

Results and Discussion

Cereal Rye

Significant main effects were present for injury 10, 30, 60, and 90 DAT for cereal rye (Tables 27 and 28). Cereal rye injury was ≤13% for all herbicides. The least amount of injury was with saflufenacil, acetochlor, pendimethalin, and pyroxasulfone. Injury from these herbicides was ≤7%. Injury was greatest, in this study, from flumioxazin at each of these ratings (9 to 13%). Significant differences among treatments were not present for injury 150 DAT with injury ranging from 0 to 4%. There was no difference in cereal rye biomass among herbicide treatments. A correlation between cereal rye injury 150 DAT and biomass was not present (R^2=0.26). Acetochlor and *s*-metolachlor are not currently labeled in cereal crops. However, research has suggested that possibilities could exist for utilizing them in some scenarios (Barapour et al. 2012; Ritter and Menbere 2002).

Italian ryegrass control was significantly influenced by herbicide 30 DAT (Tables 29 and 30). Each main effect was significant 150 DAT, but interaction among the main effects was not significant. At each of these rating intervals, the addition of any herbicide improved the control of Italian ryegrass over that of a cereal rye cover crop alone. Pooled across cover and no cover treatments, control was the greatest with pyroxasulfone or s-metolachlor 30 DAT (Table 30). Control from all other treatments was $\leq$67% at this time. However, control from pyroxasulfone was greater than that of *s*-metolachlor 150 DAT. Additionally, pooled over all herbicide treatments, a cereal rye cover crop improved Italian ryegrass control 16% over that of no cover treatments. While these herbicides can be safely applied in a cereal rye cover cropping system, they do not provide adequate control of Italian ryegrass.

An interaction among the main effects was detected for henbit control 150 DAT (Figure 2). Pendimethalin provided control similar to the best treatments with or without a cover crop. Control of henbit from all other herbicides was improved by the addition of a cover crop. Control from flufenacet, proxasulfone, *s*-metolachlor, and saflufenacil without a cover was similar to that of acetochlor, flumioxazin, metribuzin, or pendimathalin without a cover. Although there were differences among herbicides with or without a cereal rye cover crop, contrast statements revealed that cereal rye cover crop alone (94%) was similar to all cereal rye cover crop + herbicide treatments indicating that herbicides did not improve henbit control over that of a cereal rye cover crop alone.

All herbicides in this study could be applied to a cereal rye cover crop without reducing biomass. The treatment with the greatest control of Italian ryegrass was pyroxasulfone + cereal rye cover (91%, data not shown). Moreover, no herbicide treatment improved control of henbit over that of cereal rye alone. While these herbicides can be safely applied in a cereal rye cover cropping system, they do not provide adequate control of Italian ryegrass.

Wheat

Wheat injury was low but significant by herbicides 10, 30, and 90 DAT. As seen with cereal rye, overall wheat injury from tested herbicides was relatively low ($\leq$14%). Saflufenacil caused almost no injury (0-1%) (Tables 27 and 28). Injury from acetochlor, flufenacet, metribuzin, pendimethalin, and pyroxasulfone was similar to that of saflufenacil for at least one rating interval and all of these treatments caused $\leq$8% percent injury at any rating interval. Flumioxazin was the most injurious 10, 30, and 90 DAT (14%). Injury from *s*-metolachlor was similar to that of flumioxazin 30 DAT. However, injury levels were similar and $\leq$5% across all treatments 150 DAT. A significant main effect on cover crop biomass was not detected. Wheat biomass ranged from 3700 to 4600 kg ha^{-1}, with the mean biomass for wheat treated with no herbicide being 3800 kg ha^{-1}. Biomass and 150 DAT injury were not correlated (R^2=0.08).

The main effects of herbicide and cover crop were present for Italian ryegrass control at each rating interval, however, there were no interactions among the main effects (Tables 29 and 30). Contrast statements indicated that all herbicides improved Italian ryegrass control over that of a wheat cover crop alone at each rating interval. Pooled across cover and no cover crop treatments, pyroxasulfone maximized control 30 and 150 DAT in a wheat cover crop, however, *s*-metolachlor provided control similar to pyroxasulfone 30 DAT. Control from *s*-metolachlor was less than that of pyroxasulfone 150 DAT, but greater than that of all other treatments. All other treatments provided $\leq$62% of Italian ryegrass control 150 DAT. Pooled across herbicide treatments, control of Italian ryegrass was increased 4 and 16%, respectively, 30 and 150 DAT by the presence of a cover crop.

An interaction among the main effects of cover crop and herbicide was detected at the 150 DAT rating interval (Figure 3). With the exception of pendimethalin, control of henbit was significantly improved with a wheat cover crop. However, control from pendimethalin was similar to that of the best treatments with or without a wheat cover crop. With the exception of pyroxasulfone, all other wheat cover crop + herbicide treatments controlled henbit $\geq$ 96%. However, contrasts statements indicated that the addition of herbicides did not improve henbit control over a wheat cover crop alone (92%, data not shown).

No herbicide in this study reduced wheat biomass suggesting that cover crop safety exists. Pyroxasulfone was the most effective herbicide for Italian ryegrass. However, control from pyroxasulfone + wheat cover crop was only 89% and no herbicides improved henbit control of that over the wheat cover crop alone. Although there are herbicides that can be safely applied to a wheat cover crop, they do not improve weed control to the point of acceptability.

Hairy vetch

Significant main effects of herbicide were present at each rating for hairy vetch injury (Tables 27 and 28). Injury 10 DAT was greatest from flumioxazin followed by flufenacet (35%) and metribuzin (29%) which were similar. Injury from flufenacet was similar to that of metribuzin from 10 to 60 DAT and similar to flumioxazin 150 DAT. Injury was numerically lowest from saflufenacil at each rating interval and significantly less at 30 and 60 DAT. At 150 DAT injury from acetochlor, pendimethalin, pyroxasulfone, and *s*-metolachlor were similar to that of saflufenacil. A significant main effect was detected for hairy vetch biomass. Acetochlor, pendimethalin, pyroxasulfone, *s*-metolachlor, saflufenacil, and the no herbicide treatment produced similar and greater hairy vetch biomass than flumioxazin or metribuzin. Biomass and injury 150 DAT were strongly correlated for hairy vetch (R^2=0.97). In contrast to cereal rye or wheat data, significant differences were present for hairy vetch biomass and injury 150 DAT. This correlation indicates that cover crop injury does impact the amount of biomass produced in the spring.

Italian ryegrass control was significantly affected by herbicide at all rating intervals and by a hairy vetch cover crop 150 DAT, but no interactions among the main effects was present at any rating interval (Tables 29 and 30). Contrast statements indicated that all herbicide treatments significantly improved Italian ryegrass control over that of a hairy vetch cover crop alone. Pooled over cover and no cover treatments, control 30 DAT was maximized and similar for pyroxasulfone and *s*-metolachlor, with all other treatments providing $\leq$72% control. Similarly, at 150 DAT pyroxasulfone maximized control and was greater than all other treatments. Pooled over all herbicide treatments, control was increased 7% from utilizing a cover crop compared to a herbicide alone.

Significant main effects of herbicide and cover crop were detected for henbit control 150 DAT, but interactions among the main effects were not present (Table 31). Pooled across cover and no cover crop effects, henbit control was the greatest with acetochlor, flumioxazin, and pendimethalin. Control from acetochlor and flumioxazin was significantly greater than all other herbicide treatments, except pendimethalin. Additionally, pooled over all herbicide treatments, the presence of a hairy vetch cover crop increased henbit control 19% over treatments that were applied without the vetch cover crop. Although differences among herbicides were present, and the presence of a vetch cover crop significantly increased control of henbit, contrast statements indicated that only acetochlor, flumioxazin, and pendimethalin applied to a vetch cover crop significantly improved (by 15, 12, and 14%, respectively) control of henbit over that of a vetch cover crop alone (84%).

The herbicides acetochlor, pendimethalin, pyroxasulfone, *s*-metolachlor, and saflufenacil did not reduce biomass when compared to that of a hairy vetch cover crop treated with no herbicide. Only acetochlor and pendimethalin improved control of henbit, and pyroxasulfone improved and maximized Italian ryegrass control when utilized with a hairy vetch cover crop. These data suggest saflufenacil could safely be applied prior to planting a hairy vetch cover crop for controlling other weed species, such as horseweed, however, it should not be expected to improve control of other broadleaf winter weeds over that of a vetch cover crop alone.

Crimson clover

Crimson clover was significantly injured at all rating intervals except 30 DAT (Tables 27 and 28). Injury 10 DAT was greater from flumioxazin than metribuzin, and these treatments were more injurious than all other herbicides. However, at this rating, injury from all other treatments ranged from 28 to 34%. Injury 30 and 60 DAT followed a similar pattern to that of 10 DAT, with flumioxazin causing more injury than metribuzin and all other treatments. Additionally, at this timing metribuzin caused similar level of injury to flufenacet, and greater than that of the rest of the treatments. Flumioxazin and metribuzin were more injurious than *s*-metolachlor 90 DAT and similar to all other treatments. Although there were differences among treatments 150 DAT, injury ranged from 17 to 37% indicating that all herbicides caused significant injury to crimson clover.

A significant main effect of herbicide for Italian ryegrass control was detected at each rating interval and a significant main effect of cover crop was detected 150 DAT but an interaction among the main effects was not present at any rating (Tables 4 and 5). Pooled across cover and no cover treatments, control 30 DAT was greatest from pyroxasulfone and *s*-metolachlor. Control from *s*-metolachlor 30 DAT was similar to pyroxasulfone and flufenacet. Pyroxasulfone provided more control than any other herbicide 150 DAT. Control 150 DAT was increased with a crimson clover cover crop, however, control from all treatments was $\leq$73% which is not acceptable. A crimson clover cover crop should not be used in areas where Italian ryegrass is prevalent.

Conclusion

Cereal rye or wheat produced biomass that was similar to that of nontreated cover crop when treated with any of the tested herbicides. Italian ryegrass control was improved with herbicides over that of any cover crop alone but control levels were not optimal. Herbicide treatments were more variable in improving control of henbit. The greatest control achieved from any treatment was 89 or 91% (wheat or cereal rye, respectively, cover + pyroxasulfone, data not shown). Although these treatments maximized control with cereal cover crops, control would not be adequate for areas where significant Italian ryegrass infestations are present (Bond et al. 2014). Although pyroxasulfone, acetochlor, and *s*-metolachlor provide a similar weed control spectrum (Geier et al. 2006; Mueller and Steckel 2011; Steele et al. 2005), pyroxasulfone consistently provided greater control of Italian ryegrass across each cover crop species in this study. Acetochlor and *s*-metolachlor are not labeled for use in cereal rye or wheat. However, previous research has indicated that they could possibly have additional uses in cereal species for residual control. Ritter and Menbere (2002) reported no injury from *s*-metolachlor when applied to wheat at 0.43 kg ha^{-1} and $\geq$ 13% when applied at 1.12 kg ha^{-1}. Also, Barapour et al. (2012) found that rice is tolerant to encapsulated acetochlor at various rates. Bond et al. (2014) reported 95% control of GR Italian ryegrass from 1.42 or 0.16 kg ha^{-1} of *s*-metolachlor or pyroxasulfone 140 DAT. However, they also noted in this study that an additional control measure would be necessary in the spring to provide total control of Italian ryegrass prior to planting. Though pendimethalin has been documented for its effectiveness against ryegrass species, most research suggests that it is most effective when combined with other control measures (Barnes et al. 2001; Bond et al. 2005, 2014; Clemmer et al. 2004). In this study pendimethalin was effective for increasing control of henbit. Although herbicides proved too injurious to use on a crimson clover cover crop, herbicide options are available for use in a cereal rye, wheat, and/or hairy vetch cover crop. These herbicide applications can help control winter annual broadleaf weeds such as henbit. However, even a cover crop + herbicide was not effective in controlling

Italian ryegrass. A single cover crop species should not be utilized in areas where this weed is problematic. Utilizing a cereal + legume cover crop combination can create a synergistic effect increasing cover crop biomass and ensuing weed control (Clark et al. 1993, 1997; Ranells and Wagger 1996; Sanju et al. 2005; Teasdale and Abdul-Baki 1998; Wiggins et al. 2016; Zotarelli et al. 2009). Herbicide could be used with a hairy vetch + cereal rye or wheat cover crop that would produce more biomass than covers in this study. Although this could possibly present an option for allowing cover crops in areas where Italian ryegrass is present, more research is needed to confirm or reject this hypothesis.

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Appendix

Table 26: Herbicide common and trade names, application rates and timings, and manufacturer information for treatments examining the tolerance of four cover crop species to fall applied herbicides in Tennessee and Mississippi in 2014 to 2015 and 2015 to 2016.

Common name	Trade name	Rate	Timing	Manufacturer
		g ai ha^{-1}		
Acetochlor	Warrant	1250	POST	Monsanto, St. Louis, MO (www.monsanto.com)
Flufenacet	Define	300	POST	Bayer CropScience, Rhein, Germany. www.cropscience.bayer.com)
Flumioxazin	Valor SX	710	PRE	Valent U.S.A. Corporation, Walnut Creek, CA (www.valent.com)
Metribuzin	Tricor	210	POST	United Phosphorus Inc., King of Prussia, PA (www.upi-usa.com)
Pendimethalin	Prowl	1060	PRE	BASF Crop Protection, Research Triangle Park, NC (www.basf.com)
Pyroxasulfone	Zidua	120	POST	BASF Crop Protection, Research Triangle Park, NC (www.basf.com)
S-metolachlor	Dual Magnum	1070	POST	Syngenta Crop Protection, Greensboro, NC (www.syngentacropprotection.com)
Saflufenacil	Sharpen	38	PRE	BASF Crop Protection, Research Triangle Park, NC (www.basf.com)

Table 27: Effects of fall applied herbicides on a cereal rye, wheat, hairy vetch, or crimson injury and biomass in experiments conducted in 2014 to 2015 and 2015 to 2016 in Mississippi and Tennessee.

Main Effect		Cereal rye	Wheat	Hairy vetch	Crimson clover
	Parameter	p-value			
Herbicide					
	Injury 10 DAT	<.0001	<.0001	<.0001	<.0001
	Injury 30 DAT	<.0001	<.0001	<.0001	0.0534
	Injury 60 DAT	0.0131	0.1599	<.0001	0.0119
	Injury 90 DAT	<.0001	0.0001	<.0001	<.0001
	Injury 150 DAT	0.3336	0.3548	<.0001	0.0131
	Biomass	0.1274	0.7366	<.0001	.

Table 28: Injury and biomass from fall applied herbicides on four cover crop species in the Mississippi delta region and west Tennessee[a,b].

Cover Crop		10	30	60	90	150	Biom
		% injury					kg ha
Cereal rye	Acetochlor	5ab	4ab	6bc	3ab	2	5000
	Flufenacet	2ab	9c	7bc	6cd	3	4000
	Flumioxazin	12d	13d	10d	9d	3	4000
	Metribuzin	8c	9c	4ab	4b	4	3600
	Pendimethalin	5bc	3a	6abc	3ab	3	3100
	Pyroxasulfone	4ab	4ab	6bc	3ab	2	4100
	S-Metolachlor	6bc	7bc	7cd	5bc	4	4200
	Saflufenacil	1a	2a	2a	0a	0	4300
	Nontreated	.	.	.	.	.	3900
Wheat	Acetochlor	6b	5abc	5	4b	3	3900
	Flufenacet	5ab	8cde	4	3b	2	4200
	Flumioxazin	14c	11e	6	7c	4	4400
	Metribuzin	8b	6bcd	5	2ab	1	4600
	Pendimethalin	6ab	3ab	5	4b	3	4300
	Pyroxasulfone	5ab	5abcd	5	3b	2	4000
	S-Metolachlor	8b	8de	6	4b	5	3700
	Saflufenacil	1a	1a	0	0a	0	3700
	Nontreated	.	.	.	.	.	3800
Hairy vetch	Acetochlor	13b	10b	9bc	5ab	2ab	3400ab
	Flufenacet	35c	22c	18cd	8b	8bc	2600bc
	Flumioxazin	47d	31c	34e	21c	14cd	1900cd
	Metribuzin	29c	24c	31de	23c	19d	1600d
	Pendimethalin	12b	8b	11b	9b	1a	3700a
	Pyroxasulfone	10ab	12b	13b	6ab	1a	3600a

Table 28 Continued: Injury and biomass from fall applied herbicides on four cover crop species in the Mississippi delta region and west Tennessee[a,b].

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each cover crop.

Cover Crop		10	30	60	90	150	Biom
		% injury					kg ha
	S-Metolachlor	11b	12b	9b	6ab	5ab	3100ab
	Saflufenacil	0a	0a	0a	0a	0a	3300ab
	Nontreated	.	.	.	.	.	3400ab
Crimson clover	Acetochlor	30a	32a	21a	25ab	17a	.
	Flufenacet	28a	39ab	29a	32ab	20a	.
	Flumioxazin	77c	67c	55b	52b	37bc	.
	Metribuzin	63b	42b	39b	39b	33abc	.
	Pendimethalin	32a	28a	20a	26ab	18a	.
	Pyroxasulfone	31a	34a	31a	30ab	26abc	.
	S-Metolachlor	34a	38a	32a	16a	24ab	.
	Nontreated	.	.	.	.	.	.

Columns not followed by letters were not significantly different at $p \leq 0.05$.
[b] Abbreviation: Biom, cover crop biomass.

Table 29: Significance of the main effects of herbicide and cover crop on Italian ryegrass control from fall applied herbicides.

Rating Interval[a]	Effects	Cereal rye	Wheat	Hairy vetch	Crimson clover
		———	——— p-value	———	———
30 DAT					
	Herb	<.0001	<.0001	<.0001	<.0001
	Cover	0.2065	0.0391	0.5998	0.4462
	Herb*Cover	0.3049	0.3374	0.3271	0.6657
150 DAT					
	Herb	<.0001	<.0001	<.0001	<.0001
	Cover	<.0001	<.0001	0.0018	0.0138
	Herb*Cover	0.7724	0.8012	0.8305	0.4525

[a] Abbreviation: DAT, days after POST treatment.

Table 30: Italian ryegrass control from fall applied herbicides onto four cover crop species in 2014 to 2015 and 2015 to 2016 in the Mississippi delta and west Tennessee[a,b].

Effect		Cereal rye		Wheat		Hairy vetch		Crimson clover	
		30	150	30	150	30	150	30	150
		%							
Herb									
	Acetochlor	61de	50de	63de	50de	58cd	34d	56de	33d
	Flufenacet	71bc	62c	72bc	62c	72b	50c	66bc	50c
	Flumioxazin	67cd	52d	68cd	53d	63c	37d	62cd	34d
	Metribuzin	45f	44e	47f	44e	32e	24e	37f	23e
	Pendimethalin	59e	44e	59e	44e	50d	31de	51e	29de
	Pyroxasulfone	83a	82a	83a	82a	87a	73a	83a	73a
	S-Metolachlor	78ab	73b	79ab	72b	82a	58b	75ab	57b
Cover									
	Cover Crop	68	66a	69a	66a	64	47a	62	45a
	No Cover Crop	65	50b	65b	50b	63	40b	60	40b

[a] Abbreviation: Herb, main effect of Herbicide.
[b] Means within a column followed by the same letter are not significantly different at p ≤ 0.05. Letters are only reflective of means within each main effect. Data for each main effect are pooled over the other main effect shown.

Table 31: Henbit control from a hairy vetch cover crop in a no-till environment in west Tennessee[a].

Main Effect		Henbit
		——%——
Herbicide		
	Acetochlor	92a
	Flufenacet	78c
	Flumioxazin	91a
	Metribuzin	81bc
	Pendimethalin	89ab
	Pyroxasulfone	80c
	S-Metolachlor	80c
	Saflufenacil	78c
Cover		
	Cover	93a
	No Cover	74b

[a] Means within a column followed by the same letter are not significantly different at $p \leq 0.05$. Letters are only reflective of means within each main effect. Data for each main effect are pooled over the other main effect shown.

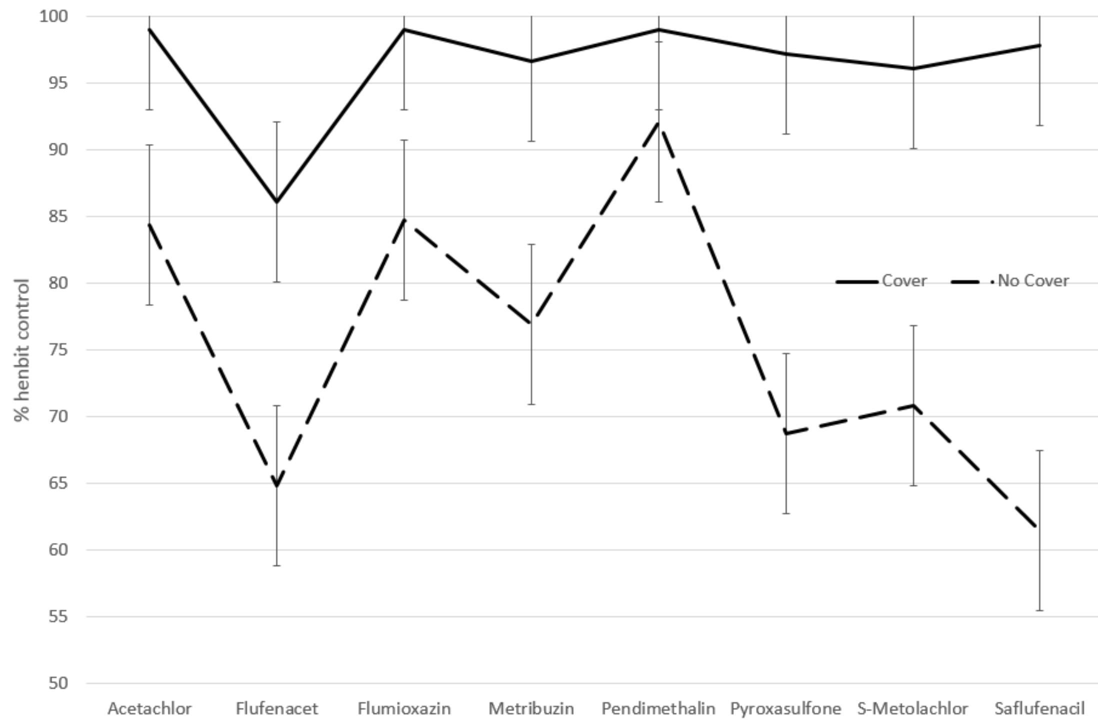

Figure 2: Interaction among the main effects of herbicide and cover crop for henbit control with a cereal rye cover crop 150 DAT in west Tennessee.

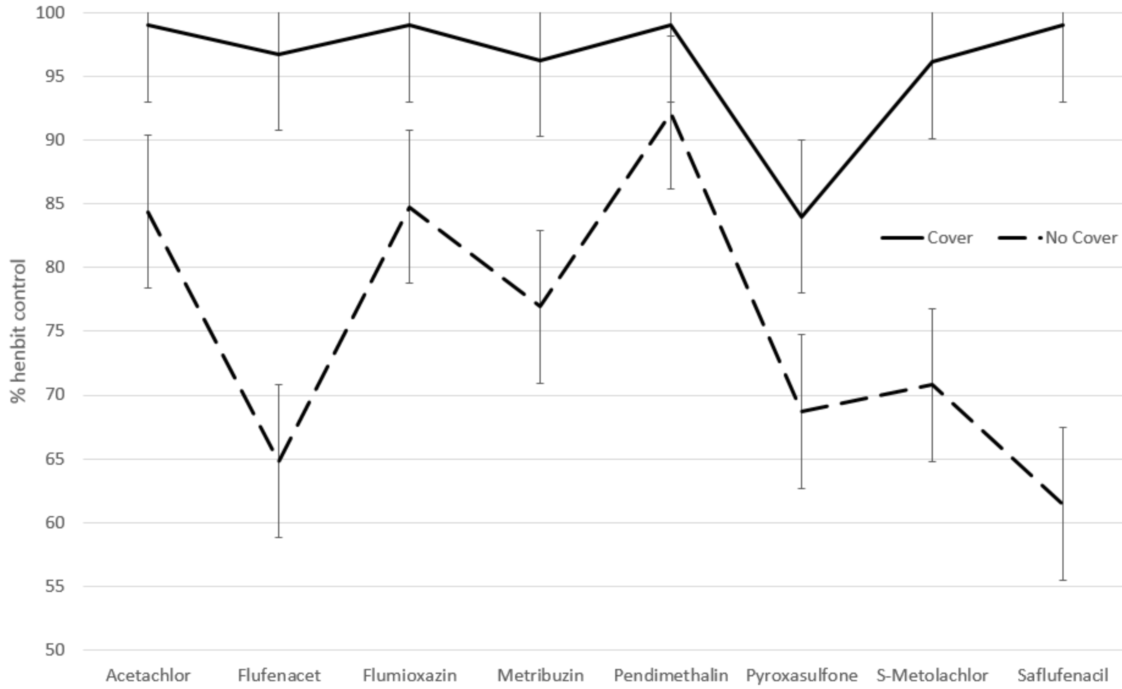

Figure 3: Interaction among the main effects of herbicide and a wheat cover crop for henbit control in west Tennessee.

CONCLUSION:
UTILIZING COVER CROPS TO IMPROVE SUSTAINABILITY OF CONVENTIONAL WEED MANAGEMENT PROGRAMS

Effects of Cereal rye, hairy vetch, and cereal rye + hairy vetch cover crop combinations on corn growth and development

The results of this study are similar to other researcher's findings, specifically that high biomass cover crops can be utilized in corn and produce yields that are similar to that of conventional no-till programs when weed control is maintained (Clark et al. 1993; Decker et al. 1994; Ebelhar et al. 1984; Gallagher et al. 2003; Johnson et al. 1993; Mitchel and Tell 1977; Utomo et al. 1989; Wiggins et al. 2016a). Clark et al. (1993) reported that corn yields from a vetch or cereal rye + hairy vetch cover crop were similar to that of standard no-till and greater than that of corn yields in a cereal rye alone cover crop, when terminated 10 d prior to planting; however differences were not as great when termination was conducted ~38 d prior to planting. In this study, yields from hairy vetch or cereal rye alone cover crop were similar to that of the NC when terminated 0 or 14 DPP; however, yields from cereal rye + hairy vetch were similar to that of the NC and that of the greatest treatments at all termination timings.

Utilizing cereal rye + hairy vetch cover crop can create a synergistic effect increasing cover crop biomass (Clark et al. 1993; Clark et al. 1997; Ranells and Wagger 1996; Sanju et al. 2005; Teasdale and Abdul-Baki 1998; Wiggins et al. 2016; Zotarelli et al. 2009). This research indicates that while cereal rye, hairy vetch, or cereal rye + hairy vetch combinations can be terminated 0 to 28 d prior to planting without impacting yields compared to standard no-tillage systems.

Delayed termination timing can allow cover crop biomass and weed suppression to be increased. However, delaying termination timing can also adversely affect corn stand, vigor, and height. Cereal rye + hairy vetch or hairy vetch alone terminated 14 DPP should be utilized for optimal corn growth, development, and yield in a weed control cover crop system.

Evaluation of a roller crimper for cereal rye and hairy vetch cover crop termination prior to corn

Weed suppression was increased by delaying cover crop termination until corn planting; however, utilizing a roller crimper did not improve weed control or corn yields. Mischler et al. (2010) reported that when cereal rye termination was delayed from late-April to mid-May, resulting biomass from the cover crop nearly doubled in most instances and ultimately led to increased weed control. Also, in the aforementioned study, biomass from cereal rye, in the late-April termination ranged from 2593 to 5013 kg ha^{-1}. Biomass from either cover crop in this study ranged from 2650 to 3600 kg ha^{-1} and 2350 to 2900 kg ha^{-1} for cereal rye and hairy vetch, respectively, in glyphosate alone termination treatments. The biomass from this study is about one third to one half that (6,000 to 6,790 kg ha^{-1}) reported from research conducted in more southern latitudes of the U.S. (Price et al 2012; 2016). Although cereal rye provided greater control of Palmer amaranth and junglerice, corn yields were greater in hairy vetch treatments.

Although corn growth, development, and yield can be influenced by improper termination timing and species of cover crops, the critical weed-free period of corn can be manipulated with nitrogen. Evans et al. (2003) found that 120 kg ha^{-1} delayed the onset of the critical period for weed control in corn when compared to the 0 kg ha^{-1} in all site years, and also delayed the critical period for weed control in three of four site years when compared to 60 kg ha^{-1}. It was noted in this study that corn yield is sensitive to both nitrogen and weed interference. The effects on corn yield in this study were likely effected by the added nitrogen in the hairy vetch treatments.

Although glyphosate fb a roller crimper can be used to effectively terminate a cereal rye or hairy vetch cover crop, it did not improve weed control or corn yields over that of glyphosate alone. Additionally, of all the treatments, maximum control of Palmer amaranth or junglerice was 87 or 79%, respectively, 28 DAP indicating that additional control measures such as in-season herbicides should be used in tandem with cover crops to provide season long weed control (Wiggins et al. 2016); however, a roller crimper does not provide any added benefits to producers in latitudes near Tennessee producing high yield corn.

Evaluation of a roller crimper for cereal rye and hairy vetch cover crop termination prior to soybeans

Biomass significantly increased with each delayed termination interval, and cereal rye provided greater biomass than hairy vetch when pooled over all termination intervals. There were no significant differences in cover crop control 14 DAP and all treatments provided $\geq$98% control. Although control of each weed species was assessed 7 DAP in each site year, no weeds were present at this timing in any treatment, except for the no cover, nontreated control.

In addition to increasing weed control, the roller crop also can benefit the cash crop in that it is not having to grow through the substantial amount of standing biomass that was produced by cereal rye. Although 35 DAP weed control of Palmer amaranth was less for glyphosate fb the roller crimper than the roller crimper alone and junglerice control was not significantly different, yields from these termination methods were similar in cereal rye. Although termination method, timing, and cover crop species did influence weed control in this research, the greatest control from any treatment was 67 or 56% control of Palmer amaranth or junglerice, respectively. This control is not acceptable on an agronomic level indicating a need for additional management strategies, such as in-season herbicides, should still be used for season long weed control for season long control (Norsworthy et al. 2014; Reddy et al. 2003; Wiggins et al. 2016; Yenish et al. 1996). A roller crimper does provide benefits and can be utilized for terminating a cereal rye or hairy vetch cover crop 0 to 14 d prior to planting soybeans in Tennessee. However, for greatest weed control and soybean yields, producers should utilize a cereal rye cover, terminated with a roller crimper 0 to 7 d prior to planting soybeans in tandem with in-season herbicides.

Utilizing glyphosate plus dicamba tolerant soybeans in a cover cropping system to control Palmer amaranth

Although differences in Palmer amaranth control were not apparent at the end of the season, early season Palmer amaranth control ratings (21 and 28 DAT) followed a similar trend to that of soybean yields. Van Acker et al. (1993) reported in 4 of 6 site years, the critical period of weed removal to prevent 2.5% yield loss in soybeans was $\geq$27 d after emergence. However, in this same study, the critical period of weed removal to a 5% yield loss was $\geq$ 40 d after emergence in 3 of 6 site years. POST treatments for control of Palmer amaranth were applied 29 to 39 d after planting, meaning the weed removal in this study fell in a period that could cause 2.5 to 5% yield loss. The differences in yield are thought to be attributed to early season weed control.

Glyphosate + dicamba can be an effective tool for terminating high biomass cereal + legume cover crops when used 14 DPP to 14 DAP. Additionally, in all treatments, one effective POST herbicide application + a cover crop was sufficient to provide $\geq$ 97% control of GR Palmer amaranth at the end of the growing season while still maintaining soybean yields above the average for Tennessee (Anonymous 2016). The ability to use glyphosate + dicamba shortly before or after planting for cover crop control in DGT soybeans allows producers increased flexibility in managing high biomass cover crops for control of Palmer amaranth. However, producers should be aware of other possible pests such as insects when delaying cover crop termination until near soybean planting. When utilizing a wheat + hairy vetch cover crop in DGT soybeans, producers should delay cover crop termination until 7 to 14 DPP and make at least one POST application of glyphosate + dicamba to maximize Palmer amaranth control and soybean yields.

Evaluating the use of fall applied herbicides for controlling Italian ryegrass in cover crops

All herbicide treatments evaluated on a cereal rye or wheat cover crop produced biomass that was similar to that of nontreated cover crop and improved Italian ryegrass control over that of any cover crop alone. However, herbicide treatments were more variable in improving control of henbit. The greatest control achieved from any treatment was 89 or 91% (wheat or cereal rye, respectively, cover + pyroxasulfone, data not shown). Although these treatments maximized control with cereal cover crops, control would not be adequate for areas where significant Italian ryegrass infestations are present (Bond et al. 2014). Although pyroxasulfone, acetochlor, and s-metolachlor provide a similar weed control spectrum (Geier et al. 2006; Mueller and Steckel 2011; Steele et al. 2005), pyroxasulfone consistently provided greater control of Italian ryegrass across each cover crop species in this study. Acetochlor and s-metolachlor are not labeled for use in cereal rye or wheat. However, previous research has indicated that they could possibly have additional uses in cereal species for residual control. Ritter and Menbere (2002) reported no injury from s-metolachlor when applied to wheat at 0.43 kg ha^{-1} and $\geq$ 13% when applied at 1.12 kg ha^{-1}.

Also, Barapour et al. (2012) found that rice is tolerant to encapsulated acetochlor at various rates.

Bond et al. (2014) reported 95% control of GR Italian ryegrass from 1.42 or 0.16 kg ha^{-1} of s-metolachlor or pyroxasulfone 140 DAT. However, they also noted in this study that an additional control measure would be necessary in the spring to provide total control of Italian ryegrass prior to planting. Though pendimethalin has been documented for its effectiveness against ryegrass species, most research suggests that it is most effective when combined with other control measures (Barnes et al. 2001; Bond et al. 2005, 2014; Clemmer et al. 2004). In this study pendimethalin was effective for increasing control of henbit. Although herbicides proved too injurious to use on a crimson clover cover crop, herbicide options are available for use in a cereal rye, wheat, and/or hairy vetch cover crop. These herbicide applications can help control winter annual broadleaf weeds such as henbit. However, even a cover crop + herbicide was not effective in controlling Italian ryegrass. A single cover crop species should not be utilized in areas where this weed is problematic.

Utilizing a cereal + legume cover crop combination can create a synergistic effect increasing cover crop biomass and ensuing weed control (Clark et al. 1993, 1997; Ranells and Wagger 1996; Sanju et al. 2005; Teasdale and Abdul-Baki 1998; Wiggins et al. 2016; Zotarelli et al. 2009). Herbicide could be used with a hairy vetch + cereal rye or wheat cover crop that would produce more biomass than covers in this study. Although this could possibly present an option for allowing cover crops in areas where Italian ryegrass is present, more research is needed to confirm or reject this hypothesis.

Conclusion

Cover crops can improve the efficacy, durability, and sustainability of weed control programs. However, as with all other practices, they should not be solely relied on for weed control. Glyphosate resistance in weeds evolved due to recurrent glyphosate usage, with little to no diversity in weed management practices. Avoiding or at least delaying the development of resistance in weeds (to any herbicide or management practice) requires a diverse weed management program comprised of herbicidal and nonherbicidal weed control strategies. Cover crops are one nonherbicidal strategy for controlling weeds, however, crop rotation, water management, crop planting date and seeding rate, cultivar choice, nutrient management, tillage, and row spacing should also play a role in this strategy (Vencill et al. 2012). This research indicates that cover crops can play an important role in controlling difficult weeds such as Palmer amaranth when they are managed correctly. Similarly to herbicides, managing a cover crop for maximum effectiveness is crop specific (both cover crop and cash crop). Terminating a cover crop is especially important prior to planting corn. Incorrect termination can have negative impacts on both corn growth, development, and yield, as well as the ensuing weed control. Additionally, as corn in Tennessee is planted earlier than soybeans or cotton, cover crops prior to corn, will not produce the quantities of biomass or weed control as they would prior to soybeans. Cereal and/or legume cover crops should be terminated at least 14 d prior to planting. While the additional control method in corn would increase sustainability, immediate weed control benefits in corn would not be as prominent as they would in soybeans. In soybeans, immediate benefits can be realized. Cover crop termination in soybeans can be delayed until at or after planting depending on the herbicide tolerance being utilized. In glufosinate- or glyphosate-tolerant soybeans termination of a cereal or legume cover crop can be delayed until planting. Cereal cover crops provide greater weed control and soybean yields than legumes prior to soybeans. Additionally, if a cereal cover crop, such as cereal rye, is utilized, termination should be conducted 0 to 7 d prior to planting with a mechanical roller crimper to maximize weed control and soybean yields. However if glyphosate plus dicamba tolerant soybeans become available, termination would be better conducted after planting with a herbicide mixture applied to a cereal + legume cover crop mix to achieve acceptable weed control. Although cover crops can provide many benefits for controlling difficult summer annual weeds, such as Palmer amaranth, controlling winter weeds, such as Italian ryegrass can be more difficult in a cover cropping system. Although herbicides can safely be used on cereal rye, wheat, and hairy vetch, acceptable control of Italian ryegrass in any cover crop species was not achieved. Cover crops should not be utilized in areas where Italian ryegrass is prevalent.

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VITA

Garret was born and raised in rural northwest Tennessee near Union City, by his loving parents Bob and Amy. He has an 8 year old son, Clayton, an older sister, Dana, and twin younger sisters, Hope and Megan. He spends majority of his free time with his friends and family and/or outdoors. He received a B.S. degree in Plant and Soil Science with a row crop concentration from the University of Tennessee, Martin in 2012. After graduation, he began a M.S. degree with a concentration in Weed Science at Mississippi State University under direction of Dr. Jason Bond. In the spring of 2014, Garret completed his M.S. degree and started pursuit of a PhD in Weed Science at the University of Tennessee with Dr. Larry Steckel as his advisor. Beginning in 2007 and continuing through the fall of 2011 Garret worked as a crop scout to assess and help with management decisions in cotton, corn, soybean, and wheat production in northwest Tennessee, southeast Missouri, and northeast Arkansas. His thesis research was centered on the use of saflufencil in rice and aided in achieving a supplemental label that allowed for postemergence applications. Garret is a member of state, regional, and nation agronomic and graduate student societies, and was the president of SWSS Graduate Student Organization from 2014 to 2015. He was a member of the Mississippi State University weed team that claimed 3rd place overall in the 2013 SWSS Weed Contest. He placed 2nd in the M.S. paper presentation section of the 2014 SWSS, 2nd Ph.D section of the 2016 SWSS, and 1st Beltwide graduate paper contest in 2015. He placed twice in the internal graduate student paper presentation contest at Mississippi State. He has currently authored or coauthored 4 refereed journal articles, and authored or co-authored 21 extension or newsletter publications, and 29 professional society abstracts. Upon graduation, Garret plans to spend as much time enjoying his family and friends while trying to find the most suitable job for himself.