Integrating Cover Crops and Herbicides for Weed Control in Soybean and Cotton

by

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Abstract

In mid-South, southeastern, and northeast United States soybean production regions, the evolution of herbicide-resistant weeds has become a significant management challenge for growers. The issue of rising herbicide costs for managing herbicide-resistant weeds is also a growing concern, leading to the utilization of cover crops as an integrated weed management strategy for addressing these challenges. Field experiments were conducted at two locations in Alabama in 2022 to evaluate winter cereal cover crops including a mixture, and herbicide system integration in soybean. Treatments included five cover crops: oats, cereal rye, crimson clover, radish, and a cover crop mixture. Cover crops were evaluated for their weed-suppressive characteristics compared to a winter fallow treatment. Additionally, four herbicide treatments were applied: a pre-emergence (PRE) herbicide, a post-emergence (POST) herbicide, PRE plus POST herbicides, and a non-treated (NT) check. The PRE herbicide was *S*-metolachlor, the POST treatment contained a mixture of dicamba and glyphosate. The PRE plus POST system contained the PRE application followed by POST application. Our results show that cereal rye and the cover crop mixture provided weed biomass reduction compared to all cover crop treatments across both locations. Furthermore, we observed greater soybean yield following the cereal rye cover crop than the winter fallow treatment at one location. POST and PRE+POST herbicide treatment resulted in greater weed biomass reduction and improved soybean yield than the PRE herbicide treatment alone and NT check at both locations.

A field study conducted in Alabama at three locations from autumn 2021 through the crop harvest in 2022 aimed to evaluate the combined effect of cover crop residue and herbicides for weed control and improved cotton lint yield. The experiment was conducted in split plot design with main plots consisting of six cover crop treatments: cereal rye, crimson clover, oats, radish,

cover crop mixture, and winter fallow. The subplots included four herbicide treatments: 1) PRE, pendimethalin + fomesafen, 2) POST, dicamba + glyphosate + *S*-metolachlor, 3) PRE followed by POST, and 4) NT check. Cover crops, excluding radish, exhibited greater weed biomass reduction than winter fallow with corresponding herbicide treatments of either PRE, POST, or PRE+POST as compared to control (winter fallow and NT check). Considering PRE+POST treatment, cereal rye, crimson clover, oats, and cover crop mixture provided >95% weed biomass reduction as compared to control. Cereal rye outperformed and showing higher weed biomass reduction than radish relative to control. PRE+POST herbicide treatment resulted in greater lint yield than other treatments. Cereal rye resulted in a greater lint yield than winter fallow at one out to three locations. In conclusion, integrating herbicides along with the incorporation of high residue cover crops such as cereal rye, is an effective weed management strategy to control troublesome weeds.

A greenhouse experiment was conducted to evaluate the germination and growth response of troublesome southeastern weeds to various cereal rye residue levels. Trays having Palmer amaranth, sicklepod, ivyleaf morningglory, and large crabgrass seeds mixed with organic garden soil were covered uniformly by four different biomass of cereal rye residue. The following field experiment was conducted at two locations in Alabama in a split-plot design, with the main plot factor being four seeding rates of cereal rye to obtain various cereal rye biomass. In the sub-plot factor, a preemergence herbicide flumioxazin and NT check were considered. The greenhouse results illustrated that Palmer amaranth, sicklepod, and large crabgrass showed decreased seed germination and lesser weed biomass under higher biomass of cereal rye. In both greenhouse and field conditions, germination of ivyleaf morningglory was not decreased with increasing cover crop biomass. Palmer amaranth was most responsive to germination, which decreased with increasing cover biomass, due to their small seed size. Cereal rye biomass with Palmer amaranth counts was strongly negatively correlated with a coefficient of 0.83, while weakly negatively correlated for ivyleaf morningglory with 0.49. In conclusion, increasing biomass of cereal rye residue is effective in suppressing Palmer amaranth seed germination. Flumioxazin herbicide treatment showed 90-95% control while NT check exhibited approximately 30-40% control of Palmer amaranth and ivyleaf morningglory.

Growers often report their preferences of cover crop seeding rates below the standard recommendation to reduce the cost of implementation. Despite the extensive research conducted on cover crops, there continues to be a wide range of suggested seeding rates for winter annual cover crops in the southern region of the United States. Moreover, as cover crop mixtures are gaining popularity due to multiple benefits, finding a balance between managing competition and potential tradeoffs between overall biomass production and seed costs can be accomplished by adjusting the seeding rates of each species in a mixture. A collaborative research trial was conducted in 2020 and 2022 across various states in the southern United States. Five legumes species were evaluated: hairy vetch, crimson clover, common vetch, winter pea, and berseem clover at four seeding rates. Each leguminous cover crop was planted separately with or without cereal rye in a mixture at a seeding rate of 33.63 kg ha^{-1}. The findings from this study showed that incorporating cereal rye within a mixture with legume cover crop resulted in a significant increase in cover biomass compared to using the legume cover crop alone across all locations. However, the trial did not indicate any considerable impact of the seeding rate on cover crop biomass production. Averaged across locations, we found that crimson clover and hairy vetch produced greater cover biomass than berseem and common vetch when planted as monocultures.

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Abbreviations

IWM Integrated Weed Management

PRE Preemergence

POST Postemergence

EVS E.V. Smith Research and Extension Center

WREC Wiregrass Research and Extension Center

TVREC Tennessee Valley Research and Extension Center

CC Crimson clover

CV Common vetch

HV Hairy vetch

WP Winter pea

BC Berseem

CLRDV Cotton leaf roll dwarf virus

GFP Green fluorescent protein

Chapter 1: Literature Review

Introduction

Conservation Tillage: Historically, crops were grown under conventional tillage or inversion tillage practices using primary and secondary tillage involving moldboard plowing, disking, and cultivation to break up soil clods and hardpan (Abdalla et al., 2013). However, continuous use of conventional tillage practices could negatively impact soil productivity due to soil erosion and loss of soil organic matter. Additionally, conventional tillage causes soil disturbance and changes soil organic matter distribution, and plant nutrient availability on the soil surface. It adversely impacts enzymatic and microbial activity, which are responsible for the organic matter transformation, cycling, and release of nutrients for plant uptake (Price et al., 2011; Mathew et al., 2012). Therefore, adverse influences of conventional tillage have resulted in improved adoption of conservation tillage in the crop production system, in Alabama, 86% of cropland is managed under a form of conservation tillage practices (CTIC, 2017). A conservation tillage system is defined as a system that leaves at least 30% of the soil surface covered with residue after planting and it is an essential conservation practice to reduce soil erosion (Uri et al., 1999). Moreover, conservation tillage has been adopted successfully with the development of herbicide-resistant crops and after the introduction of broad-spectrum herbicides for weed control such as glyphosate (Givens et al. 2017). Initially, conservation systems were adopted to prevent soil erosion and rainfall run-off losses to sustain soil quality and moisture availability (Kaspar et al. 2001). Specifically in the southeastern United States which has low fertility soils that are more prone to erosion and aggregate disturbance, the conservation tillage practices alter soil characteristics resulting in improved soil quality (Mathew et al., 2012). The benefits of conservation tillage practices include lowering the cost of production, decreasing soil temperature variations, improving soil organic matter, and retaining soil moisture (Schwab et al., 2022; West et al., 2002) and higher economic returns as compared to conventional tillage (Raper et al. 1994; Smart and Bradford 1999). However, over time, herbicide-resistant weeds and perennial weeds have become the primary challenge to sustain the adoption of conservation tillage (Bajwa 2014; Price et al. 2011; Shaw et al. 2012). Growers faced a real threat to conservation tillage due to herbicide-resistant weeds (Duzy et al., 2015). In the meantime, cover crops have gained significant popularity among row crop farmers in the United States.

Cover crops in Conservation Tillage Systems: In the southeastern United States, cover crops are typically grown during fallow period (winter months) and terminated before planting of main crop in summer using chemical treatment and then cover crop residue flatten on soil surface via mechanical method. Cover crops are not harvested immediately for economic profit. Row crop growers are increasingly adopting high residue cover crops exhibiting suppressive weed characteristics combined with conservation tillage to maintain crop yield potential (Price et al. 2006, Norsworthy et al., 2012; Vann et al., 2019).

In the US, the cover crop acres were around 4 million hectares in 2012 and over the 5 years which increased by 50% and reached 6.23 million hectares in 2017 (Wallander et al., 2021). According to Hamilton et al. (2017) this increment is probable to reach 40 million hectares by 2025. Cover crops can enhance the soil's physical, chemical, and biological properties by increasing the soil organic matter content and nitrogen availability. Cover crops with conservation tillage have long been utilized to mitigate soil erosion problems, reduce water runoff losses, and improve water infiltration, soil moisture content, soil organic carbon, and nitrogen cycling over the past few decades (Balanco et al. 2015; Dabney et al. 2001; Sainju and Singh 1997). Cover crops planted during winters after harvesting of the main crop scavenge soil residual N else it may leach into groundwater and cause contamination. Also, cover crops help in the atmospheric sequestration of C and N based on specific cover crops, hence decreasing the need for N fertilizer for main crops during summer (Kuo et al., 1997). More specifically, cover crops have also been identified as one of the potential weed suppression management tactics due to their ability to hinder the early-season germination and establishment of weeds, control weed growth by blocking light transmission and physically suppressing weed emergence, compete for resources and nutrients (Norsworthy et al. 2011; Price et al. 2016; Reddy 2001; Teasdale and Mohler 2000) and release allelopathic chemicals (Burgos et al. 2000). The dense mat of cover crop residue that inhibits the germination and establishment of weeds, more specifically small-seeded weed species because they have less stored resources for germination and growth (Bhowmik and Inderjit 2003; Teasdale and Mohler 2000). Therefore, the adoption of integrated weed management strategies utilizing cover crops with conservation tillage has been identified as an important approach to suppress troublesome weeds and improve soil health.

The benefits of cover crop are highly dependent upon biomass of cover crop residue. Previous research studies claimed that cover crop biomass accumulation is a very critical factor for the intensity of weed suppression with cover crops (Nicholas et al., 2020; Osipitan et al., 2018). The essential biomass of cover crops mulch for weed control throughout the season with no inclusion of herbicides should be as 8000 kg ha^{-1} (Mirsky et al., 2013). The increased cover crops biomass provided greater weed suppression through forming a residue mat that impeded the weed seedling emergence and increases the duration of weed control (Hayden et al., 2012; Teasdale et al., 1991). However, biomass production of cover crop showed considerable variation due to different weather conditions, cropping system, cover crop type and management (Ruis et al., 2019). In fact specific research illustrated that cover crop biomass production could significantly fluctuate, even considering the similar geographical area (Finney et al., 2016; Thomas et al., 2016, 2017).

The three major families used for cover crops are Poaceae, Fabaceae, and Brassicaceae. The choice of a cover crop for farmers depends on the purpose and need of a cover crop, context-specific factors, and the costs linked with managing a specific cover crop. Functions and benefits of cover crop species within each family are different (Snapp et al., 2005).

Because weed suppression and physical shading of soil are relative to amount of cover crop biomass residue, thereby cereal rye and other small grains cover crops are mainly utilized by growers due to their high biomass production (Murrell et al., 2017). CTIC (2023) and Ruis et al. (2019) also observed that small grains are the most adopted cover crops among farmers because of their rapid growth habits and winter hardiness. Cereal cover crops decomposition rate is slow due to the wide C: N ratio; hence provides a longer weed suppression effect throughout the season (Teasdale et al., 2007). Moreover, due to higher biomass accumulation, cereal cover crops increased soil organic matter by providing C (Sainju et al., 2000). However, due to the high C: N ratio of grass cover crops they create a risk of N immobilization for a short duration (Ranells and Wagger, 1996).

Legume cover crops help in N fixation and supplying N to succeeding crops and increase the plant available N resulted to improve crop yield potential (Clark et al., 1994). After the termination of the cover crop, legume residues decompose faster as compared to grass residues because of their lower C: N ratio (Teasdale et al., 2007). Legumes in a mixture with grasses can advantage the grass by providing additional N via biological fixation for cover crop growth during the spring time and reducing the short-period N immobilization (Ranells and Wagger, 1997). Brassica cover crop species could reduce the soil compaction in hardpan levels and scavenge plant nutrients as compared to rye monoculture by extending the roots deeper into the soil horizon (Schomberg et al., 2006; Chen and Weil, 2010; Blanco-Canqui et al., 2015).

From past few years, cover crop mixtures have been usually adopted among farmers to get the combined advantages of specific cover crop in a mixture and increase the diversification of ecosystem functions (Vann et al., 2019; Finney et al., 2016; MacLaren et al., 2019). Integrating various species of cover crop can also increase their ability to perform their functions effectively. But the performance of specific cover crop species in a mixture showed significant variations. It has been observed that small grains dominated and contributed a major proportion in a mixture when planted late; while brassica cover crops had less cover biomass in mixtures than monoculture; however, biomass of legume differed according to planting date (Murrell et al., 2017 and Finney et al., 2016). Because sometime, establishing a diverse mixture of plant species can be challenging due to competition among plants for nutrients and resources (Hall, 1974). Consequently, selecting appropriate seed rates and cover crop species for a mixture is critical to obtain adequate biomass residue and diversify the advantages of each cover crop. Specifically, the mixture of cereal and legume cover crops is gaining attention nowadays as it maintains N availability and accumulate sufficient biomass residue than planting solo cover crop species in monoculture systems (Clark et., 2017; Poffenbarger et al., 2015). Previous research studies by Reeves et al. (2005) and Webster et al. (2013) stated that the combination of a small grain with legume cover crop usually enhanced the total cover crop biomass compared to various legume species planted in monoculture system. Furthermore, in a combination of legumes and non-legumes cover crops, legumes provide additional N through fixation, resulting in improved N nutrition of nonlegumes and biomass accumulation of bicultural cover crops (Ta and Faris, 1987; Russelle and Hargrove, 1989). Therefore, mixing legumes and cereals has been found a profitable management decision to increase N content and decrease C: N ratio of cereal cover crops included rye, because cereal cover crops, usually have less N content and wide C: N ratio (Clark et al., 1994; Kuo and Jellum, 2002). Particularly, it has been observed that hairy vetch or crimson clover (*Trifolium incarnatum* L.) in a mixture with rye enhanced N content and reduced C: N ratio, hence reduce the N immobilization (Sullivan et al., 1991; Ranells and Wagger, 1996) enhance total cover crop biomass and decrease N leaching compared to hairy vetch monoculture system (Sainju et al., 2005).

Integration of Cover Crops and Herbicides for Weed Control: Historically, conventional tillage was the most used method for weed control in the crop production system. Later, herbicide development promoted the adoption of conservation tillage with herbicide usage. However, widespread usage of broad-spectrum herbicides, specifically glyphosate, resulted in the herbicide-resistant weed species (Heap & Duke, 2017; Norsworthy et al., 2008). Thus, alternative methods of weed control to diversify weed management strategies are necessary while maintaining the adoption of conservation tillage practices and crop yield. With the fast increase in herbicide-resistant weeds throughout the United States, weed management recommendations have transferred towards diversified agricultural approaches (Heap 2023; Norsworthy et al., 2012). Integrated Weed Management (IWM) is the most promising strategy that includes multiple practices and tools such as cover crops with different mode of action of herbicides to reduce the selection pressure for resistance (Norsworthy et al., 2012). Previous research studies have shown the ability of cover crops to suppress weeds. Research studies in Alabama showed that cereal rye and crimson clover cover crop had significantly less weed biomass than winter fallow treatment (Kumari et al., 2023a and 2023b). The research study observed that a cereal rye cover crop significantly suppressed Palmer amaranth weed compared to the winter fallow across several locations Georgia (Hand et al., 2019). Pittman et al. (2020) found that suppression of small-seeded weed species can be accomplished up to 6 weeks however approximately 7,500 kg ha^{-1} amount of cover crop residue needed to achieve a weed suppression of 50%. Considering fall-inversion tillage**,** cereal rye and crimson clover provided significantly greater Palmer amaranth visual control (≥97%) than winter fallow (Aulakh et al., 2012). Furthermore, cover crops can complement the herbicides for weed control by reducing herbicide usages by eliminating the need for either preemergence (PRE) or postemergence (POST) herbicide applications in soybean (Price et., 2006; Reddy et al., 2001). In cotton, application of only glyphosate-based POST herbicide regimes once accomplished enough weed control, while current challenges require the addition of preemergence herbicides in the weed management strategies (Cahoon and York, 2019; Culpepper et al., 2007, 2020; Price et al., 2021). To remain the adoption of conservation tillage it is essential to integrate the cover crops such as cereal rye, residual herbicides, and inversion tillage as recommended by state cooperative extension systems to bury the weed seeds for example Palmer amaranth under the soil profile for control of herbicide-resistant and troublesome weeds (Cahoon and York, 2019; Culpepper et al., 2020; Price et al. 2011, 2016a; Smith et al. 2019).

Previous research study observed that cover crops can enhance crop productivity and decrease the postemergence herbicides requirements in no-till corn and soybean (Gallangher et al., 2003). Integrating the PRE herbicides having soil residual activity, with cover crops, is one potential approach to delay the selection pressure for resistance to POST herbicides. The use of effective PRE herbicides allows growers to control weeds as they germinate and establish, hence reducing weed competition with the main crop. Additionally, it gives greater flexibility for POST herbicides, could avoid the requirement for an early POST application (Knezevic et al., 2019; Perkins et al., 2021).

Objectives: Diversifying agricultural practices to feed the rising world population and ensure global food security through a more efficient and sustainable production system is the primary concern. Throughout the United States, widespread and continuous use of chemical herbicides has led to the development of herbicide resistant weeds that pose a significant risk to crop production systems. Cover crops have been identified a potential tool to provide many advantages that could increase the functionality and efficiency of agricultural systems. Integrating cover crops with different herbicides could be a potential strategy to tackle troublesome and resistant weeds to reduce selection pressure for resistance. Simultaneously, cover crop biomass is a determining factor of weed suppression, thus estimate of adequate cover residue and seeding rate to acquire that biomass is necessary for farmers.

The objectives of the studies were, 1) to evaluate the effect of different cover crop and herbicide treatment for weed control in soybean; 2) to estimate the combined effect of cover crops and herbicides for effective weed management in cotton; 3) to evaluate the effect of different biomass residue of cereal rye and a preemergence herbicide on the germination of troublesome southeastern weeds; 4) to estimate the effect of legume cover crop species seeding rate and their mixture with cereal rye on cover crop biomass production throughout the southern United States. The goal of this multistate trial included legume cover crop species selection and providing seeding rate recommendations to farmers.

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Chapter 2. Integrating Cover Crops and Herbicides for Weed Control in Soybean

Introduction

Soybean is among the most important agricultural crops worldwide. It provides a palatable protein-rich seed, making it highly beneficial for both human consumption and animal feed. However, troublesome and herbicide resistant weed species challenge soybean production. Potential soybean yield losses due to weed infestation in the United States are estimated at $16.2 billion (Soltani et al. 2017). Weeds not only compete for limited resources like light, water, and nutrients during the crop growing season (Burnside 1973) but also adversely impact soybean production through interrupting harvesting operations (Nave and Wax 1971) and altering the protein content of soybean seed (Gibson et al. 2008). Herbicides have been the most common method for weed control in soybean production among other methods (Landau et al. 2022). However, the management of problematic weeds is a significant challenge for growers due to the over-reliance on herbicides, which has led to the selection of herbicide-resistant weeds that are common throughout soybean production regions in the US (Beckie et al. 2006; Heap et al. 2014; Shaw et al. 2012).

The issue of diminishing herbicide utility and rising herbicide costs for managing herbicide-resistant weeds has become a growing concern, leading to the resurgence of integrated weed management strategies to address it (Harker 2013; Menalled et al. 2016; Neve et al. 2014). Included in integrated strategies is an increased use of tillage to bury weed seeds at depth beyond that of successful germination and emergence which threatens adoption and retention of conservation systems (Price et al. 2011, 2016). However, the adoption of cover crops continues to gain attention for their weed suppressive attributes including disrupting establishment and growth of weeds while maintaining crop yield (Aulakh et al. 2015; Norsworthy et al. 2010, 2011;

Price et al. 2011, 2016, 2021). Weed suppression after cover crop termination has primarily been shown to be due to plant residue biomass that prevents seed germination and establishment by altering light quantity at the soil surface and providing a physical barrier (Norsworthy et al. 2011; Price et al. 2006; Teasdale 2018). Furthermore, in addition to improving soil fertility (Mirsky et al. 2012) and crop productivity, cover crops provide other advantages such as complement chemical weed control method and reducing herbicide utilization by removing the requirement for either preemergence (PRE) or postemergent (POST) herbicide applications in the weed management system in soybean (Price et. 2006; Reddy et al. 2001).

Cover crop utilization has been increasing in the United States. In 2017, farmers reported the planting of 15.4 million acres of cover crops, indicating a 50-percent increase from the 10.3 million acres reported in 2012 (Wallander et al. 2021). However, the effect of cover crops on weed control has varied according to management practices and location (Schomberg et al. 2006), and regional and global meta-analyses supported this phenomenon (Nichols et al. 2020; Osipitan 2018; Osipitan et al. 2019). Numerous researchers reported increased weed suppression from high-residue cereal cover crops in strip tillage systems compared to winter fallow systems (Kumari et al. 2023a, 2023b; Norsworthy et al. 2011; Price et al. 2012; Reeves et al. 2005). Integration of cover crops, particularly cereals, contributed to early-season weed control and may reduce the selection pressure of glyphosate for herbicide resistance in the conservation tilled cotton (Norsworthy et al. 2017). Nichols et al. (2020) reported that grass cover crop species significantly reduce weed biomass in corn-soybean production systems in the Midwest. Grass cover crop species provide greater weed suppression than broadleaf cover crop species (Osipitan et al. 2019). This is likely due to a rapid increase in biomass within a relatively short period. Increased biomass leads to a dense mat of biomass on the soil surface that suppresses weed seed germination and emergence. Additionally, due to the high C:N ratio of cereal grains, their decomposition rate is slow, allowing plant residue persistence for longer time (SARE 2007). In contrast, according to Price et al. (2006), no cover crop (rye, black oat, and wheat) was effective in weed suppression without an herbicide application in conservation-tillage soybean. Osipitan et al. (2018) suggested that in agronomic and horticultural production systems there was little to no significant difference between single cover crop species and cover crop species mixtures in terms of early weed control considering a meta-analysis. A study by Vann et al. (2019) indicated that the variation in total biomass composition under different environmental conditions explains the importance of selecting cover crop species and optimal cover crop mixture seeding rate recommendations to each site.

Although numerous experiments have been conducted to evaluate the weed-suppressive qualities of winter annual cover crops, limited studies have been conducted in Alabama to estimate the effect of different cover crops and their mixture combined with herbicide applications to control weeds. Therefore, field research was conducted in Alabama to evaluate the influence of cover crops (cereal rye, oats, crimson clover, radish, and mixture) and the integration of these cover crops with PRE, POST and PRE+POST herbicide applications on weed control and soybean yield.

Materials and Methods

Experimental Sites

The field experiments were conducted from cover crop planting in fall 2021 through crop harvest in 2022 at two sites in Alabama including "E.V. Smith (EVS) Auburn University Research and Extension Center, Shorter, AL (Field Crops Unit; 32.4417°N, 85.8974°W)" and "Tennessee Valley Research and Extension Center (TVREC), Belle Mina (34°41′ N 86°53′ W)". The soil characteristics at the EVS research site were sandy loam (coarse-loamy, siliceous, subactive, thermic Paleudults), pH 6.2, and 0.8% organic matter. The soil type at TVREC was Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults) and pH 6.0, and 2.3% organic matter.

Experimental Design and Treatments

The experimental design was a split-plot design with three replications of each treatment at each location. The plot size was 7.3 × 3.7 meters. Six cover crops treatments were considered in the main plot while four different herbicide treatments were considered in the sub-plot of the experimental design. The six different cover crops treatments included: 1) crimson clover (*Trifolium incarnatum* L.), 2) cereal rye (*Secale cereale* L), 3) oats (*Avena strigosa* Schreb.), 4) radish (*Raphanus sativus*), 5) a cover crop mixture, and 6) winter fallow. The cover crop mixture was a combination of cereal rye, oats, crimson clover, and radish. The four herbicide treatments included: 1) *S*-metolachlor applied PRE at 1.07 kg ae ha^{-1} (Dual II Magnum; Syngenta Crop Protection, Greensboro, NC, USA), 2) dicamba (Xtendimax; Bayer Crop Science, St. Louis, MO) applied POST at 0.559 kg ae ha^{-1} application + glyphosate (Roundup Powermax®; Bayer Crop Science, St. Louis, MO) at 1.68 kg ae ha^{-1}, 3) PRE followed by POST, and 4) a non-treated (NT) check. In total, there were 24 different treatments of cover crops and herbicides at each site.

Crop Management

All cover crops were planted with the JD 7730 and a Great Plains® no-till drill (Great Plains Salina, KS 67401) in the second week of November at both locations. Based on extension recommendation, the seeding rate includes: ‘Wrens Abruzzi’ cereal rye at 100 kg ha^{-1}, ‘Cosaque’ oats at 67.25 kg ha^{-1}, ‘Dixie’ crimson clover with inoculant at 22.42 kg ha^{-1}, and ‘Daikon’ radish at 9.0 kg ha^{-1}. In the cover crop mixture, seeding rates were cereal rye at 39.8 kg ha^{-1}, oats at 33.2 kg ha^{-1}, crimson clover at 11.2 kg ha^{-1}, and radish at 3.6 kg ha^{-1}. Germination percent of cereal rye 80%, oats 85%, crimson clover 80%, and radish 80% respectively. To maximize biomass production, all cover crop treatments were fertilized with N as 34 kg ha^{-1} in the form of ammonium nitrate. All cover crop plots were mechanically rolled by using a three-section straight bar roller-crimper (Ashford and Reeves 2003) to flatten the biomass residue on the soil surface in the first week of May at both sites. Just after mechanical rolling, cover crop termination was further attained with an application of glyphosate applied at 1.12 kg ae ha^{-1}. At TVREC experimental site, the soybean variety "Pioneer 45T88E" was planted during the second week of May, whereas at EVS, same soybean variety was planted in the first week of June. Soybeans were planted into a strip-tillage system across both sites. Soybean was seeded at 116,160 seed ha^{-1}(26 seeds m^{-1}). There was no significant interaction between locations and treatments, and the average soybean stands counts achieved at three weeks after planting across both locations with a row spacing of 0.91 m ranged from 69,262 to 95,691 plants ha^{-1}.

The application of PRE herbicide *S*-metolachlor was accomplished immediately following soybean seeding while the POST dicamba + glyphosate treatment was applied approximately four weeks after soybean planting. All herbicides were applied with a CO_2 pressurized backpack sprayer equipped with TTI 11004 nozzles (TeeJet, Glendale Heights, IL) at 276 kPa calibrated to deliver 280 L ha^{-1}. At all locations, soybeans were harvested from the center two rows from each plot to determine yield with a small-plot combine.

Data Collection

Immediately prior to cover crop termination, biomass samples were collected by cutting all aboveground parts of the plants near the ground within each cover crop plot. Samples were taken from one randomly selected 0.25-m^2 section from each cover crop treatment. The harvested cover crop samples were then placed in a dryer set at 65°C for 72 h, after which their dry weight was measured and recorded. Subsequent summer annual weed density and weed biomass was collected based on a randomly selected 0.25-m^2 quadrats from each subplot between rows then dried similarly to the cover crop biomass and dry weight of weed biomass was recorded. Visual control ratings were recorded regularly in two-week intervals throughout the season (data not shown). Weed biomass and weed density was determined at seven weeks after soybean planting.

Data Analysis

Analyses were conducted using R statistical software version 3.4.1 with the “agricolae” package. All data were subjected to analysis of variance (ANOVA) to evaluate the effect of herbicides and cover crops on weed density and biomass and soybean yield. Log transformation was used for the weed biomass as data was not normally distributed, then it was back transformed to show original means. Due to the significant interaction of locations with treatments, data was analyzed separately for each site. Means were separated using Tukey’s HSD at $\alpha = 0.05$ to check the treatment effects on weed density and biomass and soybean yield. Figures were build using Sigma Plot software (version 3.0; Systat Software, San Jose, CA).

Pearson’s correlation coefficients were used to assess the relationship among weed biomass, weed density, soybean yield, and cover crop biomass across all sites using the corr.test function in Rstudio. Additionally, correlation plot was built using corrplot library. In the graph, the size of the circle and the color intensity within the circle was used to represent the strength of the correlation, with larger circles and darker colors indicating stronger correlations. The presence of a cross or an “X” within a circle indicated no correlation between the variables. The correlation from 1 to -1, in which 1 represented positive correlation and -1 represented negative correlation, and 0 means no correlation between variables.

Results and Discussion

Cover Crop Biomass

Upon conducting an analysis of variance (ANOVA) to examine the impact of various cover crops on biomass production, we obtained a significant result with a p-value < 0.0001. Above ground biomass production was significantly different among cover crops evaluated. At TVREC, the recorded cover crop biomass of cereal rye, mixture, and oats was found to be similar, measuring 4,150, 3,356, and 3,873 kg ha^{-1}, respectively **(Figure 2-1A)**. Clover and radish had comparable biomass residue as 1,351 and 875 kg ha^{-1}. Additionally, radish had again the lowest biomass at this location.

At EVS, the average cover crop biomass of rye and a mixture at the time of termination was recorded similar as 6,290 kg ha^{-1} and 6,787 kg ha^{-1}, respectively **(Figure 2-1B)**. Additionally, clover and oat cover crops had comparable biomass residue of 4,364 and 4,441 kg ha^{-1} respectively. Out of all the cover crops evaluated, radish exhibited the lowest residue biomass, measuring 1,986 kg ha^{-1} at the same site.

The variations we observed in cover crop biomass between different cover crop species were expected, due to the species growth and/or development characteristics. We found the highest and sufficient amount of biomass residue in the case of cereal rye and cover crop mixture at both locations. Previous research stated that greater than 4500 kg ha^{-1} cover crop biomass is required to predictably suppress weeds (Norsworthy et al. 2011; Price et al. 2005). The greater observed biomass residue for the cereal rye cover crop is most likely due to its characteristics as a winter hardy small grain cereal (Mirsky et al. 2009; Sattell et al. 1998).

Weed Biomass

Some cover crop species provided a significant reduction in annual weed germination and establishment compared to winter fallow. Mainly morningglory (*Ipomoea* spp.) was the dominant weed species at EVS. Prickly sida (*Sida spinosa* L.) was the most abundant weed species at TVREC. Palmer amaranth [*Amaranthus palmeri* (S.) Watson] was present at both locations.

TVREC Site. Cover crop and herbicide treatments influenced weed biomass production at TVREC. The interaction between cover crops and herbicides was not significant **(Table 2-1)**. We observed greater weed biomass in winter fallow treatments (518 kg ha^{-1}) than mixture (202 kg ha^{-1}), rye (202 kg ha^{-1}), and oats (247 kg ha^{-1}) **(Figure 2-2A).** Clover (369 kg ha^{-1}) and radish (358 kg ha^{-1}) resulted in greater weed biomass than the use of rye cover crop. Although there were no differences in terms of weed biomass reduction among clover, radish, oats, and mixture cover crops. Cereal rye was more effective in suppressing the weed species present than crimson clover, radish, and winter fallow treatments. Our results were similar to Blum et al. (1997), who reported the average density of prickly sida seedlings were 77% lower following rye residue during the growing season compared to fallow. Similarly, Palhano et al. (2018) reported that cereal rye cover crops provided greater weed suppression than fallow plots, with 83% less germination of Palmer amaranth than the winter fallow treatment. Additionally, a prior study conducted at the same location also revealed that conservation tillage systems incorporating a rye cover crop result in reduced emergence of early-season pigweed due to the presence of a dense mat of cover crop biomass (Price et al. 2007). Because greater cover crop biomass at planting was more effective at suppressing the emergence and establishment of weed seedlings, specifically during the earlier part of the crop growing season, cover crop biomass was considered the key factor associated in weed biomass reduction. NT checks (580 kg ha^{-1}) had greater weed biomass than both POST (106 kg ha^{-1}) and PRE+POST (87 kg ha^{-1}) herbicide treatments **(Figure 2-2B)**. There was no significant difference in terms of weed biomass reduction between NT check and the PRE alone herbicide treatment, where weed biomass measured 492 kg ha^{-1}. However, the effect of the PRE alone treatment to control weeds was seen up to three to four weeks after planting as compared to NT check (data not shown). In coarse-textured soils of the mid-Atlantic and southern Coastal Plain, S-metolachlor applied as PRE offered only 2 to 4 weeks of weed control (Clewis et al. 2006).

EVS Site. Weed biomass was influenced by the main effects of cover crop and herbicide at the EVS site. There was no significant interaction between cover crops and herbicides in relation to their effect on weed biomass **(Table 2-2)**. The fallow treatment (1108 kg ha^{-1}) resulted in greater weed biomass than the rye (465 kg ha^{-1}) and mixture (824 kg ha^{-1}) treatments **(Figure 2-3A)**. Clover, oats, radish, and a mixture of cover crops provided similar weed biomass reduction. We recorded the lowest weed biomass following the rye cover crop treatment at this site. Due to greater C:N ratio of cover crop cereal rye and slow decomposition (Sievers et al. 2018), it provides a longer effect on weed suppression. Cover crop mixture resulted in greater weed biomass reduction than the winter fallow treatment. Our results suggested that mixture of cover crops has the potential to increase the aboveground biomass residue production as compared to biomass produced by clover and radish when grown as a monoculture. The presence of a significant amount of cover crop mixture biomass indicated that the presence of grain cover crop in a mixture with legumes enhances the cold tolerance of legumes, compared to legumes cover crop in a monoculture system (Hayden et al. 2015). In addition, the cover crop mixture such as cereal and legumes maintains the C:N ratio and causes a slower decomposition rate than a legume monoculture. Hence, mixtures may increase persistence of residue on soil surface and release of nitrogen (Clark et al. 2007; Poffenbarger et al. 2015).

Radish had the lowest biomass in both locations, and we did not find the effect of radish on either season long weed suppression. Due to forage radish sensitivity to frost, it experiences slow growth when exposed to temperatures below –4°C for an extended period (Weil et al. 2009). Our field results also agree with the previously reported poor growth of radish when planted late in Alabama (Decker et al. 2022). Furthermore, a study previously suggested that quick decomposition of forage radish cover crops produces low residue biomass and weed-free seed bed for planting in the early spring (Lawley et al. 2012). Additionally, previous research stated that radish cover crop alone provided good early season weed suppression but is not effective for weed control throughout the growing season (Malik et al. 2009). Generally, it has been observed that cover crops provide early-season weed control that may allow elimination of a PRE herbicide in cropping system (Reeves et al. 2005; Teasdale 2005).

NT check (1682 kg ha^{-1}) resulted in the highest weed biomass, whereas PRE alone treatment (1277 kg ha^{-1}) resulted in greater weed biomass as compared to POST alone (360 kg ha^{-1}) and both PRE+POST treatment (270 kg ha^{-1}) **(Figure 2-3B)**. Previous research also observed that *S*-metolachlor (PRE) controlled morningglory 64% and Palmer amaranth 68% only after three to four weeks after application (Clewis et al. 2007). It has been shown that high residue of cover crops can intercept PRE herbicide, preventing it from reaching the ground (Banks and Robinson 1982; Ghadiri et al. 1984). Crutchfield et al. (1985) reported that interception of *S*-metolachlor due to wheat straw before reaching the soil surface leading to a loss of weed control. Application of dicamba as a POST herbicide enhanced the consistency of weed control and effectively managed smooth pigweed, morningglory, and various broadleaf weed species (Johnson et al. 2010; Striegel et al. 2022).

Soybean Yield

TVREC Site. Cover crop species and herbicide program influenced soybean yield at the TVREC. The interaction between cover crop and herbicide was not significant. **(Table 2-2)**. Among different cover crops, we found rye treatment (1,791 kg ha^{-1}) resulted in greater yield than clover (1,055 kg ha^{-1}), radish (984 kg ha^{-1}), and winter fallow treatments (1,008 kg ha^{-1}) **(Figure 4A)**. Soybean yield was likely greater in cereal rye cover crop treatments because of increase biomass production and decreased weed competition. There were no significant differences for soybean yield between oats (1,476 kg ha^{-1}), mixture (1,420 kg ha^{-1}), clover (1,055 kg ha^{-1}), radish (984 kg ha^{-1}) and the winter fallow treatments (1,008 kg ha^{-1}). Both PRE+POST herbicide treatments (1,781 kg ha^{-1}) resulted in greater soybean yield than only PRE herbicide treatment (745 kg ha^{-1}) and NT check (770 kg ha^{-1}) **(Figure 2-4B)**. The PRE+POST treatment resulted in a 131% greater yield than the NT check, while the POST alone herbicide treatment resulted in a 142% greater yield compared to the NT check. Late-season weeds began to emerge and compete with soybeans, causing yield loss. As a result, the use of only PRE herbicide application did not have a significant effect on increasing soybean yield in cover crop systems.

EVS Site. At this location, there was no significant effect of cover crops while impact of herbicide treatments was observed for soybean yield. No interaction between cover crops and herbicides were found to influence soybean yield **(Table 2-2)**. No effect of cover crops on soybean yield was observed **(Figure 2-5A)**. PRE+POST (2,810 kg ha^{-1}) and POST alone (2,937 kg ha^{-1}) treatments resulted in greater soybean yield than plots that were treated with PRE alone (1,973 kg ha^{-1}) and NT check (1,735 kg ha^{-1}) **(Figure 2-5B)**. Specifically, PRE+POST treatment had 62% greater soybean yield compared to the NT check, while the PRE alone treatment resulted in 14% greater soybean yield compared to the NT check. Our results suggested that the application of only POST and both PRE+POST herbicide treatment was effective on morningglory, Palmer amaranth, and Prickly sida control and maintained soybean yield at both sites.

Correlation

The correlation between cover crop biomass, weed biomass, weed counts, and soybean yield has been estimated and represented in a correlation graph **(Figure 2-6)**.

A negative correlation between cover crop biomass and weed density was observed at the TVREC site, indicating greater cover crop biomass production results in a reduction in weed biomass. The correlation value of cover crop biomass with weed density and weed biomass were -0.4 and -0.35 respectively **(Figure 2-6A)**. Cover crop biomass also had a positive correlation with soybean yield of 0.39. The high cover crop biomass not only inhibits weed germination but also significantly contributes to maintaining soybean yield by effectively suppressing weed growth. MacLaren et al. (2019) demonstrated that cover crop biomass is a determining factor for weed suppression and reducing weed growth. Weed density and weed biomass has a positive correlation of 0.82 which means the greater the density of weeds substantially resulted in more weed biomass. On the other hand, weed density and weed biomass have negative correlation with soybean yield with the value of -0.75 and -0.80 respectively. As anticipated weed density and weed biomass have an inverse correlation with soybean yield. Greater weed density and biomass have been shown to negatively impact soybean yield.

There was no correlation of cover crop biomass with weed density, weed biomass, and soybean yield at EVS site **(Figure 2-6B)** due to greater weed density. Weed density and weed biomass were positively correlated with the value of 0.96. Both weed density and weed biomass had a negative correlation with soybean yield with values of -0.84 and -0.88 respectively.

Conclusions

Cereal rye and cover crop mixture were the most effective in reducing weed density and weed biomass. Dicamba + glyphosate and S-metolachlor followed by dicamba + glyphosate treatments provided greater weed control and soybean yield compared to only S-metolachlor and NT check. Cover crops are effective in suppressing early-season weeds but may not provide control throughout the season. Therefore, integrating high residue cover crops such as cereal rye and cover crop mixture with dicamba + glyphosate herbicides would be an effective strategy for weed control and maintaining yield in soybeans.

Suggested cover crops are not only effective in weed control but also provide practical benefits such as preventing runoff losses, soil erosion control, increasing organic matter, and conserving soil moisture in the southeastern region which has typically poor soils with mineralogical features, despite abundant precipitation. At the same time, the potential negative impacts of cover crops included equipment limitations and an increase in the cost of production for farmers.

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Tables:

TABLE 2-1. Significance of tests of fixed effects and their interaction in ANOVA for weed biomass as influenced by cover crops and herbicides across both locations. [a,b]

	P values	
	EVS	TVREC
Cover crop	0.0002*	0.0012*
Herbicide	<.0001*	<.0001*
Cover crop × herbicide	0.0733	0.0644

[a]P values followed by * are significant (α = .05).

[a]Abbreviations: EVS, E.V. Smith Research Center; TVREC, Tennessee Valley Research and Extension Center

TABLE 2-2. Significance of tests of fixed effects and their interaction in ANOVA for soybean yield as influenced by cover crops and herbicides across both locations. [a,b]

	P values	
	EVS	TVREC
Cover crop	0.6278	0.0132*
Herbicide	<.0001*	<.0001*
Cover crop × herbicide	0.8987	0.3081

[a]P values followed by * are significant (α = .05).

[a]Abbreviations: EVS, E.V. Smith Research Center; TVREC: Tennessee Valley Research and Extension Center

Figures

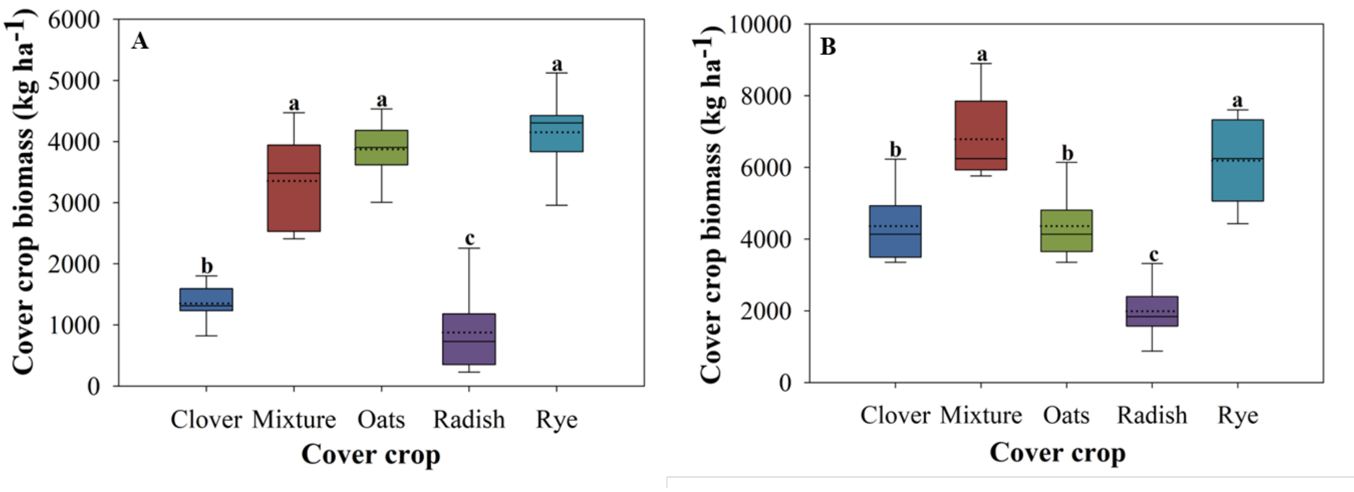

Figure 2-1. Dry weight of cover crop residue at the time of termination at Tennessee Valley Research and Extension Center (A) and E.V. Smith Research Center (B). Means followed by the different Tukey letters showed a significant effect. In the box plot, solid line indicates the median and dotted line represents the mean.

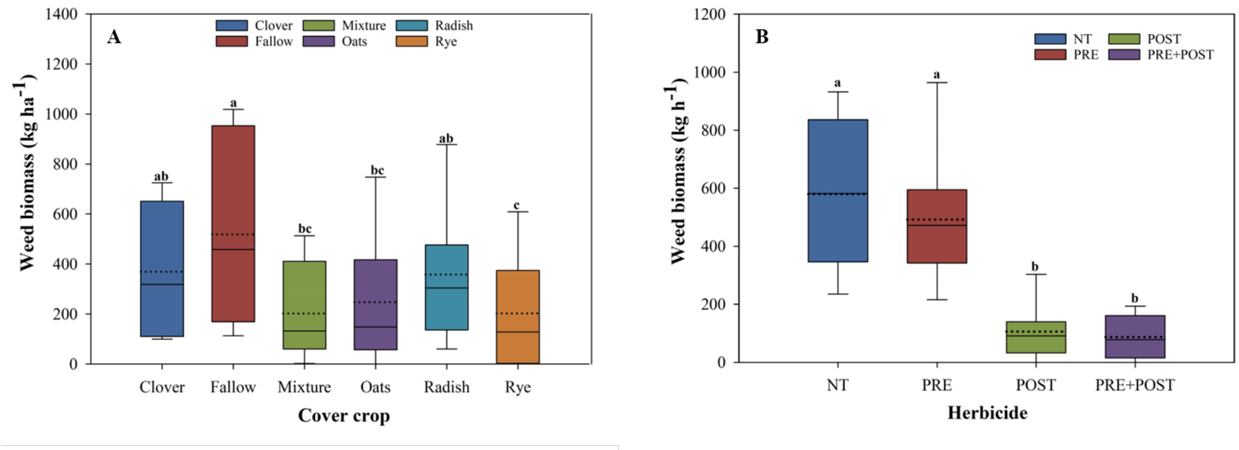

Figure 2-2. Effect of cover crops (A) and herbicides (B) on weed biomass at Tennessee Valley Research and Extension Center. Means followed by the different Tukey letters showed a significant effect. In the box plot, solid line indicates the median and dotted line represents the mean. In the box plot, solid line indicates the median and dotted line represents the mean.

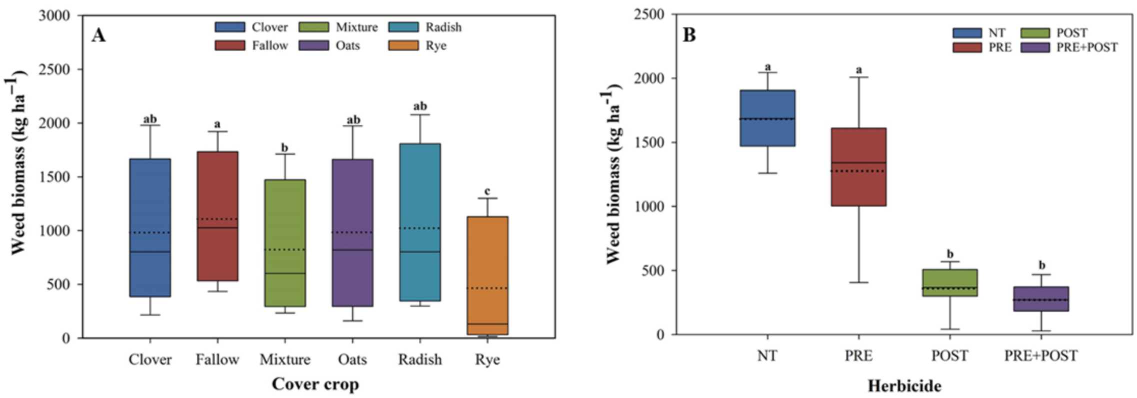

Figure 2-3. Effect of cover crops (A) and herbicides (B) on weed biomass at E.V. Smith Research Center. Means followed by the different Tukey letters showed a significant effect. In the box plot, solid line indicates the median and dotted line represents the mean.

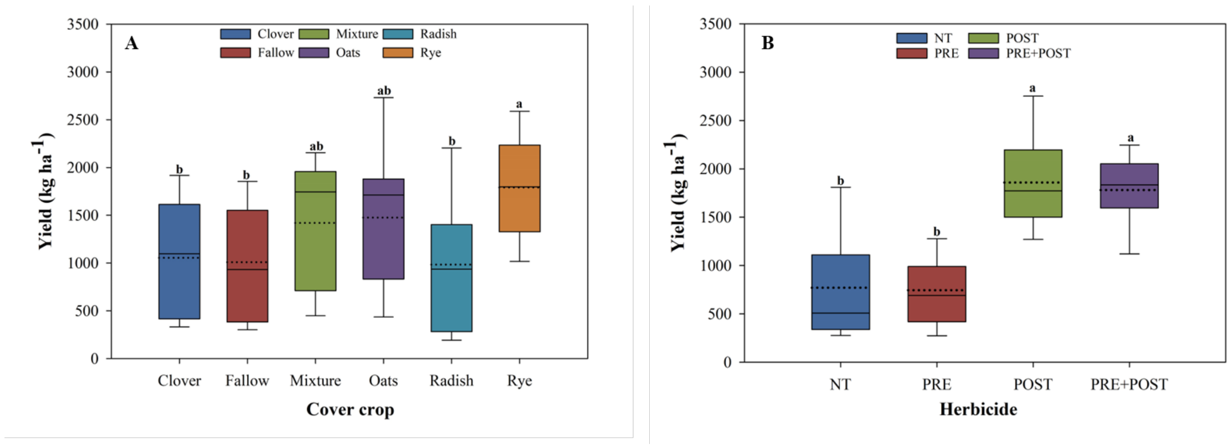

Figure 2-4. Effect of cover crops (A) and herbicides (B) on soybean yield at Tennessee Valley Research and Extension Center. Means followed by the different Tukey letters showed a significant effect. In the box plot, solid line indicates the median and dotted line represents the mean.

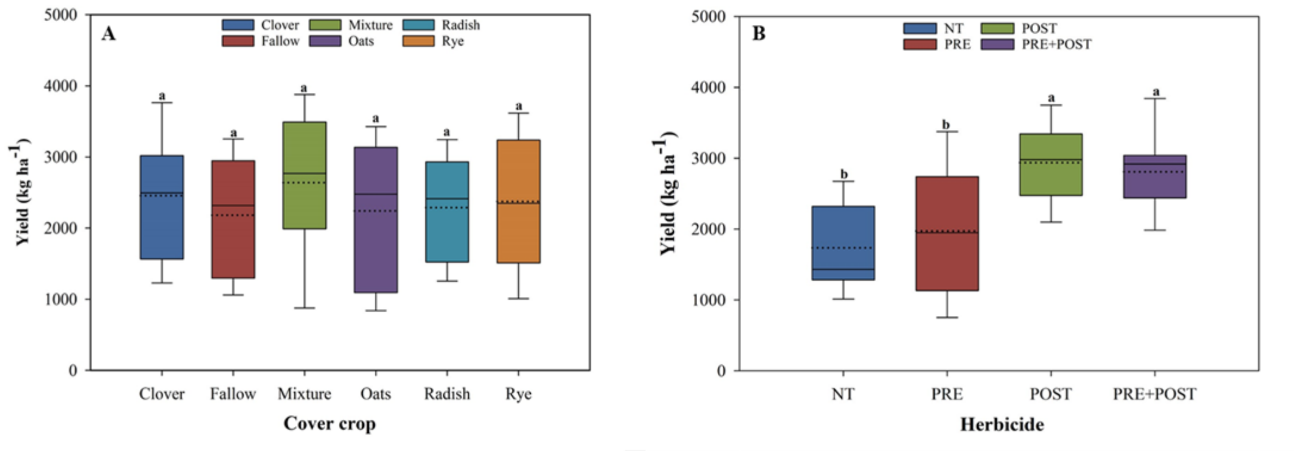

Figure 2-5. Effect of cover crops (A) and herbicides (B) on soybean yield at E.V. Smith Research Center. Means followed by the different Tukey letters showed a significant effect. In the box plot, solid line indicates the median and dotted line represents the mean.

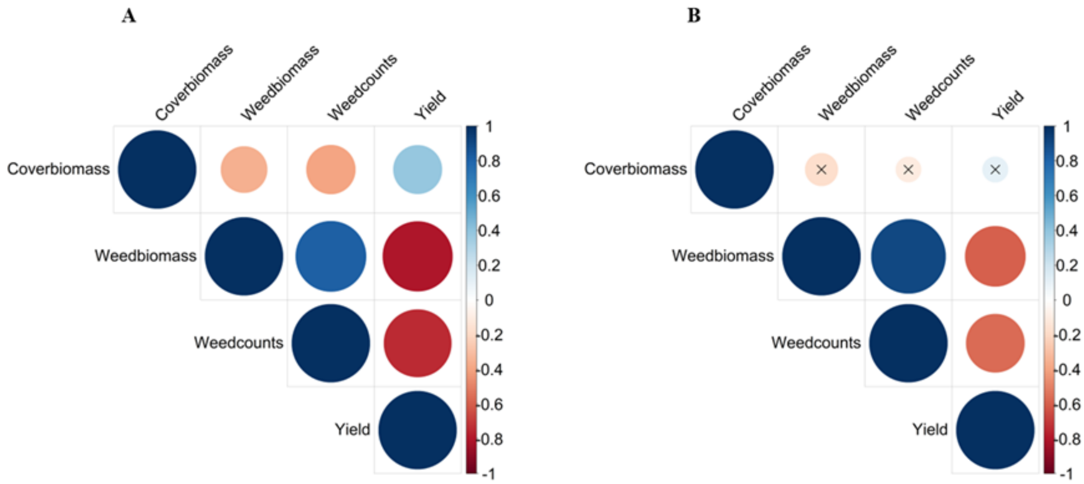

Figure 2-6. Pearson correlation coefficients between variables at Tennessee Valley Research and Extension Center (A) and E.V. Smith Research Center (B). Color intensity indicates the strength of correlation, with blue representing a strong positive correlation and red representing a strong negative correlation.

Chapter 3: Synergistic Effect of Cover Crops Residue and Herbicides for Effective Weed Management in Southern U. S. Cotton Production Systems

Introduction

In the southern United States, Palmer amaranth [*Amaranthus palmeri* (S.) Wats.], morningglories (*Ipomoea* spp.), nutsedge (*Cyperus* spp.), and sicklepod [*Senna obtusifolia* (L.)] are some of the troublesome and prevalent weed species in the cotton production system (Webster 2012). The widespread glyphosate-resistant Palmer amaranth also questions weed management (Culpepper et al. 2006; Norsworthy et. al. 2008; Price et al. 2011).

Historically, cotton (*Gossypium hirsutum* L.) was grown under conventional tillage practices involving moldboard plowing, disking, harrowing, and cultivation. But, greater cost of production, lower product prices, development of herbicide-resistant crops, and other concerns related to soil health, such as soil loss to erosion and decreased soil organic matter content, required the adoption of alternative tillage decisions such as conservation tillage. Some strip-tillage production systems incorporate a row subsoiler to disrupt soil compaction within the crop row only without significantly disturbing the soil surface residue (Raper et al. 2007). However, the widespread threat of glyphosate-resistant Palmer amaranth poses a significant risk to conservation tillage, resulting in observed challenges of inadequate weed control in crop production adopting this practice (Price et al. 2011).

Meanwhile, the adoption of cover crops has consistently increased in the last decade and gained popularity in the southeast United States (Wallander et al. 2021). The area of cover crop was around 4 million hectares in 2012 and reached 6.23 million hectares in 2017, representing a 50% increase. Furthermore, the anticipated growth in estimates is approxmately 40 million hectares by 2025 in the United States (Hamilton et al. 2017). Cover crops with conservation tillage have long been utilized to mitigate soil erosion problems, reduce water runoff losses, and improve water infiltration, soil moisture content, soil organic carbon, and nitrogen cycling over the past few decades (Dabney et al. 2001; Sainju and Singh 1997). Cover crops have also been investigated due to their ability to hinder the early-season establishment of weed population and control weed growth by diminishing light transmission and quality, modifying soil temperature, competing for essential nutrients, and physically suppressing weed emergence (Teasdale and Mohler 2000) and releasing allelopathic chemicals (Sturm et al. 2018). The level of weed suppression provided by the cover crop is determined by the amount of cover biomass, residue persistence, management practices (Saini et al. 2006), and cover crop type. Cover crop response can vary according to specific regions and management methods (Schomberg et al. 2006). According to Price et al. (2006), winter cereal cover crops were not effective in suppressing weed species without the inclusion of an herbicide treatment. Cover crops alone could provide only early-season weed control; thus, integration of herbicide programs with cover crops should be considered for better weed control throughout the crop growing season.

Therefore, field experiments were conducted to evaluate the synergistic effects of six different cover crops, including cereals, legumes, brassicas, and cover crop mixtures, combined with preemergence (PRE) and postemergence (POST) herbicide treatments. The study aimed to integrate cover crops and herbicide programs for effective weed control in southern cotton grown within a conservation system while maintaining cotton lint yield.

Materials and Methods

Location

Field experiments were conducted in 2021-2022 at three different sites in Alabama, including E.V. Smith (EVS) Auburn University Research and Extension Center, Shorter, AL

(Field Crops Unit; 32.4417°N, 85.8974°W), Wiregrass Research and Experimental Station (WREC) Headland, AL (31°30′ N, 85°17′ W), and Tennessee Valley Research and Extension Center (TVREC), Belle Mina, AL (34°41′ N 86°53′ W). The soil characteristics at the EVS research site were Compass sandy loam (coarse-loamy, siliceous, subactive, thermic Paleudults), pH 6.2, and 0.8% organic matter. At the WREC site, the soil was a Dothan fine sandy loam (fine-loamy, siliceous, thermic Plinthic Paleudult) with pH 6.0 and 1.1% organic matter. Lastly, the soil type at TVREC was Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudults), pH 6.0, and 2.3% organic matter. The sampling depth for these properties was up to 10 cm from the surface.

Experimental Design and Treatments

The experimental design was split-plot with three replications of each treatment at each location. Cover crops were considered in the main plot factor, and herbicide treatments were considered in the subplot factor. The six cover crop treatments included: oats (*Avena strigosa* Schreb.), cereal rye (*Secale cereale* L.), crimson clover (*Trifolium incarnatum* L.), radish (*Raphanus sativus* L.), cover crop mixture, and winter fallow. The cover crop mixture combined cereal rye, oats, crimson clover, and radish. The four herbicide treatments included: **1)** PRE herbicide included pendimethalin at 0.95 kg ai ha^{-1} (Prowl® H2O, BASF Ag. Products, Research Triangle Park, NC, USA) + fomesafen 0.28 kg ai ha^{-1} (Reflex®, Syngenta Crop Protection, Inc., Greensboro, NC, USA), **2)** POST herbicide included dicamba at 0.96 kg ai ha^{-1} (Xtendimax; Bayer Crop Science, St Louis, MO, USA) + glyphosate 1.55 kg ae ha^{-1} (Roundup Powermax®; Monsanto Company, St. Louis, MO, USA) + *S*-metolachlor 1.07 kg ae ha^{-1} (Dual II Magnum®, Syngenta Crop Protection, Inc., Greensboro, NC, USA), **3)** PRE followed by POST and **4)** a non-treated (NT) check. In total, there were 24 different treatments of cover crops and herbicides at each site.

Crop Management

Cover crops were planted using JD 7730 and a Great Plains® no-till drill (Great Plains Salina, KS 67401) with GreenStar GPS at each location in the second-third week of November 2021. The seeding rate of cereal rye 'Wrens Abruzzi' 100 kg ha^{-1}, oats 'Cosaque' 67.25 kg ha^{-1}, crimson clover 'Dixie' with inoculant 22.42 kg ha^{-1}, radish 'Daikon' 9.0 kg ha^{-1}. In the cover crop mixture, cereal rye 33.6 kg ha^{-1}, oats 22.2 kg ha^{-1}, crimson clover 6.7 kg ha^{-1}, and radish 4.48 kg ha^{-1} were planted. The germination for all cover crops was >80%. Cover crop treatments were fertilized with N 35 kg ha^{-1} as ammonium nitrate in spring to maximize biomass production. All cover crop plots were mechanically rolled using a three-section straight bar roller-crimper to flatten the biomass residue on the soil surface at each location in the second week of April. Just after the mechanical rolling of cover crops, termination was enhanced with an application of glyphosate at 0.91 kg ae ha^{-1} plus glufosinate (Liberty; Bayer Crop Science, Research Triangle Park, NC) 0.57 kg ai ha^{-1}.

The cotton variety "Phytogen 480 F3E" was planted at each site during the second week of May 2022. PRE herbicide (pendimethalin + fomesafen) application just after planting of cotton and POST herbicides (dicamba + glyphosate + *S*-metolachlor) applications approximately four weeks after planting of cotton. All herbicides were applied with a CO_2-pressurized backpack sprayer equipped with TTI 11004 nozzles (TeeJet, Glendale Heights, IL) at 276 kPa calibrated to deliver 280 L ha^{-1}. Cotton was harvested with a small plot combined from the middle two rows from each plot with a harvesting area of 125 sq. ft. to estimate the yield at each location. From each plot, a sub-sample was taken for ginning, and then lint yield was determined.

Data Collection

Before terminating the cover crop, biomass samples were collected by cutting all aboveground parts of the plants near the ground from each cover crop plot. It was done by choosing a randomly selected 0.25 m^2 quadrat per plot. The harvested cover crop samples were placed in a dryer set at 65 °C for 72 hours, and their dry weight was measured and recorded. Cotton stand counts were taken three weeks after planting (WAP). The visual control rating was given at four and seven WAP of cotton. The weed biomass was collected at seven WAP based on randomly selected 0.25-m^2 quadrat from each subplot between the middle two rows after that dry weight of weed biomass was recorded.

Data Analysis

The analysis utilized R statistical software version 3.4.1 along with the "agricolae" package. Cover crop biomass was subjected to analysis of variance (ANOVA) to test the impact of different types of cover crops. ANOVA was applied to assess the impact of herbicides and cover crops on relative weed biomass and lint yield. The formula to calculate relative weed biomass reduction is below:

$$\text{Weed biomass relative to check (\%)} = \frac{\text{Weed biomass}_{(\text{Control})} - \text{Weed biomass}_{(\text{Treatment})}}{\text{Weed biomass}_{(\text{Control})}} \times 100$$

Control in the above formula is winter fallow with NT check. Due to the significant interaction of locations with treatments, the data were examined separately for each site. Means were separated using Tukey's HSD post-hoc comparison test at $\alpha < 0.05$ to explore the effects of treatments on relative weed biomass reduction and lint yield. Figures were generated using Sigma Plot software (version 13.0; Systat Software, San Jose, CA).

Results and Discussion

Cover Crop Biomass

TVREC: Cereal rye, oats, and cover crop mixture performed similarly for biomass production and resulted in 4,286, 4,112, and 3,508 kg ha^{-1}, respectively, which were greater than those of crimson clover and radish **(Figure 3-1A).** However, crimson clover produced biomass of 1,861 kg ha^{-1} which was greater than that of radish (695 kg ha^{-1}).

WREC: Cereal rye, oats, and cover crop mixture produced comparable biomass resulting in 5,638, 4,496, and 5,438 kg ha^{-1}, respectively **(Figure 3-1B)**. However, crimson clover produced a biomass of 4,003 kg ha^{-1}, which was less than that of cover crop mixture and cereal rye, but higher than that of radish (2,748 kg ha^{-1}).

EVS: Cover crop cereal rye, oats, and mixture produced biomass 6,133, 6,150, and 6,069 kg ha^{-1}, respectively, which was greater than that of crimson clover and radish biomass **(Figure 3-1C)**. However, crimson clover produced a biomass of 4,299 kg ha^{-1} which was greater than that of radish (2,277 kg ha^{-1}). The amount of cover crop biomass from each cover crop type was different at each site. While the trend of cover crops was similar with cereal rye, oats, and cover crop mixture produced greater biomass than crimson clover and radish. A meta-analysis suggested that cover crop biomass can vary by the location of the study (Osipitan et al. 2018, 2019).

Relative Weed Biomass Reduction

TVREC: A significant interaction between cover crops and herbicides was found ($p < 0.001$). At this location, Palmer amaranth and prickly sida (*Sida spinosa* L.) were the dominant weeds. Cereal rye, crimson clover, oats, and cover crop mixture with both PRE+POST herbicide treatment provided excellent weed control with 99% relative weed biomass reduction **(Figure 3-2A)**. Radish and winter fallow with PRE+POST herbicide treatment provided 93% and 81% relative weed biomass reduction, respectively. Field experiments researching cover crops and herbicide interactions are not new. Recent research has explained and validated cover crops and herbicides can work together synergistically to reduce weed seed germination, establishment, and survival of weed seedlings by explaining the underlying mechanisms such as physical suppression (Bunchek et al. 2020; Wallace et al. 2019). Considering only POST herbicide treatment, cereal rye, crimson clover, oats, and cover crop mixture provided >90% relative weed biomass reduction. Radish and winter fallow plots with POST herbicide resulted in 75% and 58% relative weed biomass reduction, respectively. A tank mixture of glyphosate and dicamba can provide excellent control of weed species that dicamba alone could not control effectively (Underwood et al. 2017). Glyphosate and dicamba mixture increased the glyphosate-resistant Palmer amaranth control by 40% (Johnson et al. 2010). For exclusive PRE herbicide treatment, cereal rye, crimson clover, oats, and cover crop mixture provided >90% reduction in relative weed biomass, which was greater than radish and winter fallow in which only 79% and 74%, respectively. PRE herbicides such as pendimethalin and fomesafen effectively manage small-seeded weed species and grasses. Pendimethalin provided >80% control of glyphosate-resistant Palmer amaranth three weeks after application (Whitaker et al. 2010). Fomesafen controls Palmer amaranth 80-98% at 50 days after planting (Barkley et al. 2017). Among the NT check of cover crops, cereal rye outperformed oats and radish. Cereal rye reduced relative weed biomass by 28% due to higher residue biomass of cereal rye while radish showed only a 7% reduction. High residues cover crops such as cereal rye and crimson clover effectively controlled weeds and sustained crop yield (Kumari et al. 2023a, 2023b). Similarly, Norsworthy et al. (2011) observed that cereal rye exhibited a 34% control of Palmer amaranth. The rate of cover crop biomass decomposition is an important factor in limiting weed control attained from the cover crop residue (Mohler and Teasdale 1993). With the winter hardiness of cereal rye and slow decomposition due to the high C: N ratio, the plant residue persists (SARE, 2007), and forms a dense mat on the ground that prevents the germination of weed seeds.

WREC: A significant interaction between cover crops and herbicides ($p < 0.001$). Sicklepod and Palmer amaranth were the dominant weeds. In the PRE+POST herbicide treatment, cereal rye, crimson clover, and cover crop mixture provided 96% to 98% relative weed biomass reduction, which was greater than winter fallow (90%) **(Figure 3-2B).** With POST herbicide treatment, cereal rye, and crimson clover achieved >90% relative weed biomass reduction. Cover crop mixture, oats, and radish with POST herbicide provided relative weed biomass reduction in the range of 81-85%, significantly greater than winter fallow (75%). Glyphosate mixed with dicamba provided sicklepod control effective and more consistent (82-98%) three weeks after application (Leon et al. 2017). Considering only PRE herbicide treatment, cereal rye, and crimson clover showed a 77-79% reduction in relative weed biomass. The cover crop mixture and oats reduced the relative weed biomass by 71% and 65%, respectively; greater than winter fallow, which resulted in 57%. According to Wilcut et al. (1995), pendimethalin was ineffective in controlling large-seeded and broadleaf weed species. Moreover, fomesafen does not offer sufficient full-season sicklepod control (Faircloth et al. 2001). Among NT checks, cereal rye showed a 15% reduction in relative weed biomass, greater than cover crop mixture (8%) and radish (1%). For season-long weed control in the absence of herbicide, the required cover crop biomass threshold use should be approximately 8000 kg ha^{-1} (Mirsky et al. 2013; Reberg-Horton et al. 2012).

EVS: A significant interaction between cover crops and herbicides ($p < 0.001$). Palmer amaranth was the dominant weed throughout the field. In the case of PRE+POST herbicide treatment, cereal rye, crimson clover, oats, and cover crop mixture resulted in >98% relative weed biomass reduction, which was statistically greater than radish (89%) and winter fallow treatment (73%) **(Figure 2C)**. Considering only POST herbicide treatment, cereal rye and oats showed greater relative weed biomass reduction (66-68%) than crimson clover (53%), radish (58%), and winter fallow (40%). In the case of only PRE herbicide treatment, cereal rye performed better and effectively reduced weed biomass by 84%. Crimson clover, oats, and cover crop mixture with PRE herbicide were similar in terms of relative weed biomass reduction, which was 73%; however, it was greater than radish (51%) and winter fallow (55%). The reduced efficacy of weed control with POST treatment compared to PRE suspects the presence of resistant Palmer amaranth at this site. Palmer amaranth management poses challenges due to its robust seedling establishment and growth, season-long emergence, rapid seed restoration in the soil, and competence to develop herbicide resistance (Jha and Norsworthy 2009; Norsworthy et al. 2014). Among NT checks of cover crops, all cover crops reduced the relative weed biomass in the range of 11-17% except radish (1%).

Cotton Lint Yield

TVREC: The overall effect of cover crop and herbicide was significant ($p < 0.001$). Among cover crops, cereal rye performed better for lint yield (1,392 kg ha^{-1}) compared to winter fallow (1,045 kg ha^{-1}) **(Figure 3-3A)**. Previous research conducted in Alabama found that cereal rye provided more yield benefits compared with winter fallow (Kumari et al. 2023a). Plots receiving both PRE+POST herbicide applications showed the highest lint yield (1,726 kg ha^{-1}) due to season-long weed control which subsequently enhanced the yield **(Figure 3-3B)**. Lint yield was 1,345 kg ha^{-1} under only POST and 1,242 kg ha^{-1} under only PRE herbicide treatment, without any significant difference. NT checks had the statistically lowest lint yield of 504 kg ha^{-1}.

WREC: Overall herbicide effect was significant ($p < 0.001$), while no cover crop effect **(Figure 3-4A)**. PRE+POST and only POST herbicide treatment exhibited the highest lint yield of 2,277 and 1,900 kg ha^{-1} respectively which was greater than only PRE (838 kg ha^{-1}) and NT check (115 kg ha^{-1}) **(Figure 3-4B)**.

EVS: Overall herbicide effect was significant ($p < 0.001$), while no cover crop effect **(Figure 3-5A).** Plot received both PRE+POST herbicide applications resulting in the highest lint yield, 860 kg ha^{-1} **(Figure 3-5B)**. Lint yield was 768 kg ha^{-1} following the PRE herbicide treatment, which was statistically greater than only POST treatment, which remained at 463 kg ha^{-1}. NT checks had the lowest lint yield of 45 kg ha^{-1}. Aulakh et al. (2012) found that pendimethalin + fomesafen as PRE herbicides resulted in a greater yield compared to the NT check in a cotton field infested with Palmer amaranth.

Conclusions

High residue cover crops such as cereal rye led to early-season weed suppression only. Considering herbicide treatments of either pendimethalin + fomesafen (PRE), dicamba + glyphosate + *S*-metolachlor (POST), and PRE followed by POST**,** cover crops, excluding radish, provided greater relative weed biomass reduction than winter fallow. Specifically, cereal rye, crimson clover, oats, and cover crop mixture when treated with pendimethalin + fomesafen (PRE) followed by dicamba + glyphosate + *S*-metolachlor (POST) herbicides, provided excellent weed control throughout the cotton growing season compared to radish and winter fallow plots.

The practical implication of this study is that the integration of suggested high-residue cover crops into herbicide regimes in conservation tillage cotton is not only a better weed management approach but also provides other soil health benefits in the southern United States. Future research needs to be conducted on the inclusion of other herbicide programs with cover crops under different management practices such as crop rotation to provide more options to growers for weed control recommendations.

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Figures:

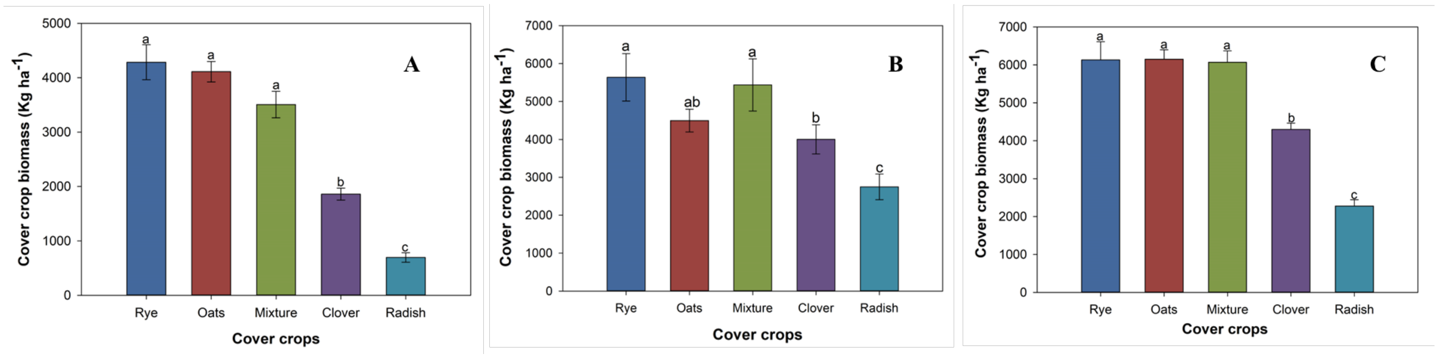

Figure 3-1. Cover crop biomass production at Tennessee Valley Research and Extension Center (A), Wiregrass Research and Experimental Station (B), E.V. Smith Research and Extension Center (C). Means followed by the different Tukey letters showed a significant effect.

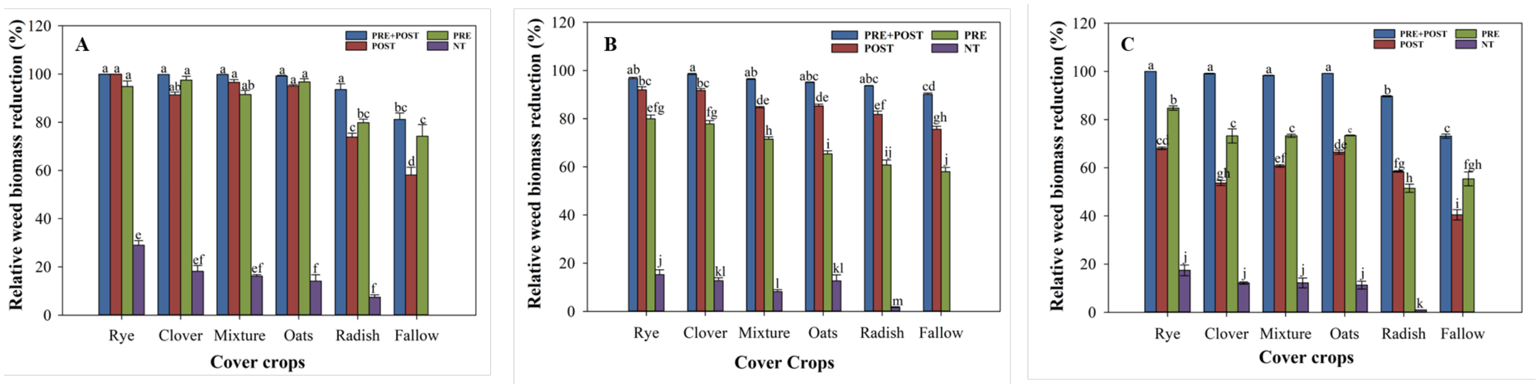

Figure 3-2. Interaction of cover crops and herbicides on relative weed biomass reduction at Tennessee Valley Research and Extension Center (A), Wiregrass Research and Experimental Station (B), E.V. Smith Research and Extension Center (C). Means followed by the different Tukey letters showed a significant effect.

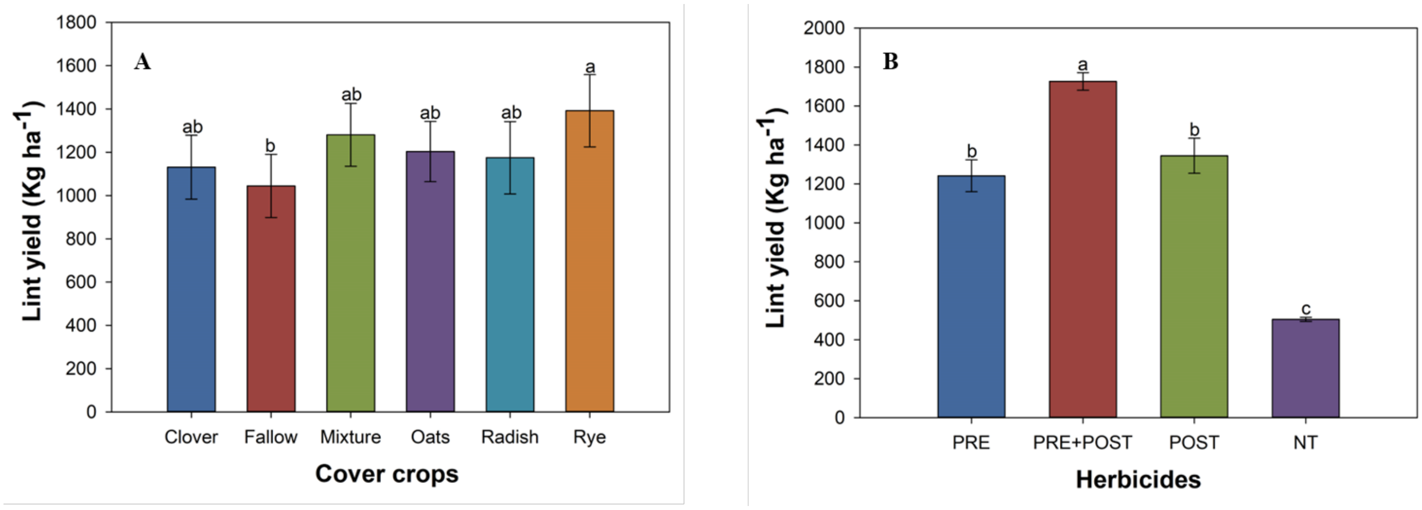

Figure 3-3. The effect of cover crops and herbicides on lint yield at Tennessee Valley Research and Extension Center. Means followed by the different Tukey letters showed a significant effect.

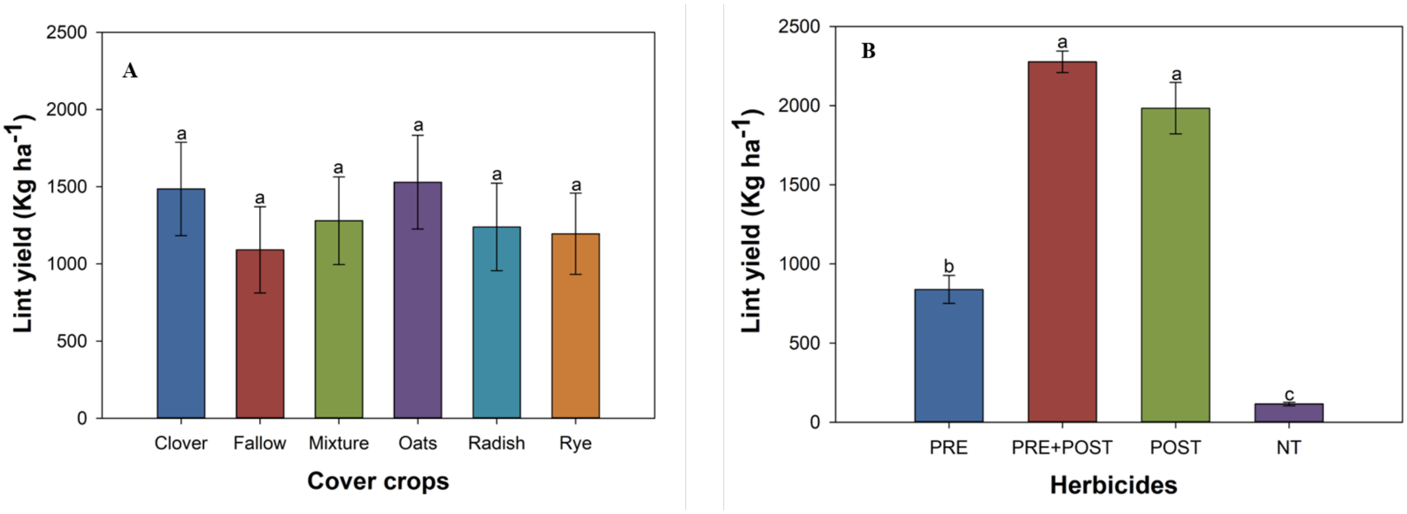

Figure 3-4. The effect of cover crops and herbicides on lint yield at Wiregrass Research and Experimental Station. Means followed by the different Tukey letters showed a significant effect.

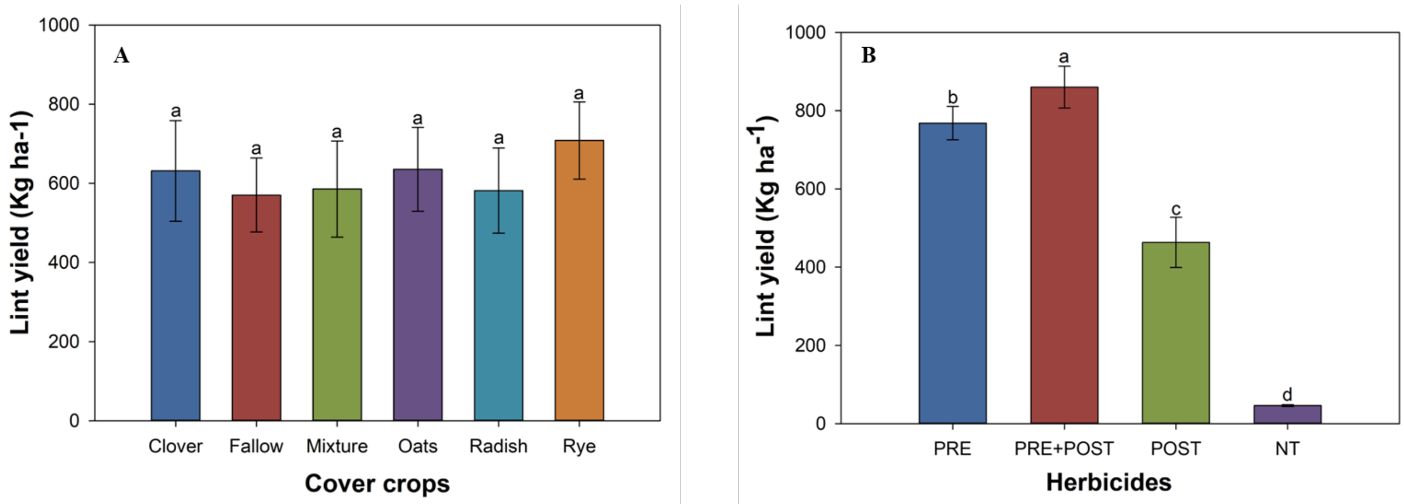

Figure 3-5. The effect of cover crops and herbicides on lint yield at E.V. Smith Research and Extension Center. Means followed by the different Tukey letters showed a significant effect.

Chapter 4: Effect of Various Biomass of Cereal Rye Residue and Preemergence Herbicide on the Germination of Troublesome Southeastern Weeds

Introduction

In the southern United States, predominantly Palmer amaranth [*Amaranth* Palmeri (S.) Watson], morningglories (*Ipomoea* spp.), nutsedge (*Cyperus*. spp.), sicklepod [*Senna obtusifolia* (L.)], and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] are major troublesome weed species threatening crop production systems (Webster 2012). Furthermore, increasing reliability towards chemical herbicides has become a major issue due to the development of herbicide-resistant weeds. Considering the challenges of herbicide-resistant weed species, specifically, glyphosate-resistant Palmer amaranth, and consistent public pressure to reduce herbicide utilization, there is an urgent need for integrated weed management (IWM) strategies (Norsworthy et al. 2012; Price et al. 2011). Herbicide-resistance management programs should incorporate all available cultural, mechanical, and chemical selection methods for efficient and sustainable weed control. Implementing the best management practices is necessary, with a primary focus on understanding the biology of the weeds (Norsworthy et al. 2012). Zeidali et al. (2021) suggested that it is essential to understand the influence of management practices on seed germination to establish IWM practices. Germination is a complex process of physical and physiological changes and is considered a vital growth stage (Finch-Savage et al. 2006). It is controlled by internal as well as external factors; thus, targeting weed's seed germination could be an effective strategy for weed management.

Conservation tillage utilizing high-residue cover crops is a proven IWM strategy (Norsworthy et al. 2011; Price et al. 2016a). Cover crop residue provides physical suppression of weed germination and establishment by blocking light, competing for resources (Teasdale and

Mohler 2000), and releasing allelochemicals to retard weed growth (Sturm et al. 2018). Previous research found that high residue cover crops in no-till or strip-till cropping systems were effective in facilitating weed suppression through mulching effect (Kumari et al. 2023a, 2023b; Price and Norsworthy 2013; Price et al. 2021), specifically cereal rye (Kumari et al., 2024). Additionally, cover crop provides soil health benefits such as increasing soil organic matter, conserving soil moisture, and preventing soil erosion losses in the southeastern United States (Farmaha et al. 2022). Many growers prefer a cereal rye cover crop as it produces high biomass residue due to its vigorous vegetative growth and winter hardiness. Moreover, a high C: N ratio and slower decomposition rate of cereal rye residue after termination (SARE 2007) provide season-long weed control. However, the weed suppressing ability of cover crops depends on various factors such as weed type, amount of cover crop biomass, allelopathic effect, and shading effect (Teasdale 1996). According to Schomberg et al. (2006), the cover crop biomass production depends on region, weather conditions, and applied management practices.

Hence, evaluation of cover crop performance across diverse environmental conditions is needed. Integration of soil residual herbicide with cover crops to manage glyphosate-resistant Palmer amaranth is an increasing trend for growers. Combining high-residue cover crops such as cereal rye with preemergence herbicide to control Palmer amaranth and other troublesome weeds could be an effective strategy for weed management. Our objective was to evaluate the influence of different biomass of cereal rye residue and soil-applied herbicide on the germination and growth of ivyleaf morningglory and Palmer amaranth. In the greenhouse study, we determined the influence of different biomass residues of cereal rye on the germination and growth of troublesome southeastern weeds including Palmer amaranth, ivyleaf morningglory, sicklepod, and large crabgrass.

Material and Methods

Greenhouse Experiment. A greenhouse experiment was conducted in the Plant Sciences Center at Auburn University, Auburn, AL. The experiment was conducted two times from June to August of 2021. Five replications of each treatment were placed in a randomized block design in each run. The dimensions of soil flats were 55.88 × 29.21 × 3.81 cm, respectively. Weed seeds were planted at 70.69, 12.25, 12.25, and 64.32 million seeds ha^{-1} for Palmer amaranth, morningglory, sicklepod, and crabgrass. Weed seeds were thoroughly mixed with organic soil and placed over the top of soil flats which had been filled with Miracle Grow® organic soil. Cereal rye biomass was harvested by hand from a field in May 2021, oven-dried for 3 days at 60°C, and then trimmed to match the length of the soil flat. Then soil flats were covered uniformly by four different biomass levels of rye straw (2800 as low, 5600 as medium, 8400 as high, and 11200 as highest kg ha^{-1}) and a check with no residue added.

Field Experiment. A field experiment was conducted at E.V. Smith (EVS) Auburn University Research and Extension Center (Field Crops Unit; 32.4417°N, 85.8974°W) near Shorter, Alabama and Wiregrass Research and Experimental Station (WREC) Headland, AL (31°30′ N, 85°17′ W) from autumn 2022 through summer 2023. The soil characteristics at the EVS site were Compass sandy loam (coarse-loamy, siliceous, subactive, thermic Paleudults), pH 6.2, and 0.8% organic matter. At the WREC site, the soil was a Dothan fine sandy loam (fine-loamy, siliceous, thermic Plinthic Paleudult) with pH 6.0 and 1.1% organic matter. The soil sampling depth of pH and organic matter was up to 10 cm.

The experiment was conducted in a split-plot design with six replications, main plots were four seeding rates (45, 90, 135, and 180 kg ha^{-1}) and a winter fallow check. In the subplot, flumioxazin herbicide and a non-treated (NT) check were considered. The cereal rye 'Wrens

Abruzzi' was planted utilizing JD 7730 and a Great PlainsR no-till drill (Great Plains Salina, KS 67401) with GreenStar GPS in the third week of November 2022 at both locations. The cover crop was mechanically rolled using a three-section straight bar roller-crimper to level the biomass residue on the soil surface in the third week of April 2023. After the mechanical rolling of cover crops, burndown was performed with an application of glyphosate (Roundup Powermax®; Monsanto Company, St. Louis, MO, USA) 0.91 kg ae ha^{-1} and glufosinate (Liberty; Bayer Crop Science, Research Triangle Park, NC) 0.57 kg ai ha^{-1}. Flumioxazin (Valor^{R}, Valent U.S.A. Corporation, Walnut Creek, CA) at 71.5 g a.i ha^{-1} was applied four weeks after cover crop termination. At the EVS location, precipitation was received during the week of herbicide application **(Figure 4-1)**; however, at the WREC location, approximately 12 mm of irrigation was provided within 24 hours of herbicide application.

Data Collection and Analysis

In the greenhouse experiment, data collection such as weed counts and weed biomass was performed every ten days for 30 days. Mostly, germination of ivyleaf morningglory and sicklepod occurred 10 days after planting. However, germination for Palmer amaranth and large crabgrass was also observed at 20 and 30 days after planting, with weed germination decreasing over time. Subsequently, all weed counts were summed to show the total counts for each weed species in the graphs. In the field study, visual weed control ratings (0-100%), weed counts for each species, and weed biomass collection in between three to four weeks after herbicide application based on randomly selected 0.25 m^2 quadrats per plot at each location. In both greenhouse and field experiments, weed biomass collected samples were placed into a drier at 65°C for 72 h, and then the dry weight of weed biomass was recorded. Data was analyzed using the PROC GLIMMIX model and means were separated using Tukey's HSD post-hoc test at $\alpha <$

0.05 in the SAS statistical software version 9.4 (SAS Institute, Cary, NC). SigmaPlot software (version 13.0; Systat Software, San Jose, CA) was used for curve-fitting regressions and to estimate coefficient values and coefficient of determination (R^2) which were utilized to assess the fitness of each regression curve.

Results and Discussion

Greenhouse Study

Ivyleaf morningglory: There was no significant effect ($p > 0.05$) of biomass treatments on weed counts and weed biomass reduction of ivyleaf morningglory. Under all biomass treatments, approximately 8.6 to 9.3 million ha^{-1} weed counts and 420 to 477 kg ha^{-1} weed biomass were observed **(Figures 4-2A and B).** Due to the large seed size of ivyleaf morningglory, their physical suppression with biomass of cereal rye residue was not anticipated.

Seed size is a major attribute of its quality because large seeds favor vigor germination, establishment, and growth rate due to more stored resources (Ellis et al. 1992; Sanderson et al. 2002).

Palmer amaranth: A significant effect ($p < 0.001$) under various biomass treatments in terms of weed suppression and weed biomass reduction was observed. The low, medium, high, and highest cover crop biomass reduced the weed counts by 47, 69, 84, and 92% respectively compared to fallow treatment **(Figure 4-2A)**. Furthermore, low, medium, high, and highest cover crop biomass decreased the weed biomass by 38, 61, 74, and 85% respectively compared to fallow treatment **(Figure 4-2B)**. Cover crop biomass was effective in suppressing the Palmer amaranth seeds due to its small size and reduced plant growth. A previous study found that cereal rye residue was more consistent in the suppression of Palmer amaranth and provided 59 to 80%

control, which subsequently will produce a smaller number of seeds according to Wiggins et al. (2017).

Sicklepod: A significant effect ($p < 0.05$) of various biomass levels on reducing weed counts and biomass was found. The highest and high cover crop biomass reduced the weed counts by 33% and 21% compared to fallow treatment **(Figure 4-2A)**. Cover crop biomass included the highest and high treatment decreased the weed biomass by 54 and 40% compared to fallow treatment **(Figure 4-2B)**. Sicklepods have also large seed sizes and previous research studies have suggested that the amount of cover crop residues have more impact on suppressing small-seeded weed species compared to large-seeded weed species (Bhowmik and Inderjit 2003; Teasdale and Mohler 2000).

Large Crabgrass: A significant effect ($p < 0.05$) of various biomass treatments on reducing weed counts and biomass was observed. The highest, high, and medium cover crop biomass reduced the weed counts by 70, 56, and 53% compared to fallow treatment **(Figure 4-2A)**. While the highest and high cover crop biomass treatment decreased the weed biomass by 71% and 56% compared to the fallow treatment **(Figure 4-2B)**. For the suppression of large crabgrass, sufficient biomass is required to suppress its germination. According to Pittman et al. (2020), large crabgrass required 5,570 kg ha^{-1}, and 11,440 kg ha^{-1} biomass at termination to achieve 50% suppression at 6 and 8 weeks after termination, respectively. Haramoto et al. (2019) claimed that there were variations in annual grass suppression by cover crop residues. Large crabgrass germination was either the same or decreased following cereal rye residue compared to fallow treatment (Brainard et al. 2016).

Non-linear regression: A three-parameter logistic model used for fitting weed counts and weed biomass for each species individually against cover crop biomass.

Equation:

$$y = \frac{\alpha}{1+\left(\frac{x}{x^0}\right)^b}$$

Where y was the weed counts and weed biomass, x^0 represented the inflection point, b was the slope of the curve or growth rate, α was the asymptote, and x depicted the amount of biomass residue.

All coefficients were found to be statistically significant ($p < 0.05$), indicating a robust relationship of weed counts and weed biomass with cereal rye residue in the case of Palmer amaranth with $R^2 = 0.99$ for both regressions (**Figure 4-3A and B; Table 4-1 and 4-2**). Based on the logistic curve, to reduce the Palmer amaranth counts by 50 and 90% compared to fallow treatment it required 3,112, and 10,490 kg ha^{-1} of cover crop biomass. It was observed that weed counts and weed biomass of Palmer amaranth decreased with increasing biomass of cereal rye residue. However, the slope was non-significant ($p > 0.05$) for weed counts and weed biomass of ivyleaf morninglory with $R^2 = 0.39$ for counts and $R^2 = 0.90$ for weed biomass The slope was non-significant for sicklepod ($p > 0.05$) with $R^2 = 0.96$ for weed counts and $R^2 = 0.92$ for weed biomass. Hence, there was no relationship between increasing cereal rye biomass with the reduction of weed counts and weed biomass for ivyleaf morningglory or sicklepod.

Field Experiment

There was a significant effect of seeding rate on cover crop biomass production; however, the effect of location and their interaction was not significant. The seeding rate of 90 kg ha^{-1} of cereal rye provided significantly greater cover crop biomass as compared to the 180 kg ha^{-1} seeding rate **(Figure 4-4)**.

Palmer amaranth and ivyleaf morningglory were the dominant weeds throughout the field studies at both locations. A logistic three-parametric curve was fitted on weed counts of Palmer amaranth and morningglory and biomass of Palmer amaranth against cereal rye biomass residue.

Equation:

$$y = \frac{\alpha}{1+\left(\frac{x}{x^0}\right)^b}$$

Where y represents weed counts and biomass for Palmer amaranth and counts of ivyleaf morningglory, x^0 represents the inflection point, b represents the slope of the curve or growth rate, α represents the asymptote, and x depicts the amount of biomass residue.

While for the morning glory biomass, the Gompertz equation was the best fit and was fitted against cover crop biomass.

Equation:

$$y = \alpha\, e^{-e^{-(x - x_0|b)}}$$

Where y represents weed biomass for ivyleaf morningglory, x^0 represents the inflection point, b represents the slope of the curve or growth rate, α represents the asymptote, and x depicts the amount of biomass residue.

All coefficients were found to be statistically significant ($p < 0.05$), indicating a robust relationship between biomass residue of cereal rye and Palmer amaranth counts with $R^2 = 0.85$ and 0.76 (**Figure 4-5A and 5B; Table 4-3**). The results from both greenhouse and field studies suggested that as cereal rye biomass increased, there was a significant trend of decreasing Palmer amaranth counts and weed biomass. For a 10% and 50% relative Palmer density reduction approximately 1,300 and 2,600 kg ha^{-1} cereal rye biomass is required. Moreover, based on the predicted curve, 75% maximum reduction in relative Palmer density was observed and approximately 7,100 kg ha^{-1} biomass was required to achieve this suppression. Previous literature also claimed that the extent of early season weed suppression is strongly influenced by the cover crop biomass production; with greater weed suppression with higher biomass (MacLaren et al. 2019; Osipitan et al. 2019). Cover crops could be a part of herbicide resistance mitigation strategy because they can decrease weed density and weed growth, thus lowering seed production which decreases the possibility of development of herbicide resistance (Owen et al. 2014; Riar et al. 2013). Weed suppression by cover crops depends on the production of ground cover biomass and the persistence of the residue. High biomass residue of cereal rye cover crop could provide Palmer amaranth control throughout the crop growing season due to its high C: N ratio and slower decomposition of residue.

The slope of regression curve was found to be non-significant ($p > 0.05$) for both morningglory counts and biomass with R^2 = 0.44 and 0.51 respectively **(Figure 4-5C and 5D; Table 3).**

In other words, this suggests that the effect of increasing cover crop biomass on suppressing weed counts and biomass was not effective. Following the same trend as the greenhouse experiment, counts and biomass of ivyleaf morningglory was not responsive for germination with increasing biomass residue of cereal rye due to their large seed size as discussed above.

Correlation: The correlation between cover crop biomass, visual control rating, weed biomass, and weed counts of morningglory and Palmer amaranth has been estimated and represented in a correlation graph **(Figure 4-6).** In the graph, the size of the circle and the color intensity in the circle were used to depict the correlation strength, with bigger circles and darker colors indicating stronger correlations between variables. The blue color indicated a positive correlation while the red color showed a negative correlation between variables. Furthermore, the correlation represented from 1 to -1, in which 1 represented a positive correlation and -1 represented a negative correlation, and 0 means no correlation between variables.

Palmer amaranth: There was a strong negative correlation of cover crop biomass with weed counts and weed biomass with a value of -0.83 and -0.72 respectively, showing higher cover crop biomass means more suppression of Palmer and more weed biomass reduction **(Figure 4-6A).** As anticipated, cover crop biomass positively correlated with visual control rating with a value of 0.76 which means the greater the cover biomass better the visual weed control effect. The visual control rating, which exhibited strong negative correlations with weed counts and weed biomass, resulted in values of -0.81 and -0.83, respectively. Weed counts and weed biomass showed a positive correlation of 0.75.

Ivyleaf Morningglory: There was a negative correlation of cover crop biomass with weed counts and weed biomass with a value of -0.49 and -0.64 respectively **(Figure 4-6B).** It suggested that cereal rye residue may not reduce the germination of ivyleaf morningglory significantly but could negatively impact the growth of ivyleaf morningglory. Furthermore, cover crop biomass was positively correlated with a visual control rating of 0.68. Visual control rating was negatively correlated with weed counts and weed biomass, with correlations of -0.58 and -0.66, respectively. A weak positive correlation of 0.40 between weed counts and weed biomass was found.

Flumioxazin effect: A sigmoidal three-parametric curve was fitted for Palmer amaranth control against cover crop biomass in the NT check **(Figure 4-7A; Table 4)**. The curve demonstrated that the cover crop will only provide around 40-60% control of Palmer amaranth. Therefore, herbicide is still required to achieve excellent control of this troublesome weed. In the case of the flumioxazin herbicide-treated check, we found that it worked well regardless of cover crop biomass, showing a straight-line relationship **(Figure 4-7B; Table 5)**. Herbicide wash-off from cover crop residue is expected due to precipitation/irrigation after herbicide application, leading to its release into the soil. Furthermore, overall effect of herbicide effect was found significant ($p < 0.01$). Herbicide interaction was not significant with seeding rate of cover crop; however, the overall effect of herbicide was found significant. Palmer amaranth control was 95% when treated with herbicide while 40% in NT check **(Table 4-6)**. Significantly lesser counts of Palmer amaranth were found in herbicide-treated plots compared to the NT check. Ivyleaf morningglory control was 90% when treated with herbicide while 30% under NT check. Similarly, fewer counts of ivyleaf morningglory were observed in plots that received herbicide treatment than NT check. Preemergence applied flumioxazin controls many broadleaf weed species such as morningglories and pigweeds (Cranmer et al. 2000; Wilcut et al. 2000). Previous research study found that flumioxazin as preemergence showed high efficacy and provides 94% control of Palmer amaranth at 3 to 4 weeks after application (Whitaker et al. 2010).

Conclusions and Practical Implications

It is well-known that cover crop cereal rye has the potential to provide several advantages, such as scavenging nutrients and preventing runoff losses and leaching in agricultural crop production systems. If farmers are seeking weed suppression in the absence of herbicides, approximately 7000 kg ha^{-1} biomass of cereal rye is required to achieve 75% suppression of Palmer amaranth up to seven weeks after cover crop termination. Previous literature also found that to maintain full season weed control without any herbicide application, the cover crop biomass threshold should be around 8000 kg ha^{-1} (Mirsky et al. 2013; Reberg-Horton et al. 2012). According to Palhano et al. (2018), the higher C:N ratio of cereal rye, which is linked to slow residue decomposition, allows it to persist throughout most of the growing season. This persistence has been shown to suppress Palmer amaranth until 8 weeks after planting.

According to Ryan et al. (2017), increasing cereal rye biomass reduced weed biomass, including pigweeds, and weeds were totally suppressed above 15000 kg ha^{-1} of cover crop biomass. Certainly, Palmer amaranth suppression increases with higher biomass levels. Our findings also found that an increase in the amount of cereal rye residue shows a decreasing trend of Palmer amaranth counts and weed biomass under both greenhouse and field condition. However, achieving biomass exceeding 10000 kg ha^{-1} is challenging, and farmers may need to incur additional costs for fertilization and earlier planting to enhance cover crop biomass. Managing weed suppression while balancing the cost of fertilization and the timing of planting and termination of cover crops is crucial. It requires finding a balance between achieving significant weed suppression and obtaining optimum residue biomass without incurring extra costs. This balance is essential for the decision-making process.

Moreover, we found that flumioxazin herbicide provides consistent and excellent weed control regardless of cereal rye biomass residue. Considering the importance and soil health benefits of cover crop cereal rye, integration of cover crop with preemergence-applied flumioxazin herbicide could be an effective strategy to control glyphosate-resistant Palmer amaranth, which is a major challenge for growers in the southern United States.

However, research studies and growers have observed significant variability in cover crop biomass production among sites and even between different years. Therefore, to make site-specific decisions, other management practices and the inclusion of herbicides should be tested for each soil type.

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Tables:

Table 4-1. Estimated values of three parameters logistic model used for fitting weed counts against cereal rye residue biomass in the greenhouse condition.

Weeds	a	b	x0	R^2
Palmer amaranth	33.23	1.63	3101.63	0.99
Morningglory	9.09	61.54	11743.47	0.39
Sicklepod	4.98	1.00	26596.75	0.96
Crabgrass	33.70	1.38	6105.50	0.98

Table 4-2. Estimated values of three parameters logistic model used for fitting dry weight of weeds against cereal rye residue biomass in the greenhouse condition.

Weeds	a	b	x0	R^2
Palmer amaranth	558.73	1.48	3986.19	0.99
Morningglory	476.85	61.19	11574.19	0.90
Sicklepod	117.08	1.87	11155.89	0.92
Crabgrass	747.65	3.66	8920.19	0.87

Table 4-3. Estimated values of three parameters sigmoidal curve used for fitting counts and biomass of Palmer amaranth and ivyleaf morningglory against cereal rye residue biomass under field condition.

	Coefficients				
	Weeds	**a**	**b**	**x0**	**R^2**
Counts	Palmer amaranth	17041.93	0.72	743.91	0.85
	Morningglory	814316.28	0.86	2471.26	0.44
Biomass	Palmer amaranth	422.93	0.92	977.13	0.77
	Morningglory	228176012.7	-48645.8	-124709.3	0.52

Table 4-4. Estimated values of three parameters sigmoidal curve used for fitting Palmer control (%) against cereal rye residue in NT checks.

	a	b	x0	R^2
NT checks	46.9	177.83	1118.4	0.85

Table 4-5. Estimated values of parameters for a linear line fitted to flumioxazin-treated checks for Palmer control (%) against cereal rye residue.

	a	b	R^2
Treated checks	94.89	5.7e-005	0.0037

Table 4-6. Effect of herbicides on weed suppression at seven weeks after cover crop termination.

Weed species	Weed Control (%)		Weed Counts (ha^{-1})		Weed Biomass (kg ha^{-1})	
	[a]Herbicide	NT	[a]Herbicide	NT	[a]Herbicide	NT
Palmer amaranth	95a	40b	1334b	5217a	27b	132a
Morningglory	90a	30b	46000b	330666a	79b	224a

Means followed by different letters in a row are statistically different at significance level of 0.05 within a weed species

[a]Herbicide: PRE applied flumioxazin (Valor[R]) at 71.5 g a.i ha^{-1} approximately four weeks after cover crop termination.

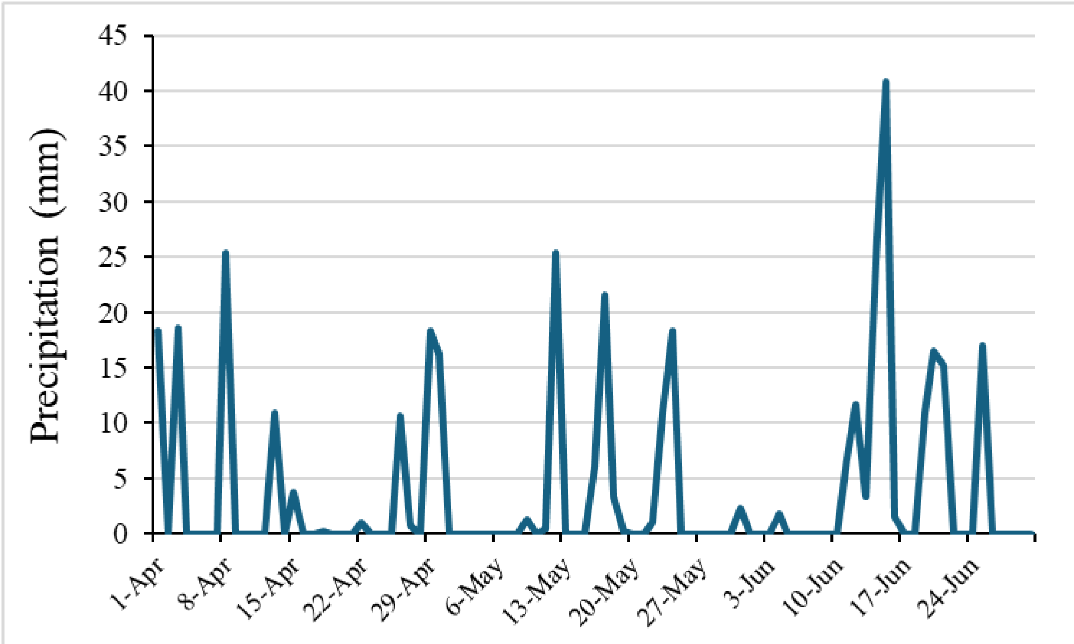

Figure 4-1. Precipitation data (mm) at EVS location, Auburn, AL during 2023 growing season.

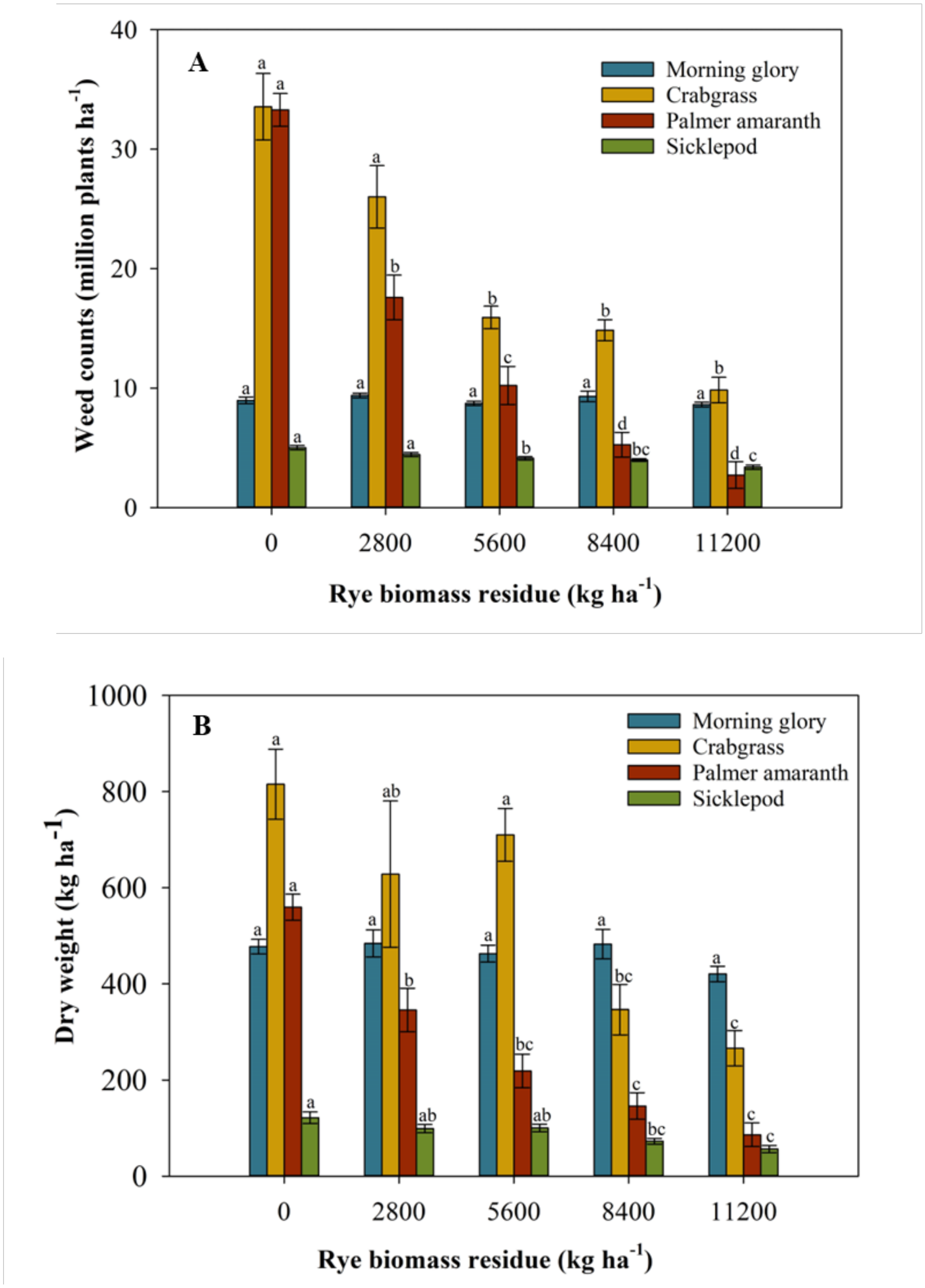

Figure 4-2. Weed counts **(A)** and dry weight of weed biomass **(B)** including Palmer amaranth, ivyleaf morningglory, sicklepod, and large crabgrass under different treatments of cereal rye biomass in the greenhouse condition. Means followed by the same letter within a weed species are not statistically different.

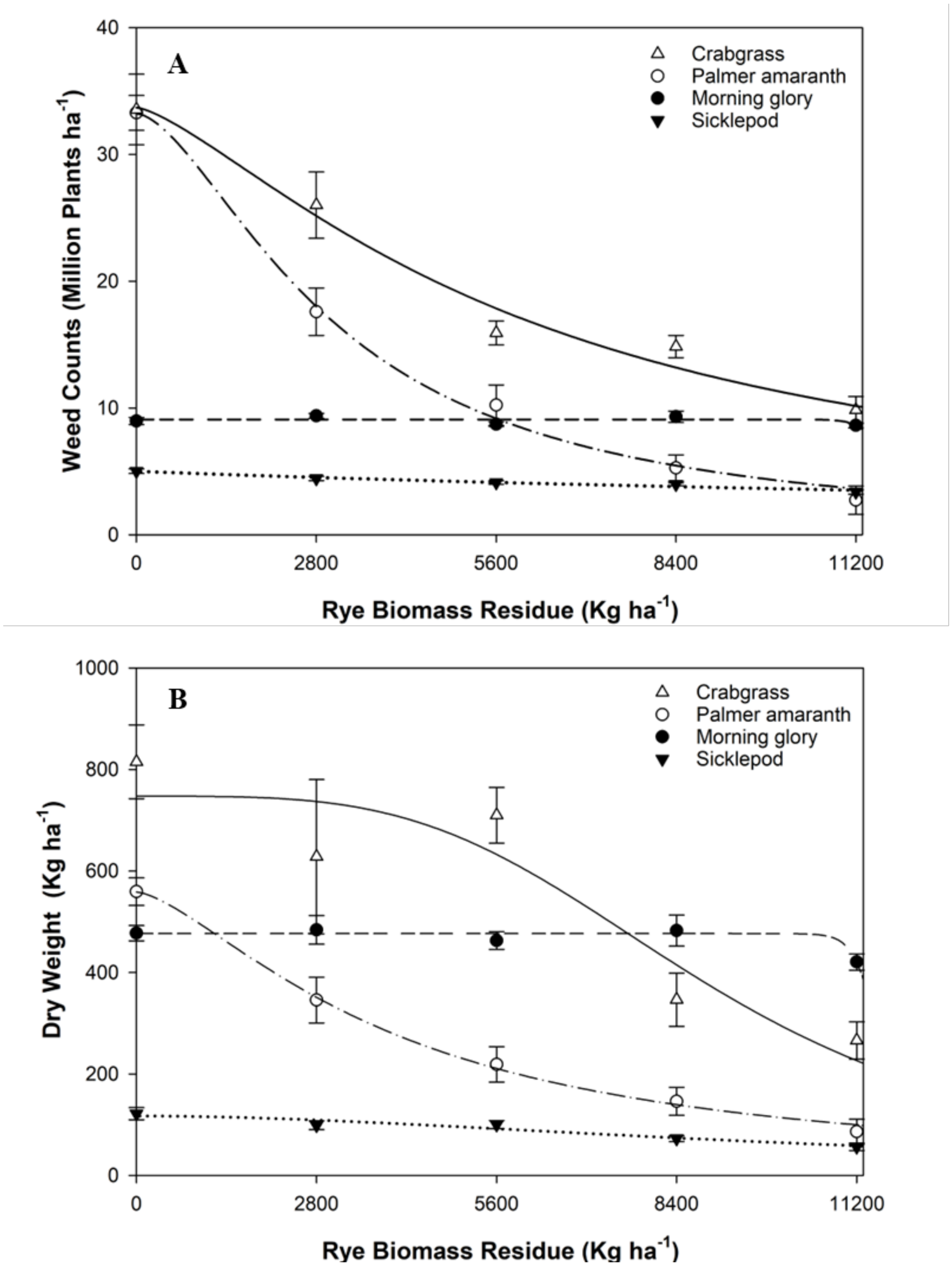

Figure 4-3. A three-parametric logistic non-linear regression curve fitted to evaluate the effect of cereal rye biomass residue on weed seedling counts **(A)** and dry weight of weed biomass for Palmer amaranth, ivyleaf morningglory, sicklepod, and large crabgrass in the greenhouse condition **(B)**.

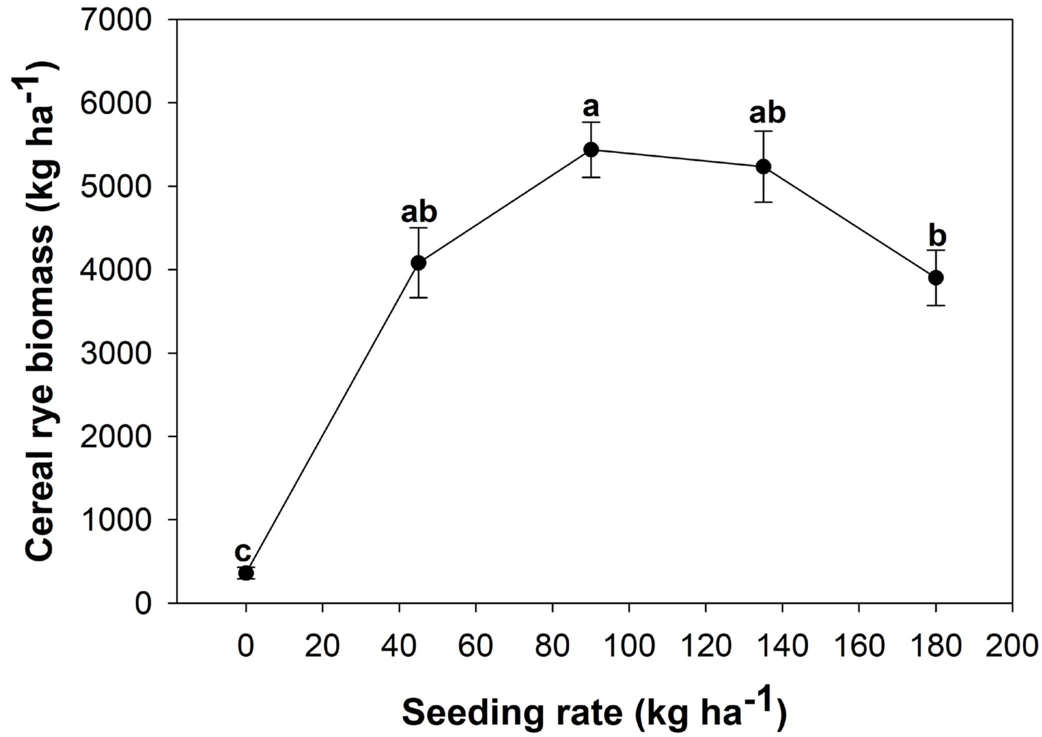

Figure 4-4: Effect of various seeding rate of cover crop on cover crop biomass production

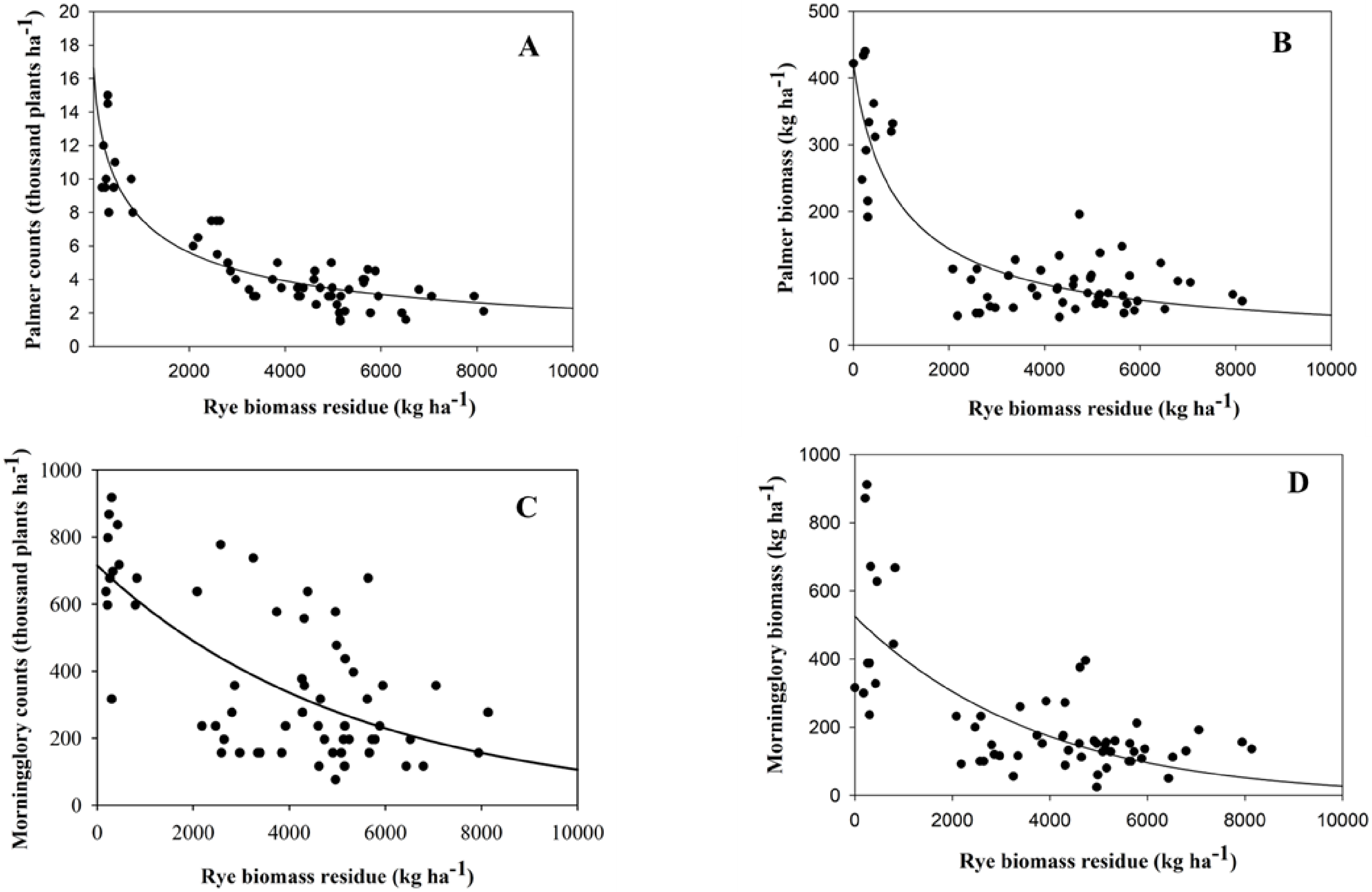

Figure 4-5. The three-parametric sigmoidal regression curve was fitted to estimate the trend of cereal rye biomass residue on counts **(A)** and biomass **(B)** of Palmer amaranth; counts **(C)** and biomass **(D)** of ivyleaf morningglory field condition at seven weeks after cover crop termination.

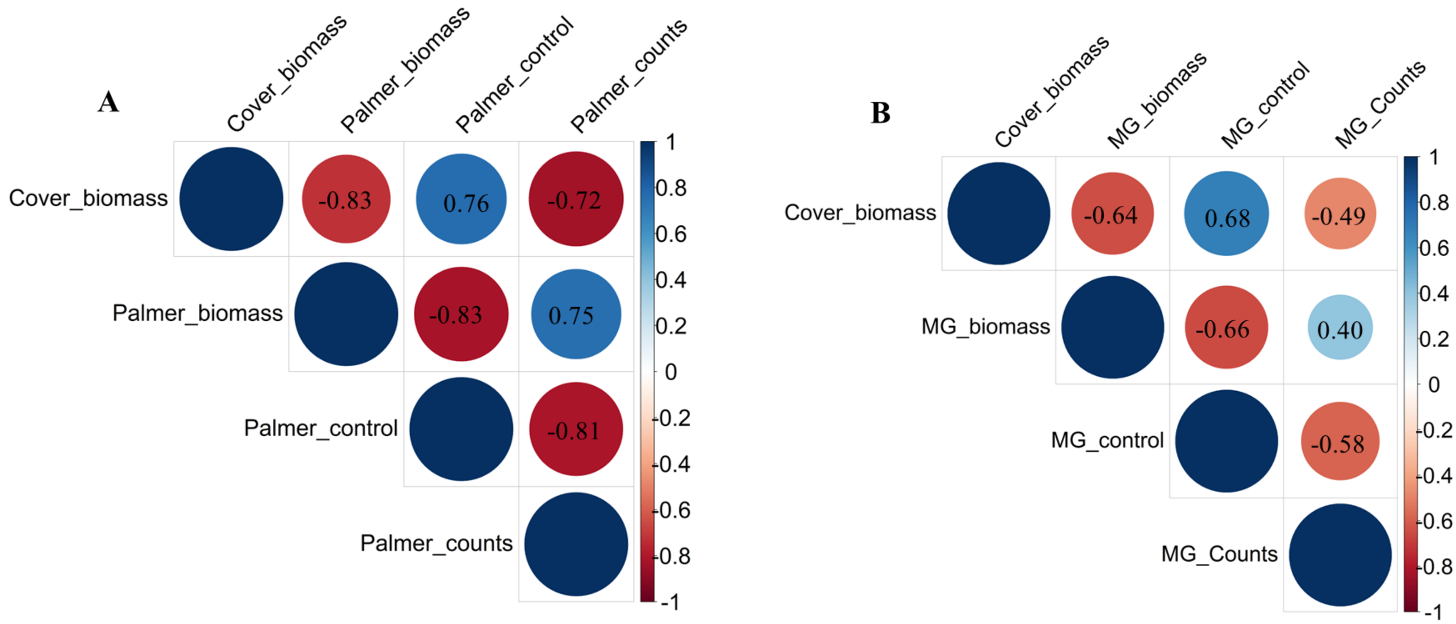

Figure 4-6. Pearson correlation coefficients between variables for the Palmer amaranth **(A)** and ivyleaf morningglory (depicted as MG) **(B)** under field condition.

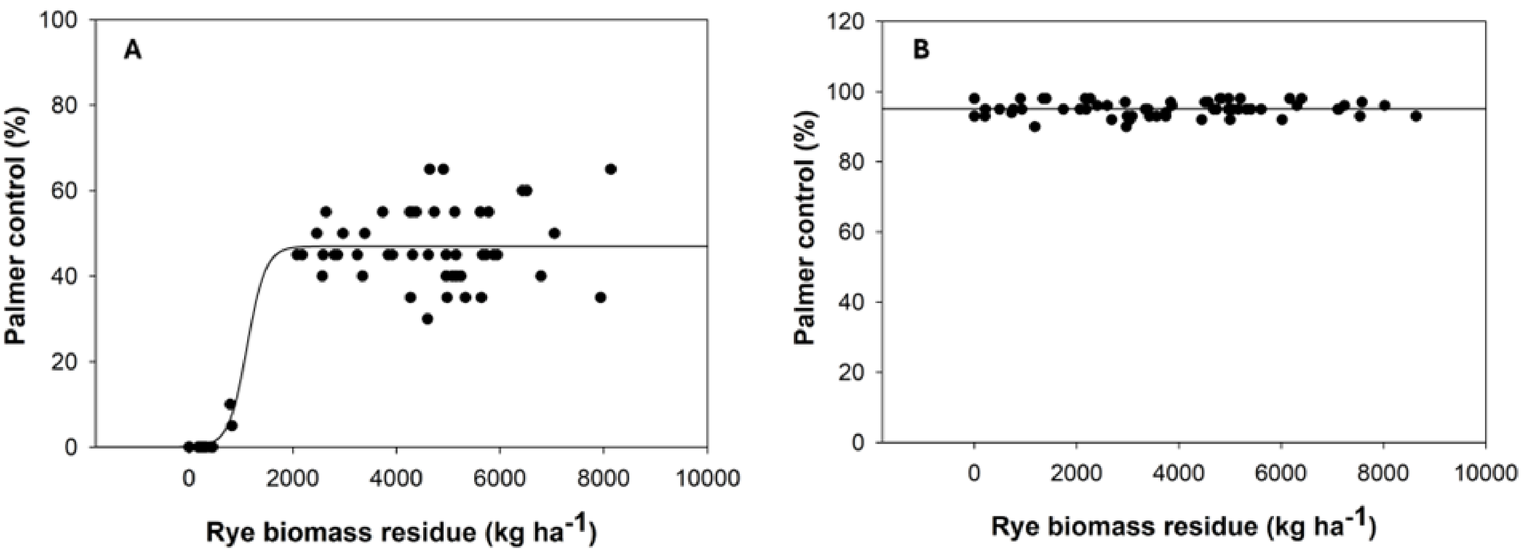

Figure 4-7. Trend of Palmer control (%) against cover crop biomass in the NT check **(A)** and flumioxazin treated checks **(B)** at seven weeks after cover crop termination.

Chapter 5: Winter Annual Legume Cover Crop Species Selection and Seeding Rates for the South

Introduction

For many decades, cover crops have been recognized for their benefits to the environment and agricultural crop production (Kaye et. al., 2017). Growing cover crops during winter fallow can suppress weeds, decrease soil erosion, improve soil moisture, enhance aggregate stability, and increase soil organic carbon. It can also help reduce the losses of nitrate leaching, enhance soil microbial population, and improve overall soil health (Blanco-Canqui et al., 2015 and 2020; Sharma et al., 2018). Cover crop utilization in farming practices can contribute to achieving farm profitability and mitigate adverse environmental impacts, including soil chemical runoff and erosion (Bergtold et al., 2017). The high C:N ratio of cereal grains results in a slow degradation of cover crops, allowing for increased plant residue persistence compared to legume cover crops (SARE 2007). Moreover, the rapid growth and winter hardiness of cereal cover crops produces a greater amount of biomass and forms a dense mat on the soil surface. On the other hand, legume cover crops decompose very fast but have the ability to fix a high level of nitrogen and release it to the succeeding main crop (Foote et al., 2014; Parr, 2011). There is an increasing interest in cover crop mixtures to obtain complementary benefits from different cover crop species (Finney et al., 2017; Tosti, 2014). Specifically, the mixture of cereal and legume cover crops is gaining attention as it maintains nitrogen availability and produces enough biomass residue (Clark et., 2017; Poffenbarger et al., 2015). However, establishing a diverse mixture of plant species simultaneously can pose a challenge because of competition among plants for resources (Hall, 1974). The seeding proportion in a mixture significantly influences biomass production, and inadequate seeding rates can result in a more competitive species dominating within the mixture and restricting the potential ecosystem benefits.

Furthermore, different species show varying expressions within a mixture compared to when they are grown in monoculture. Studies have suggested that cover crop mixtures have potential to improve biomass production compared to monocultures, but the expression of various species in mixtures vary among functional types of cover crops (Smith et al., 2014; Wortman et al., 2012). Managing competition and balancing potential tradeoffs between overall biomass production and seed costs can be accomplished by leveraging the seeding rates of each species in a mixture (Bybee-Finley et al., 2022). Therefore, selecting suitable cover crop species and seed rates for a mixture is essential in achieving sufficient biomass and diversifying the benefits of cover crops. Moreover, determining the optimal seeding rates for cover crops can enhance productivity and potentially reduce seed expenses. Identifying cover crops and seed rates that provide satisfactory biomass production is crucial in achieving specific goals in the crop production system.

Despite extensive cover crop research, there is still a wide range of recommended seeding rates for winter annual cover crops, and farmers regularly report using seed rates below standard recommendations to reduce cost. Our objective was to examine how different seed rates of leguminous cover crops impact biomass production when grown alone and when combined with cereal rye cover crops in mixtures across multiple locations in the southern United States.

Materials and Methods:

The field experiment was conducted at eleven different locations including Alabama, Arkansas, Kentucky, North Carolina, Tennessee, Texas, Louisiana, Maryland BARC, Maryland PMC, Georgia, and Georgia PMC in 2019 to 2020 and 2021 to 2022 throughout the southern United States **(Table 5-1)**. The field experiments were conducted in a randomized strip-plot design with two blocks per site. Cereal rye was planted perpendicular to leguminous cover crop plots in a strip across the entire block. The strips were randomly assigned to one side of the block or the other. There were two experimental factors 1) seeding rates for the legume cover crop and 2) strip of the legume cover crop. The levels of seeding rates included full, high, low, and lowest **(Table 5-2)**. The strip factor had two levels such as the mixture of legume cover crop with cereal rye and solo legume cover crop. There were five different leguminous cover crops, including hairy vetch, crimson clover, winter pea, common vetch, and berseem.

Data Collection:

Before termination of the cover crop, biomass samples were taken by clipping all aboveground plant parts near the soil surface from each cover crop plot using a randomly selected 0.25-m^2 quadrat per plot. The cover crop samples were placed into a drier at 65 C for 72 h, then the dry weight was recorded. Some states partitioned the legumes and cereal rye biomass from the mixture samples, and some also reported the composition of weed biomass in a mixture and from the legumes monoculture.

Statistical Data Analysis:

Cover crop biomass data were analyzed in SAS 9.4 software (SAS Institute, Cary, NC) using the generalized linear mixed model. Cover crop biomass was subjected to Analysis of variance (ANOVA) to evaluate the effect of cover crop seed rate and cereal rye mixture on biomass for each leguminous cover crop species separately. In the model of each legume species, the fixed effects were seed rate, cereal rye strips, location, and their interactions while random effects included block. Additionally, all legume species were compared with and without cereal rye. Means were separated using the Tukey HSD test at $\alpha<0.05$.

Results and Discussion:

Berseem: It has been found that there was a significant effect of seeding rates of berseem on biomass production **(Table 5-3)**; however, the linear trend of cover crop biomass with increasing seeding rate was not significant **(Figure 5-2a)**. The full, high, low, and lowest seeding rates had different cover crop biomass production, such as 3421.2, 3670, 3491, and 2916.5 kg ha^{-1}, respectively. The lowest seeding rate (3.4 kg ha^{-1}) had significantly less cover crop biomass than high and full seeding rates **(Figure 5-2b)**. Furthermore, the presence or absence of cereal rye in a mixture with berseem significantly affected cover crop biomass production. Overall, with and without the cereal rye mixture, the recorded cover crop biomass was 4311.55 and 2437.80 kg ha^{-1}, respectively. The total cover biomass was statistically higher in the mixture of cereal rye with berseem compared to a monoculture of berseem. A study in Arkansas claimed that the mixture of cereal rye and berseem had improved the total cover crop biomass production than planting berseem solo (Chintala et al., 2022). The results illustrated that the locations influenced the total cover crop biomass with significantly higher biomass observed under Tennessee (7050 kg ha^{-1}), AL_1 (5810 kg ha^{-1}), AR_2 (4665.6 kg ha^{-1}), and GA_1 (4426 kg ha^{-1}) compared to NC_1 (1895.4 kg ha^{-1}), Louisiana (1654 kg ha^{-1}), and Texas (1359.1 kg ha^{-1}) **(Table 5-4)**. Moreover, it was not surprising to find that cover crop biomass varied by site year. Vann et al. (2019) stated that the variations in total cover crop biomass composition across different environmental conditions demonstrated the importance of the selection of cover crop species and seeding rate recommendations of cover crop mixture according to location.

Crimson Clover: It has been observed that there was no significant effect of different seeding rates of crimson clover on biomass production **(Table 5-3),** and the linear trend of cover crop biomass with increasing seeding rate was not significant **(Figure 5-2c).** The cover crop biomass differed by location, and the effect of strips of rye was found to be significant. Overall, with and without the cereal rye mixture, the estimated biomass was 4682 and 4050 kg ha^{-1}, respectively, and it was statistically higher in a mixture compared to the solo crimson clover. According to Hodgskiss et al. (2021) considering crimson clover in a mixture with cereal rye provided at least 40% greater cover crop biomass compared to planting crimson clover in a monoculture system. Previous research studies by Aulakh et al. (2013) and Bressler & Blesh, (2022) also supported the results by claiming that crimson clover in combination with cereal rye produced higher biomass compared to planting them in monoculture. Moreover, the results from this study indicated that the total cover crop biomass was statistically higher at Tennessee (7557.3 kg ha^{-1}) and GA_PMC (7240.24 kg ha^{-1}) compared to AR_1 (1814.9 kg ha^{-1}), Texas (1776 kg ha^{-1}), and Louisiana (1507.4 kg ha^{-1}) **(Table 5-4)**.

Hairy vetch: The various seeding rates did not show any differences in cover crop biomass production **(Table 5-3**) and the linear trend of cover crop biomass with increasing seeding rate was not significant **(Figure 5-2d)**. The cover crop biomass has a significant effect with and without cereal rye in a mixture of hairy vetch. The observed biomass was 5039.31 kg ha^{-1} when hairy vetch was in a mixture with cereal rye and was 3396 kg ha^{-1} when hairy vetch was planted solo; cover biomass was statistically higher in a mixture of cereal rye with hairy vetch compared to the monoculture of hairy vetch. Prior research experiments also suggested that planting hairy vetch in combination with rye produced significantly higher cover crop biomass than planting them alone (Sainju et al., 2005). Considering the advantages of a mixture, the average C: N ratio (25–30:1) of the cereal rye and hairy vetch mixtures showed balanced mineralization and immobilization of N (Poffenbarger et al., 2015b; Rosecrance et al., 2000) which favors maintaining enough biomass.

The cover crop biomass was influenced by locations. . It has been found that GA_PMC (6169 kg ha^{-1}), Tennessee (6162.5 kg ha^{-1}), Maryland_BARC (5474.3 kg ha^{-1}), GA_1 (5467.3 kg ha^{-1}), AR_2 (5016 kg ha^{-1}), and AL_2 (4710.6 kg ha^{-1}) had higher total cover crop biomass than GA_2 (3330 kg ha^{-1}), NC_1 (3313.7 kg ha^{-1}), Louisiana (2398.2 kg ha^{-1}), Texas (2214.5 kg ha^{-1}), and AR_1 (1736.1 kg ha^{-1}) **(Table 5-4)**.

Winter pea: The different seeding rates showed no differences in cover crop biomass production **(Table 5-3)**, and the linear trend of cover crop biomass with increasing seeding rate was not significant **(Figure 5-2e)**. The presence or absence of cereal rye in a mixture with winter pea had a significant effect on cover crop biomass. Overall, with and without the cereal rye mixture, the recorded cover crop biomass was 4617.51 and 3277.03 kg ha^{-1}, respectively; cover biomass was statistically higher in a mixture of cereal rye with winter pea compared to solo winter pea. Karpenstein-Machan and Stuelpnagel, (2000) suggested intercropping winter peas with a low seed rating of cereal rye, as winter peas are extremely prone to lodging. Furthermore, the rye cover crop provides support and helps prevent lodging, resulting in winter peas mixed with rye providing greater cover crop biomass than a monoculture of winter peas.

The cover crop biomass was influenced by the various location. The results indicated that Tennessee (7388 kg ha^{-1}) and Maryland_BARC (5507.5 kg ha^{-1}) had higher cover crop biomass than Texas (2429.6 kg ha^{-1}), Louisiana (1811.2 kg ha^{-1}), and AR_1 (1293.5 kg ha^{-1}) **(Table 5- 4)**.

Common vetch: There was no significant effect of different seeding rates of common vetch on biomass production **(Table 5-3)**, and the linear trend of cover crop biomass with increasing seeding rate was not significant **(Figure 5-2f)**. Moreover, there was a significant effect when common vetch was planted alone or in a mixture with cereal rye in terms of cover crop biomass accumulation. It has been observed that the estimated biomass in the mixture of common vetch with cereal rye and solo common vetch was 4550.91 kg ha^{-1} and 2383.32 kg ha^{-1}, respectively; cover biomass was statistically higher in a mixture of cereal rye with common vetch compared to solo common vetch. The combination of cereal rye with common vetch increased the total cover crop biomass level than planting solo common vetch (Chintala et al., 2022). The differences in cover crop biomass among various locations suggested that Maryland_BARC (5239 kg ha^{-1}), GA_1 (5214.62 kg ha^{-1}), and Tennessee (5072.5 kg ha^{-1}) had higher total cover crop biomass than Louisiana (2104 kg ha^{-1}), NC_2 (2093.8 kg ha^{-1}), Texas (1799.1 kg ha^{-1}), AR_1 (1444.7 kg ha^{-1}), and NC_1 (355 kg ha^{-1}) **(Table 5-4)**. Among all legume species we found a similar trend that legume species in a mixture with cereal rye produced significantly higher total cover crop biomass than monoculture of legumes. Supporting our finding, Hayden et al. (2012) and Poffenbarger et al. (2015) stated that cereal and legume cover crops mixture improved the aboveground total cover crop biomass as compared to either species planted solo.

Comparison Between Legume Species:

We found a significant interaction of legume species with cereal rye strips. When different legume species were planted with cereal rye, they performed similarly and produced comparable total biomass in a range of 4709.2 to 4270 kg ha^{-1} averaged across all locations (**Figure 5-3**). As winter pea is more likely to lodging, the lower biomass production of winter pea was anticipated however it was comparable to that of other legume cover crops species. A previous study stated that winter pea can provide comparable cover biomass as hairy vetch and crimson clover legumes in combination with small grains like cereal rye in those environmental conditions where the growth of winter pea is not inhibited by cold (Vann et al., 2019).

Moreover, the results from this study demonstrated that crimson clover (3673 kg ha^{-1}) and hairy vetch (3235.4 kg ha^{-1}) in monoculture system produced higher cover crop biomass than berseem

(2637.4 kg ha^{-1}) and common vetch (2422.5 kg ha^{-1}) legume species. The results were supported by a study in North Carolina that illustrated among legume cover crops, crimson clover performed outstanding and produced the highest cover biomass in four site years followed by hairy vetch in three out of four site years as compared to other legume species including common vetch and berseem (Parr et al., 2011).

Effect of Legume Species and Cereal Rye Strip on Weed Biomass:

The states that also reported weed biomass separately out of total biomass were AL_2, AR_2, GA_2, KY_1, Maryland _PMC, KY_2, Louisiana, and Tennessee. The interaction between legume species and strips of cereal rye was not significant, however, the overall effect of legume species and strips was found to be significant. It has been observed that significantly higher weed biomass when legume species were planted alone than in legumes and cereal rye mixture **(Figure 5-4)**. Due to the fast-growing nature of grasses such as cereal rye, our results found that a mixture of legume species with cereal rye produced significantly higher total cover biomass than legume species planted in monoculture systems. Hence, greater weed suppression was expected in a mixture of legumes with cereal rye. A previous research study by Baraibar et al. (2017) supported our finding and demonstrated that because of the rapid growth of cereal rye helps in the suppression of weed germination and growth in the spring and cereal rye also dominates in the mixture with legume species. More specifically, the weed species during the winter season face resource competition such as nutrient availability with cover crops (Haramoto, 2019 and Sherman et al., 2020) that resulted in weed suppression. It has been observed that hairy vetch had significantly lower weed biomass than crimson clover, common vetch, and berseem.

Grain and Legume Biomass Composition

In the mixture of legumes with cereal rye, some states such as AL_1, Maryland_BARC, GA_1, Louisiana, KY_1, Maryland_PMC, NC_2, Texas, AR_2, GA_2, KY_2, Tennessee, and AL_2 also reported grain and legumes composition separately in the mixture. In mixture of berseem with cereal rye, the legume biomass was 20.9% and grain biomass was 79.0% **(Figure 5-5)**. The legume biomass was 33.1% and grain biomass was 67% in a mixture of crimson clover with rye. In a mixture containing common vetch and rye, the legume biomass accounted for 20% while the grain biomass included 80%. In a mixture of hairy vetch with rye, the legume biomass was 39% and the grain biomass was 61%. Lastly, in a mixture of winter pea and rye, the legume biomass was 26% and the grain biomass was 74%.

The results illustrated that in a mixture of rye with different legumes species, cereal rye dominated in the mixture and contributed a major proportion of total cover crop biomass, and it has been found in other studies (Karpenstein-Machan and Stuelpnagel, 2000; Murrell et al., 2017; Poffenbarger et al., 2015). Therefore, when proposing multispecies mixture of cover crops including legume and rye, it should be considered that the interspecific ability of performance is very competitive for cereal rye. Furthermore, it has been observed that among all legume species in a mixture with rye, hairy vetch had a higher composition than others, and it performed well when mixed with cereal rye. Previous research study by Creamer et al. (1997) also found that the spring biomass was primarily dominated by cereal rye, while legumes like hairy vetch (*Vicia villosa* Roth) had higher expression in mixtures compared with clovers (*Trifolium* spp.). Moreover, the results from this study showed that common vetch and berseem in a mixture with cereal rye performed poorly and did not produce enough biomass.

Weed, Grain, and Legume Biomass Composition

Some states, including AL_2, AR_2, GA_2, KY_1, Maryland_PMC, KY_2, Lousiana, and Tennessee also reported separate biomass for each legume species, cereal rye, and weeds when considering different legumes with a mixture of cereal rye. In a mixture of berseem with rye, out of total dry weight the weed biomass was 9.0%, legume biomass was 19.5%, and the grain biomass was 72.5% **(Figure 5-6)**. In the mixture of crimson clover with rye, it has been observed that the weed biomass was 8.9%, legume biomass was 30.3%, and the grain biomass was 60.7%. Furthermore, weed biomass was 9.3%, legume biomass was 15.1%, grain biomass was 75.6% in a mixture of common vetch with rye. In the combination of hairy vetch with rye, the accounted weed biomass was 4.4%, legume biomass was 42.7%, and grain biomass was 58.8%. Lastly, in the case of winter pea mixed with rye, the recorded weed biomass was 6.4%, legume biomass was 23.8%, and grain biomass was 69.7%. The result from this study suggested that hairy vetch in mixture with cereal rye performed better and had the lowest weed biomass composition. Previous research also claimed that mixture of hairy vetch and cereal rye suppressed weeds more effectively as compared to hairy vetch when planted solo, however it depends on seeding ratio in the mixtures (Hayden et al., 2012; Lawson et al., 2015; Mirsky et al., 2011). While common vetch in mixture with cereal rye performance was poor and the highest weed biomass.

Weed and Legume Biomass Composition

When legumes were planted solo without the mixture of rye, the states that reported weed and legume biomass separately were Lousiana, KY_1, Maryland_PMC, AR_2, GA_2, KY_2, Tennessee, and AL_2. In case of berseem, the weed biomass accounted for 48%, while legume biomass contained 52% **(Figure 5-7)**. Regarding crimson clover, the reported weed biomass was 25% and legume biomass was 75%. In the case of common vetch, the weed biomass accounted for 52%, while legume biomass contained 48%. Considering hairy vetch, the weed biomass was

16% and legume biomass was 84%. Regarding winter peas, the weed biomass was 33% and legume biomass was 67%. The results suggested that hairy vetch performed excellently and had less weed biomass while common vetch followed by berseem performed poorly and half of the biomass contributed by weeds.

Conclusions

Overall, seed rate had no effect on biomass production, reducing seeding rate of legumes can save cost for farmers. Cereal rye with legumes showed greater biomass compared to solo legume species at every location. Moreover, cereal rye improved total cover crop biomass production when mixed with legumes across all seeding rates. At the same time, different site years showed their effect in terms of cover crop biomass production. In a mixture of legume with rye, it has been observed that rye dominates the biomass production among all legume species. Among legumes species, hairy vetch and crimson clover performed well in the southern region. Significantly less weed biomass when legume cover crop species planted with rye compared to solo legume species.

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Table 5-1. Planting and harvesting dates of cover crops for each year and experimental site.

Location	Experimental Site	Lat, Long	Planting Date	Harvesting Date	Soil Type
AL_1	E.V. Smith Research Center, Shorter, AL	32.422047, -85.888937	11 Nov 2019	10 Apr 2020	Marvyn sandy loam (coarse-loamy, siliceous, subactive, thermic Paleudults)
AL_2	Wiregrass Research and Extension Center Station Headland, AL	31.3547021, -85.3263676	19 Oct 2021	04 Apr 2022	Dothan fine sandy loam (fine-loamy, siliceous, thermic Plinthic Paleudult)
AR_1	Booneville Plant Materials Center Arkansas	35.075246, -93.995539	10 Oct 2019	01 April 2020	Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudult)
AR_2	University of Arkansas Vegetable Research Center	36.0625843, -94.157441	12 Oct 2021	15 Apr 2022	Roxana silt loam (coarse-silty, mixed, superactive, nonacid, thermic Typic Udifluvents)
KY_1	University of Kentucky North Farm	38.1282, -84.4905	01 Oct 2019	07 Apr 2020	Lowell-Bluegrass silt loam
KY_2	University of Kentucky North Farm	38.1285, -84.4944	14 Oct 2021	25 Apr 2022	Lowell-Bluegrass silt loam
NC_1	Jimmy Carter Plant Materials Center	32.105943, -84.259829			
NC_2	The Cunningham Research Station (CRS), Lenoir County	35.299426, -77.570423	01 Nov. 2019	04 May 2020	Goldsboro loamy sand (fine-loamy, siliceous, thermic Aquic Paleudults).
Tennessee	The East Tennessee AgResearch and Education Center-Plant Sciences Unit	35.964997, -83.852927	13 Oct 2021	04 Apr 2022	
Texas	Plant Materials Center		15 Nov 2019	21 April 2020	
Louisiana	Louisiana - Golden Meadow Plant Materials Center	31.9516061, -91.2267797	18 Nov 2019	02 Feb 2020	
Maryland_ BARC	USDA Beltsville Agricultural Research Center (BARC)	39.0184978, -76.9435577	10 Oct 2019	07 May 2020	Elkton silt loam (fine-silty, mixed, active, mesic Typic Endoaquults)
Maryland_PMC	University of Maryland Central Maryland Research and Education Center, Beltsville	39.016084, -76.851249	15 Oct 2019	29 April 2020	Sandy loam soil (fine-loamy, siliceous, semiactive, mesic Typic Hapludults)
GA_1	Scull Shoals Experimental Forest	33.727307, -83.299583	25 Oct 2019	07 May	
GA_2	Scull Shoals Experimental Forest	33.868960, -83.451014	26 Oct 2021	25 Mar 2022	
GA _PMC	Georgia - Jimmy Carter Plant Materials Center,	32.105943, -84.259829	24 Oct.	14 April	Red Bay Sandy Loam (fine-loamy, kaolinitic, thermic Rhodic Kandiudult) soil

Table 5-2. Seeding rate of different legumes species.

	Seeding rates (kg/ha)			
Legumes	High	Full	Low	Lowest
‘Dixie’ Crimson Clover	33.6	22.4	11.2	5.6
‘AU Merit’ Hairy vetch	33.6	22.4	11.2	5.6
Common vetch	33.6	22.4	11.2	5.6
‘Frosty’ Berseem	20.2	13.5	6.7	3.4
‘Wyo’ Winter pea	134.5	89.6	44.8	22.4

Table 5-3. Significance of tests of fixed effects and their interaction in ANOVA for cover crop biomass as influenced by the effect of mixture with cereal rye, different seed rates, and across multiple locations.

	P value				
Factor	Crimson clover	Hairy vetch	Winter pea	Common vetch	Barseem
Cereal rye mixture	0.1024	0.0010 *	0.0002*	<.0001*	<.0001*
Seed rate	0.7045	0.7248	0.9168	0.5100	0.0312*
Location	<.0001*	<.0001*	<.0001*	<.0001*	<.0001*
Rye mixture*seeding rate	0.3099	0.1624	0.2879	0.2132	0.8362

Note. P values followed by * are significant ($\alpha < .05$).

Table 5-4. Pairwise comparison of total cover crop biomass (kg ha^{-1}) by cover crop species.

	CC[a]	BC	CV	HV	WP
AL_1	4761bc[b]	5810ab	4396ab	3756abcd	4031bc
AL_2	5711ab	3235de	3931ab	4711abc	3337bcd
AR_2	5061bc	4666bc	4583ab	5016abc	4967abc
AR-1	1815hi	2428fg	1445ef	1736f	1293f
Maryland_BARC	4768bcd	3155def	5239a	5474abc	5507ab
GA_2	3669hg	3017efg	3674abcd	3330def	3246cd
GA-PMC	7240a	3209de	4227abc	6169a	4413bc
NC_2	3470def	2784efg	2094def	3549bcde	3432dc
KY_1	3964cde	3677dc	3963ab	3825abc	4427bc
KY2	3908cdef	3646de	3583abcd	3941abcd	4004bcd
Louisiana	1507i	1654i	2104cde	2398ef	1811e
Maryland_PMC	4217ef	3071gh	3426bcd	4022bcde	3360d
NC_1	3479fg	1895hi	355f	3314cde	3844bcd
Tennessee	7557a	7050a	5072a	6162a	7388a
Texas	1776hi	1359j	1799cdef	2214def	2430d
GA_1	4768bc	4426bc	5215a	5467ab	4309bc

[a] CC, crimson clover; BC, berseem; CV, common vetch; HV, hairy vetch; and WP, winter pea.
[b] Within each cover crop species, means followed by different letter within a species are statistically different (P<.05).

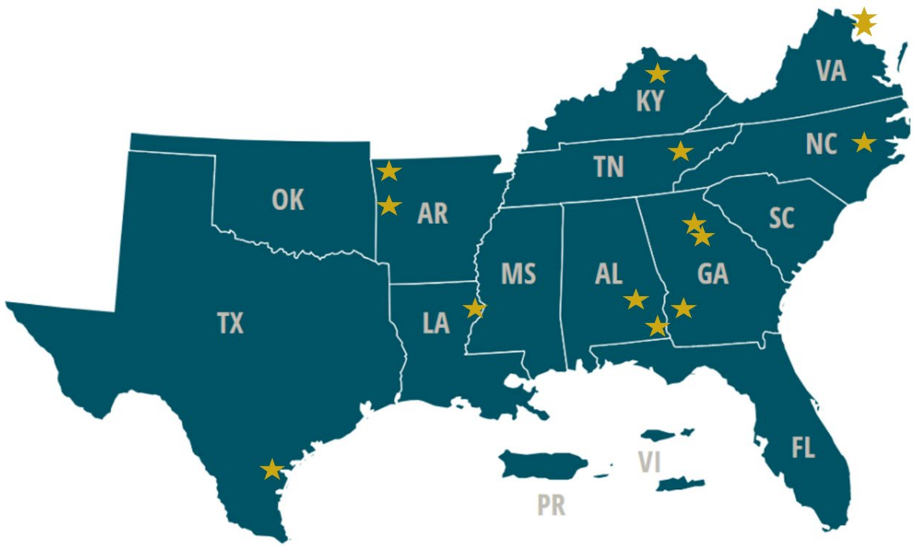

Figure 5-1. Different locations throughout the southern United States (11 states and total 16 site year).

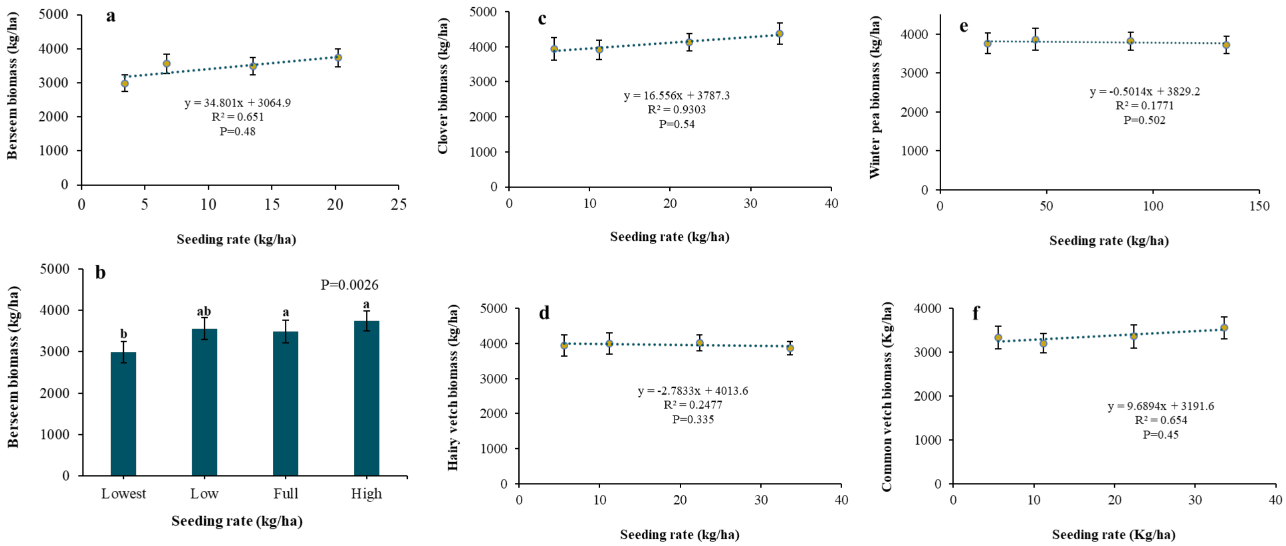

Figure 5-2. The overall effect of different seeding rates and their linear trend with total cover crop biomass production. Means followed by different letter are statistically different at α < .05 in (b). (a and b=Berseem; c=crimson clover; d=hairy vetch; e=winter pea; f=common vetch)

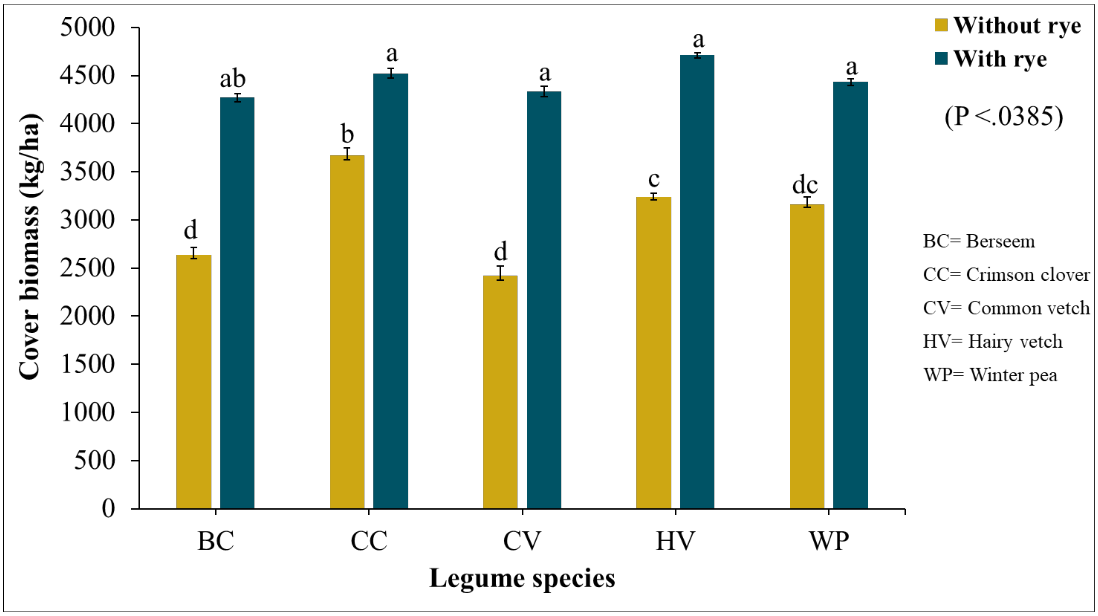

Figure 5-3. Strip of rye and legume interaction of cover crop biomass with and without strip cereal rye. Means followed by different letter within a species are statistically different at α < .05.

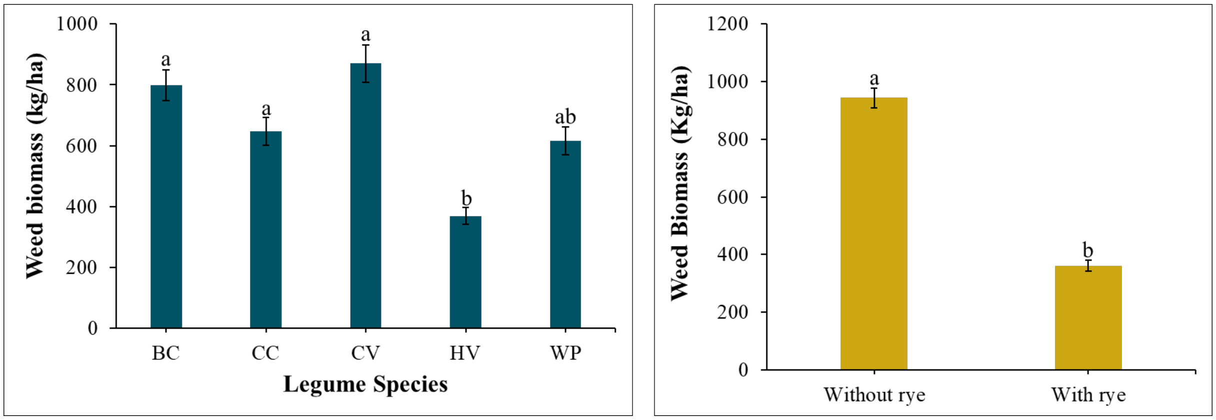

Figure 5-4. The overall effect of different legumes species and strips of rye on weed biomass (kg ha^{-1}) production. Means followed by different are statistically different at α < .05.

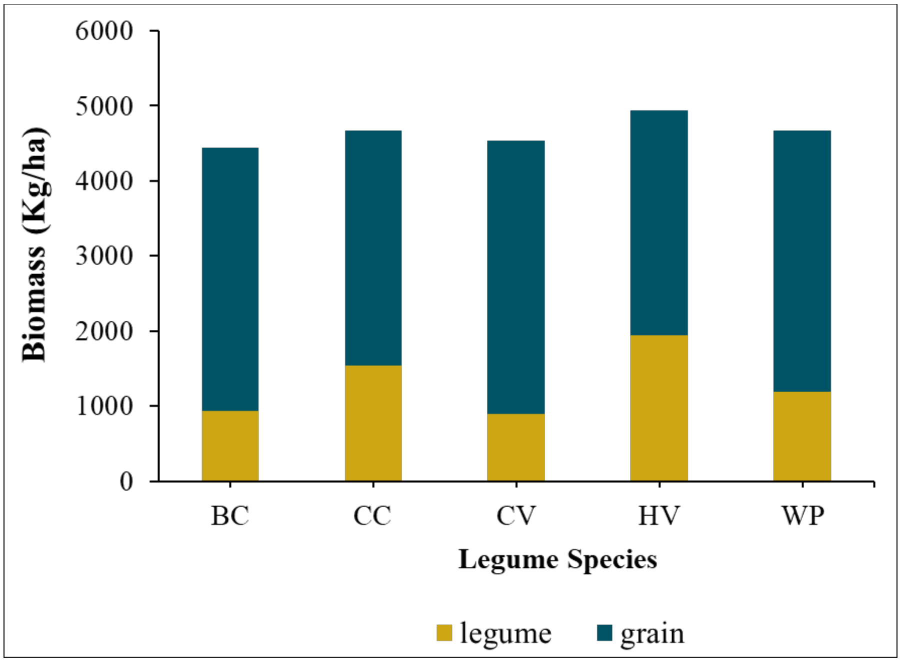

Figure 5-5. The composition of legume and grain biomass for each legume's species. (BC, berseem; CC, crimson clover; CV, common vetch; HV, hairy vetch; and WP, winter pea). The states included AL_1, Maryland_BARC, GA_1, Louisiana, KY_1, Maryland_PMC, NC_2, Texas, AR_2, GA_2, KY_2, Tennessee, and AL_2 reported proportion of grain and legumes from mixture.

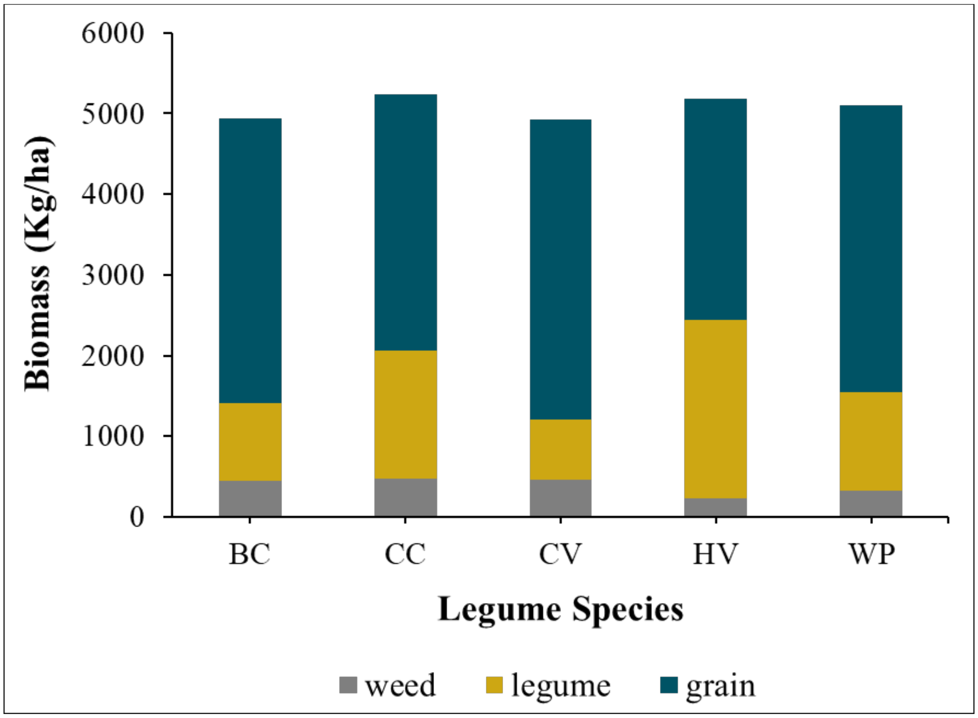

Figure 5-6. The composition of weed, legume, and grain biomass for each legume's species. (BC, berseem; CC, crimson clover; CV, common vetch; HV, hairy vetch; and WP, winter pea). The states, included AL_2, AR_2, GA_2, KY_1, Maryland_PMC, KY_2, Louisiana, and Tennessee reported separate biomass for each legume species, cereal rye, and weeds from cover crop mixture.

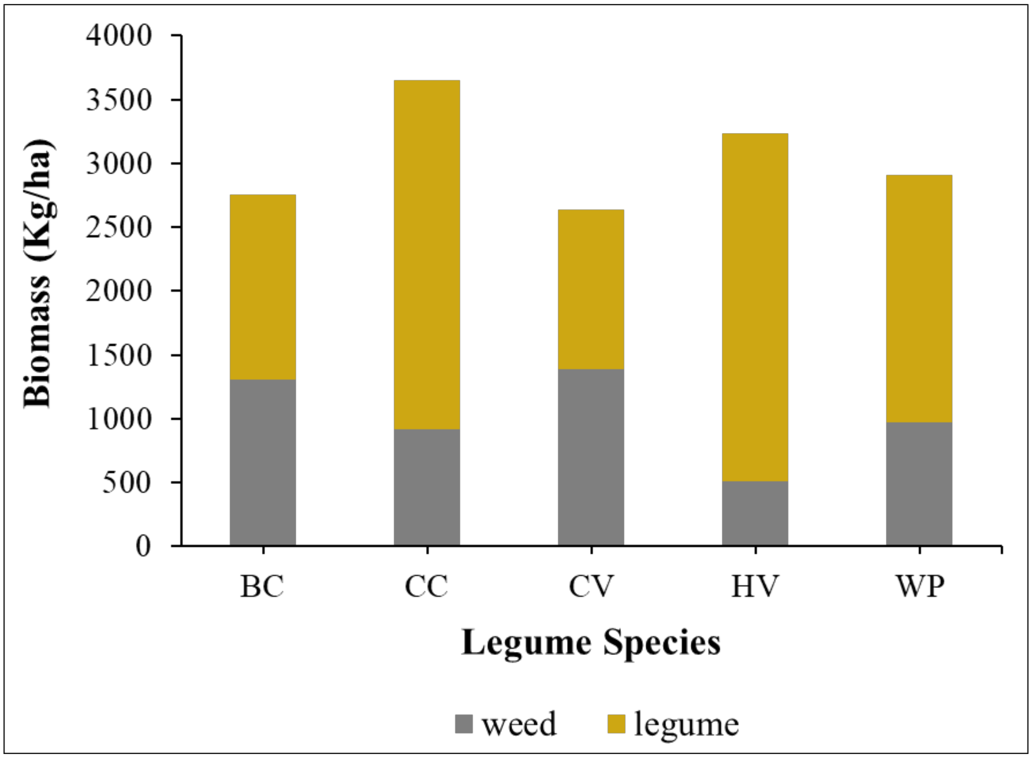

Figure 5-7. The composition of legume and weed biomass for each legume's species. (BC, berseem; CC, crimson clover; CV, common vetch; HV, hairy vetch; and WP, winter pea). The states reported weed and legume biomass separately were Louisiana, KY_1, Maryland_PMC, AR_2, GA_2, KY_2, Tennessee, and AL_2.