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Value of Cover Crops in Suppressing Weeds and Protecting Cotton Yields and Likelihood of Residual Herbicide Carryover to Cover Crops

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Value of Cover Crops in Suppressing Weeds and Protecting Cotton Yields and Likelihood of Residual Herbicide Carryover to Cover Crops

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of the requirements for the degree of
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by

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ABSTRACT

Weed-resistance management has become a topic of concern for modern agriculture. Cost related to herbicide usage has increased greatly due to evolution and proliferation of resistant weeds. Therefore, experiments were conducted to investigate the potential for using cover crops to suppress problematic weeds in cotton as well as chemical options for cover crop dessication, and sensitivity of cover crops to residual herbicides were evaluated. No differences were observed for cereal rye biomass production and consequently weed suppression between broadcast and drilled planting methods. Total amount of cover crop biomass was vital to effectively suppress weeds. Hence, of the cover crops evaluated, cereal rye proved to be superior to others for weed suppression due to its ability to produce large amounts of biomass. Cereal rye biomass production increased as the seeding rate increased, which led to greater weed suppression at a seeding rate of 112 kg ha^{-1} and 168 kg ha^{-1} compared to 56 kg ha^{-1}. Control of cover crops prior to row crop planting can be difficult depending upon the cover crop species. Paraquat plus metribuzin and glufosinate adequately controlled the legume cover crops hairy vetch (*Vicia villosa* Roth) and Austrian winterpea (*Lathryrus hirsutus* L). Cereal cover crops were completely controlled by glyphosate alone. Rapeseed was not effectively controlled by any of the termination options evaluated. Based on a herbicide carryover trial from corn, residual herbicides commonly applied in corn that will be rotated to a cover crop and eventually cotton have low risk to interfere with the cover crop establishment and development after corn harvest.

Nomenclature: Austrian winterpea, *Lathryrus hirsutus* L; cereal rye, *Secale cereale* L.; hairy vetch, *Vicia villosa* Roth; rapeseed, *Brassica napus* L; cotton, *Gossypium hirsutum* L.

Key words: Cover crop, emergence, cereal rye, legume cover crop, cereal rye, oilseed rape

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Chapter 1

General Introduction and Litature Review

Cotton (*Gossypium hirsutum* L.) is one of the most important crops globally, with the United States accounting for about 35% of all fiber produced (USDA-ERS 2015). Global cotton production was 103.7 million bales (one bale is equal to 218 kg) in 2014, with the top five producing countries being China followed by India, United States, Pakistan, and Brazil. The U.S. cotton industry is responsible for 200,000 employees throughout several sectors and produces more than $25 billion dollars in products and services every year. The demand for cotton products has been consistent since the end of the 1990's. Cotton mills around the world have increased their business significantly. However, in the U.S., demand has dropped due to competition from imported products (USDA-ERS 2012).

The current cotton production system relies heavily on transgenic cultivars to maintain high yields. The two most widely used commercially available herbicide-resistant (HR) traits are glyphosate-resistant (GR) and glufosinate-resistant cotton. According to USDA-NASS (2015), 94% of all cotton planted in the U.S. was transgenic cultivars that contained at least one herbicide trait.

The first generation of glyphosate resistance in cotton (Roundup Ready) was conferred through expression of a bacterial 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) enzyme from Agrobacterium sp. strain CP4 (Padgette et al. 1995). The second generation (Roundup Ready Flex®) was obtained by utilizing promoters to enhance expression of the EPSPS in reproductive tissues, which allowed application of glyphosate up to reproductive development (Chen et al. 2006). Besides the superior weed control, economics and simplicity of the production system contributed extensively to adoption of glyphosate-resistant cotton.

Brookes and Barfoot (2014) reported that the widespread adoption of glyphosate-resistant cotton resulted in a global gain of $231.8 million dollars and the U.S. received about 67% of this amount. However, even with this significant increase in profits, just $9.6 million dollars were earned by producers due to increases in seed cost and a decrease in cotton price. Brookes and Barfoot (2014) also reported the increase in farm income from 1996 to 2012 was $1.3 billion dollars and the area planted in 2012 was 80% of total cotton acreage. The economic benefit of glyphosate-resistant cultivars was calculated by comparing traditional weed management programs, which includes preemergence (PRE) herbicides, to weed management programs relying on repeated applications of glyphosate alone. Regardless of the effective control obtained by glyphosate alone, this kind of management was not sustainable due to the intense selection pressure on one herbicide. Repeated use of glyphosate across vast acres ultimately led to the widespread occurrence of glyphosate-resistant weeds, most notably Palmer amaranth (*Amaranthus palmeri* S. Wats.).

Glufosinate is a contact, nonselective herbicide that can be applied over the top of glufosinate-resistant cotton (LibertyLink™). The resistance was obtained through incorporation of the phosphinothricin-N-acetyl-transferase (PAT) gene of *Streptomyces viridochromogenes* into cotton. The PAT gene is converted to a protein that quickly acetylates glufosinate molecules. Thus, PAT inhibits glutamine synthetase by rapidly inactivating the herbicide before it can bind to glutamine synthase (Dröge et al. 1992). Glufosinate can be applied from emergence through the bloom stage of glufosinate-resistant cotton (Anonymous 2013). Applications after the bloom stage can cause flower abortion and subsequent yield loss.

Commercial introduction of GR cotton by Monsanto in 1997 completely changed weed management in the crop. Weed control in cotton historically had been achieved by a combination of cultivation, soil-applied herbicides, postemergence (POST)-directed herbicides, and hand weeding. The development of GR cropping system allowed growers to adopt a single POST herbicide program, no longer requiring PRE applications, complex tank-mixtures, or cultivation for adequate weed control. Culpepper and York (1998) reported that sequential applications of glyphosate at 3 to 4 and 6 to 7 weeks after cotton planting provided 98% or greater control of common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), common cocklebur (*Xanthium strumarium* L.), Palmer amaranth, smooth pigweed (*Amaranthus hybridus* L.), and prickly sida (*Sida spinosa* L.).

As a result of the high efficiency of glyphosate along with reduced production cost, the introduction of HR cotton facilitated an extensive adoption of conservation tillage in the crop. Compared to conservation tillage, conventional tillage requires more labor and increased trips across the field since it requires multiple tillage operations in a short period of time, which can be difficult to achieve due to weather delays. Initially, the intensive use of glyphosate was effective on a large array of weeds. However, repetitive applications of glyphosate alone in cotton, soybean (*Glycine max* L. Merr.), and corn (*Zea mays* L.) resulted in a herbicide monoculture on a vast number of hectares. This management placed tremendous selection pressure on the weed population which eventually led to GR weeds.

Weed resistance can evolve in two ways - target-site resistance and non-target site resistance. Target site resistance can occur by a gene mutation that confers a change in a certain enzyme, preventing the association of the herbicide with the binding site (Powles and Yu 2010). Evolution of a target-site resistance is obtained through use of the same herbicide and/or mode of action repeatedly which increases the selection pressure in the weed population. Non-target site herbicide resistance can be attributed to a variety of factors that ultimately decreases the amount of herbicide that reaches the target site (Yuan 2007). Herbicide is an external substance that causes great amount of stress inside the plant. Consequentily, plants activate different pathways as a responses to the stress. Metabolism resistance can be viewed as a detoxification process that avoid herbicide molecules to achieve the target site in proper concentrations. The biggest challenge in the battle against herbicide-resistant weeds is the evolution of multiple resistance, which consists of an individual plant having multiple resistance mechanisms (Powles and Yu 2010).

Currently, cotton producers face a significant problem with HR weeds, especially Palmer amaranth. This rapidly growing pest can reach heights over 2 meters, an attribute that makes it extremely competitive against crops for resources such as light, nutrients, and water (Fast et al. 2009). Another aspect that places Palmer amaranth as the most troublesome weed in the Midsouth is its high seed production and extended germination period. Jha and Norsworthy (2009) observed Palmer amaranth emergence from May to October in South Carolina, which makes control a season-long endeavor in cotton. According to Webster and Grey (2015), a simple escape of 10 female Palmer amaranth plants per hectare may result in 3.1 million seed added to the seedbank in cotton fields. Seed longevity studies have shown that viability of Palmer amaranth seeds can drastically diminish when buried in the soil. However, even if less than 0.03% of the initial seedbank remains viable after four years, it is possible that a sufficient number of plants can emerge and repopulate the seedbank through seed production of the survivors (Jha et al. 2014).

The first case of GR Palmer amaranth in the U.S. was confirmed in Georgia (Culpepper et al. 2006). Currently, due to its aggressive proliferation and rapid resistance evolution, GR Palmer amaranth has been documented in Arizona, Arkansas, Alabama, California, Delaware, Florida, Illinois, Kentucky, Kansas, Louisiana, Maryland, Michigan, Mississipi, Missouri, Ohio, New Jersey, New Mexico, North Carolina, South Carolina, Tennessee, Texas, Virginia, and Wisconsin (Norsworthy et al. 2008; Heap 2016). The widespread existence of GR Palmer amaranth prompted changes in weed control strategies in Midsouth cotton production. A survey conducted by Sosnoskie and Culpepper (2014) showed that glyphosate usage as a POST in-crop herbicide in Georgia decreased from 95% to 75% of the hectares after the appearance of GR Palmer amaranth. The same survey reported that 1% of their acreage was planted with glufosinate-resistant cotton prior to GR appearance; however, after resistance, use of glufosinate-resistant cotton increased to at least 30%. In addition, hand-weeding increased after resistance appearance. According to Geordia county agents, in 2006, 6% of the cotton area had hand-weeding operations which increased to 66% by 2010. Currently, adequate control of GR Palmer amaranth relies on complex herbicide programs that contain residual herbicides. Cost related to herbicide usage has increased more than three-fold as a result of GR weeds in cotton (Norsworthy et al. 2016).

Palmer amaranth has become a threat to conservation tillage simply because of the high adaptability of this pest to the conservation tillage system (Price et al. 2011). Several studies have shown that seeds that are located on the soil surface or shallow depths (0.5 to 2.5 cm) can prolifically germinate and emerge; in contrary, seeds located below a 2.5-cm depth are not likely to germinate (Buhler et al. 1996; Oryokot et al. 1997). The evolution of resistance and proliferation of GR Palmer amaranth might push growers to readopt conventional tillage in the attempt of enhancing Palmer amaranth control. Furthermore, weed control in conservation tillage has proven to be challenging because weed populations are likely to shift after few years of reduced tillage. Such shifts in weed composition may demand different weed management practices including complete change of herbicide programs to achieve control over species that were once minor problems in previously tilled areas (Locke et al. 2002).

The spread of GR Palmer amaranth and the recent confirmation of protophorynigen oxidase (PPO)-resistant Palmer amaranth in the Midsouth threatens the ability of growers to manage weeds utilizing the currently available herbicide technologies (Salas et al. 2016). Hence, successful weed management strategies will rely heavily on integrated management approaches using cultural, mechanical, and chemical methods of control (Norsworthy et al. 2012).

Cover crop acreage has substantially increased over the last few years due to the intent of growers to capitalize on federal conservation payments and incorporate sustainable practices into their agricultural system (SARE 2015). Cover crops have been used in agriculture for many years due to the benefits related to reduced soil erosion, carbon sequestration, water management, and pest control (Clark 2008; Dabney 2001; Mennan 2009; Ducamp 2012). The combination of cover crops with conservation tillage has proven to have an important fit in cotton production systems in the southern U.S. Soils where cotton is traditionally grown tend to be low in organic matter and severe soil erosion is common as a result of low biomass production of cotton and a long history of intensive cultivation (Langdale et al. 1991). Mutchler and McDowell (1990) reported that a conventional cotton production system can provide soil losses up to 74 ton ha^{-1} year $^{-1}$; however, the combination of no-till with hairy vetch (*Vicia villosa* Roth) and winter wheat (*Triticum aestivum* L.) reduced soil loss to acceptable levels (below 11 ton ha^{-1} $year^{-1}$). According to Mbuthia et al. (2015), after 31 years of tillage research, conservation tillage practices were found to increase soil C and N by approximately 19% and 10%, respectively, under no-till and cover crops (hairy vetch and wheat) compared to tilled system without cover crops. It is expected that reducing tillage would result in an increase of soil total carbon due to the decrease of organic carbon decomposition rate; however, the impact of tillage on total soil carbon has been shown to be highly dependent on climate, soil texture, cropping system, and duration of conservation tillage (Acosta-Martinez et al. 2011; Al-Kaisi et al. 2005; West and Post 2002).

Numerous studies have been conducted to understand how the use of cover crops can effectively increase sustainability of agriculture by reducing herbicide use and decreasing the selection pressure caused by herbicides. Cover crop residues covering the soil surface can alter weed emergence patterns due to changes in environmental conditions such as light availability, soil moisture, and soil temperature early in the season (Teasdale 1996). Dhima (2006) reported that winter cover crops, such as cereal rye (*Secale cereale* L.) and barley (*Hordeum vulgare* L.), have the capacity to release inhibitory substances known as allelochemicals that can affect the initial growth of grass weeds like barnyardgrass (*Echinochloa crus-galli* L. Beauv.) and foxtail (*Setaria* ssp) without having any negative aspect on corn yield.

Legume cover crops have been used to increase organic matter and nitrogen concentration in the soil (Caamal-Maldonado et al. 2001). Numerous studies have been conducted to quantify the amount of nitrogen fixed by legumes, with the amount of fixation dependent on legume species and environmental conditions. It has been estimated that some legume cover crops can fix as much as 115 kg N ha^{-1} year^{-1} from the N_2 in the air. Torbert (1996) reported that crimson clover (*Trifolium inrcanatum* L.) increased corn yield by 30% when compared with a no cover crop treatment. However, Reddy (2001) reported that with soybean, a yield decrease was observed in treatments containing a legume cover crop when compared to no cover crop plots, leading to a negative net return in treatments with cover crop. Reddy et al. (2003) observed a 50% reduction in grass weeds, such as barnyardgrass, broadleaf signalgrass (*Urochloa platyphylla* Nash.), and browntop millet (*Urochloa ramosa* L.), and 55% reduction in entireleaf morningglory (*Ipomoea* ssp) emergence when using crimson clover. Creamer (1996) reported eastern black nightshade (*Solanum ptychanthum* Dun.) control of 54% and 75% when using crimson clover and hairy vetch, respectively.

Cereal cover crops are utilized in many agronomic cropping systems because of their high amount of biomass production. Sainju et al. (2005) reported 16% higher biomass production of cereal rye than hairy vetch. Creamer (1996) stated that cereal rye suppressed growth and emergence of yellow foxtail (*Setaria pumila* Poir) by 90%. Cereal cover crops can reduce redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters emergence by 78% when compared with no-cover crop plots (Moore et al. 1994). Dhima (2006) also reported that winter cereal mulches reduce emergence of barnyardgrass and bristly foxtail (*Setaria parviflora* Poir.) up 80% and 67%, respectively. Cereal rye appears to have the capacity of releasing secondary metabolites that accumulate close to the soil surface inhibiting weed seed germination and growth (Weston and Duke 2003).

Brassica cover crops have a high propensity to suppress a wide assortment of pests (insects, diseases, and weeds). This pest suppression is largely due to plants in the Brassicaceae family having the ability to produce glucosinolates which degrade to form isothiocyanates that can be strong pesticides (Fahey et al. 2001). Isothiocyanates are known to inhibit seed germination (Peterson et al. 2001). Krishnan et al. (1998) reported that mustard species reduced weed biomass in soybean by 49% at 6 weeks after soybean emergence. Hence, there is evidence that Brassica cover crops reduce weed density and slow weed emergence through allelochemical substances (Haramoto and Gallandt 2005).

Despite all the benefits that cover crops provide, adoption of cover crops remain limited due to their potential cost and management requirements (Larson et al. 2001). A primary consideration when adopting a new pest management strategy is the profitability of the management proposed. The no-tillage system by itself has the potential of reduce cost because it requires less energy compared to conventional tillage systems. However, the total cost of inputs differs by region and cash crop in question (Raper et al. 2000; Uri 2000; Manley et al. 2005). Similarly, the direct costs related to cover crop establishment can be influenced by the cover crop species, seeding rate, and planting method (Ball 1986). Indirect cost related to extra management such as cover crop termination should also be taken into consideration because herbicide cost can drastically change depending upon the cover crops to be desiccated. According to Reddy (2001), the additional cost of seeds, planting, and desiccation of cover crops can range from \$215 ha^{-1} to \$311 ha^{-1} for legumes and \$142 ha^{-1} to \$198 ha^{-1} for cereals which led to a negative net return in soybean. In contrast, in a study with no-till cotton, Varco et al. (1999) found a positive net return of \$837 ha^{-1} and \$904 ha^{-1} for wheat and hairy vetch, respectively.

Cover crop termination is crucial for successful crop management since a poorly terminated cover crop can become a weed and lessen the yield potential of the current agronomic crop (Singer 2007). The timing for cover crop termination is generally recommended from 2 to 4 weeks before crop planting due to reasons such as excessive residue interfering with planting operation, extreme moisture depletion, allelopathy effects, and increases in the occurrence of insect pests (McCarty et al. 2004; Reeves 1994). Crop crops have been terminated using a roller crimper prior to crop planting; albeit, low efficacy and high energy requirement of the roller crimper has often caused growers to adopt herbicides for cover crop termination. Additionally, a roller crimper would not be a viable option in the Midsouth where cotton is typically grown in raised beds to facilitate furrow irrigation and drainage. White and Worsham (1990) reported that glyphosate applied at 1.7 kg ae ha^{-1} provided only 65% control of hairy vetch and 70% control of crimson clover, which led to the hairy vetch plots terminated with glyphosate having the lowest crop yield. Conversely, 2,4-D applied at 1.1 kg ae ha^{-1} provided 99% control of hairy vetch and 82% control of crimson clover with no negative affect on cotton yield. Price et al. (2009) reported that glyphosate applied at 0.84 kg ae ha^{-1} can effectively control cereal cover crops (oats [*Avena sativa* L.], wheat, and cereal rye), providing 95% or greater control after 3 weeks of application. Hence, the proper herbicide choice for cover crop termination is highly related to cover crop species and herbicides must be chosen carefully to avoid unnecessary cost and possible yield decrease.

Another major concern among growers is the possible carryover effect of residual herbicides on cover crop establishment after crop harvest. Residual herbicides are routinely applied to most agronomic crops in the southern U.S. According to Walsh et al. (1993), metribuzin plus chlorimuron applied at 0.40 kg ai ha^{-1} and 0.039 kg ai ha^{-1} pre-plant incorporated to soybean resulted in an average alfalfa (*Medicago sativa* L.) biomass reduction of 72%. In contrast, the same herbicide treatment did not affect hairy vetch and cereal rye. The rate of herbicide degradation in soil is dependent on soil characteristics such as pH, soil texture, organic matter, and cation exchange capacity (Walker and Barnes 1981; Green 1974). The effect of pH on herbicide persistence in the soil is known to play an important role for sulfonylurea and imidazolinone herbicides. Soil persistence of herbicides like imazaquin and imazethapyr have been found to be greater in low pH soils because greater adsorption results in lower availability for microbial degradation (Loux and Reese 1992). Soil texture also appears to be significant on herbicide persistence in the soil. Rogers et al. (1986) concluded that herbicide injury to hairy vetch and wheat from trifluralin, fluometuron, and linuron differed significantly among the soil textures evaluated (Sharkey silty > Dundee silty > Loring silt loam). Westra et al. (2014) found that the half-life of pyroxasulfone at 0.28 kg ai ha^{-1} ranged from 104 to 137 days in a fine clay loam and from 46 to 48 days in a fine sandy loam. In summary, the carryover effect of herbicides to cover crops varies with weather and soil conditions.

It is well documented that cover crops reduce weed emergence and increase crop yields. However, depending on the weed density of the field, cover crops might show limited efficacy on weed suppression. Thus, herbicide use becomes inevitable to obtain an adequate and consistent level of weed control. Reddy (2003) reported that crimson clover and cereal rye provided 25 to 73% weed suppression; however, when these treatments were combined with herbicide programs, the control of entireleaf morningglory, broadleaf signalgrass, barnyardgrass, and hyssop spurge (*Chamaesyce hyssopifolia* L.) improved to 92% or better. Integrating cover crops into a crop rotation system can be a useful tool to assist producers with weeds that are often difficult to manage with herbicides alone.

Literature Cited

Buhler DD, Mester TC, Kohler KA (1996) The effect of maize residues and tillage on emergence of *Setaria faberi*, *Abutilon theophrasti*, *Amaranthus retroflexus* and *Chenopodium album*. Weed Res 36:153-165

Caamal-Maldonado JA, Jiménez-Osornio JJ, Torres-Barragán A, Anaya AL (2001) The use of allelopathic legume cover and mulch species for weed control in cropping systems. Agron J 93:27-36

Clark A, ed (2008). Managing Cover Crop Profitably 3th edn. Beltsville, MD: Sustainable Agriculture Research and Education (SARE). Pp 98-103

Creamer NG, Bennett MA, Stinner BR, Cardina J, Regnier EE (1996) Mechanisms of weed suppression in cover crop-based production systems. HortSci 31:410-413

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, Hanna WW (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci 54:620-626

Culpepper AS, York AC (1998) Weed management in glyphosate-tolerant cotton. J Cotton Sci 2:174-185

Dhima KV, Vasilakoglou IB, Eleftherohorinos IG, Lithourgidis AS (2006) Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop Sci 46:345-352

Ducamp F, Arriaga FJ, Balkcom KS, Prior SA, Van Santen E, Mitchell CC (2012) Cover crop biomass harvest influences cotton nitrogen utilization and productivity. Inter J Agron Article ID 420624. doi:10.1155/2012/420624.

Fahey JW, Zalcmann AT, Talalay P (2001) The chemical diversity and distribution of glucosinolates and isothiocyanates among plants. Phytochem 56:5-51

Fast BJ, Murdock SW, Farris RL, Willis JB, Murray DS (2009) Critical timing of Palmer amaranth (*Amaranthus palmeri*) removal in second-generation glyphosate-resistant cotton. J Cotton Sci 13:32-36

Haramoto ER, Gallandt ER (2005) Brassica cover cropping: II. Effects on growth and interference of green bean (*Phaseolus vulgaris*) and redroot pigweed (*Amaranthus retroflexus*). Weed Sci 53:702-708

Heap I (2017) International Survey of Herbicide Resistant Weeds. Available at http://www.weedscience.com/summary/home.aspx. Accessed: January 14, 2017

Herridge DF, Peoples MB, Boddey RM (2008) Global inputs of biological nitrogen fixation in agricultural systems. Plant Soil 311:1-18

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Jha P, Norsworthy JK, Garcia J (2014) Depletion of an artificial seed bank of Palmer amaranth (*Amaranthus palmeri*) over four years of burial. Am J Plant Sci 5:1599-1606

Krishnan G, Holshouser DL, Nissen SJ (1998) Weed control in soybean (*Glycine max*) with green manure crops. Weed Technol 18:97-102

Locke MA, Reddy KN, Zablotowicz RM (2002) Weed management in conservation crop production systems. Weed Biol Manag 2:123-132

Mbuthia LW, Acosta-Martinez V, DeBruyn J, Schaeffer S, Tyler D, Odoi, E, Mpheshea M, Wlaker F, Eash N (2015) Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. Soil Bio Biochem 89: 24-34.

Mennan H, Ngouajio M, Kaya E, Isik D (2009) Weed management in organically grown kale using alternative cover cropping systems. Weed Technol 23:81-88

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012). Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60 (Special Issue I):31-62

Oryokot JO, Murphy SD, Swanton CJ (1997) Effect of tillage and corn on pigweed (*Amaranthus* spp.) seedling emergence and density. Weed Sci 45:120-126.

Petersen J, Belz R, Walker F, Hurle K (2001) Weed suppression by release of isothiocyanates from turnip-rape mulch. Agron J 93: 37-43

Price AJ, Balkcom KS, Culpepper SA, Kelton JA, Nichols RL, Schomberg H (2011) Glyphosate-resistant Palmer amaranth: a threat to conservation tillage. J Soil Water Conserv 66:265-275

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15:660-668

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci 51:987-994

Sainju UM, Whitehead WF, Singh BP (2005). Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron J 97:1403-1412

Salas RA, Burgos NR, Tranel PJ, Singh S, Glasgow L, Scott RC, Nichols RL (2016) Resistance to PPO-inhibiting herbicide in Palmer amaranth from Arkansas. Pest Manag Sci 72:864-869

Sosnoskie LM, Culpepper AS (2014) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) increases herbicide use, tillage, and hand-weeding in Georgia cotton. Weed Sci 62:393-402

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. J Prod Agri 9:475-479

Torbert HA, Reeves DW, Mulvaney RL (1996) Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron J 88:527-535

USDA-ERS United States Department of Agriculture-Economic Research Service. Cotton and Wool http://www.ers.usda.gov/topics/crops/cotton-wool.aspx. Accessed March 15, 2016
USDA-NASS United States Department of Agriculture-National Agricultural Statistics Service. 2013. Quick Stats. http://quickstats.nass.usda.gov/. Accessed March 16, 2016

Walker A, Barnes A (1981) Simulation of herbicide persistence in soil: a revised computer model. Pestic Sci 12:123-132.

Walsh JD, Defelice MS, Sims BD (1993) Influence of tillage on soybean (*Glycine max*) herbicide carryover to grass and legume forage crops in Missouri. Weed Sci 44:144-149

Webster TM, Grey TL (2015). Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) morphology, growth, and seed production in Georgia. Weed Sci 63:264-272

Weston LA, Duke SO (2003) Weed and crop allelopathy. Critical Rev Plant Sci 22:367-389

Chapter 2

Value of Cover Crops in Suppressing Palmer Amaranth and Protecting Cotton yield

Abstract

With the recent confirmation of protoporphyrinogen oxidase (PPO)-resistant Palmer amaranth in the Midsouth, there is increased concern about the sustainability of weed management in cotton production systems. The use of cover crops can be a worthy option to alleviate this problem since cover crops can suppress weed emergence through allelochemicals and/or a physical residue barrier. Field experiments were conducted in 2014 and 2015 at the Arkansas Agricultural Research and Extension Center in Fayetteville to evaluate the value of various cover crops in suppressing weed emergence and protecting cotton yield. No cover, cereal rye, wheat, oats, hairy vetch, crimson clover, Austrian winterpea, and rapeseed were used as winter cover crop treatments. In both years, cereal rye and wheat had the highest biomass production whereas the amount of biomass present in spring did not differ among the remaining cover crops. All cover crops initially diminished Palmer amaranth emergence. However, cereal rye had the greatest suppression, with 83% less emergence than in no cover crop plots. Physical suppression of Palmer amaranth and other weeds with cereal residues is most likely the greatest contributor to reducing weed emergence in this experiment. Seedcotton yield in the legume and rapeseed cover crop plots were similar when compared with the no cover crop treatment. The seedcotton yield collected from cereal cover crop plots was lower than from other treatments due to decresed cotton stand.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* S. Wats.; Austrian winterpea, *Lathryrus hirsutus* L.; cereal rye, *Secale cereale* L.; cotton, *Gossypium hirsutum* L.; crimson clover, *Trifolium incarnatum* L., hairy vetch, *Vicia villosa* Roth; oats, *Avena sativa* L.; rapeseed, *Brassica napus* L.; wheat, *Triticum aestivum* L.

Key words: Cover crops, emergence, cereal, legume, brassica

Introduction

Historically, effective weed management in cotton was obtained through the combination of tillage and diverse types of herbicide applications, such as preplant incorporated (PPI), preemergence (PRE), postemergence (POST), and post-directed (PD) (McWhorter and Albernathy 1992). However, the wide adoption with glyphosate-resistant (GR) crops in the mid-1990's replaced these diverse herbicide applications with sequential applications of glyphosate over-the-top of the crop. The effectiveness of GR technology along with reduced cost due to less tillage facilitated an extensive adoption of conservation tillage by decreasing the reliance on PPI- and PRE-applied herbicides for weed control (Fernando-Cornejo and Caswell 2006; Young 2006). Repetitive exposure to a single mode of action is considered the main factor for selection of resistant weed biotypes (Powles et al. 1996). In 1996, the first case of weed resistance involving glyphosate was identified in Australia. Currently, there are 36 cases of GR weeds around the world with 16 of them present in the U.S. (Heap 2016).

In 2006, the first case of GR Palmer amaranth was documented in Geordia (Culpepper et al. 2006). Since then, several other locations have confirmed the presence of the GR biotype (Mohseni-Moghadam et al. 2013; Nandula et al. 2012; Nichols et al. 2009; Norsworthy et al. 2008; Steckel et al. 2008). Glyphosate-resistant Palmer amaranth has received great attention over the last 10 years because of rapid resistance evolution and wide proliferation of this pest within the primary agricultural regions of the U.S. Palmer amaranth is an erect, branched, summer annual broadleaf plant that can reach heights greater than 2 m. Rapid growth, a well developed root system, and high water use efficiency allow Palmer amaranth to compete efficiently for water, nutrients, and light with crops (Elmore 1990; Klingaman and Oliver 1994). The appearance and spread of GR Palmer amaranth has changed weed management in cotton because a total POST herbicide program is no longer sustainable (Culpepper et al. 2006; Webster and Sosnoskie 2010). Conservation tillage systems have proven to function extremely well on lessening soil erosion and improving soil physical, chemical, and biological properties, all indicators of soil quality (Mbuthia et al. 2015). However, this system is now in jeopardy because ot the inability to control Palmer amaranth using current technology may force growers to readopt high intensity tillage practices in order to obtain adequate control (Prince et al. 2011).

Glufosinate can be an effective option for controlling Palmer amaranth POST in glufosinate-resistant cotton. However, efficacy of glufosinate on Palmer amaranth is greatly dependent upon weed size and weather conditions. For instance, it was found that glufosinate at 291 g ai ha^{-1} completely controlled 2- to 5-cm tall Palmer amaranth, but control decreased to 87% when applied to 8- to 10-cm tall Palmer amaranth (Cobert 2004). Coetzer et al. (2001) also reported that glufosinate applied at 205 g ai ha $^{-1}$ at 35% relative humidity provided 55% Palmer amaranth control. However, the same rate applied at 90% relative humidity provided 84% Palmer amaranth control. Hence, relying on a total POST herbicide program with one mode of action is not appropriate, since this weed demonstrated to be extremely aggressive and survival of few plants can mean high infestation the following year. A zero tolerance program has to be adopted by growers to avoid entry of viable seeds into the soil seedbank, meaning that different methods of control are required throughout the growing season due to season-long emergence of Palmer amaranth (Jha and Norsworthy 2009; Norsworthy et al. 2014). Strategies are required to control the existing population of GR Palmer amaranth as well as to avoid spread of resistant biotypes. Integrating residual herbicides with cultural practices such as cover crops should be considered by farmers to improve weed control and incorporate sustainable practices into cotton production.

The use of winter cover crops in conversation tillage was initially aimed at reducing erosion control and improving soil health. However, over time cover crops have obtained greater attention due to the physical weed suppression offered by the cover crop biomass (Reddy 2001; Teasdale and Mohler 2000). Cover crop residue can affect weed germination and growth by modification of the soil microenvironment. Light availability, soil moisture, and temperature are some of the attributes that can lead to suppressed weed seed germination (Masiunas et al. 1995; Creamer et al. 1996).

Legume cover crops have been widely used to provide nitrogen (N) credits to the subsequent crop. The N content of legume cover crop residues ranges from 36 to 226 kg ha^{-1} (Power et al. 1991; Torbert et al. 1996). The amount of N in legume cover crop residues depends on crop species, residual soil N, and timing of cover crop termination (Sainju et al. 2005). Rochester et al (2001) reported that legume cover crops can provide considerable savings on N fertilizers required to optimize cotton lint yields and improve soil quality. Successful weed control achieved by legume cover crops are often attributed to the biomass production which can suppress weed germination. However, legume cover crops generally have low persistence on the soil surface due to a low C:N ratio (Touchton et al. 1984). Hence, weed control provided by legume cover crops is likely to be most effective during the early part of the growing season (Reddy 2001; Burgos and Talbert 1996). Reddy et al. (2003) reported a 50% reduction in emergence of barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], broadleaf signalgrass [*Urochloa platyphylla* (Nash) RD Webster], and browntop millet (*Urochloa ramosa* L.) and 55% reduction in morningglory (*Ipomoea* ssp.) emergence at 7 weeks after soybean (*Glycine max* (L.) Merr.) planting when using crimson clover.

Cereal cover crops are known to produce high amounts of aboveground biomass, with cover crops like cereal rye producing 20% to 30% of the total biomass below ground (Meisinger et al. 1991). This characteristic suits cereal cover crops as an excellent option for N scavenging as well as to increase water infiltration, aeration and soil aggregation, and soil protection (Dabney et al. 2001; Langdale et al. 1991; Roberson et al. 1991; Snapp et al 2005). The high aboveground biomass production of cereal cover crops is also an excellent means of suppressing Palmer amaranth (Norsworthy et al. 2011; DeVore et al. 2012). It is well established that the degree of suppression of annual weeds is highly dependent upon the amount of residue produced by the cover crop (Tesdale and Molher 2000). Cover crops such as cereal rye and barley (*Hordeum vulgare* L.) can provide soil coverage up to 93% and 83%, respectively (Nelson et al. 1991). Price et al. (2007) observed fewer Palmer amaranth plants (90,000 plants ha^{-1}) in conservation tillage systems that had cereal rye residue covering the soil surface at cotton planting than winter fallow conservation tillage (1,073,000 plants ha^{-1}). Another factor related to weed suppression provided by cereal cover crops is the release of allelochemicals produced by root exudation and plant residue decay that ultimately reduces seed germination (Chon and Kin 2004).

Brassica cover crops have the unique ability to produce glucosinolates, which are hydrolyzed to form a wide assortment of allelopathic isothiocyanates (Malik et al. 2008; Haramoto and Gallandt 2004; Norsworthy et al. 2005; Wanniarachchi and Voroney 1997; Giamoustaris and Mithen 1995; Angus et al. 1994). Norsworthy (2003) conducted a greenhouse study evaluating the effect of soil-incorporated residue of wild radish (*Raphanus raphanistrum* L.) on weed and crop emergence, where wheat demonstrated to be the most tolerant crop followed by corn (*Zea mays* L.) and cotton. Cotton emerged in a 1% wild radish (weight/weight basis of soil) amended soil, but most plants soon died reducing the cotton stand to less than 25% compared to a nontreated check. Even higher germination reduction was observed with prickly sida (*Sida spinosa* L.) and sicklepod (*Senna obtusifolia* L.), averaging 98% over all wild radish residue rates. In the field, Norsworthy et al. (2011) found that the production of 747 g m^{-2} and 677 g m^{-2} of biomass by turnip (*Brassica rapa* L.) and white mustard (*Sinapis alba* L.) provided 79 and 80% control of Palmer amaranth, respectively, when herbicides were not applied in cotton.

Cover crops can provide early-season weed suppression and protect cotton yield (Bauer and Roof 2004; Raper et al. 2000; Reeves et al. 2005; Vasilakoglou et al. 2006). The amount of biomass produced by the cover crop is a great tool to gauge the level of weed control that can be achieved. However, great variability has been observed in cover crop biomass production among years and locations, which often makes weed suppression with cover crops less consistent than with herbicides. Hence, it is imperative that cover crop performance be evaluated over a wide range of conditions and locations. Although there are considerable data about the impact of cover crops on weed emergence and cotton yield, additional information on the effect of cover crop on Palmer amaranth emergence throughout the season is needed to develop a more appropriate conservation tillage system for the sustainable management of this troublesome weed in cotton. Hence, the objective of this study was to evaluate the influence of cereal, legume, and brassica cover crops on Palmer amaranth emergence throughout the growing season and resulting impact of the cover crops on seedcotton yield. The hypothesis for this research was that cover crops would differ in suppression of Palmer amaranth emergence in cotton as a function of the biomass present at the time of planting.

Material and Methods

A field experiment was conducted in 2014 and 2015 at the University of Arkansas Research and Extension Center in Fayetteville, AR to determinate the efficacy of different cover crops for Palmer amaranth suppression in cotton. In 2014, the experiment was conducted in a Nixa very gravelly silt loam soil (loamy-skeletal, siliceous, active, mesic Glossic Fragiudults) and in 2015, the soil series was a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults). The experiment was conducted under dryland conditions and amounts of rainfall are shown in Table 1. The experimental design was a randomized complete block with a strip plot, where the main plot factor was cover crop species and the strip-plot factor was the use or nonuse of residual herbicides. Four replications were used with plot sizes of 3.6 by 9.9 m. The treatments consisted of seven cover crops species plus a no cover crop control. All cover crops were planted on October 8, 2013 and September 12, 2014 using a 10-row Almaco Light-Duty Grain Drill with a single drop cone (Almaco headquarters, Nevada, Iowa). The drill was set to plant the cover crops at 2.5 cm depth. Prior to cover crop sowing, the field was tilled to an approximate 10-cm depth using a disk followed by two passes of a field cultivator at a 5-cm depth to allow for a smooth seedbed. The seeding rate of each cover crops species are described at table 2.3.

Cover crops were terminated with glyphosate at 870 g ae ha^{-1} plus dicamba at 280 g ae ha^{-1} at 21 days prior to cotton planting followed by a subsequent application of paraquat at 480 g ai ha^{-1} one day prior to cotton planting. Aboveground cover crop biomass was sampled from two random 1 m^2 quadrats in each main plot at cotton planting. Biomass of the natural vegetation was collected in the no cover crop plots. ST 4946 GLB2 (Stoneville, Bayer Research Triangle Park, NC) cotton was planted with a four-row planter (John Deere 6403, Deere and Company, Moline, IL 61265) equipped with double-disk opener set to 91-cm-wide row spacing at a seeding rate of

123,000 seeds ha^{-1}. Cotton was planted on May 22, 2014 and June 3, 2015. After cotton emergence, crop density was assessed in 2 m of randomly selected row within each plot and converted to cotton plants per hectare. The residual portion of each main plot was treated with fluometuron at 1,120 g ai ha^{-1} immediately following cotton planting followed by *S*-metolachlor at 1,070 g ai ha^{-1} plus glufosinate at 594 g ai ha^{-1} at 14, 28, and 42 days after planting (DAP) followed by flumioxazin at 71 g ai ha^{-1} plus MSMA at 2,240 g ai ha^{-1} at 56 DAP as a directed layby application. Glufosinate was applied at 594 g ha^{-1} to the nonresidual portion of each main plot at 14, 28, and 42 DAP (Table 2). The residual program was designed to prevent weed emergence throughout the season to accurately assess the impact of each cover crop on seedcotton yield. The nonresidual portion of each plot allowed temporal and total weed emergence to be assessed in each cover crop. Herbicide treatments were applied using a CO_2-pressurized backpack sprayer equipped with a handheld boom that contained four 110015 flat-fan nozzles (Teejet Technologies, Springfield, IL 62703) spaced 48-cm apart and calibrated to deliver 140 L ha^{-1} at 276 kPa.

Palmer amaranth density was measured in two 0.5 m^2 quadrats marked with flags randomly placed within the nonresidual portion of each plot after cotton planting. Palmer amaranth emergence was counted and plants removed from both quadrats in each plot every two weeks until 8 weeks after planting. Herbicide treatments were applied immediately after counts. Seedcotton was hand harvested from 6 m of row from the residual and nonresidal portions of each plot.

Data were subjected to ANOVA using MIXED procedure in JMP 12 PRO (JMP, Version 12. SAS Institute Inc., Cary, NC) to test for main effects of cover crops. The responses of biomass production, cotton stand, and seedcotton yield were analyzed with an ANOVA to test for significance of the factor cover crop. Palmer amaranth emergence data were fit with a repeated measures model using the Fit Mixed procedure in JMP 12 Pro to describe the number of individuals emerging during an emergence event over time. A first order autoregressive (AR[1]) covariance structure was assumed because observations closer in time are expected to have a higher correlation than treatments further apart in time. Hence, Palmer amaranth emergence was analyzed by cover crop as well as by evaluation timing and means were separated using Fisher`s protected LSD (α=0.05). A regression line was fit to describe the relationship between cotton density and cover crop biomass using SigmaPlot v. 10.0 (Systat Software Inc., San Jose, CA).

Results and Discussion

Cover Crop Biomass. Analysis across years showed a significant effect of cover crop species on cover crop biomass production ($P<0.0023$). Averaged over the two years, the maximum biomass production at cotton planting was provided by cereal rye with 4,860 kg ha^{-1} (Table 2.3). Wheat provided the second highest biomass production with 4,040 kg ha^{-1} followed by oats (3,450 kg ha^{-1}), Austrian winterpea (3,120 kg ha^{-1}), hairy vetch (3,110 kg ha^{-1}), crimson clover (3,140 kg ha^{-1}), and rapeseed (3,250 kg ha^{-1}). Winter fallow produced the least amount of biomass (820 kg ha^{-1}). Amount of cover crop biomass production is highly dependent on climate variables such as growing degree days and rainfall events. Management also plays an important role in biomass production, since seeding rate, cultivar, and termination timing of cover crops can influence the amount of biomass produced (Brennan and Boyd 2012). The literature contains a large number of reports showing diverse amounts of cover crop biomass production. The amount of biomass produced by each cover crop in this study seemed to be in the range commonly reported by several researchers (Sanju et al. 2005; Davis 2010; Isik et al. 2009; Mirsky et al. 2011).

Palmer Amaranth Emergence. No significant interaction was observed between cover crop species and year; hence, Palmer amaranth emergence was averaged over years. The number of Palmer amaranth emerged was influenced by the interaction of cover crop and evaluation timing (P<0.0423). All cover crops significantly suppressed Palmer amaranth emergence at 0 to 2 WAP compared to the no cover crop, ranging from 65 to 100% emergence reduction (Table 3.3). No Palmer amaranth emergence occurred in the cereal rye and wheat plots by the first evaluation timing. It is likely that the amount of residue was the key factor in this case since cereal rye and wheat were the cover crops that provided the highest amounts of biomass which likely affected light penetration to the soil surface and the extent ofde diurnal temperature fluctations.

All cover crops continued to reduce Palmer amaranth emergence at 2 to 4 WAP. However, the level of suppression by cover crop residue started to dissipate after 4 WAP, especially among legume cover crops. During 4 to 6 WAP, the number of emerged Palmer amaranth in Austrian winterpea and crimson clover plots were not different from the no cover crop plots. During 6 to 8 WAP, similar results were observed with hairy vetch also not providing any Palmer amaranth suppression. Reddy (2001) reported similar results where the suppression provided by several cover crops on browntop millet (*Urochloa ramosa* L.) averaged 87% compared to the no cover crop at 3 WAP. By 6 WAP, the browntop millet suppression declined to 45% compared to the no cover crop. That effect is likely linked to the biomass decomposition over time. As the amount of biomass over the top of the soil decreases due to the decomposition process, the weed suppression capacity also decreases (Teasdale and Mohler 2000). The rate of biomass decomposition cover depends on several factors such as chemical and physical composition of soil and cover crop biomass, C:N ratio, microfaunal, and climate (Johnson et al. 2007; Rosecrance et al. 2000; Parr and Papendick 1978). Residues with a high C:N ratio are often linked with a slow rate of decomposition, explaining why the cereal cover crops (high C:N ratio) persisted and provided Palmer amaranth suppression up to 8 WAP. The residue from these cover crops persisted on the soil surface longer than legume cover crops (low C:N ratio) as seen in other research (Creamer and Baldwin 2000).

Hence, even though cover crops can suppress weeds during early spring, they do not provide acceptable full-season Palmer amaranth suppression (Burgos and Talbert 1996; Yenish et al. 1996; Reeves et al. 2005). Nevertheless, a highly productive cover crop system can be integrated with PRE herbicides to provide early season control and flexibility in timing of POST herbicides. Teasdale et al. (2005) reported a synergistic effect of hairy vetch residue and metolachlor on suppression of smooth pigweed (*Amaranthus hybridus* L.) emergence. Reeves et al. (2005) also reported that weed control obtained with cereal rye in combination with PRE herbicides was similar to the no cover crop plot with PRE and POST herbicides at 60 DAP.

Cotton Density. Further analysis of the two year data revealed a significant interaction between cover crop species and year on cotton density ($P<0.0445$). Hence, the effect of cover crop on cotton density is presented separately. In 2014, all cover crops reduced cotton emergence compared to no cover crop (Table 4). Cereal rye, the highest biomass producer, reduced the cotton stand by 47% compared to the no cover crop plot. Oats was not statistically different from cereal rye with a cotton stand loss of 42%. Among legume cover crops, crimson clover and Austrian winterpea lowered cotton stand establishment 31 and 36%, respectively. Hairy vetch compared to no cover crop reduced emergence by 38% which was not different from Austrian winterpea, but significantly lower than crimson clover. Among all the cover crop treatments, rapeseed was the least detrimental to cotton emergence; however, it still provided 18% reduction which was significantly lower than no cover crop.

In 2015, a similar trend was observed in cotton emergence where all cover crop residues decreased cotton emergence compared to the no cover crop treatment (Table 2.4). Wheat and cereal rye reduced cotton stand by 20 and 25%, respectively. Comparable results were reported by Boquet et al. (2004) where a reduction of 15% was observed for cotton stands planted into wheat (4,800 kg ha^{-1} of biomass) plots. Oats and the three legume cover crop species were not significantly different from each other, ranging from 11% to 15% cotton stand reduction. Rapeseed provided a 7% cotton stand reduction.

The negative impact of all cover crops on cotton stand establishment was partly likely linked to conditions at time of planting in 2014. A light rainfall event started as the plots were being planted, which hampered the ability of the double disk openers to effectively cut through the residue. Instead, the double disk openers tended to cause a "hair pinning" effect, reducing the ability of the press wheels on the planter to cover the cotton seed, especially in plots having high amounts of residue. The result of this effect is a condition where the residue causes the inability to achieve adequate seed-soil contact leading to a negative impact on crop emergence (Kornecki et al. 2009).

The causes of occasional cotton stand reductions as a function of cover crop biomass are not well understood but may be partially a result of the planter setup. The use of new (sharper) double disk openers would likely have aided the ability to cut through cover crop residue because this planting setup is routinely used by several large acreage cotton farmers in Arkansas (J.K. Norsworthy, personal communication). Additionally, soil temperature and allelopathy, along with the hair pinning effect discussed previously, might be considered as factors that contributed to the reduction in cotton emergence in cover crops (Wanjura and Buxton 1972; Stevens 1992). Teasdale and Mohler (1993) reported that high residue cover crop reduced light transmittance and soil temperature amplitude compared to a fallow field. Low soil root-zone temperatures early in the season can also negatively impact root and shoot growth, leading to reduced cotton stand establishment (Gosselin and Trudel 1985; Tachibana 1982).

Previous research conducted by Hicks et al. (1989) showed that cotton emergence was reduced up to 21% when wheat stubbles were incorporated into the seedbed. However, when the residues were left on the soil surface, no negative effects were observed. This result may lead to the conclusion that allelopathic effect of cover crop residue is likely to be more of a concern when the residue is incorporated into the soil because of the greater soil contact in tilled systems (White and Worsham 1989). However, there are reports that contradict this result. According to Boquet et al. (2004), cotton seedling establishment was higher when the biomass of wheat and hairy vetch was incorporated into the soil compared to non-incorporation. Steven et al. (1992) reported that cotton no-till planted into hairy vetch residue provided 30% cotton stand reduction compared to a conventional system planted to fallow. Hence, it is difficult to attribute the effect of allelopathic substances in cotton since there are inconsistent reports on this subject. The most likely reason for cotton stand reduction in this study was the physical interference of the cover crop biomass in the planting operation. Regression analysis performed between cotton density and amount of cover crop biomass at timing of planting shows that as the amount of residue increased cotton emergence decreased (Figure 2.1).

Seedcotton Yield. In 2014, overall yields were extremely low likely because of a cooler than normal summer and dry growing conditions (Table 2.4). The effect of cover crop on seedcotton yield was negative since all the cover crops decreased seedcoton yield compared to no cover crop. The detrimental impact that cover crop biomass had on cotton stand is probably the cause of yield reduction. Bridge et al. (1973) show that cotton yield increased as the population increased up to 118,000 plants ha^{-1}. As population further increased, yield started to decrease gradually. In addition, positive yield response to increased plant density varies depending upon soil fertility level.

In 2015, brassica and legume cover crops did not differ from the fallow treatment in seedcotton yield (Table 2.4). There is an extensive research showing that all brassica species can produce glucosinolates (Brown and Morra 1997; Rosa et al. 1997). These compounds have proven to be toxic to cotton (Norsworthy 2003) as well as other organisms (Francis et al. 2001; Boyd et al. 1994; Zasada and Ferris 2004). However, brassica cover crops differ in toxicity level to cotton. Norsworthy et al. (2011) observed that cotton yield was not affected by mustard (*Brassica juncea* L.), but yields were lower in plots followed by turnip (*Brassica napus* L.), possibly due to allelopathy. Rapeseed appears to be safe to use in a cover cropping system prior to cotton planting.

A seedcotton yield decrease was observed for cereal cover crop plots. This result contrasts sharply with several other reports where there are no negative effects on cotton yield due to cover crops (Reeves et al. 2005; Bauer and Reeves 1999; Raper et al. 2000; Daniel et al. 1999). The negative effect in this specific case may be attributed to the stand loss observed in the cereal cover crops (Table 2.4).

Practical Implications. As discussed previously, it is well known that cover crops have the potential of providing numerous benefits to agricultural systems. However, it is important to have a goal set whenever deciding to use cover crops. The species selected to serve as the cover crop will be crucial to achieve the goal desired. If the intention is to use a cover crop to bring early season weed suppression, it seems that cereal cover crops are the best option. Two years of data showed that no Palmer amaranth emerged in the cereal rye and wheat plots within the first two weeks after planting. The suppression effect in the cereal cover crop plots was still significant up to 8 WAP. Brassica and legume cover crops also provided Palmer amaranth suppression early in the season; however, the level of suppression was drastically reduced after 2 WAP mostly due to the higher decomposition rate of these cover crops compared to cereal cover crops (Creamer and Baldwin 2000; Kuo et al. 1997). Unfortunately, in the high biomass production plots there was greater difficulty in establishing a stand of cotton. It is possible that this was a result of the moist conditions that occurred at the time of planting and proper equipment should alleviate this problem (Creamer and Dabney 2002).

Literature Cited

Angus JF, Gardner PA, Kirkegaard JA, Desmarchelier JM (1994) Biofumigation: Isothiocyanates released frombrassica roots inhibit growth of the take-all fungus. Plant Soil 162:107-112

Bauer PJ, Roof ME (2004) Nitrogen, aldicarb, and cover crop effects on cotton yield and fiber properties. Agron J 96:369-376

Boquet DJ, Hutchinson RL, Breitenbeck GA (2004) Long-term tillage, cover crop, and nitrogen rate effects on cotton. Agron J 96:1443-1452

Boyd RS, Shaw JJ, Martens SN (1994) Nickel hyperaccumulation defends *Streptanthus polygaloides* (Brassicaceae) against pathogens. Am J Bot 81:294-300

Brennan EB, Boyd NS (2012) Winter cover crop seeding rate and variety affects during eight years of organic vegetables: I. Cover crop biomass production. Agron J 104:684-698

Bridge RR, Meredith WR, Chism JF (1973) Influence of planting method and plant population on cotton (*Gossypium hirsutum* L.). Agron J 65:104-109

Burgos NR, Talbert RE (1996) Weed control and sweet corn (*Zea mays* var. *rugosa*) response in a no-till system with cover crops. Weed Sci 44:355-361

Chon SU, Kim YM (2004) Herbicidal potential and quantification of suspected allelochemicals from four grass crop extracts. J Agron Crop Sci 190:145-150.

Coetzer E, Al-Khatib K, Loughin TM (2001) Glufosinate efficacy, absorption, and translocation in amaranth as affected by relative humidity and temperature. Weed Sci 49:8-13.

Corbett JL, Askew SD, Thomas WE, Wilcut JW (2004) Weed efficacy evaluations for bromoxynil, glufosinate, glyphosate, pyrithiobac, and sulfosate. Weed Technol 18:443-453

Creamer NG, Baldwin KR (2000) An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortSci 35:600-603

Creamer NG, Bennett MA, Stinner BR, Cardina J, Regnier EE (1996) Mechanisms of weed suppression in cover crop-based production systems. HortSci 31:410-413

Creamer NG, Dabney SM (2002) Killing cover crops mechanically: Review of recent literature and assessment of new research results. Am J Alternative Agr 17:32-40

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, Hanna WW (2006) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Science 54:620-626

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plan 32:1221-1250

Daniel JB, Abaye AO, Alley MM, Adcock CW, Maitland JC (1999) Winter annual cover crops in a Virginia no-till cotton production system: II. Cover crop and tillage effects on soil moisture, cotton yield, and cotton quality. J Cotton Sci 3:84-91

Davis AS (2010) Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Sci 58:300-309

Davis AS (2010) Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Sci 58:300-309

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832-838

Elmore CD 1990 Weed identification guide. South Weed Sci Soc 3 AMAPA.

Fernandez-Cornejo J, M. Caswell (2006) The first decade of genetically engineered crops in the United States. USDA. Economic Research Service, Economic Information Bulletin, Number 11. Washington, DC. Accessed: Feb 23, 2016

Francis F, Lognay G, Wathelet JP, Haubruge E (2001) Effects of allelochemicals from first (Brassicaceae) and second (*Myzus persicae* and *Brevicoryne brassicae*) trophic levels on *Adalia bipunctata*. J Chem Ecol 27:243-256

Giamoustaris A, Mithen R (1995) The effect of modifying the glucosinolate content of leaves of oilseed rape (*Brassica napus* ssp. *oleifera*) on its interaction with specialist and generalist pests. Ann Appl Biol 126:347-363

Gosselin A, Trudel MJ (1985) Influence of root-zone temperature on growth, development and yield of cucumber plants cv. Toska. Plant Soil 85:327-336

Haramoto ER, Gallandt ER (2004) Brassica cover cropping for weed management: A review. Renew Agr Food Syst 19:187-198

Heap I (2015) International Survey of Herbicide Resistant Weeds. Available at http://www.weedscience.com/summary/home.aspx. Accessed: March 19, 2016

Hicks SK, Wendt CW, Gannaway JR, Baker RB (1989) Allelopathic effects of wheat straw on cotton germination, emergence, and yield. Crop Sci 29:1057-1061

Isik D, Kaya E, Ngouajio M, Mennan H (2009) Weed suppression in organic pepper (*Capsicum annuum* L.) with winter cover crops. Crop Prot 28:356-363

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Johnson JMF, Barbour NW, Weyers SL (2007) Chemical composition of crop biomass impacts its decomposition. Soil Sci Soc Am J 71:155-162

Kornecki TS, Raper RL, Arriaga FJ, Balkcom KS, Price AJ (2005) Effects of rolling/crimping rye direction and different row-cleaning attachments on cotton emergence and yield. In Proc. Southern Conservation Tillage Conf., 27th. Florence, SC pp. 27-29

Kuo S, Sainju UM, Jellum EJ (1997) Winter cover crop effects on soil organic carbon and carbohydrate in soil. Soil Sci Soc Am J 61:145-152

Langdale GW, Blevins RL, Karlen DL, McCool DK, Nearing MA, Skidmore EL, Williams JR (1991) Cover crop effects on soil erosion by wind and water. Cover crops for clean water. Soil and Water Conserv. Soc., Ankeny, IA, 15-22

Malik MS, Norsworthy JK, Culpepper AS, Riley MB, Bridges Jr W (2008) Use of wild radish (*Raphanus raphanistrum*) and rye cover crops for weed suppression in sweet corn. Weed Sci 56:588-595

Masiunas JB, Weston LA, Weller SC (1995) The impact of rye cover crops on weed populations in a tomato cropping system. Weed Sci 43:318-323

McWhorter CG, Albernaty JR (1992) Weeds of Cotton: Characterization and Control. The Cotton Foundation Reference Book Series; no. 2. Pp 47-69 ISBN 0-939809-02-08

Meisinger JJ, Hargrove WL, Mikkelsen RL, Williams JR, Benson VW (1991) Effects of cover crops on groundwater quality. Cover Crops for Clean Water. Soil and Water Conservation Society. Ankeny, Iowa, 793-799

Mirsky SB, Curran WS, Mortenseny DM, Ryany MR, Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci 59:380-389

Mohseni-Moghadam M, Schroeder J, Ashigh J (2013) Mechanism of resistance and inheritance in glyphosate resistant Palmer amaranth (*Amaranthus palmeri*) populations from New Mexico, USA. Weed Sci 61:517-525

Nandula VK, Reddy KN, Koger CH, Poston DH, Rimando AM, Duke SO, Bond JA, Daniela N Ribeiro DN (2012) Multiple resistance to glyphosate and pyrithiobac in Palmer amaranth (*Amaranthus palmeri*) from Mississippi and response to flumiclorac. Weed Sci 60:79-188

Nelson WA, Kahn BA, Roberts BW (1991) Screening cover crops for use in conservation tillage systems for vegetables following spring plowing. HortSci 26:860-862

Nichols RL, Bond J, Culpepper AS, Dodds D, Nandula V, Main CL, Marshall MW, Mueller TC, Norsworthy JK, Price A, Patterson M, Scott RC, Smith KL, Steckel LE, Stephenson D, Wright D, York AC (2009) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) spreads in the southern United States (U.S.). Resistant Pest Manage Newsl 18:8-10

Norsworthy JK, Griffith GM, Scott RC, Smith KL, Oliver LR (2008) Confirmation and control of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Arkansas. Weed Technol 22:108-113

Norsworthy JK (2003) Allelopathic potential of wild radish (*Raphanus raphanistrum*). Weed Technol 17:307-313

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur EE (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Sci 62:237-249

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate-resistant Palmer amaranth. Weed Sci 64:540-550

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK, Still J (2011) Evaluation of cereal and Brassicaceae cover crops in conservation-tillage, enhanced, glyphosate-resistant cotton. Weed Technol 25:6-13

Norsworthy JK, Meehan IV JT (2005) Use of isothiocyanates for suppression of Palmer amaranth (*Amaranthus palmeri*), pitted morningglory (*Ipomoea lacunosa*), and yellow nutsedge (*Cyperus esculentus*). Weed Sci 53:884-890

Parr JF, Papendick RI (1978) Factors affecting the decomposition of crop residues by microorganisms. Crop Res Manag Sys 6:101-129

Power JF (1991) Growth characteristics of legume cover crops in a semiarid environment. Soil Sci Soc Am J 55:1659-1663

Powles SB, Preston C, Bryan IB, Jutsum AR (1996). Herbicide resistance: impact and management. Advanc agron 58:57-93.

Price AJ, Arriaga FJ, Raper RL, Balkcom KS, Kornecki TS, Reeves DW (2009) Comparison of mechanical and chemical winter cereal cover crop termination systems and cotton yield in conservation agriculture. J Cotton Sci 13:238-245

Price AJ, Balkcom KS, Culpepper SA, Kelton JA, Nichols RL, Schomberg H (2011) Glyphosate-resistant Palmer amaranth: a threat to conservation tillage. J Soil Water Conserv 66:265-275

Price AJ, Monks CD, Patterson MG (2007) Early Season Pigweed Control in Conservation Tillage Cotton. Pages 13–15 in No. 32–2007 Cotton Research Report, Alabama Agricultural Experiment Station, Agricultural Communications. http://www.ag.auburn.edu/aaes/communications/ listsofpubs/researchreports31-35.htm#32. Accessed Feb 23, 2016

Raper RL, Reeves DW, Burmester CH, Schwab EB (2000) Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy requirements. Appl Eng Agric 16:379-385

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15:660-668

Reddy KN (2003) Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean (*Glycine max*). Weed Technol 17:28-35

Reeves DW, Price AJ, Patterson MG (2005) Evaluation of three winter cereals for weed control in conservation-tillage nontransgenic cotton. Weed Technol 19:731-736

Roberson EB, Firestone MK (1991) Cover crop management of polysaccharide-mediated aggregation in an orchard soil. Soil Sci Soc Am J 55:734-739

Rochester IJ, Peoples MB, Hulugalle NR, Gault R, Constable GA (2001) Using legumes to enhance nitrogen fertility and improve soil condition in cotton cropping systems. Field Crop Res 70:27-41

Rosecrance RC, McCarty GW, Shelton DR, Teasdale JR (2000) Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. Plant Soil 227:283-290.

Sainju UM, Whitehead WF, Singh BP (2005) Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron J 97:1403-1412

Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, Leep R, O'Neil, K (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron J 97: 322-332.

Steckel LE, Main CL, Ellis AT, Mueller TC (2008) Palmer amaranth (*Amaranthus palmeri*) in Tennessee has low level glyphosate resistance. Weed Technol 22:119–123

Stevens WE, Johnson JR, Varco JJ, Parkman J (1992) Tillage and winter cover management effects on fruiting and yield of cotton. J Produc Agric 5:570-575

Tachibana S (1982) Comparison of effects of root temperature on the growth and mineral nutrition of cucumber cultivars and figleaf gourd. J Japan Soc Hort Sci 51:299-308

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. J Prod Agric 9:475-479

Teasdale JR, Pillai P, Collins RT (2005) Synergism between cover crop residue and herbicide activity on emergence and early growth of weeds. Weed Sci 53:521-527

Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85:673-680

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385-392

Torbert HA, Reeves DW, Mulvaney RL (1996) Winter legume cover crop benefits to corn: rotation vs. fixed-nitrogen effects. Agron J 88:527-535.

Touchton JT, Rickerl DH, Walker RH, Snipes CE (1984) Winter legumes as a nitrogen source for no-tillage cotton. Soil Till Res 4:391-401

Vasilakoglou I, Dhima K, Eleftherohorinos I, Lithourgidis A (2006) Winter cereal cover crop mulches and inter-row cultivation effects on cotton development and grass weed suppression. Agron J 98:1290-1297

Wanjura DF, Buxton DR (1972) Water uptake and radicle emergence of cottonseed as affected by soil moisture and temperature. Agron J 64:427-431

Wanniarachchi, SD, Voroney RP (1997) Phytotoxicity of canola residues: Release of water-soluble phytotoxins. Can J Soil Sci 77:535-541

Webster TM, Sosnoskie LM (2010) Loss of glyphosate efficacy: a changing weed spectrum in Georgia cotton. Weed Sci 58:73-79

White RH, Worsham AD, Blum U (1989) Allelopathic potential of legume debris and aqueous extracts. Weed Sci 37:674-679

Yenish JP, Worsham AD, York AC (1996) Cover crops for herbicide replacement in no-tillage corn (*Zea mays*). Weed Technol 10:815-821

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307

Zasada IA, Ferris H (2004) Nematode suppression with brassicaceous amendments: application based upon glucosinolate profiles. Soil Biology Biochem 36:1017-1024

Table 2.1. Monthly rainfall data for 2014 and 2015.

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
	mm												
2014[a]	33	58	89	7	3	97	87	87	104	62	53	91	184
2015[b]	184	10	75	14	1	82	81	330	172	205	137	58	48

[a] Planting date: May 23th

[b] Planting date: June 3th

Table 2.2. Source of herbicide used in the experiment.

Common name	Trade name	Formulation	Rate	Manufacture	Address
			g ai or ae ha^{-1}		
Paraquat	Gramoxone	SL	700	Syngenta Crop Protection	Greensboro, NC
Glyphosate	Roundup PowerMAX	SL	870	Monsanto Company	St. Louis, MO
Fluometuron	Cotoran	FL	1120	Makhteshim Agan of North America	Raleigh, NC
Glufosinate	Liberty	SL	595	Bayer CropScience	Research Triangle Park, NC
S-metolachlor	Dual Magnum	EC	1070	Syngenta Crop Protection	Greesboro, NC
Flumioxazin	Valor	WDG	71	Valent	Walnut Creek, CA
Monosodium acid methanearsonate	MSMA	SL	2240	Drexel Chemical Company	Memphis, TN

Abbreviation: SL, soluble liquid; EC, emulsifiable concentrate; WDG, water dispersible granule

Table 2.3. Influence of cover crop on Palmer amaranth emergence at 2, 4, 6, and 8 weeks after planting (WAP) cotton and total Palmer amaranth emergence at Fayetteville, AR, averaged over 2014 and 2015.

			Palmer amaranth density				
			Evaluation timings[a] (WAP)				
Cover crops	Seeding rate	Biomass	0 to 2	2 to 4	4 to 6	6 to 8	Total emergence
	---------- kg ha^{-1} ----------		---------------------------- plants m^{-2} ----------------------------------				
No cover crop	---	820 d[b]	5.9 aA	5.6 aA	7.0 aA	3.9 aB	22.4 a
Austrian winterpea	84	3120 c	2.0 bA	3.4 bAB	6.4 abC	4.4 aB	16.2 b
Crimson clover	22	3110 c	2.1 bA	3.6 bAB	6.0 abC	3.4 abAB	15.1 b
Hairy vetch	17	3140 c	1.6 bA	3.1 bB	5.2 bC	3.2 abB	13.1 b
Cereal rye	90	4860 a	0.0 cA	0.6 cAB	1.9 dB	1.3 cAB	3.8 d
Oats	90	3450 c	0.6 bcA	1.6 cA	3.4 cB	2.1 bcAB	7.7 cd
Wheat	90	4040 b	0.0 cA	1.6 cB	2.1 cdB	1.3 cAB	5.0 d
Rapeseed	11	3250 c	1.3 bA	3.5 bB	3.9 cB	2.1 bcA	10.8 c

[a] Lowercase letters are used to compare cover crops within an evaluation timing and uppercase letters are used to compare evaluation timing within a cover crop. Means followed by the same letter are not different according to Fisher's protected LSD test at $\alpha \leq 0.05$.

[b] The biomass in the no cover crop treatment was obtained by collecting the natural vegetation present at cotton planting.

Table 2.4. Cotton density in 2014 and 2015 growing season at Fayetteville, AR as a function of cover crop.

	2014	2015	2014	2015
Cover crop	Cotton density		Seedcotton yield	
	---- 1,000 plants ha⁻¹ ----		------------- kg ha⁻¹ ------------	
No cover crop	119 a	123 a	1160 a	1750 a
Austrian winterpea	77 cd	105 c	860 c	1750 a
Crimson clover	82 c	109 bc	1000 b	1750 a
Hairy vetch	74 de	107 c	950 c	1830 a
Cereal rye	60 f	93 d	650 d	1170 c
Oats	68 ef	105 c	900 bc	1420 b
Wheat	77 cd	98 d	880 bc	1140 c
Rapeseed	98 b	115 b	910 bc	1740 a

[a] Means followed by the same letter, either lowercase or uppercase, are not different according to Fisher's
protected LSD test at $\alpha \leq 0.05$.

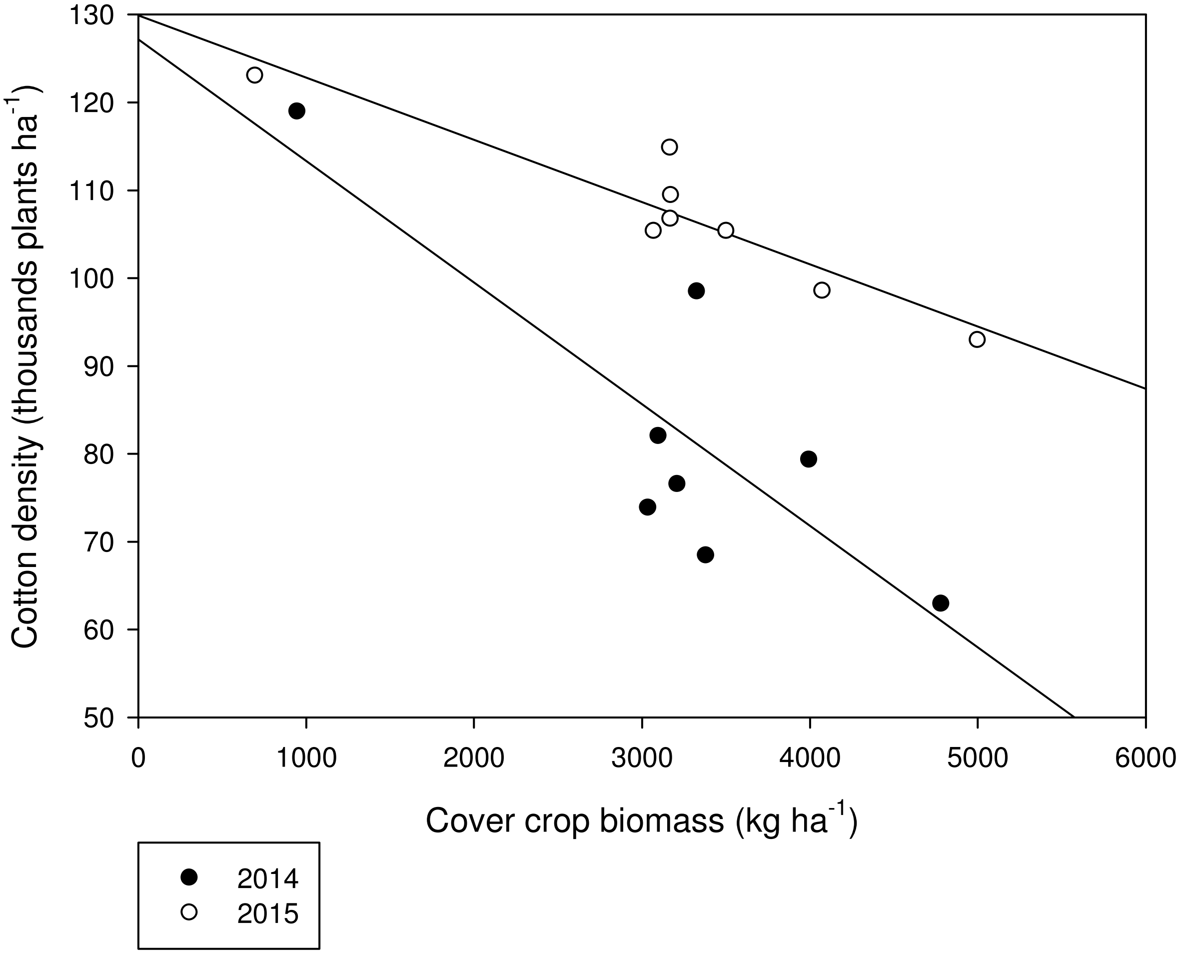

Figure 2.1. Relationship between cotton density and cover crop biomass at cotton planting for 2014 and 2015.
2014: y=-13.85x + 127186; r^2= 0.70
2015: y=-7.09x + 129886; r^2= 0.87

Chapter 3

Impact of Cereal Rye Seeding Rate and Planting Method on Weed Control in Cotton

Abstract

Cost related to herbicide usage has increased greatly due to evolution and proliferation of glyphosate-resistant Palmer amaranth. The use of cover crops in conservation tillage offers many advantages such as weed suppression through physical and allelopathic effects. Federal conservation payments are available in some states for growers that want to include cover crops as a means to reduce tillage and increase weed suppression. A field study was initiated in fall 2013 and 2014 at the Arkansas Agricultural Research and Extension Center in Fayetteville to determine the impact of cereal rye seeding rate and planting method on weed control and cotton yield. Cereal rye seeding rates were 56, 112, and 168 kg ha^{-1} in absence or presence of a herbicide program. Planting methods consisted of drilled and broadcast. No differences were observed between planting methods in any parameter evaluated. In both years, cereal rye biomass production increased as seeding rate increased. When herbicides were not applied, cereal rye at 56 kg ha^{-1} provided the least weed control. Cereal rye at 112 and 168 kg ha^{-1} provided comparable levels of weed control. At 8 weeks after cotton planting, all plots treated with a standard herbicide program had weed control greater than 99% for all species, regardless of the seeding rate. Yields from plots with the standard herbicide program were greater than from plots without herbicide. Yield improvement was observed due to use of cereal cover crop in the system compared to no cover crop in 2014 whereas no differences were observed in 2015.

Nomenclature: Palmer amaranth, *Amaranthus palmeri* S. Wats; cereal rye, *Secale cereale* L.; cotton, *Gossypium hirsutum* L.

Key words: Cover crop, emergence, cereal rye

Introduction

Recently, cotton growers have struggled with weed management mainly due to herbicide-resistant weeds (Sosnoskie and Culpepper 2014). The recent confirmation protoporphyrinogen oxidase (PPO)-resistant Palmer amaranth in the Midsouth along with wide-spread glyphosate-resistant (GR) Palmer amaranth have increased concerns about sustainability of weed management in cotton production systems (Salas et al. 2016). Relying only on herbicides, especially one mode of action, is no longer a sustainable option for controlling Palmer amaranth. Hence, integrating herbicide programs with cultural practices is necessary to preserve the existing technologies and herbicides. The use of cover crops in conservation tillage has become of interest to growers who intend to capitalize on federal conservation payments and incorporate sustainable practices into agricultural systems. Weed suppression as well as nitrogen credits are two of the most desirable short-term benefits realized by farmers when using cover crops in row crops (Snapp et al. 2005). Long-term effects such as increased organic matter, reduced soil erosion, and carbon sequestration are also extremely significant; however, they are often overlooked since these benefits are cumulative and difficult to measure (Mazzoncini et al. 2011; Sainju et al. 2002).

Extensive research has been conducted to evaluate the impact of cover crops on weed control in several crops. Reports about the level of weed suppression offered by cover crops are variable. However, the majority of research conducted on this subject agrees that cover crops have potential to suppress weeds and aid most weed control programs. Cover crops can provide weed suppression through several means. Cover crop residues can act as a physical barrier to weed seed germination and weed growth, limit the amount of light transmitted to the soil, lead to production of allelochemical substances that are toxic to weed seed, and narrow the temperature amplitude which can reduce weed seed germination (Creamer et al. 1996; Teasdale and Mohler 1993).

Cereal rye is an important cover crop in a large array of cropping systems because it can contribute to organic matter, reduce soil erosion, suppress weeds, and enhance water infiltration and conservation (Dabney et al. 2001; Korres and Norsworthy 2015; Putman et al. 1983). The broad utility of cereal rye is also an important characteristic because it can be grown on soils having low fertility and low pH, and it has high frost and drought resistance compared to others cereal cover crops such as wheat (*Triticum aestivum* L.) and oats (*Avena sativa* L.) (Clark 2008; Fowler et al. 1999; Bushuk 2001). Cereal rye also can germinate in untilled soil as well as in many soil moisture and soil temperature levels (Blackshaw 1991).

When using a cover crop to achieve weed suppression, maximum biomass production is preferred because there is a positive correlation between biomass production and weed suppression (Teasdale and Mohler 2000). Based on the available literature, cereal rye can produce a wide range of biomass. Price et al. (2012) reported that in Tennessee cereal rye biomass production ranged from 4,177 to 10,886 kg ha^{-1}. In South Carolina, Bauer and Reeves (1999) reported cereal rye biomass production of 2,390 to 4,130 kg ha^{-1}, and in Arkansas, Norsworthy et al. (2011) reported cereal rye biomass production of 7,880 to 8,460 kg ha^{-1}. Among all fall-seeded cereal cover crops, cereal rye appears to have the highest potential biomass production (Bauer and Reeves 1999; Prabhakara et al. 2015). It is also important that the cover crop residue has high soil coverage to better suppress weed emergence. Nelson et al. (1991) stated that among several cover crops, cereal rye provided the greatest soil coverage ranging from 65% to 93%.

Increasing the cover crop density can improve biomass production and planting uniformity which can enhance the weed suppression capacity of the cover crop residue. In California, Boyd et al. (2009) found that population density and groundcover increased linearly as the seeding rate of cereal rye (90, 180, 270 kg ha^{-1}) increased. They also evaluated cereal rye biomass production at three different harvest dates. At first harvest (December 1, 2003 and November 29, 2004) in both years, biomass production increased as the seeding rate increased, resulting in a significant decrease in weed biomass production on the higher seeding rate treatment. Conversely, no differences were observed among seeding rate treatments on the last harvest (February 17, 2004 and March 1, 2005) with cereal rye biomass production both years producing an average biomass of 7,300 kg ha^{-1}. The comparison of weed biomass differed between years though. In 2004, weed biomass ranged from 0 to 0.3 kg ha^{-1} among seeding rate treatments. However, in 2005, the 90 kg ha^{-1} allowed weed biomass production of 11.5 kg ha^{-1}, which was significantly higher than the 180 kg ha^{-1} (1.0 kg ha^{-1}) and 270 kg ha^{-1} (0.3 kg ha^{-1}) seeding rate.

Akemo et al. (2000) also investigated the impact of cereal rye seeding rate (29, 57, and 114 kg ha^{-1}) on biomass production and weed control in Ohio. Results obtained in the study supported the concept of increased biomass production of cereal rye with higher seeding rate, resulting in significant weed biomass reduction. Similarly, Ateh and Doll (1996) conducted a two-year study to investigate the effect of cereal rye seeding rates of 56, 112, and 168 kg ha^{-1} on groundcover and weed control in soybean (*Glycine max* L. Merr.) in Wisconsin. They observed that during the first year of study, groundcover increased as the seeding rate increased, resulting in higher weed control in the 168 kg ha^{-1} seeding rate. However, in the following year, the 56 kg ha^{-1} seeding rate provided greater groundcover compared to the 112 kg ha^{-1} and 168 kg ha^{-1}

seeding rate. This result was attributed to greater tillering at lower seeding rate favored by adequate soil moisture.

Planting method also can affect biomass production and soil coverage of cover crops. Broadcast, no-till drill, and conventional tillage with drill seeding are some of the most commonly used methods to establish cover crops. Reports about effectiveness of these planting methods have shown that drill seeding appears to provide superior cereal cover crop establishment due to the lack of soil coverage when broadcasting. Keisling et al. (1997) reported that using a broadcast planting method reduced wheat emergence compared to a drill planting method. However, Wilson et al. (2013) found that broadcasting cereal rye can be effective if a rainfall event occurs within a week of broadcast seeding.

Cereal rye has become an important option for weed suppression in conservation tilled cotton (McCarty et al. 2003; Monks and Patterson 1996). Although there are many reports on weed suppression by cereal rye residue, not many have investigated the effect of seeding rate and planting method on weed management and yield in cotton. Increasing the cereal rye biomass production through increased seeding rate might provide higher weed suppression. In addition, the level of weed suppression may differ by planting method. Hence, research was conducted to investigate the impact of cereal rye seeding rate and planting method on weed control and cotton yield.

Material and Methods

A field experiment was conducted on separate sites beginning in fall 2013 and 2014 at the University of Arkansas Research and Extension Center in Fayetteville, AR. The soil series in Fayetteville was a Leaf silt loam (fine, mixed, active, thermic Typic Albaquults) with 34% sand, 53% silt, 13% clay, 1.1% organic matter, and a pH of 6.9. The experiment was conducted under a lateral irrigation system. The amounts of rainfall and irrigation supplied during the growing season are provided in Table 3.1. The experimental design was a two-factor factorial randomized complete block with a strip plot structure. The main-plot factor was three cereal rye seeding rates in presence and absence of a standard herbicide program, and the strip-plot factor was drill and broadcast seeding of cereal rye. The standard herbicide program is described in Table 3.2. Four replications were used with plot sizes of 3.6 by 9.9 m. The cereal rye was sown on October 8, 2013 and September 12, 2014. For the drill seeded portion of the plot, an Almaco Light-Duty Grain Drill with a single drop cone (Almaco Headquarters, Nevada, Iowa 50201) was used, and for the broadcast seeded portion, the cereal rye was distributed by hand over the broadcast portion of the main plot. Prior to cereal rye sowing, the field was tilled to an approximate 15-cm depth using a disk harrow followed by two passes of a field cultivator at a 5-cm depth to allow for a smooth seedbed.

The entire test was desiccated 21 days prior to cotton planting with glyphosate and dicamba at 0.870 kg ae ha^{-1} and 280 kg ae ha^{-1}, respectively, followed by an application of paraquat at 0.48 kg ai ha^{-1} one day prior to planting. Aboveground cover crop biomass was sampled from two random 1 m^2 quadrats in each main plot at planting. Biomass of the natural vegetation was also collected in the no cover crop plots. ‘ST 4946 GLB2’ (Stoneville, Bayer Research Triangle Park, NC) cotton was planted with a four-row planter (John Deere 6403, Deere and Company, Moline, IL 61265) equipped with double-disk openers set to a 91 cm row spacing at a seeding rate of 123,000 seeds ha^{-1}. Cotton was planted on May 23, 2014 and June 3, 2015. Herbicide treatments were applied using a CO_2-pressurized backpack sprayer equipped with a handheld boom that contained four 110015 flat-fan nozzles (Teejet Technologies, Springfield, IL 62703). Nozzles were spaced 50-cm apart and calibrated to deliver 140 L ha^{-1} at 276 kPa.

After cotton emergence, cotton stand was assessed on 2 linear meter of row randomly selected within the plot. Palmer amaranth density was measured in two 0.5 m^2 quadrats marked with flags randomly placed within the drill and broadcast planting side of each plot. Palmer amaranth emergence was monitored in the two quadrants every two weeks until 8 weeks after planting (WAP). Palmer amaranth seedlings were manually removed after each count, and herbicide treatments were applied immediately after counts (see Table 3.2 for herbicide treatment information). Control of Palmer amaranth, broadleaf signalgrass (*Urochloa platyphylla* (Nash) RD Webster), and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] was visually evaluated 2, 4, 6, and 8 WAP. Seedcotton was hand harvested from 6.6 m of the center rows in each sub-plot. Seedcotton yields were determined by weighing the seedcotton and converting the weights to kilograms per hectare.

Data were subjected to ANOVA using the MIXED procedure in JMP 12 PRO (JMP, Version 12. SAS Institute Inc., Cary, NC). The significance of main effects and potential interactions were tested for biomass production, cotton stand, grass control, cumulative Palmer amaranth emergence, and seedcotton yield at $\alpha=0.05$. Palmer amaranth emergence data were also fit with a repeated measures model using the MIXED procedure in JMP 12 PRO to describe the number of individuals emerging during an emergence event. A first order autoregressive (AR[1]) covariance structure was assumed because observations closer in time are expected to have a higher correlation than treatments further apart in time. Hence, Palmer amaranth emergence was analyzed by cereal rye seeding rate as well as by assessment timing and means were separated by Fisher`s protected LSD ($\alpha=0.05$).

Results and Discussion

Biomass. No differences were observed in planting method for cereal rye biomass production in either of the seeding rates evaluated. Hence, the biomass production was averaged over drill and broadcast planting method. The effect of seeding rate on biomass production interacted with year ($P<0.0012$), with 2014 being significantly greater than 2015. These results agree with those of Boyd et al. (2009) where they reported biomass production from cereal rye at seeding rates of 90, 180, and 270 kg ha^{-1} increased linearly as the seeding rate increased. The non-significant effect of planting method on biomass production is similar to that observed by Abbas et al. (2009) that reported no differences in biomass production between drill and broadcast seeded wheat.

Cereal rye biomass ranged from 3,060 to 4,460 kg ha^{-1} and 2,460 to 3,620 kg ha^{-1} in 2014 and 2015, respectively. These results sharply contrast with results observed at Marianna, AR by Norsworthy et al. 2011, where they observed an average biomass production of 8,170 kg ha^{-1} of cereal rye. Such discrepancy in biomass production might be due to differences in environmental conditions in Fayetteville and Marianna as well as the cereal rye management. According to Norsworthy et al. 2011, test sites were broadcast fertilized with 34 kg ha^{-1} K and 67 kg ha^{-1} prior to cereal rye planting whereas the test in discussion was also broadcast fertilized but with 34 kg ha^{-1} of K and P. Secondly, the soil in Fayetteville is generally less productive than that at the Marianna site. Thirdly, the performance of a particular winter cover crop is difficult to predict because of a variety of factors, including cover crop cultivar, soil properties, and growing conditions can interact and influence the growth of cover crops. Analysis of the growing degree days (MacMaster and Wilhelm 1997). for both years showed that 2014-2015 had more GDD than 2013-14 (Figure 3.1). However, the amount of GDD in both years should have been sufficient for maximum biomass production (Malhi et al. 2006; Mirsky 2011).

Cotton Density. The interaction of planting method by cereal rye seeding rate was not significant for cotton density, but the main effect of seeding rate was significant ($P<0.0344$). Hence, cotton density was averaged over drill and broadcast planting methods. Years are presented separately because of a significant year by seeding rate interaction (Table 3.3).

All seeding rates significantly decreased cotton density relative to the no cover crop treatment in 2014. The 56 kg ha^{-1} cereal rye seeding rate was the least detrimental, with 8% cotton stand reduction. Both the 112 and 168 kg ha^{-1} cereal rye seeding rates provided the highest cotton density reduction with 15% and 17%, respectively. In 2015, the 56 kg ha^{-1} cereal rye seeding rate did not show any significant negative effect compared to the no cover crop treatment. However, cereal rye at 112 and 168 kg ha^{-1} reduced the cotton stand by 11% and 14%, respectively. The slight improvement in cotton density in the cover crop plots in 2015 is likely due to the lower amount of biomass present at timing of planting which is similar to findings in other research (Kornecki et al. 2009). A planter set up to better plant into standing cereal rye may have improved cotton stands because others have observed that it is possible to plant into greater amounts of cereal rye biomass than present in this research without a negative effect on crop emergence (Mirsky et al. 2013; Ogle et al. 2012; Raimbult et al. 1989).

Palmer Amaranth Emergence. Similar to cotton density, there was no effect of planting method on Palmer amaranth emergence in both years, and the effect of seeding rate on Palmer amaranth density interacted with year (P. However, the effect of assessment timing on Palmer amaranth density did not interact with year; hence, data were averaged over 2014 and 2015 (Table 3.4).

All seeding rates decreased Palmer amaranth emergence over the four assessment timings compared to the no cover crop treatment (Table 3.4). However, cereal rye seeded at 168 kg ha^{-1}

was superior to 56 kg ha^{-1} in suppressing Palmer amaranth emergence. In 2015 over the four assessment timings, the 56 kg ha^{-1} seeding rate did not differ from the no cover crop treatment, and emergence from the 112 kg ha^{-1} and 168 kg ha^{-1} seeding rates were 58% and 74% lower than the no cover crop.

Suppression of Palmer amaranth emergence by the cereal cover crop was most effective at the earliest evaluations. Averaged over seeding rate, Palmer amaranth emergence at the first assessment timing was lower than second and third assessment timings (Table 3.4). The 2 to 4 and 4 to 6 WAP period allowed the highest Palmer amaranth emergence with 3.3 and 3.1 plants m^{-2}, respectively. These results agree with other reports that convey cover crops are most effective in suppressing weeds early in the growing season. Reedy (2001) reported that browntop millet (*Urochloa ramosa* L.) suppression provided by cereal rye in soybean at 3 WAP averaged 77%, but by 6 WAP control had declined to 62%.

The effect of cereal rye seeding rate in combination with herbicide application on total Palmer amaranth emergence is described in Table 3.5. In 2014, the seeding rate of 112 kg ha^{-1} did not show differences in Palmer amaranth emergence between plots with and without herbicide application. This was an exception because in all the remaining seeding rate treatments the combination of a cereal rye cover crop with a herbicide program resulted in lower Palmer amaranth emergence compared to plots without herbicide application. The same effect was observed in 2015 within each cereal rye seeding rate treatment where the herbicide application proved to be beneficial to suppression of Palmer amaranth emergence (Table 3.5). Hence, these results support the concept that the utilization of cover crops ought to be performed with a herbicide program.

Cumulative Palmer Amaranth Emergence. In 2014, cereal rye residue from all seeding rates reduced Palmer amaranth emergence throughout the season (Figure 3.2). At 2 WAP cotton, cereal rye seeded at 56, 112, and 168 kg ha^{-1} decreased Palmer amaranth emergence by 76%, 86%, and 90% compared to the no cover crop. The highest Palmer emergence in the no cover crop plots occurred between 2 and 4 WAP averaging 8.8 plants m^{-2}. During this period, cereal rye plots at 56, 112, and 168 kg ha^{-1} seeding rate reduced Palmer amaranth emergence by 49%, 74%, and 91%, respectively. After 4 WAP, the suppression provided by the cereal rye residue started to dissipate. After all assessment, cumulative Palmer amaranth in the no cover crop plots were 21.7 plants m^{-2}. The highest Palmer amaranth emergence reduction occurred in the 112 and 168 kg ha^{-1} seeding rate with 74% and 73% compared to the no cover crop. The reduction provided by 56 kg ha^{-1} seeding rate was significantly lower than the 112 and 168 kg ha^{-1} with 48% reduction in Palmer amaranth emergence. Similar results were obtained by DeVore et al. (2012) where cereal rye reduced Palmer amaranth emergence by 74% at 3 WAP, and cereal rye residue still reduced Palmer amaranth emergence by 67% at 12 WAP.

In 2015, all the seeding rates reduced Palmer amaranth emergence compared to no cover crop up to the 8 WAP (Figure 3.3). At the first assessment, the 56 kg ha^{-1} seeding rate was not as effective as 112 and 168 kg ha^{-1}. Reduction of Palmer amaranth emergence at the 112 and 168 kg ha^{-1} seeding rates were 80% and 93% compared to the no cover crop while at 56 kg ha^{-1}, reduction was 40%. At 8 WAP, cumulative Palmer amaranth emergence showed that the seeding rates of 56, 112, and 168 kg ha^{-1} reduced Palmer amaranth emergence by 47%, 58%, and 65%, respectively. The inferior Palmer amaranth suppression in this year is attributed to the overall lower biomass production of cereal rye. According to the Teasdale and Mohler (2000), the success of weed suppression by cover crops is directly related to the amount of biomass produced, since higher quantities of residue would reduce the ability of weed seedlings to grow through the mulch.

Grass Control. Broadleaf signalgrass and barnyardgrass control were averaged due to the similar response of both weeds to the herbicide treatment and cereal rye. The density of both grass weeds was slightly higher in 2015 than in 2014. In 2014, at 8 WAP the grass density in the nontreated plots averaged 12 broadleaf signalgrass and 4 barnyardgrass plants m^{-2}. At the same time in 2015, densities of broadleaf signalgrass and barnyardgrass were 28 and 6 plants m^{-2}, respectively (data not shown).

The application of a standard herbicide program resulted in excellent grass control in all plots, regardless of the cereal rye seeding rate, with the exception of 2 WAP in 2014 where no differences were observed (Table 3.6). Plots treated with the standard herbicide program averaged 97% or higher grass control for each of the four evaluations, regardless of cereal rye seeding rate. Grass control diminished over the course of the growing season in plots lacking a cereal rye cover crop.

In 2015, a similar trend was observed, with the exception of the first evaluation where grass control in herbicide-treated plots differed among cereal rye seeding rates (Table 3.6). At 2 WAP, the 168 kg ha^{-1} seeding rate in combination with the standard herbicide program provided superior grass control compared to the no cover crop treatment with herbicide. Similar results were obtained by Reeves et al. (2005) where the addition of cereal rye provided enhanced weed control compared to a herbicide program alone. The low grass control observed at 2 WAP in the herbicide plots in 2015 is likely due to above average rainfall after the PRE herbicide application, which might have led to leaching of the herbicide out of the zone in which weed germination typically occurs (Stewart et al. 2010). Following the POST herbicide applied at 2

WAP, grass control averaged 95% or higher through 8 WAP. The improved grass control with the herbicide program in combination with the cereal rye was evident at 8 WAP, proving again that grass control is partially attributable to the cereal rye cover crop.

Seedcotton Yield. Only the main effects of seeding rate and herbicide program impacted seedcotton yield in 2014. All seeding rates increased yields compared to the no cover crop (Table 3.7). The improvement in cereal rye biomass production due to the increased seeding rate demonstrated to be beneficial to seedcotton yield in 2014. Seedcotton yield improvement due to use of cereal rye has been reported previously. Sainju et al. (2006) reported that in a no-till system, cotton plots with cereal rye had a cotton lint yield of 1,110 kg ha^{-1} compared to 814 kg ha^{-1} in winter fallow.

Herbicide application also had a significant effect on seedcotton yield. Plots that received the standard herbicide program had an average seedcotton yield of 1,400 kg ha^{-1} while plots with no herbicide had a seedcotton yield of 940 kg ha^{-1}. Similar results were reported by Reeves et al. (2005) where the non-application of herbicides in cereal rye cover crop plots resulted in reduced seedcotton yield compared to plots where herbicides were applied.

The effect of cereal rye seeding rate on seedcotton yield was not significant in 2015 (Table 3.7). Seedcotton yield ranged from 1,200 to 1,260 kg ha^{-1} among seeding rates, including the absence of cereal rye (Table 3.7). Others have reported similar seedcotton yields in the presence and absence of a cereal rye cover crop in Arkansas (DeVore et al. 2012; Korres and Norsworthy 2015; Norsworthy et al. 2011).

The effect of herbicide program did impact seedcotton yield in 2015 (Table 3.7). Averaged over cereal rye seeding rates, plots that received the standard herbicide program produced a seedcotton yield of 1,790 kg ha^{-1}. Conversely, plots that lacked an in-crop herbicide application had an average seedcotton yield of 570 kg ha^{-1}, likely because of the poor grass control by cereal rye alone.

The impact of cereal rye residue on seedcotton yield has been widely investigated. However, inconsistent results have been reported. The large array of environmental factors that can influence cotton yield in a cover crop system might be the reason of such inconsistencies. Nitrogen management has proven to be an important factor in a cereal cover crop system in cotton (Bouquet et al. 2004). Cereal rye is known to scavenge nitrogen with its extensive fibrous root system (Meisinger et al 1991). Hence, it is likely that cereal rye might deplete the inorganic nitrogen in the soil during fall and winter months. The decomposition and consequently mineralization of nitrogen in cereal rye residue can take a long period of time since the rate of decomposition of cereal rye residue is low due to the high C:N ratio (Creamer and Baldwin 2000; Rosecranse et al. 2000; Sainju et al. 2006). Another factor to consider is rainfall and irrigation regime. Under well-watered or irrigated conditions, differences in cotton yield between no cover and cover crop plots is less likely. It is known that cover crops increase moisture infiltration and conservation (Unger and Vigil 1998). Hence, the positive effect of cover crop residues on cotton yield might be more likely in areas with low summer rainfall or inadequate irrigation management (Dabney et al. 2001).

Practical Implications. Neither of the planting methods evaluated in this experiment appear to have an advantage over the other for any parameter evaluated. The similar biomass production between the two planting methods in this study compare favorably to the findings of Fisher et al. (2011) where they concluded that broadcast seeding is an effective planting method for cereal rye. Increasing the seeding rate appears to be a worthy option to increase biomass production of cereal rye. However, based on the Palmer amaranth emergence, the highest seeding rate may not be warranted because there was no differences in emergence between the two highest seeding rates. The application of a standard herbicide program resulted in superior Palmer amaranth and grass control compared to the no herbicide program, regardless of the cereal rye seeding rate. However, having a cereal residue to give early weed suppression in cases where the efficacy of PRE herbicides fail to be activated would be a worthy practice and likewise reduce the number of weeds needing to be controlled with the POST-applied herbicides. These results support the concept that, even though cover crops can provide a high level of weed suppression early in the cotton growing season, the use of herbicides is still essential for adequate control throughout the entire growing season (Price et al. 2012). Further investigations on the effect of seeding rate on biomass production in different locations and environments should be considered. Environmental effects along with different soil fertilizer regimes for cereal rye might change the response of Palmer amaranth emergence and cotton yield to seeding rate and planting methods.

Literature Cited

Abbas G, Ali MA, Abbas G, Azam M, Hussain I (2009) Impact of planting methods on wheat grain yield and yield contributing parameters. J Anim Plant Sci 19:30-33

Akemo MC, Regnier EE, Bennett MA (2000) Weed suppression in spring-sown rye (*Secale cereale*)-pea (*Pisum sativum*) cover crop mixes. Weed Technol 14:545-549

Ateh CM, Doll JD (1996) Spring-planted winter rye (*Secale cereale*) as a living mulch to control weeds in soybean (*Glycine max*). Weed Technol 10:347-353

Bauer PJ, Reeves DW (1999) A comparison of winter cereal species and planting dates as residue cover for cotton grown with conservation tillage. Crop Sci 39:1824-1830

Blackshaw RE (1991) Soil temperature and moisture effects on downy brome vs. winter canola, wheat and rye emergence. Crop Sci 31:1034-1040

Boquet DJ, Hutchinson RL, Breitenbeck GA (2004) Long-term tillage, cover crop, and nitrogen rate effects on cotton. Agron J 96:1443-1452

Boyd NS, Brennan EB, Smith RF, Yokota R (2009) Effect of seeding rate and planting arrangement on rye cover crop and weed growth. Agron J 101:47-51

Bushuk W (2001) Rye: production, chemistry, and technology (No. Ed. 2). American Association of Cereal Chemists

Clark A, ed (2008). Managing Cover Crop Profitably 3th edn. Beltsville, MD: Sustainable Agriculture Research and Education (SARE). Pp 98-103

Creamer NG, Baldwin KR (2000) An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortSci 35:600-603

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plan 32:1221-1250

DeVore, JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832-838

Fisher KA, Momen B, Kratochvil RJ (2011) Is broadcasting seed an effective winter cover crop planting method? Agron J 103:472-478

Fowler DB, Limin AE, Ritchie JT (1999). Low-temperature tolerance in cereals: model and genetic interpretation. Crop Sci 39:626-633

Kornecki TS, Raper RL, Arriaga FJ, Balkcom KS, Price AJ (2005) Effects of rolling/crimping rye direction and different row-cleaning attachments on cotton emergence and yield. In Proc. Southern Conservation Tillage Conf., 27th. Florence, SC pp. 27-29

Korres NE, Norsworthy JK (2015) Influence of a rye cover crop on the critical period for weed control in cotton. Weed Sci 63:346-352

Mazzoncini M, Sapkota TB, Barberi P, Antichi D, Risaliti R (2011) Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. S Till Res 114:165-174

McCarty, WH, Blaine A, Byrd JD (2003) Cotton no-till production. Mississippi State University Cooperative Extension Service Publ. P1695

McMaster GS, Wilhelm WW (1997) Growing degree-days: one equation, two interpretations. Agricul Forest Meteorol, 87: 291-300.

Meisinger JJ, Hargrove WL, Mikkelsen RL, Williams JR, Benson VW (1991) Effects of cover crops on groundwater quality. Cover Crops for Clean Water. Soil and Water Conservation Society. Ankeny, Iowa, 266:793-799

Mirsky SB, Curran WS, Mortensen DM, Ryany MR, Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci 59:380-389

Monks CD, MG Patterson (1996) Conservation Tillage Cotton Production Guide. Alabama Cooperative Extension System Publ. ANR-952

Nelson WA, Kahn BA, Roberts BW (1991) Screening cover crops for use in conservation tillage systems for vegetables following spring plowing. HortSci 26:860-862

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK, Still J (2011) Evaluation of cereal and Brassicaceae cover crops in conservation-tillage, enhanced, glyphosate-resistant cotton. Weed Technol 25:6-13

Prabhakara K, Hively WD, McCarty GW (2015) Evaluating the relationship between biomass, percent groundcover and remote sensing indices across six winter cover crop fields in Maryland, United States. Int J Appl Earth Obs 39:88-102

Price AJ, Balkcom KS, Duzy LM, Kelton JA (2012) Herbicide and cover crop residue integration for Amaranthus control in conservation agriculture cotton and implications for resistance management. Weed Technol 26:490-498

Putnam AR, DeFrank J, Barnes JP (1983) Exploitation of allelopathy for weed control in annual and perennial cropping systems. J Chem Eco 9:1001-1010

Reddy KN (2001). Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 15: 660-668

Reeves DW, Price AJ, Patterson MG (2005) Evaluation of three winter cereals for weed control in conservation-tillage nontransgenic cotton. Weed Technol 19:731-736

Rosecrance RC, McCarty GW, Shelton DR, Teasdale JR (2000) Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. Plant and Soil 227:283-290

Sainju UM, Singh BP, Whitehead WF (2002) Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. S Till Res 63:167-179

Sainju UM, Whitehead WF, Singh BP, Wang S (2006) Tillage, cover crops, and nitrogen fertilization effects on soil nitrogen and cotton and sorghum yields. Euro J Agron 25:372-382

Salas RA, Burgos NR, Tranel PJ, Singh S, Glasgow L, Scott RC, Nichols RL (2016) Resistance to PPO-inhibiting herbicide in Palmer amaranth from Arkansas. Pest Manag Sci 72:864-869

Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, Leep R, Nyiraneza J, O'Neil K (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron J 97:322-332

Sosnoskie LM, Culpepper AS (2014) Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) increases herbicide use, tillage, and hand-weeding in Georgia cotton. Weed Sci 62:393-402

Sosnoskie LM, Webster TM, Grey TL, Culpepper AS (2014) Severed stems of *Amaranthus palmeri* are capable of regrowth and seed production in *Gossypium hirsutum*. Ann Appl Bio 165:147-154

Stewart CL, Nurse RE, Hamill AS, Sikkema PH (2010) Environment and soil conditions influence pre-and postemergence herbicide efficacy in soybean. Weed Technol 24:234-243.

Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85:673-680

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385-392.

Unger PW, Vigil MF (1998) Cover crop effects on soil water relationships. J Soil Water Conserv 53:200-207

Table 3.1. Monthly rainfall plus irrigation data for 3013/2014 and 2014/2015.

Year		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
		---------------------------------mm---------------------------------												
2013/2014[a]	Rain[c]	33	58	89	7	3	97	87	137	104	35	65	91	184
	Irrig[c]	0	0	0	0	0	0	0	26	0	91	26	0	0
2014/2015[b]	Rain	184	78	75	14	1	82	81	167	172	268	67	58	48
	Irrig	0	0	0	0	0	0	0	0	0	0	65	13	0

[a] Planting date: May 23, 2014

[b] Planting date: June 3, 2015

[c] Abreviattions: Rain, rainfall; Irrig, irrigation

Table 3.2. Source of herbicides used in the experiment.

Common name	Trade name	Formulation	Rate	Application timing	Manufacturer	Location
			g ai or ae ha⁻¹			
Glyphosate	Roundup PowerMax	SL	870	3 WBP	Monsanto Company	St. Louis, MO
Dicamba	Clarity	SL	280	3 WBP	BASF Corporation	Research Triangle Park, NC
Paraquat	Gramoxone	SL	700	1 DBP	Syngenta Crop Protection	Greensboro, NC
Fluometuron	Cotoran	FL	1120	PRE	Makhteshim Agan of North America	Raleigh, NC
Glufosinate	Liberty	SL	595	2 and 4 WAP	Bayer CropScience	Research Triangle Park, NC
S-metolachlor	Dual Magnum	EC	1070	2 and 4 WAP	Syngenta Crop Protection	Greensboro, NC
Flumioxazin	Valor	WDG	71	8 WAP	Valent	Walnut Creek, CA
Monosodium acid methanearsonate	MSMA	SL	2240	8 WAP	Drexel Chemical Company	Memphis, TN

Abbreviation: SL, soluble liquid; EC, emulsifiable concentrate; WDG, water dispersible granule; WBP, weeks before planting; DBP, day before planting; PRE, preemergence; WAP, weeks after planting.

Table 3.3. Biomass production and cotton stand counts as function of cereal rye seeding rates in 2014 and 15.

	Biomass		Cotton stand count	
Seeding rate	2014	2015	2014	2015
kg ha^{-1}	-------- kg ha^{-1}--------		thousands plants ha^{-1}	
0	840	690	113	116
56	3,060	2,460	104	113
112	4,000	3,310	96	103
168	4,460	3,620	94	98
LSD (0.05)	390	290	7	5

Table 3.4. The main effect of cereal rye seeding rate on Palmer amaranth emergence in 2014 and 2015, and the main effect of assessment timing on Palmer amaranth emergence at Fayetteville, AR[a].

	Density			
Seeding rate	2014	2015	Assessment timing[d]	Density
kg ha^{-1} [b]	––––––––– plants m^{-2}	––––––––––	weeks after planting	plants m^{-2}
0	5.4 (0)	4.3 (0)	0 – 2	1.6
56	2.8 (48)	2.9 (36)	2 – 4	3.3
112	1.6 (70)	1.8 (58)	4 – 6	3.1
168	1.1 (80)	1.1 (74)	6 – 8	2.4
LSD (0.05)	1.3	1.4		1.1

[a] All means within a year can be compared using Fisher's protected LSD at $\alpha \leq 0.05$

[b] Years presented separately due to the interaction of seeding rate and year

[c] Numbers in parentheses represent the percentage reduction in total Palmer amaranth emergence relative to the no cover crop treatment without herbicide.

[d] Emergence was averaged over years

Table 3.5. Total Palmer amaranth emergence as a function of seeding rate and herbicide application in 2014 and 2015 at Fayetteville, AR.[a,b]

	Total Palmer amaranth emergence			
	2014		2015	
	Herbicide application		Herbicide application	
Seeding rate	Yes	No	Yes	No
kg ha^{-1}	plants m^{-2}			
0	2.5 (88)[c]	21.7 (0)	2.3 (87)	17.3 (0)
56	2.9 (87)	11.2 (48)	0.5 (97)	9.2 (47)
112	2.4 (89)	5.6 (74)	0.9 (95)	7.3 (58)
168	1.3 (94)	5.9 (73)	0.5 (97)	6.0 (65)
LSD	3.7		2.6	

[a] All means within a year can be compared using Fisher's protected LSD at $\alpha \leq 0.05$.

[b] See Table 2 for specific herbicides, rates, and timings associated with each designation.

[c] Numbers in parentheses represent the percentage reduction in total Palmer amaranth emergence relative to the no cover crop treatment without herbicide.

Table 3.6. Grass control (broadleaf signalgrass and barnyardgrass) as function of cereal rye seeding rate and herbicide application in 2014 and 2015 at Fayetteville, AR.[a]

		Control[b,c]							
Seeding rate	Herbicide application	2 WAP		4 WAP		6 WAP		8 WAP	
kg ha^{-1}		%	SE	%	SE	%	SE	%	SE
2014									
0	No	0	0	0	0	0	0	0	0
	Yes	98	1	100	0	100	0	100	0
56	No	97	1	92	1	81	2	72	1
	Yes	99	1	98	1	98	1	99	1
112	No	98	1	92	1	83	1	77	2
	Yes	100	0	100	0	99	0	99	0
168	No	99	1	95	1	89	1	80	1
	Yes	100	0	100	0	99	0	99	0
2015									
0	No	0	0	0	0	0	0	0	0
	Yes	83	2	99	0	100	0	100	0
56	No	64	2	54	2	49	1	42	2
	Yes	82	1	99	0	100	0	100	0
112	No	65	1	54	1	52	1	49	2
	Yes	82	1	99	0	100	0	100	1
168	No	77	1	75	2	65	2	66	1
	Yes	93	1	95	2	100	0	100	0

[a] Seeding rates that did not meet the assumptions of ANOVA are reported as means followed by the standard error (SE) of the mean.

[b] See Table 2 for specific herbicides, rates, and timings associated with the herbicide application.

[c] Abbreviations: WAP, weeks after planting

Table 3.7. The main effect of seeding rate and evaluation timings on seedcotton yield in 2014 and 2015 at Fayetteville, AR.

Main effect	Seedcotton yield[a]	
	2014	2015
	---------------------- kg ha⁻¹------------------------	
Seeding rate		
0	1,030	1,200
56	1,160	1,260
112	1,200	1,240
168	1,290	1,210
LSD (0.05)	90	NS
Herbicide application		
Yes	1,400	1,790
No	940	570
LSD (0.05)	50	50

[a] All means within a year and seeding rate or herbicide application can be compared using Fisher's protected LSD at α = 0.05.

[b] See Table 2 for specific herbicides, rates, and timings associated with the herbicide application.

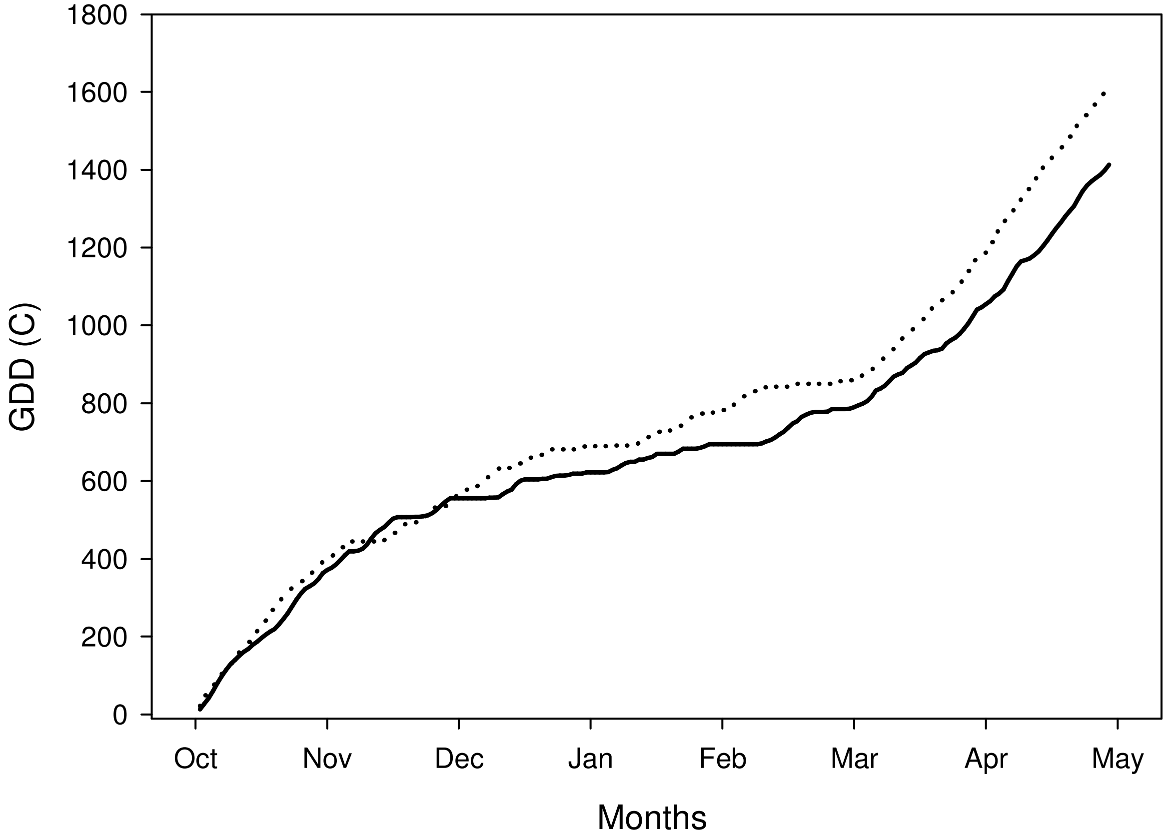

Figure 3.1. Cumulative growing degrees day (GDD) data from 2013 – 2014 (solid line) and 2014 – 2015 (dotted line). Temperature base of 0 C (MacMaster and Wilhelm 1997).

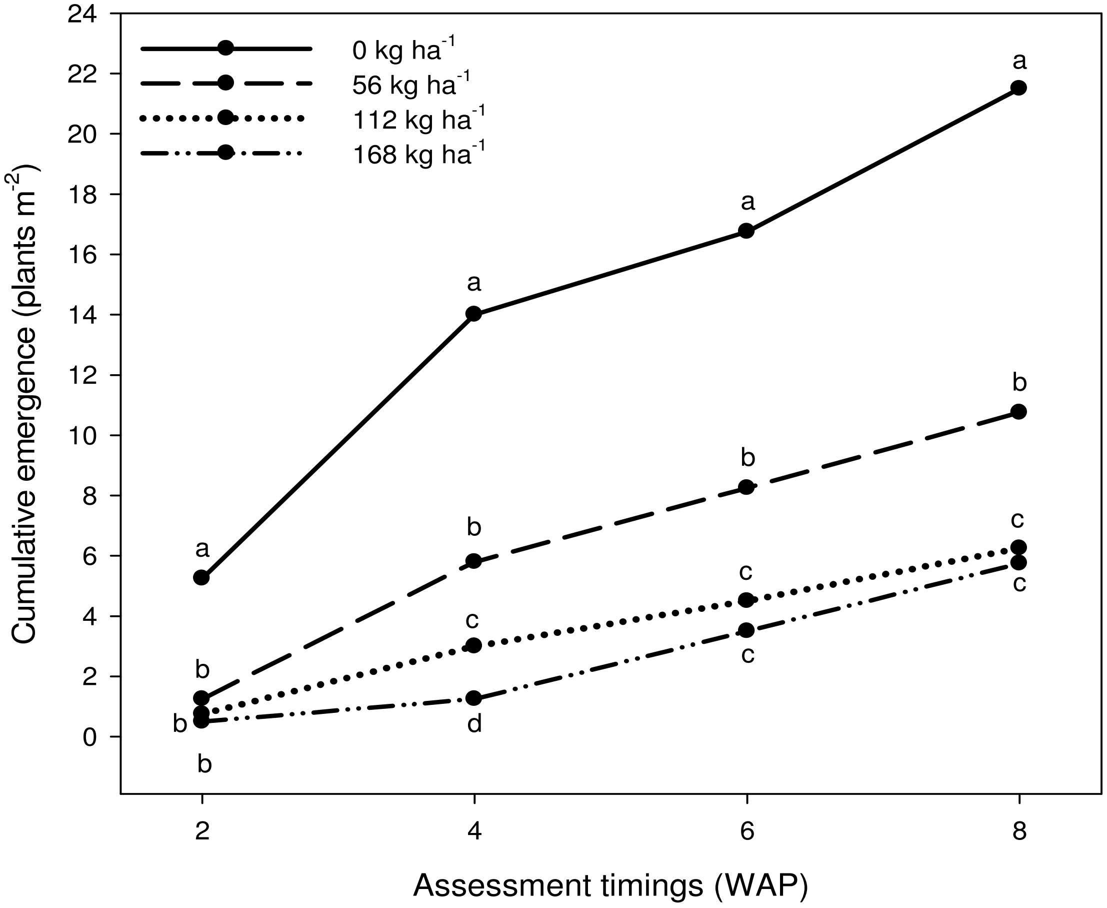

Figure 3.2. Cumulative Palmer amaranth emergence in the no herbicide plots as a function of cereal rye seeding rate in 2014. Means with the same letter within each assessment timings are not significantly different according to Fisher's protected LSD ($\alpha = 0.05$). Abbreviations: WAP, weeks after planting.

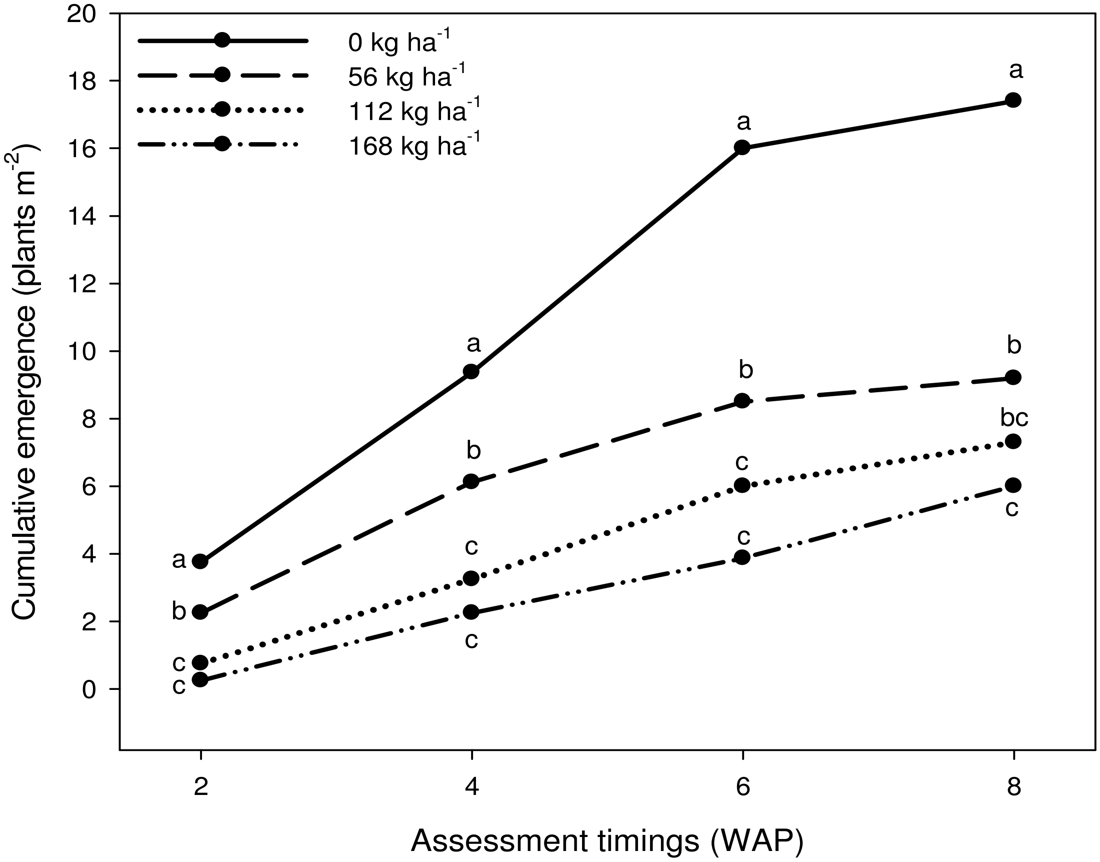

Figure 3.3. Cumulative Palmer amaranth emergence in the no herbicide plot as a function of cereal rye seeding rate in 2015. Means with the same letter within each assessment timings are not significantly different according to Fisher’s protected LSD ($\alpha = 0.05$). Abbreviations: WAP, weeks after planting.

Chapter 4

Evaluation of Chemical Termination Options for Cover Crops

Abstract

Cover crop acreage has substantially increased over the last few years due to the intent of growers to capitalize on federal conservation payments and incorporate sustainable practices into agricultural systems. Despite all the known benefits, widespread adoption of cover crops still remains limited due to potential cost and management requirements. Cover crop termination is crucial since a poorly terminated cover crop can become a weed and lessen the yield potential of the current cash crop. A field study was initiated in fall 2015 and 2016 at the Arkansas Agricultural Research and Extension Center in Fayetteville to evaluate pre-plant herbicide options for terminating cover crops. Cereal cover crops, such as wheat and cereal rye, were 97% or more controlled by glyphosate and all glyphosate-containing treatments. The legume cover crops hairy vetch, Austrian winterpea, and crimson clover were poorly controlled by glyphosate alone, ranging from 47% to 56% control. However, improved control was obtained when dicamba, 2,4-D, or saflufenacil were tank-mixed with glyphosate. Increasing the rate of an auxin herbicide in the glyphosate mixture also enhanced control of legume cover crops. Paraquat plus metribuzin was effective in terminating both cereal and legume cover crops with control of cereal cover crops ranging from 87% to 97% and legumes ranging from 90% to 96%. Rapeseed was not effectively controlled by any of the termination options evaluated. An earlier application timing could potentially enhance control of a rapeseed cover crop or growers should consider other cover crops that are easier to terminate using traditional burndown herbicides.

Nomenclature: Glyphosate, paraquat, saflufenacil, Austrian winterpea, *Lathryrus hirsutus* L.;

cereal rye, *Secale cereale* L.; crimson clover, *Trifolium incarnatum* L., hairy vetch, *Vicia villosa* Roth; rapeseed, *Brassica napus* L.; wheat, *Triticum aestivum* L.

Key words: Cover crops, termination, burndown herbicides

Introduction

In the United States (U.S.), cover crop acreage has substantially increased over the last few years due to the intent of growers to capitalize on federal conservation payments and incorporate sustainable practices into agricultural systems (SARE 2015). Various reports have been published about benefits of cover crops in diverse areas of agriculture (Hartwig and Ammon 2002; Reeves 1994). The weed suppression provided by cover crops have been widely researched as a means to decrease selection pressure placed on herbicides for weed control (Teasdale 1996; Creamer et al. 1996). The evolution and spread of glyphosate-resistant Palmer amaranth and the recent confirmation of protoporphyrinogen oxidase (PPO)-resistant Palmer amaranth in the Midsouth threatens the ability of growers to manage weeds utilizing currently available herbicide technologies (Culpepper 2008; Salas et al. 2016). Hence, successful weed management strategies must rely heavily on integrated management approaches using cultural, mechanical, and chemical methods of control (Jha and Norsworthy 2009; Price et al. 2011). Despite all the known benefits, widespread adoption of cover crops still remains limited due to potential cost and management requirements.

Termination of the cover crop is a critical component of management since a poorly terminated cover crop can become a weed and lessen the yield potential of the current cash crop (Nascente et al. 2013). In no-till production systems, cover crop termination is commonly achieved by herbicides, but mechanical methods can also be utilized. Mowing can be used to terminate cover crops without soil disturbance, but problems such as cover crop regrowth and uneven residue distribution is often faced with this method (Creamer and Dabney 2002). A roller-crimper is another option for cover crop termination in a no-till system. This implement crushes the cover crop to form a flat, uniform layer of residue over the soil surface (Ashford and Reeves 2003; Kornecki et al. 2006); however, termination of cover crops with a roller is not effective unless the cover crop has entered reproductive development (Creamer and Dabney 2002). Furthermore, this technique may be difficult in the Midsouth because most agronomic crops are grown on raised beds.

Chemical termination of cover crop has been achieved by application of herbicides several weeks prior planting. The efficacy of preplant herbicides on cover crops is likely to differ depending on the cover crop species planted. White and Worsham (1990) reported that application of glyphosate alone at 1.7 kg ae ha^{-1} controlled hairy vetch and crimson clover 65% and 70%, respectfully, but the addition of 2,4-D enhanced hairy vetch control to 99% and crimson clover to 82%.

In soybean (*Glycine max* (L.) Merr.), Reddy et al. (2001) observed that inadequate desiccation of Italian ryegrass (*Lolium perene* L. *ssp. multiflorum* Lam.) resulted in a yield reduction of 29% compared to plots without any cover crop. Price et al. (2009) also showed that inadequate termination of wheat , cereal rye, and black oats (*Avena strigosa* L.) can significantly decrease seedcotton yield. White and Worshan (1990) reported that 65% control of crimson clover reduced corn (*Zea mays* L.) yield by 38% compared to conventional tillage. Seed germination and early seedling development can also be affected by a poorly controlled cover crop because of continued uptake of water from the soil, thus depleting moisture available to crops at time of germination and seedling development (Price et al. 2009).

Another problem commonly known as “hair pinning” can be linked to poorly controlled cover crops. In this case, cover crop residue is pushed into the soil by the disk openers or coulter which creates a condition where the seed does not have appropriate soil coverage. As a result, stand loss can occur and may have a negative impact on yield (Kornecki et al. 2006). To avoid such problems, it is recommended to apply herbicides 2 to 3 weeks before row crop planting to allow sufficient time for cover crop desiccation (Clark et al. 2008). In case of inadequate cover crop control, paraquat can be applied immediately prior to planting to improve control (Bruce et al. 1990). With a recent increase in cover crop use in the U.S., information about herbicide efficacy for terminating cover crops is needed. Hence, an experiment was conducted to evaluate chemical termination options for six cover crops.

Materials and Methods

A field experiment was initiated in fall 2014 and 2015 at the University of Arkansas Agricultural Research and Extension Center in Fayetteville to evaluate chemical termination options for cover crops. In both years, the experiment was conducted on a Captina silt loam soil (Fine-silty, siliceous, active, mesic Typic Fragiudults) with 33% sand, 49% silt, 18% clay, pH of 6.0, and 1.0% organic matter. The experimental design was a randomized complete block with a strip-plot. Four replications were used with plots sizes of 1.9 by 9.9 m. Cover crops were planted on September 9, 2014 and September 19, 2015. Cover crop served as the strio plot and herbicide treatments as the sub-plot. Cover crops were sown after harvesting a corn crop. Prior to cover crop sowing, the field was lightly tilled with a disk. Cover crops were broadcasted in strips of 1.9 m by 90 m followed by one more tillage operation to provide adequate soil coverage of the cover crop seeds. Monthly rainfall data for the period of this experiment are presented in Table 4.1.

Treatments were composed of herbicides used alone or in mixtures as typical preplant options in Arkansas (Table 4.2). All applications were made at 143 L ha^{-1} using a 3-nozzle CO_2-presurrized backpack sprayer on April 12, 2015 and April 14, 2016. Cover crop species, seeding rate, and the average height of each cover crop for both years at time of herbicide application are shown in Table 4.3. Effectiveness of the herbicide treatments were evaluated at 2 and 4 weeks after treatment (WAT). Fresh aboveground biomass was collected from a 1 m^2 quadrat and measured at 4 WAT. Samples were dried at 65 C for 5 days for assessment of dry biomass. The porpose of collecting this data is to assess the impact of herbicide application on cover crop biomass at 4 WAT. Cover crop biomass might interfere in the crop planting operation which might lead to a negative effect on emergence and yield. Hence, indentify the herbicide treatments that provided the lowest fresh biomass can aid to the decision of which herbicide is the most adequate for cover crop desiccation.

All data were subjected to an analysis of variance using JMP 12 PRO (SAS Institute Inc., Cary, NC). The analysis of percent control and biomass were performed by cover crop because the objective of the study was to identify the best herbicide option for each cover crop. Herbicide treatment was considered a fixed effect in the model while replication was considered a random effect. No interaction was observed between herbicide treatment and year for percent control and biomass; hence, year was also considered a random effect. Means were separated using Fisher's protected LSD at α=0.05, and orthogonal contrasts were conducted for unique groups of herbicide programs ($\alpha = 0.05$).

Results and Discussion

Legume Cover Crops. Both dicamba and 2,4-D alone, regardless of rate tested, provided less than 80% control of each legume cover crop through 4 WAT (Table 4.4). Doubling the rate of either dicamba or 2,4-D often improved control of Austrian winterpea; however, none of these herbicides would be deemed as a stand-alone option for termination of legume cover crops at the rates tested. White and Worsham (1990) reported that application of 2,4-D and dicamba on crimson clover at a similar growth stage to that evaluated here (flowering and 51 to 61 cm height) provided only 70% and 72% control, respectively.

Glyphosate alone also did not control legume cover crops effectivley. The control provided by glyphosate on all three legume cover crops ranged from 47% to 56% at 4 WAT (Table 4.4). The addition of an auxin herbicide to glyphosate increased control compared to glyphosate alone, but the same effect was not observed when compared to the auxin herbicides alone. The three-way mixture of glyphosate, dicamba, and 2,4-D provided similar control compared to the two-way mixture of glyphosate plus dicamba and glyphosate plus 2,4-D, regardless of the rate of the auxin herbicides. The only exception was the superior control provided by the three-way tank-mix compared to glyphosate plus the lower rate of dicamba on hairy vetch. The addition of saflufenacil also enhanced control compared to glyphosate alone.

Glufosinate alone was a good option for legume cover crop termination as evidenced by >90% control of hairy vetch and crimson clover at 4 WAT (Table 4.4). Austrian winterpea was controlled 81% by glufosinate at 4 WAT with the lower control being attributed to inadequate coverage of dense biomass with the contact herbicide. With the exception of Austrian winterpea, the addition of 2,4-D or dicamba to glufosinate did not offer improved control compared to glufosinate alone, regardless of the auxin herbicide rate in most cases. The mixture between glyphosate and glufosinate also did not differ from glufosinate alone; yet, it was superior to glyphosate alone.

With paraquat alone being less systemic than glufosinate, the inability to provide adequate coverage and control of the dense legume cover crop biomass was evident (Table 4.4). Control was not as effective as glufosinate for legume cover crops. Austrian winterpea, crimson clover, and hairy vetch were controlled 79%, 68%, and 86%, respectively, at 4 WAT. The application of paraquat in combination with metribuzin significantly increased control of all legume cover crops. Putnam and Ries (1967) reported that application of paraquat with a photosystem II (PSII)-inhibiting herbicide, such as simazine or diuron, was more effective for controlling quackgrass (*Agropyron repens* (L.) Beauv.) than either herbicide applied alone. Additionally, Norsworthy et al. (2007) showed that paraquat translocation increases as well as efficacy when mixed with PSII-inhibiting herbicides. Increasing the rate of metribuzin when mixed with paraquat did not further improve control of the legume cover crops.

Fresh biomass varied in response to herbicides for each legume cover crop (Table 4.5). All herbicide treatments reduced the fresh biomass weight of legume cover crops compared to the nontreated check. Fresh Austrian winterpea biomass treated with paraquat or paraquat plus metribuzin was the lowest among herbicide treatments. Similar results were observed for crimson clover and hairy vetch; however, glufosinate and glufosinate-containing treatments did not differ from paraquat and paraquat-containing treatments for fresh biomass weight. The addition of an auxin herbicide to glyphosate decreased the fresh weight of Austrian winterpea and crimson clover compared to glyphosate alone, regardless of the rate of 2,4-D and dicamba. Comparable results were not observed with hairy vetch. Glyphosate plus dicamba at both rates did not differ from glyphosate alone for fresh weights.

Dry biomass likewise varied among herbicide treatments for each legume cover crop (Table 4.5). Austrian winterpea dry biomass when treated with dicamba (280 g ae ha^{-1}), glyphosate plus dicamba (280 g ae ha^{-1}), and glyphosate plus dicamba (210 g ae ha^{-1}) plus 2,4-D (330 g ae ha^{-1}) did not differ from the nontreated check. All remaining treatments had significantly less dry biomass than the nontreated check. However, treatments containing paraquat and glufosinate showed greater dry biomass weight reduction. The dry biomass weight of crimson clover did not differ from the nontreated check for 2,4-D (530 g ae ha^{-1}), dicamba (280 g ae ha^{-1}), glyphosate, and glyphosate plus flumioxazin plus thifensulfuron plus tribenuron (44 g ai ha^{-1}, 5 g ai ha^{-1}, and 5 g ai ha^{-1}) treatments. Paraquat plus metribuzin at both rates provided the lowest amounts of dry cimson clover biomass. Compared to the nontreated check, hairy vetch dry biomass was not negatively affected by dicamba (280 g ae ha^{-1}), glyphosate, and glyphosate plus flumioxazin plus thifensulfuron plus tribenuron (44 g ha^{-1}, 5 g ha^{-1}, and 5 g ha^{-1}). Conversely, glufosinate- and paraquat-containing treatments effectively reduced the dry weight of hairy vetch.

Orthogonal contrasts performed between contact and systemic herbicides showed that using a contact herbicide alone or in tank mixture provided superior results for all parameters evaluated (Table 4.6). The efficacy of a systemic herbicide is linked to the capability of the active ingredient to move thorough the plant whereas contact herbicides are relatively immobile and quick acting, rapidly desiccating foliage (Dodge and Harris 1970; Funderburk and Lawrence 1964; Young 1994). When applied to the foliage, systemic herbicides will be translocated throughout the plant; however, such movement is dependent on the translocation capacity of the target plant at a specific growth stage (Foy 1961). The translocation of systemic herbicides is often greatest when plants are actively growing. In addition, the degradation of herbicides within older plants is often greater than in young plants (Singh and Singh 2004). These two factors might be considered to explain why systemic herbicides have low activity on high biomass cover crops (Ahmadi et al. 1980; Culpepper and York 2001). It is likely that earlier application of these systemic herbicides would at least have improved control, but in turn there would be less biomass production which would limit weed suppression.

Unlike systemic herbicides, contact herbicides are nonmobile and requires adequate coverage of all foliage to obtain a high level of control. Developing plants might eventually show regrowth since the roots and shoot system are generally unaffected (Bruce and Kells 1990). However, in this experiment, the overall performance of contact herbicides on legume cover crops at 4 WAT was superior to systemic herbicides (Table 4.6). Based on orthogonal contrasts, the efficacy of auxin herbicides, specifically 2,4-D and dicamba, differed among legume cover crops.

Cereal Cover Crops. Both cereal cover crops were easily terminated by any glyphosate-containing treatment. Glyphosate alone at 867 g ae ha^{-1} or in mixture with other herbicides delivered at least 99% control of cereal rye at 4 WAT (Table 4.7). Similar results were observed with winter wheat; however, the mixture of glyphosate and glufosinate appeared antagonistic based on only 92% control from the tank-mixture compared to 99% control from glyphosate alone. Whitaker et al. (2011) also observed a reduction in glyphosate plus glufosinate efficacy on grasses compared to glyphosate alone. According to Everman et al. (2009), such decrease in efficacy of glyphosate by glufosinate is due to reduced translocation of glyphosate within the plant.

Paraquat alone demonstrated limited efficacy on the cereal cover crops. However, similar to legume cover crops, the paraquat plus metribuzin mixture increased control of cereal rye and wheat over paraquat alone. Similar results were observed by Norsworthy et al. (2011) when evaluating herbicide options for control of failed stands of corn. Similarly, Eubank et al. (2011) also observed this synergistic effect with the addition of metribuzin to paraquat on control of glyphosate-resistant Italian ryegrass.

Glufosinate was not an effective option for terminating the cereal cover crops (Table 4.7). Cereal rye and wheat control by glufosinate alone or in mixture with auxin herbicide ranged from 76% to 78% control. As seen in other research, glufosinate is less effective in controlling grasses than is glyphosate (Riar et al. 2011; Whitaker et al. 2011). Glyphosate-containing treatments and paraquat plus metribuzin (both rates) treatments had the lowest fresh weight in the study ranging from 938 to 1,225 g m^{-2} (Table 4.8). Although significantly less fresh biomass weight was observed in the treated plots compared to the nontreated check, dry biomass weights did not show such differences among treatments on both cover crops (Table 4.8). The fact that cereal rye and wheat are erect plants, have a wide carbon nitrogen ratio, and have a low rate of decomposition may explain the narrow differences in dry biomass weight between treated and nontreated plots (Parmas 1975).

Rapeseed. Overall, rapeseed was the most difficult-to-kill cover crop. None of the herbicide treatments controlled rapeseed adequately, as evident by ratings of 71% or less control at 4 WAT (Table 4.9). The fresh weight of rapeseed when treated with glyphosate or dicamba alone was not different from the nontreated check; hence, individuals planting a cover crop blend that contains rapeseed may have difficulty in terminating this cover crop. Clark et al. (2007) reported that rapeseed provend to be difficult to kill with glyphosate, requiring timely management and multiple applications for adequate control. Similar to legume cover crops, orthogonal contrasts conducted with rapeseed data showed that contact herbicide-containing treatments were superior to the systemic treatments in all parameters evaluated (Table 4.10). In addition, rapeseed was more sensitive to 2,4-D than dicamba. Beckie et al. (2004) reported that 2,4-D applied at 560 g ae ha^{-1} effectively controlled volunteer rapeseed at the 6-leaf stage. Hence, earlier application of the preplant herbicides might further enhance rapeseed control.

Practical Implications. Cover crop termination by herbicides can be challenging depending upon the cover crop species. The use of herbicides such as glyphosate, paraquat, 2,4-D, and dicamba alone to terminate cover crops might not provide sufficient control of legume cover crops. However, based on these data, effective control of legume cover crops can be obtained with mixtures of glufosinate plus dicamba or 2,4-D and paraquat plus metibuzin. The use of a contact herbicide for controlling legume cover crops at the bloom stage proved to be superior to systemic herbicides.

In contrast, cereal cover crops can be easily controlled with glyphosate. The addition of auxin herbicides to glyphosate in an attempt to broaden the spectrum of winter weed control will negatively impact cereal rye and wheat control. Paraquat plus metribuzin is also effective in terminating both cereal cover crops and would be an option when planting soybean following cover crop termination. The use of other PSII-inhibiting herbicides like atrazine, diuron, or fluometuron also are known to cause a synergistic affect when tank-mixed with paraquat; hence, these herbicides would be additional options depending on the subsequent crop to be planted (Norsworthy et al. 2011).

Growers should avoid planting rapeseed based on the difficulty in successfully terminating this cover crop. If rapeseed is included in a cover crop blend, alternative methods of cover crop termination may be needed. Based on the lack of response of rapeseed to herbicides, further research is needed to evaluate termination options for other mustards (*Sinapis* spp.) and radishes (*Raphanus* spp.) which could serve as a cover crop replacement for rapeseed.

Another important factor to consider is the interval needed between cover termination and crop planting. Most of the treatments showed substantial differences in control between 2 and 4 WAT (Tables 4.4, 4.7, and 4.9). Allowing sufficient time between application and complete kill of the cover crop can help with avoiding problems with lack of available soil moisture during the crop germination period and negative effects on crop establishment (Clark et al. 1997). In this experiment, to ensure maximum biomass production, all cover crops were sprayed at the bloom stage. Perhaps an earlier application would improve control of these difficult-to-kill cover crops; albeit, the amount of biomass produced by the cover crops would be lessened.

Literature Cited

Ahmadi MS, Haderlie LC, Wicks GA (1980) Effect of growth stage and water stress on barnyardgrass (*Echinochloa crus-galli*) control and on glyphosate absorption and translocation. Weed Sci 28:277-282

Ashford DL, Reeves DW (2003) Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am J Alternative Agr 1:37-45

Bruce JA, Kells JJ (1990) Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technol. 1: 642-647

Clark A, ed (2008). Managing Cover Crop Profitably 3th edn. Beltsville, MD: Sustainable Agriculture Research and Education (SARE). Pp 51-57

Clark AJ, Decker AM, Meisinger JJ, McIntosh MS (1997) Kill date of vetch, rye, and a vetch-rye mixture: I. Cover crop and corn nitrogen. Agron J 3:427-434

Creamer NG, Bennett MA, Stinner BR, Cardina J, Regnier EE (1996) Mechanisms of weed suppression in cover crop-based production systems. HortSci 3:410-413

Creamer NG, Dabney SM (2002) Killing cover crops mechanically: Review of recent literature and assessment of new research results. Am J Alternative Agric 1:32-40

Culpepper AS, Whitaker JR, MacRae AW, York AC (2008) Distribution of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. J Cotton Sci 12:306-310

Foy CL (1961) Absorption, distribution, & metabolism of 2, 2-dichloropropionic acid in relation to phytotoxicity. I. Penetration & translocation of Cl36-and C14-labeled dalapon. Plant Physiol 36:688-697

Hartwig NL, Ammon HU (2002) Cover crops and living mulches. Weed Sci 50:688-699

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of Palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644-651

Kornecki TS, Price AJ, Raper RL (2006) Performance of different roller designs in terminating rye cover crop and reducing vibration. Appl Eng Agric 5:633-641

Nascente AS, Crusciol CA, Cobucci T, Velini ED (2013) Cover crop termination timing on rice crop production in a no-till system. Crop Sci 6:2659-69

Norsworthy JK, Smith KL, Griffith G (2011) Evaluation of combinations of paraquat plus photosystem II-inhibiting herbicides for controlling failed stands of maize (*Zea mays*). Crop Prot 30:307-310

Parnas H (1975) Model for decomposition of organic material by microorganisms. S Bio Biochem 7:161-169

Price AJ, Arriaga FJ, Raper RL, Balkcom KS, Kornecki TS, Reeves DW (2009) Comparison of mechanical and chemical winter cereal cover crop termination systems and cotton yield in conservation agriculture. J Cotton Sci 13:238-245

Price AJ, Balkcom KS, Culpepper SA, Kelton JA, Nichols RL, Schomberg H (2011) Glyphosate-resistant Palmer amaranth: a threat to conservation tillage. J Soil Water Conservation 4:265-275

Reddy KN (2001) Effects of cereal and legume cover crop residues on weeds, yield, and net return in soybean (*Glycine max*). Weed Technol 4:660-668

Reeves DW (1994) Cover crops and rotations. Advances in Soil Science: Crops Residue Management. pp. 125-172

Riar DS, Norsworthy JK, Griffith GM (2011) Herbicide programs for enhanced glyphosate-resistant and glufosinate-resistant cotton (*Gossypium hirsutum*). Weed Technol 25:526-534

Salas RA, Burgos NR, Tranel PJ, Singh S, Glasgow L, Scott RC, Nichols RL (2016) Resistance to PPO-inhibiting herbicide in Palmer amaranth from Arkansas. Pest Manag Sci 72:864-869

SARE (2015) Cover Crop Survey Analysis. Sustainable Agriculture Research and Education. http://www.sare.org/Learning-Center/From-the-Field/North-Central-SARE-From-the-Field/2015-Cover-Crop-Survey-Analysis. Accessed August 4, 2016

Sharma SD, Singh M (2007) Effect of timing and rates of application of glyphosate and carfentrazone herbicides and their mixtures on the control of some broadleaf weeds. HortSci 42:1221-1226

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. J Prod Agric 4:475-479

Whitaker JR, York AC, Jordan DL, Culpepper AS (2011) Weed management with glyphosate- and glufosinate-based systems in PHY 485 WRF cotton. Weed Technol 2:183-191

White RH, Worsham AD (1990) Control of legume cover crops in no-till corn (*Zea mays*) and cotton (*Gossypium hirsutum*). Weed Technol 4:57-62

Young DC (1994) Systemic herbicides and methods of use. United States patent US 5,288,69

Table 4.1. Monthly rainfall data for 2014-2015 and 2015-2016.

Year[a]	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	----	----	----	mm	----	----	----	----
2014-2015[b]	114	184	78	75	14	1	82	81
2015-2016[c]	47	58	106	322	7	15	84	99

[a] Experiment was conduct under dryland conditions

[b] Cover crop planting date: September 9, 2014

[c] Cover crop planting date: September 19, 2015

Table 4.2. Herbicide information for all products used in experiment.

Common name	Trade name	Manufacturer	City, State
2,4-D	Weedar	Nufarm Inc.	Burr Ridge, IL
Dicamba	Clarity	BASF Corporation	Research Triangle Park, NC
Dicamba	Clarity	BASF Corporation	Research Triangle Park, NC
Flumioxazin + Thifensulfuron + Tribenuron	Afforia	DuPont Crop Protection	Wilmington, DE
Glufosinate	Liberty	Bayer CropScience LP	Research Triangle Park, NC
Glyphosate	Roundup PowerMax	Monsanto Company	St. Louis, MO
Metribuzin	Metribuzin 75	Loveland Products, Inc.	Greeley, CO
Paraquat	Gramoxone	Syngenta Crop Protection, LLC	Greensboro, NC
Rimsulfuron + Thifensulfuron	Leadoff	DuPont Crop Protection	Wilmington, DE
Saflufenacil	Sharpen	BASF Corporation	Research Triangle Park, NC
Thifensulfuron + Tribenuron	FirstShot	DuPont Crop Protection	Wilmington, DE

Table 4.3. List of cover crops with their respective seeding rate and cover crop height at termination with herbicide treatments.

		Year	
Cover crops	Seeding rate	2015	2016
	kg ha^{-1}	---------------- cm	---------------
Cereal rye	90	154	135
Wheat	90	77	65
Australian winterpea	84	56	56
Hairy vetch	22	48	47
Crimson clover	15	57	62
Rapeseed	11	142	130

Table 4.4. Control of legume cover crops at 2 and 4 weeks after treatment (WAT) with various herbicides at Fayetteville, AR, averaged over 2015 and 2016.

		Austrian winterpea		Crimson clover		Hairy vetch	
Herbicide[a]	Rate	2 WAT	4 WAT	2 WAT	4 WAT	2 WAT	4 WAT
	g ai or ae ha^{-1}	--------------------------- % --------------------------					
2,4-D[b]	530	59	60	37	49	59	71
2,4-D[b]	1060	67	71	44	54	68	78
Dicamba[c]	280	51	60	36	49	53	62
Dicamba[c]	560	58	74	38	59	65	69
Glufosinate	594	64	81	70	93	75	95
Glufosinate + 2,4-D[c]	594 + 530	68	88	72	90	77	97
Glufosinate + 2,4-D[c]	594 + 1060	71	93	73	93	78	99
Glufosinate + Dicamba[c]	594 + 280	60	89	63	88	71	90
Glufosinate + Dicamba[c]	594 + 560	64	89	73	93	72	97
Glyphosate	867	52	56	30	47	35	56
Glyphosate + 2,4-D	867 + 530	46	66	41	63	60	75
Glyphosate + 2,4-D	867 + 1060	55	76	49	71	71	82
Glyphosate + dicamba	867 + 280	56	75	46	64	63	70
Glyphosate + dicamba	867 + 560	60	82	51	72	65	78
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	59	73	42	56	70	85
Glyphosate + flumioxazin + Thifen + triben	867 + 44 + 5 + 5	57	69	35	50	45	67
LSD (0.05)		6	8	11	10	9	10

[a] Abreviations: thifen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

[d] Methylated seed oil, 1.0% v/v

Table 4.4. (Cont.) Control of legume cover crops at 2 and 4 weeks after treatment (WAT) with various herbicides at Fayetteville, AR, averaged over 2015 and 2016.

Herbicide	Rate	Austrian winterpea		Crimson clover		Hairy vetch	
		2 WAT	4 WAT	2 WAT	4 WAT	2 WAT	4 WAT
	g ai or ae ha⁻¹	%					
Glyphosate + flumioxazin + Thifen + triben	867 + 44 + 5 + 5	57	69	35	50	45	67
Glyphosate + glufosinate	867 + 594	78	87	79	92	72	94
Glyphosate + rimsu + Thifensulfuron	867 + 8 + 8	50	59	44	56	45	64
Glyphosate + saflufenacil	867 + 50	67	71	58	72	64	74
Glyphosate + thifensulfuron + Triben + 2,4-D	867 + 5 + 5 + 530	64	76	38	77	65	80
Glyphosate + thifen + Triben + dicamba	867 + 5 + 5 + 280	62	73	37	83	60	75
Paraquat[c]	840	65	79	66	68	68	86
Paraquat + metribuzin[c]	560 + 420	81	90	70	90	79	94
Paraquat + metribuzin[c]	560 + 560	83	96	72	90	80	96
Saflufenacil + thifen + triben[d]	50 + 5 + 5	73	79	53	70	65	77
LSD (0.05)		6	8	11	10	9	10

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;
[b] Nonionic surfactant, 0.25% v/v
[c] Crop oil concentrate, 1.0% v/v
[d] Methylated seed oil, 1.0% v/v

Table 4.5. Legume cover crop biomass collected at 4 weeks after treatment with various herbicides at Fayetteville, AR, averaged over 2015 and 2016.

		Austrian winterpea		Crimson clover		Hairy vetch	
Herbicide[a]	Rate	Fresh	Dry	Fresh	Dry	Fresh	Dry
	g ai or ae ha^{-1}			g m^{-2}			
Nontreated		3670	500	3340	520	2800	490
2,4-D[b]	530	2200	410	1760	470	1540	420
2,4-D[b]	1060	1980	390	1750	430	1370	360
Dicamba[b]	280	2440	440	1740	490	1430	380
Dicamba[b]	560	1800	420	1740	450	1570	360
Glufosinate	594	1130	300	720	310	380	110
Glufosinate + 2,4-D[b]	594 + 530	1020	280	830	260	570	100
Glufosinate + 2,4-D[b]	594 + 1060	830	280	730	290	480	100
Glufosinate + dicamba[b]	594 + 280	1010	300	780	240	570	100
Glufosinate + dicamba[b]	594 + 560	940	280	790	270	500	90
Glyphosate	867	2670	410	2240	470	1750	420
Glyphosate + 2,4-D	867 + 530	1280	380	1580	380	1400	340
Glyphosate + 2,4-D	867 + 1060	1070	360	1450	350	1430	300
Glyphosate + dicamba	867 + 280	1260	430	1600	400	1290	390
Glyphosate + dicamba	867 + 560	1050	380	1380	350	1400	360
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	2120	440	1540	410	1570	370
LSD (0.05)		360	70	320	70	310	70

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[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

[d] Methylated seed oil, 1.0% v/v

Table 4.5. (Cont.) Legume cover crop biomass collected at 4 weeks after treatment with various herbicides at Fayetteville, AR, averaged over 2015 and 2016.

		Austrian winterpea		Crimson clover		Hairy vetch	
Herbicide[a]	Rate	Fresh	Dry	Fresh	Dry	Fresh	Dry
	g ai or ae ha^{-1}	-------------------- g m^{-2} ------------------					
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	2400	380	2100	470	1890	460
Glyphosate + glufosinate	867 + 594	1080	290	600	260	730	140
Glyphosate + rimsu + thifen	867 + 8 + 8	1700	370	2450	450	1980	460
Glyphosate + saflufenacil	867 + 50	1590	390	1430	340	1610	390
Glyphosate + thifen + triben + 2,4-D	867 + 5 + 5 + 530	1230	360	1670	410	1730	370
Glyphosate + thifen + triben + dicamba	867 + 5 + 5 + 280	1270	390	1820	380	1240	390
Paraquat[c]	840	830	320	990	350	650	150
Paraquat + metribuzin[c]	560 + 420	560	260	500	160	520	110
Paraquat + metribuzin[c]	560 + 560	520	250	550	180	500	90
Saflufenacil + thifen + triben[d]	50 + 5 + 5	1670	350	1520	380	1560	370
LSD (0.05)		360	70	320	70	310	70

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

[d] Methylated seed oil, 1.0% v/v

Table 4.6. Orthogonal contrasts for percent control and biomass of legume cover crop data collected 4 weeks after treatment. [a,b]

	Austrian winterpea			Crimson clover			Hairy vetch		
Contrast	Control	Fresh	Dry	Control	Fresh	Dry	Control	Fresh	Dry
Contact[c] v. Systemic[d]	***	***	***	***	***	***	***	***	***
2,4-D[e] v. Dicamba[f]	*	NS	*	NS	NS	NS	**	NS	NS
Low dicamba v. High dicamba[g]	***	*	NS	**	NS	*	***	NS	NS
Low 2,4-D v. High 2,4-	***	*	NS	*	NS	NS	**	NS	*

[a] Abbreviations: NS, not significant

[b] Significant at the *p= 0.05 to 0.01, **p= 0.01 to 0.001, ***p ≤0.001 levels

[c] Indicates chemical treatments containing contact herbicide alone or in mixture with systemic herbicide. Contact herbicides included paraquat, glufosinate and saflufenacil

[d] Indicates treatments containing only systemic herbicides such as glyphosate, dicamba and 2,4-D

[e] Indicates treatments containing 2,4-D

[f] Indicates treatments containing dicamba

[g] ‘Low dicamba’ indicates treatments that contained dicamba at 280 g ae ha^{-1}; ‘High dicamba’ indicates treatments that contained dicamba at 560 g ae ha^{-1}

[f] ‘Low 2,4-D’ indicates treatments that contained 2,4-D at 530 g ae ha^{-1}; ‘High 2,4-D’ indicates treatments that contained 2,4-D at 1060 g ae ha^{-1}

Table 4.7. Control of cereal cover crops at 2 and 4 weeks after treatment (WAT) with various herbicides at Fayetteville, AR, averaged over 2015 and 2016.

Herbicide[a]	Rate	Cereal rye		Wheat	
		2 WAT	4 WAT	2 WAT	4 WAT
	g ai or ae ha⁻¹	--------------------- %		--------------------------	
Glufosinate	594	70	79	58	78
Glufosinate + 2,4-D[b]	594 + 530	70	76	56	77
Glufosinate + 2,4-D[b]	594 + 1060	69	77	60	77
Glufosinate + dicamba[a]	594 + 280	71	79	58	76
Glufosinate + dicamba[a]	594 + 560	71	78	57	78
Glyphosate	867	80	100	75	98
Glyphosate + 2,4-D	867 + 530	81	100	75	99
Glyphosate + 2,4-D	867 + 1060	83	100	74	99
Glyphosate + dicamba	867 + 280	81	99	77	99
Glyphosate + dicamba	867 + 560	84	100	75	99
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	83	100	77	100
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	82	100	77	100
glyphosate + glufosinate	867 + 594	81	99	73	92
LSD (0.05)		10	9	12	10

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

[d] Methylated seed oil, 1.0% v/v

Table 4.7. (Cont.) Control of cereal cover crops at 2 and 4 weeks after treatment (WAT) with various herbicides at Fayetteville, AR, averaged over 2015 and 2016.

		Cereal rye		Wheat	
Herbicide[a]	Rate	2 WAT	4 WAT	2 WAT	4 WAT
	g ai or ae ha⁻¹	%			
Glyphosate + rimsu + thifen	867 + 18 + 18	84	100	75	100
Glyphosate + saflufenacil	867 + 50	83	100	76	99
Glyphosate + thifens + tribenuron + 2,4-D	867 + 5 + 5 + 530	82	99	79	100
Glyphosate + thifens + triben + dicamba	867 + 5 + 5 + 280	81	100	77	98
Paraquat[c]	840	78	84	57	75
Paraquat + metribuzin[c]	560 + 420	89	97	75	87
Paraquat + metribuzin[c]	560 + 560	90	98	78	86
LSD (0.05)		10	9	12	10

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;
[b] Nonionic surfactant, 0.25% v/v
[c] Crop oil concentrate, 1.0% v/v
[d] Methylated seed oil, 1.0% v/v

Table 4.8. Cereal cover crop biomass collected 4 weeks after treatment at Fayetteville, AR, averaged over 2015 and 2016.

		Cereal rye		Wheat	
Herbicide[a]	Rate	Fresh	Dry	Fresh	Dry
	g ai or ae ha^{-1}	---------------------- % ---------------------------			
Glufosinate	594	2,850	490	2,120	390
Glufosinate + 2,4-D[b]	594 + 530	1,580	440	1,530	310
Glufosinate + 2,4-D[b]	594 + 1060	1,610	430	1,450	340
Glufosinate + dicamba[a]	594 + 280	1,400	430	1,550	340
Glufosinate + dicamba[a]	594 + 560	1,560	460	1,510	340
Glyphosate	867	1,550	430	1,590	370
Glyphosate + 2,4-D	867 + 530	1,080	440	1,170	310
Glyphosate + 2,4-D	867 + 1060	1,120	420	990	300
Glyphosate + dicamba	867 + 280	1,190	440	1,070	320
Glyphosate + dicamba	867 + 560	1,010	420	1,020	330
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	1,070	450	1,180	330
Glyphosate + flumioxazin + thifens + triben	867 + 44 + 5 + 5	1,090	440	1,180	310
glyphosate + glufosinate	867 + 594	1,140	410	1,010	340
LSD (0.05)		390	60	240	50

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;
[b] Nonionic surfactant, 0.25% v/v
[c] Crop oil concentrate, 1.0% v/v

Table 4.8. (Cont.) Cereal cover crop biomass collected 4 weeks after treatment at Fayetteville, AR, averaged over 2015 and 2016.

		Cereal rye		Wheat	
Herbicide[a]	Rate	Fresh	Dry	Fresh	Dry
	g ai or ae ha⁻¹	---------------------- %		--------------------------	
Glyphosate + rimsulfuron + thifensulfuron	867 + 18 + 18	940	410	1,080	340
Glyphosate + saflufenacil	867 + 50	1,080	440	1,100	320
Glyphosate + thifen + triben + 2,4-D	867 + 5 + 5 + 530	1,110	430	1,060	340
Glyphosate + thifen + triben + dicamba	867 + 5 + 5 + 280	1,140	430	1,070	330
Paraquat[c]	840	1,260	460	1,750	330
Paraquat + metribuzin[c]	560 + 420	1,060	420	1,060	300
Paraquat + metribuzin[c]	560 + 560	1,070	420	1,000	320
LSD (0.05)		390	60	240	50

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

Table 4.9. Rapeseed control at 2 and 4 weeks after treatment (WAT) with various herbicides and biomass production at Fayetteville, AR, averaged over 2015 and 2016.

		Control		Biomass	
Herbicide[a]	Rate	2 WAT	4 WAT	Fresh	Dry
	g ai or ae ha⁻¹	---------- % --------		-------- g m⁻²--------	
Nontreated		0	0	3,400	530
2,4-D[b]	530	33	55	1,630	410
2,4-D[b]	1060	35	62	1,710	420
Dicamba[b]	280	9	16	3,090	460
Dicamba[b]	560	14	21	3,040	490
Glufosinate	594	27	48	2,470	390
Glufosinate + 2,4-D[b]	594 + 530	48	56	1,480	380
Glufosinate + 2,4-D[b]	594 + 1060	59	64	1,480	390
Glufosinate + dicamba[b]	594 + 280	37	46	2,340	410
Glufosinate + dicamba[b]	594 + 560	42	51	2,160	440
Glyphosate	867	22	36	3,120	520
Glyphosate + 2,4-D	867 + 530	32	61	1,690	440
Glyphosate + 2,4-D	867 + 1060	36	65	1,490	430
Glyphosate + dicamba	867 + 280	30	36	2,690	450
Glyphosate + dicamba	867 + 560	35	39	2,650	450
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	47	48	2,180	430
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	30	42	2,130	500
Glyphosate + glufosinate	867 + 594	35	55	1,710	420
LSD (0.05)		12	9	600	80

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

[d] Methylated seed oil, 1.0% v/v

Table 4.9. (Cont.) Rapeseed control at 2 and 4 weeks after treatment (WAT) with various herbicides and biomass production at Fayetteville, AR, averaged over 2015 and 2016.

		Control		Biomass	
Herbicide	Rate	2 WAT	4 WAT	Fresh	Dry
	g ai or ae ha⁻¹	---------- % --------		-------- g m⁻²--------	
Glyphosate + rimsu + thifen	867 + 18 + 18	30	47	1,990	490
Glyphosate + saflufenacil	867 + 25	37	58	1,720	490
Glyphosate + thifen + tribe + 2,4-D	867 + 5 + 5 + 530	46	65	1,460	440
Glyphosate + thifen + tribe + dicamba	867 + 5 + 5 + 330	33	53	2,230	450
Paraquat[c]	840	45	50	2,300	410
Paraquat + metribuzin[c]	560 + 420	47	67	1,320	380
Paraquat + metribuzin[c]	560 + 560	54	71	1,410	400
Saflufenacil + thifen + Triben[d]	25 + 5 + 5	46	60	1,360	430
LSD (0.05)		12	9	600	80

[a] Abreviations: thiefen, thifensulfuron; triben, tribenuron; rimsu, rimsulfuron;

[b] Nonionic surfactant, 0.25% v/v

[c] Crop oil concentrate, 1.0% v/v

[d] Methylated seed oil, 1.0% v/v

Table 4.10. Orthogonal contrasts for percent control and biomass of rapeseed data collected 4 weeks after treatment. [a,b]

	Rapeseed		
Contrast	Control	Fresh	Dry
Contact[c] v. Systemic[d]	***	***	***
2,4-D[e] v. Dicamba[f]	***	***	***
Low dicamba v. High dicamba[g]	*	NS	NS
Low 2,4-D v. High 2,4-D[f]	**	NS	NS

[a] Abbreviations: NS, not significant

[b] Significant at the *p= 0.05 to 0.01, **p= 0.01 to 0.001, ***p ≤0.001 levels

[c] Indicates chemical treatments containing contact herbicide alone or in mixture with systemic herbicide. Contact herbicides included paraquat, glufosinate and Saflufenacil.

[d] Indicates treatments containing only systemic herbicides such as glyphosate, dicamba and 2,4-D

[e] Indicates treatments containing 2,4-D

[f] Indicates treatments containing dicamba

[g] 'Low dicamba' indicates treatments that contained dicamba at 280 g ae ha^{-1}; 'High dicamba' indicates treatments that contained dicamba at 560 g ae ha^{-1}

[f] 'Low 2,4-D' indicates treatments that contained 2,4-D at 530 g ae ha^{-1}; 'High 2,4-D' indicates treatments that contained 2,4-D at 1060 g ae ha^{-1}

Chapter 5

Sensitivity and Likelihood of Residual Herbicide Carryover to Cover Crops

Abstract

Research was conducted to evaluate the sensitivity of cover crops to a low rate of soil-applied herbicides and investigate the likelihood of herbicide carryover to fall-seeded cover crops following an irrigated corn crop. Herbicides were applied at a 1/16X rate (to simulate 4 half-lives) one day after cover crop planting in the sensitivity study whereas a 2X rate of residual herbicides were applied at the maximum label corn height or growth stage and cover crops sown immediately after corn harvest. In the sensitivity experiment, herbicides such as atrazine, diuron, sulfentrazone, pyrithiobac, fluridone, metribuzin, and fomesafen reduced emergence of the legume cover crops Austrian winterpea, crimson clover, and hairy vetch. However, negative affects on biomass production of legume cover crops in the spring were only observed for atrazine, fluridone, and pyrithiobac. Similarly for rapeseed, atrazine, tembotrione, flumioxazin, sulfentrazone, pyroxasulfone, pyrithiobac, and fluridone decreased cover crop emergence, but biomass production was only reduced by atrazine and fluridone. Conversely, the cereal cover crops wheat, cereal rye, barley, oats, and triticale were not affected by soil-applied herbicide. Barley was the unique cereal cover crop that showed biomass reduction due to the application of mesotrione, flumioxazin, sulfentrazone, *S*-metalochlor, and fluridone. In the carryover study, with the exception of crimson clover, the cover crops Austrian winterpea, cereal rye, hairy vetch, rapeseed, and wheat showed no negative affect on biomass production following a 2X rate of residual herbicide in corn.

Nomenclature: Atrazine; diuron; flumioxazin; fluridone; mesotrione; metribuzin; pyroxasulfone; pyrithiobac; *S*-metolachlor; sulfentrazone; tembotrione; Austrian winterpea,

Lathryrus hirsutus L.; barley, *Hordeum vulgare* L.; cereal rye, *Secale cereale* L.; corn, *Zea mays* L.; crimson clover, *Trifolium incarnatum* L., hairy vetch, *Vicia villosa* Roth; oats, *Avena sativa* L.; rapeseed, *Brassica napus* L.; triticale, *Triticale hexaploide* Lart.; wheat, *Triticum aestivum* L.

Key words: Cover crops, carryover, emergence, biomass production

Introduction

Cover crops offer growers financial, agronomic, and environmental benefits, especially in a no-till production system. The environmental benefits of these conservational practices, such as decreased soil loss and less fuel usage, have been widely reported (Fu et al. 2006; Gyssels et al. 2005; Nearing et al. 2005). However, the adoption of cover crops often removes mechanical weed removal as an option, placing greater reliance on herbicides. In addition, the appearance of new cases of herbicide-resistant weeds has limited postemergence options for use in row crops and contributed to greater use of residual herbicides (Young 2006).

Establishing an adequate cover crop stand is the first step and possibly the most important factor to achieve the benefits that cover crops can offer an agricultural system (Keeling et al. 1996; Walsh et al. 1993). Adequate equipment, planting method, appropriate seedbed, planting date, and seeding rate are some factors that play a role in the cover crop establishment. In addition, some residual herbicides applied in row crops can affect cover crop germination and emergence in the fall (Rogers et al. 1986). According to Walsh et al. (1993), metribuzin plus chlorimuron applied at 0.40 kg ai ha^{-1} and 0.039 kg ai ha^{-1} pre-plant incorporated in soybean resulted in an average alfalfa (*Medicago sativa* L.) biomass reduction of 72%. In contrast, the same herbicide treatment did not affect hairy vetch and cereal rye. Allister and Kogan (2005) also observed that imazapyr (20 g ai ha^{-1}) plus imazapic (120 g ai ha^{-1}) reduced by 22%, 75% and 63% the fresh weight of pea (*Pisum sativum* L.), alfafa, and ryegrass (*Lolium multiflorum* L.), respectively. Similarly, Tharp and Kells (2000) conducted a greenhouse study and reported that *S*-metolachlor and pendimethalin applied at 2.24 kg ai ha^{-1} and 1.68 kg ai ha^{-1} reduced Italian ryegrass density up to 94% and 46%, respectively.

The rate of herbicide degradation is dependent on soil characteristics such as pH, texture, organic matter, and cation exchange capacity (Walker and Barnes 1981; Anderson 1984). The effect of soil pH on herbicide persistence is known to play an important role for sulfonylureas and imidazolinones. Soil persistence of herbicides like imazaquin and imazethapyr have been found to be greater in low pH soils because greater adsorption, which results in lower availability for microbial degradation (Loux and Reese 1992). Rogers et al. (1986) concluded that injury to hairy vetch and wheat from trifluralin, fluometuron, and linuron differed significantly among soil textures (Sharkey silty > Dundee silty > Loring silt loam). Westra et al. (2014) found that the half-life of pyroxasulfone at 0.28 kg ai ha^{-1} ranged from 104 to 137 days in a fine clay loam and from 46 to 48 days in a fine sandy loam. In summary, the carryover effect of herbicides to cover crops varies with weather and soil characteristics.

Few studies have reported the potential of herbicide carryover applied in row crops to cover crops. With cover crop acreage increasing in the U.S., this information has become important to avoid problems at cover crop establishment (SARE 2015). Hence, the objective of these studies are to identify the sensitivity of cover crops to a low rate of soil-applied herbicides on a silt loam soil and to investigate the likelihood of herbicide carryover to fall-seeded cover crops following corn harvest. It is recognized that the “sensitivity trial” does not adequately assess the risk for carryover, but does help to refine the list of herbicides that should be evaluated for carryover to cover crops. Furthermore, these results may provide an indication as to which crops have some tolerance to various herbicides, aiding weed control in the establishment phase of the cover crop.

Materials and methods

Sensitivity Study. A field experiment was initiated in the fall of 2014 and 2015 at the University of Arkansas Agricultural Research & Extension Center in Fayetteville to evaluate the sensitivity of cover crops to a low rate of soil-applied herbicides, mainly ones labeled for use in cotton (*Gossypium hirsutum* L.), corn, and soybean (*Glycine max* L. Merr.). In both years, the experiment was conducted on a Razort silt loam soil (Fine-loamy, mixed, active, mesic Mollic Hapludalfs) with 19% sand, 67% silt, 14% clay, 6.2 pH, and 1.3% organic matter. The experimental design was a randomized complete block with a strip-plot. Four replications were used with the strip plot being the cover crops species and the sub-plot being the herbicide treatment. Cover crops were planted on September 9, 2014 and September 19, 2015 using a 10-row Almaco Light-Duty Grain Drill with a single drop cone (Almaco Headquarters, Nevada, Iowa 50201). Prior to cover crop sowing, the field was tilled to an approximate 10-cm depth using a disk followed by two passes of a field cultivator at a 5-cm depth. Herbicide treatments served as the main plot (Table 5.1) and cover crops as the strip plot (Table 5.2). Herbicides were applied at a 1/16X labeled rate for either cotton, corn, or soybean. One day after cover crop planting, the herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat fan nozzles (TeeJet®, Spraying Systems Co., Wheaton, IL.) delivering 140 L ha^{-1}. The day after the herbicide application, the experimental site was irrigated (1.3 cm) using a traveling gun sprinkler to aid herbicide activation. Monthly rainfall for each year are presented in Table 5.3.

Carryover Study. A field experiment was initiated in the summer of 2014 and 2015 at the University of Arkansas Agricultural Research & Extension Center in Fayetteville to evaluate the risk of carryover of residual herbicides applied in corn to cover crops planted after harvest. In both years, the experiment was conducted on a Captina silt loam soil (Fine-silty, siliceous, active, mesic Typic Fragiudults) with 33% sand, 49% silt, 18% clay, pH 6.0, and 1.0% organic matter. Dekalb 46-36 corn hybrid was planted with a four-row planter (John Deere 6403; Deere and Company, Moline, IL 61265) equipped with double-disk openers set to a 91-cm-wide row spacing at a seeding rate of 62,000 seeds ha^{-1}. Corn was planted on April 10, 2014 and April 3, 2015. The experimental design was a randomized complete block with a strip-plot and four replications. Herbicide treatments served as the main plot (14.6 m by 7.2 m) and cover crops as the strip-plot (1.9 m by 7.2 m). The herbicide treatments were applied at the latest stage of the corn crop allowed in each herbicide label at a 2X rate (Table 5.4). Herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with AIXR 110015 flat fan nozzles (TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL.) delivering 140 L ha^{-1}. Cover crops were sown on September 9, 2014 and September 21, 2015 and included cereal rye (90 kg ha^{-1}), wheat (90 kg ha^{-1}), Austrian winterpea (84 kg ha^{-1}), hairy vetch (22 kg ha^{-1}), crimson clover (15 kg ha^{-1}), and rapeseed (11 kg ha^{-1}). Prior to cover crop sowing, the field was lightly disked in the direction of the corn rows. Cover crops were broadcasted in strips 1.9 by 90 m followed by one more light tillage operation. Monthly rainfall data are presented in Table 3.3.

Data Collection. For both experiments, all cover crops species were evaluated for stand reduction and biomass reduction relative to the nontreated control. At 14 days after treatment (DAT), cover crop density was determined by counting all emerged plants within a random 0.5 m^2 quadrat in every subplot. Similarly, aboveground biomass was collected from the same quadrat from which stand counts were taken. Aboveground biomass of summer cover crops were collected the day following the first frost each year in the sensitivity study whereas aboveground biomass of winter cover crops were collected the following spring in both experiments. Biomass samples were weighed after air-drying at 65 C for 5 days. Percentage stand and biomass reduction were calculated relative to the nontreated control plots.

Data Analyses. All stand and biomass reduction data were analyzed in JMP 12 PRO (JMP, Version 12. SAS Institute Inc., Cary, NC). The analyses of stand and biomass reduction were performed by individual cover crops since the objective of the study was to identify the sensitivity of each cover crop to the residual herbicides. Herbicide treatment was considered a fixed effect in the model while replication was considered a random effect. No interaction was observed between herbicide treatment and year on stand and biomass reduction; hence, year was also considered a random effect. Means were separated using Fisher's protected LSD at $\alpha=0.05$.

Results and Discussion

Sensitivity Study. Analysis of cover crop densities showed that several herbicides significantly reduced legume cover crop emergence (Table 5.5). The stand reduction provided by the photosynthesis II (PSII)-inhibiting herbicides atrazine, diuron, and metribuzin on legume cover crops ranged from 23% to 40%. Hairy vetch was only affected by atrazine whereas crimson clover and Austrian winterpea were affected by all PSII herbicides, except for fluometuron. Kells et al. (1990) reported that atrazine applied at 2.2 kg ha^{-1} to corn provided 5% to 72% injury to alfalfa (*Medicago sativa* L.) planted the following year.

The 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides isoxaflutole, mesotrione, and tembotrione reduced Austrian winterpea emergence by 29%, 24%, and 21%, respectively. Among HPPD-inhibiting herbicides, only isoxaflutole reduced stand of crimson clover (27%); albeit, there was no reduction in biomass the following spring. No HPPD-inhibiting herbicide had a significant effect on hairy vetch stand or biomass (Table 5.6). Riddle et al. (2013) conducted a study to evaluate the sensitivity of several vegetable crops to mesotrione. Results showed that application of a simulated carryover rate of mesotrione (28 g ha^{-1}) injured pea (*Pisium* sativum L.) by 11% and reduced yield by 19%.

Sulfentrazone was the only protoporphyrinogen oxidase (PPO)-inhibiting herbicide that decreased Austrian winterpea emergence (20%). Differently, flumioxazin, fomesafen, and sulfentrazone decreased emergence of crimson clover by 30%, 34%, and 27% whereas only fomesafen decreased hairy vetch emergence by 25%.

The very long chain fatty acid (VLCFA) herbicides acetochlor and metolachlor also differed in their effect on legume cover crop emergence. While acetochlor did not reduce emergence of any legume cover crop, *S*-metolachlor reduced Austrian winterpea and crimson clover by 18% and 22%, respectively.

The two acetolactate synthase (ALS)-inhibiting herbicides behaved differently. Pyrithiobac reduced Austrian winterpea, crimson clover, and hairy vetch emergence compared to the nontreated check, but trifloxysulfuron had no affect on legume cover crop emergence. A study conducted in Mississippi showed that application of pyrithiobac 86 g ha^{-1} to bare soil injured soybean planted 357 days after application (Smith et al. 2005).

Although several herbicides were detrimental to legume cover crop emergence, most of these reductions did not affect biomass production the subsequent spring. Among all herbicide treatments, only atrazine, fluridone, and pyrithiobac reduced biomass production of all legume cover crops evaluated (Table 5.5). Several reports confirm that atrazine residues can affect row crop and cover crop establishment (Burnside et al. 1971; Burnside et al. 1980; Smika and Sharman 1983). Robinson (2008) reported that atrazine at 560 g ha^{-1} applied to corn one year before transplanting carrot (*Dacus carota* L.), cucumber (*Cucumis sativus* L.), and onion (*Allium* *cepa* L.) reduced yield by 25%, 67%, and 32%, respectively. In addition, Rafii and Ashton (1971) observed in a greenhouse trial that soybean treated with a 1/8 X rate of fluridone had reduced shoot length, shoot weight, severe chlorosis, and inhibition of trifoliate formation. Webster and Shaw (1996) also reported that pyrithiobac applied at 140 g ha^{-1} pre-plant incorporated (PPI) to cotton reduced soybean yield the following year. Based on results by Webster and Shaw (1996) and the results of this experiment, it is likely that pyrithiobac would affect small-seeded broadleaf cover crop establishment in the fall. However, all herbicides cited above have different persistence levels depending upon the soil characteristics and environmental conditions. Factors such as soil pH, soil texture, organic matter, temperature, and rainfall amount can drastically influence herbicide persistence in the soil (Smith et al. 2005; Pussemier et al. 1997; Shea and Weber 1983).

Higher level of tolerance were observed on the cereal cover crops (Table 5.6). Among PSII herbicides, just atrazine reduced emergence of barley (20%) and oats(16%) and diuron reduced barley (13%), oats (18%), and wheat (11%) emergence. Ivany et al. (1984) reported that in a three-year study, application of atrazine at 1.12 kg ha^{-1} in corn did not show any effect on cereal rye and barley planted approximately 3 months later. The HPPD herbicide ixosaflutole reduced stands of oats by 15% and wheat stands by 11%. Mesotrione also was detrimental to cereal rye (11% emergence reduction) and oats (13% emergence reduction). The PPO herbicides flumioxazin, sulfentrazone, and fomesafen were injurious to some cereal cover crops (Table 5.6). *S*-metolachlor was the only VLCFA herbicide that reduced stand of cereal cover crops. Barley emergence was reduced 19% by *S*-metolachlor whereas oats and wheat emergence were reduced 18% and 12%, respectively. Trifloxysulfuron was the most harmful ALS-inhibiting herbicide, reducing stands of oats by 17%. Barley and oats were the only cereal cover crops that were sensitive to fluridone. Atrazine and fluridone were generally the most injurious to rapeseed based on stand and biomass reduction (Table 5.7).

Similarly to winter cover crops, the sensitivity of summer cover crops also varied depending upon the cover crop species and herbicide (Table 5.8). Low rates of atrazine, isoxaflutole, mesotrione, pyrithiobac, and fluridone reduced berseem clover (*Trifolium alexandrinum* L.) emergence. However, the reduction of emergence only translated to reduced biomass in the atrazine, pyrithiobac, and fluridone treatments. Buckwheat (*Fagopirum esculentum* L.) on the contrary was sensitivite to several herbicide treatments, with stand loss ranging from 13% to 28%. Based on biomass data though, only atrazine, mesotrione, pyrithiobac, trifloxysulfuron, and fluridone negatively affected buckwheat (Table 5.8). The remaining summer cover crops cowpea (*Vignia unguiculata* L.), sunflower (*Helianthus annuus* L.), and sunn hemp (*Crotalaria juncea* L.) were tolerant to a 1/16X rate of the evaluated herbicides. Johnson and Talbert (1996) observed that application of fomesafen at 0.28 kg ha^{-1} did not injure sunflower planted 16 weeks after the application. Seed size of the cover crops seems to be an important factor in this study as seen in other research (Ghersa and Martinez-Ghersa 2000). Regardless of the herbicide, cover crops that had smaller seed appeared to be more affected by a low rate of herbicides compared to the large-seeded cover crops (Table 5.8).

Carryover Study. Results from the carryover study show that there is a low risk of herbicide carryover from residual herbicides commonly applied in corn to winter cover crops (Table 5.9). None of the herbicides used in the study had any impact on emergence and biomass production of Austrian winterpea. Similarly, none of the herbicides reduced crimson clover emergence; however, biomass production of crimson clover was significantly reduced by atrazine (13%), pendimenthalin (10%), pyroxasulfone (12%) and *S*-metolachlor (11%). Cereal rye and wheat emergence were only affected by pyroxasulfone. No reduction in biomass occurred in any herbicide-treated plot. These results sharply contrast with Ivany et al. (1984) findings. They observed 81 to 90% dry matter reduction for cereal rye following atrazine at 4.5 kg ha^{-1} in corn. However, these results may be due to Ivany et al. (1984) conducting the field trial in a sandy soil with no irrigation.

Practical Implication. The sensitivity study shows that in the large array of cover crops evaluated there are several species that are sensitive to a low rate of residual herbicides commonly applied in soybean, corn, and cotton. It appears that small-seeded broadleaf cover crops are more likely to be affected by low concentrations of residual herbicides in the soil. Large-seeded cover crops such as cereal winter cover crops were tolerant to all herbicides used in this experiment. Long-term evaluation in different sites would provide a better understanding of the risks of planting cover crops subsequently to application of residual herbicides.

The carryover study provided evidence that herbicides commonly applied to irrigated corn have low risk for carryover to winter cover crops. The application of 2X rates of residual herbicides did not impact emergence and biomass production of cover crops. However, it is important to emphasize that persistence of herbicides in soils are likely to change depending on many factors such as soil texture, temperature, pH, organic matter, rainfall, and irrigation regime (Walker and Barnes 1981). Hence, these results cannot be generalized because all these factors are likely linked to geographic regions. For example, Cornelius and Bradley (2016) conducted a carryover study to cover crops in Missouri and observed different levels of carryover between years due to differing amounts of rainfall each year. The extent of carryover from the herbicides evaluated in their study to cover crops was generally higher than in this research. However, their research was conducted under dryland conditions whereas this study was conducted under furrow-irrigated conditions, which is typical of corn production in Arkansas.

Literature Cited

Alister C, Kogan M (2005) Efficacy of imidazolinone herbicides applied to imidazolinone-resistant maize and their carryover effect on rotational crops. Crop Prot 24:375-379

Anderson JP (1984) Herbicide degradation in soil: influence of microbial biomass. Soil Biol Biochem 16:483-489

Cornelius CD, and Bradley KW (2016) Carryover of common corn and soybean herbicides to various cover crop species. Weed Technol in press

Riddle RN, O'Sullivan J, Swanton CJ, Van Acker RC (2013) Crop response to carryover of mesotrione residues in the field. Weed Technol 27:92-100

Anderson, MB (2014) Interactions between cover crops and weed management in Iowa's conventional cropping systems. Graduate Theses and Dissertations. Paper 14087. http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=5094&context=etd. Accessed August 4, 2016

Burnside OC, Wicks GA (1980) Atrazine carryover in soil in a reduced tillage crop production system. Weed Sci 28:661-666

Fu G, Chen S, McCool DK (2006) Modeling the impacts of no-till practice on soil erosion and sediment yield with RUSLE, SEDD, and ArcView GIS. Soil Till Research 85:38-49

Ghersa CM, Martınez-Ghersa MA (2000) Gyssels G, Poesen J, Bochet E, Li Y (2005) Impact of plant roots on the resistance of soils to erosion by water: a review. Prog Phys Geogr 29:189-217

Ivany JA, Sadler JM, Kimball ER, McRae KB (1985) Atrazine persistence and residue effects on rotation crops. Can J Plant Sci 65:363-36

Keeling JW, Matches AG, Brown CP, Karnezos TP (1996) Comparison of interseeded legumes and small grains for cover crop establishment in cotton. Agron J 88:219-222

Kells JJ, Leep RH, Tesar MB, Leavitt RA, Cudnohufsky J (1990) Effect of atrazine and tillage on alfalfa *(Medicago sativa*) establishment in corn (*Zea mays*)-alfalfa rotation. Weed Technol 4:360-365

Loux MM, Reese KD (1992) Effect of soil pH on adsorption and persistence of imazaquin. Weed Sci 40:490-496

Nearing MA, Jetten V, Baffaut C, Cerdan O, Couturier A, Hernandez M, Le Bissonnais Y, Nichols MH, Nunes JP, Renschler CS, Souchère V (2005) Modeling response of soil erosion and runoff to changes in precipitation and cover. Catena 61:131-54

Rafii ZE, Ashton FM (1979) Influence of site of uptake of fluridone on early development of soybean (*Glycine max*) and cotton (*Gossypium hirsutum*). Weed Sci 27:321-327

Robinson DE (2008) Atrazine accentuates carryover injury from mesotrione in vegetable crops. Weed Technol 22:641-645

Rogers CB, Talbert R, Frans R (1986) Effect of cotton (*Gossypium hirsutum*) herbicide carryover on subsequent crops. Weed Sci 34:756-60

SARE (2015) Cover Crop Survey Analysis. Sustainable Agriculture Research and Education. http://www.sare.org/Learning-Center/From-the-Field/North-Central-SARE-From-the-Field/2015-Cover-Crop-Survey-Analysis. Accessed August 4, 2016

Shea PJ, Weber JB (1983a) Effect of soil pH on fluridone activity and persistence as determined by chlorophyll measurements. Weed Sci 31:347-350

Smith MC, Shaw DR, Miller DK (2005) In-field bioassay to investigate the persistence of imazaquin and pyrithiobac. Weed Sci 53:121-129

Tharp BE, Kells JJ (2000) Effect of soil-applied herbicides on establishment of cover crop species. Weed Technol 14:596-601

Walker A, Barnes A. (1981) Simulation of herbicide persistence in soil; a revised computer model. Pestic Sci 12:123-132

Walsh JD, Defelice MS, Sims BD (1993) Soybean (*Glycine max*) herbicide carryover to grain and fiber crops. Weed Technol 7:625-632

Westra EP, Shaner DL, Westra PH, Chapman PL (2014) Dissipation and leaching of pyroxasulfone and *S*-metolachlor. Weed Technol 28:72-81

Young BG (2006) Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol 20:301-307

Table 5.1. Herbicide information for all products used in the sensitivity study.

Common name	Trade name	Rate	Manufacturer	Address
		g ai ha^{-1}		
Acetochlor	Harness	140	Monsanto Company	St. Louis, MO
Atrazine	Aatrex	140	Syngenta Crop Protection, LLC	Greensboro, NC
Diuron	Diurex	70	Drexel Chemical Company	Memphis, TN
Flumioxazin	Valor	4.5	DuPont Crop Protection	Wilmington, DE
Fluometuron	Cotoran	70	Makhteshim Agan of North America	Raleigh, NC
Fluridone	Brake	17.5	SePRO Corporation	Carmel, IN
Fomesafen	Flexstar	25.5	Bayer CropScience LP	Research Triangle Park, NC
Imazethapyr	Pursuit	4.5	BASF Corporation	Research Triangle Park, NC
Isoxaflutole	Balance Pro	5.7	Bayer CropScience LP	Research Triangle Park, NC
Mesotrione	Callisto	6.6	Bayer CropScience LP	Research Triangle Park, NC
Metribuzin	Metribuzin 75	35	DuPont Crop Protection	Wilmington, DE
Pyrithiobac	Staple	5	DuPont Crop Protection	Wilmington, DE
Pyroxasulfone	Zidua	9.3	BASF Corporation	Research Triangle Park, NC
S-metolachlor	Dual Magnum	87	Syngenta Crop Protection, LLC	Greensboro, NC
Sulfentrazone	Spartan	17.5	FMC Corporation	Philadelphia, PA
Tembotrione	Laudis	5.7	Bayer CropScience LP	Research Triangle Park, NC
Trifloxysulfuron	Envoke	0.5	Syngenta Crop Protection, LLC	Greensboro, NC

Table 5.2. List of cover crop species with their respective seeding rate used in the sensitivity study.

Cover crop	Seeding rate
	kg ha^{-1}
Cereal rye	90
Oats	90
Barley	90
Wheat	90
Triticale	90
Australian winterpea	84
Hairy vetch	22
Crimson clover	15
Rapeseed	11
Berseem clover	11
Buckwheat	67
Sunn hemp	56
Cowpea	67
Sunflower	28

Table 5.3. Monthly rainfall for 2014-2015 and 2015-2016 for the sensitivity study.

Year	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
	———	———	———	mm	———	———	———	———
2014-2015[a]	114	165	10	73	14	1	82	81
2015-2016[b]	47[c]	58[d]	106	322	7	15	84	99

[a] Planting date: September 9, 2014

[b] Planting date: September 19, 2015

[c] 2.5 cm of irrigation was applied September 2015 for the sensitivity study

[d] 1.3 cm of irrigation was applied October 2015 for the sensitivity study

Table 5.4. Herbicide information for all products used in the carryover study.

Common name	Trade name	Rate	Application stage	Manufacturer	Address
		g ai ha^{-1}			
Atrazine	Aatrex	4480	31 cm	Syngenta Crop Protection, LLC	Greensboro, NC
Pyroxasulfone	Zidua	480	V4	BASF Corporation	Research Triangle Park, NC
Tembotrione + Thiobencarbazone-methyl	Capreno	144.4 + 35.6	V5	Bayer CropScience LP	Research Triangle Park, NC
Mesotrione	Callisto	210	V8	Bayer CropScience LP	Research Triangle Park, NC
Tembotrione	Laudis	185	V9	Bayer CropScience LP	Research Triangle Park, NC
Acetochlor	Harness	4626	76 cm	Monsanto Company	St. Louis, MO
Dimethenamid	Outlook	2208	92 cm	BASF Corporation	Research Triangle Park, NC
S-metolachlor	Dual Magnum	4283	102 cm	Syngenta Crop Protection, LLC	Greensboro, NC

Table 5.5. Influence of 1/16 X rate of residual herbicides on stand and biomass reduction of legume winter cover crops in Fayetteville, Arkansas averaged over 2014-2015 and 2015-2016.[a,b,c]

	Austrian winterpea		Crimson clover[d]		Hairy vetch[e]	
Herbicide	Stand	Biomass	Stand	Biomass	Stand	Biomass
	----------------------------------% reduction					--------------------------------
Atrazine	23	15	64	30	40	25
Diuron	24	1	34	9	18	0
Fluometuron	0	2	15	3	14	4
Metribuzin	23	2	31	0	18	0
Isoxaflutole	29	3	27	0	7	5
Mesotrione	24	3	11	0	11	0
Tembotrione	21	4	5	2	6	1
Flumioxazin	14	0	30	13	33	9
Fomesafen	14	0	34	0	25	5
Sulfentrazone	20	2	27	0	15	3
Acetochlor	16	2	9	0	12	0
Pyroxasulfone	12	2	39	0	8	2
S-metolachlor	18	0	22	0	13	0
Imazethapyr	15	0	26	0	16	0
Pyrithiobac	43	15	54	33	44	32
Trifloxysulfuron	3	5	12	3	16	4
Fluridone	30	29	54	30	26	21
LSD (0.05)	16	13	22	19	22	15

[a] Stand counts were taken 14 days after treatment.

[b] Biomass samples were collected in the spring of the following year.

Table 5.6. Influence of 1/16 X rate of residual herbicides on stand and biomass reduction of cereal cover crops in Fayetteville, Arkansas averaged over 2014-2015 and 2015-2016. [a,b]

	Barley		Cereal rye		Oat		Triticale		Wheat	
Herbicide	Stand	Biomass	Stand	Biomass	Stand	Biomass	Stand	Biomass	Stand	Biomass
	——————————————% reduction——————————————									
Atrazine	20	17	0	2	16	0	4	4	6	2
Diuron	4	13	0	2	18	2	7	0	11	0
Fluometuron	0	7	0	0	10	2	5	3	8	2
Metribuzin	10	13	5	2	0	2	2	1	1	0
Isoxaflutole	10	5	0	0	15	0	6	1	11	0
Mesotrione	12	5	11	3	13	3	7	0	5	0
Tembotrione	6	13	9	0	0	1	0	0	0	0
Flumioxazin	15	5	5	0	0	0	2	4	5	0
Fomesafen	9	13	10	0	19	4	13	0	9	0
Sulfentrazone	14	17	5	2	0	0	4	0	0	0
Acetochlor	7	0	0	0	0	2	0	0	8	0
Pyroxasulfone	9	8	2	1	0	0	7	0	7	0
S-metolachlor	19	9	0	0	18	2	10	4	12	1
Imazethapyr	0	7	3	2	0	3	5	0	1	0
Pyrithiobac	6	15	7	0	0	0	1	2	6	0
Trifloxysulfuron	2	9	0	4	17	6	0	0	9	0
Fluridone	14	13	0	0	17	0	0	0	0	3
LSD (0.05)	12	9	9	NS	11	NS	10	NS	10	NS

[a] Stand counts were taken 14 days after treatment.

[b] Biomass samples were collected in the spring of the following year.

Table 5.7. Influence of 1/16 X rate of residual herbicide on stand and biomass reduction of a rapeseed cover crop in Fayetteville, Arkansas, averaged over 2014-2015 and 2015-2016. [a,b]

	Rapeseed	
Herbicide	Stand	Biomass
	------------ % reduction -----------	
Atrazine	24	20
Diuron	15	11
Fluometuron	17	11
Metribuzin	16	6
Isoxaflutole	6	11
Mesotrione	11	4
Tembotrione	20	13
Flumioxazin	27	9
Fomesafen	17	8
Sulfentrazone	21	9
Acetochlor	7	0
Pyroxasulfone	19	10
S-metolachlor	18	13
Imazethapyr	2	11
Pyrithiobac	19	6
Trifloxysulfuron	2	0
Fluridone	37	22
LSD (0.05)	19	13

[a] Stand counts were taken 14 days after treatment.

[b] Biomass samples were collected in the spring of the following year.

Table 5.8. Influence of 1/16 X rate of residual herbicide on stand and biomass reduction of summer cover crops in Fayetteville, Arkansas, averaged over 2014-2015 and 2015-2016. [a,b]

	Berseem clover		Buckwheat		Cowpea		Sunflower		Sunn hemp	
Herbicide	Stand	Biomass	Stand	Biomass	Stand	Biomass	Stand	Biomass	Stand	Biomass
	------------------------------% reduction------------------------------									
Atrazine	38	40	27	32	8	0	18	13	3	2
Diuron	4	0	16	4	20	7	12	6	7	0
Fluometuron	14	5	16	6	15	3	12	3	10	10
Metribuzin	6	1	17	3	13	0	8	0	0	0
Isoxaflutole	20	7	9	5	13	0	18	4	13	3
Mesotrione	21	2	20	11	7	0	4	0	14	5
Tembotrione	0	3	9	0	4	0	0	0	5	7
Flumioxazin	1	7	15	8	0	1	20	9	3	6
Fomesafen	0	0	20	9	21	3	11	5	0	6
Sulfentrazone	4	0	13	6	14	5	0	2	3	5
Acetochlor	21	6	13	0	8	0	0	4	0	3
Pyroxasulfone	0	1	16	7	0	0	0	0	8	0
S-metolachlor	16	4	15	7	6	0	3	2	2	5
Imazethapyr	4	3	3	4	21	4	5	5	7	0
Pyrithiobac	29	33	15	13	24	0	20	5	21	9
Trifloxysulfuron	1	2	18	10	10	6	0	9	0	4
Fluridone	24	40	28	30	16	3	1	8	17	6
LSD (0.05)	20	12	12	10	23	6	13	NS	15	NS

[a] Stand counts were taken 14 days after treatment.

[b] Biomass samples were collected in the spring of the following year.

Table 5.9. Influence of residual herbicide applied in corn on stand and biomass reduction of winter cover crops in Fayetteville, Arkansas, averaged over 2014-2015 and 2015-2016.[a]

	Austrian winterpea		Cereal rye		Crimson clover		Hairy vetch		Rapeseed		Wheat	
Herbicide	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass	Stand	Bio-mass
	---------- % reduction ----------											
Acetochlor	4	7	8	1	1	6	4	0	4	3	1	0
Atrazine	3	2	1	0	10	13	13	5	13	7	5	4
Mesotrione	9	2	4	2	5	0	3	1	13	5	0	3
Pendimethalin	10	3	8	3	2	10	3	3	14	3	5	2
Pyroxasulfone	5	9	12	4	5	12	16	6	11	7	11	8
S-metolachlor	11	5	9	5	3	11	14	4	14	6	8	5
Tembotrione	2	7	4	0	6	9	12	2	15	5	3	4
Tembotrione + Thiencarbazone-methyl	1	0	0	1	9	8	0	3	5	0	1	0
LSD (0.05)	NS	NS	11	NS	NS	10	14	NS	NS	NS	9	NS

[a] Rates of each treatment described in Table 4

General Conclusion

Cover crop use in agricultural systems have proved to be benefitial to the sustainability of agriculture. As demonstrated, cover crops can be used to suppress weed emergence early in the season, nevertheless, it should be used integrated to an herbicide program to achieve acceptable weed control and higher yields. Cereal cover crops, especially cereal rye, confirmed to be more efficient on weed suppression due to the capacity of producing greater amount of biomass and longer persistence than legume and brassica cover crops. Physical suppression of Palmer amaranth and other weeds with cereal residues is most likely the greatest contributor to reducing weed emergence. Increasing the cereal seeding rate can be utilized to obtain greater amount of cereal rye biomass and consequently superior weed suppression. Establish a cotton crop into cereal rye residue can be difficult due to the physical interference of the residue. Reduction on cotton stand can eventually lead to yield decrease.

Proper cover crop dessication prior to crop planting is vital to achieve success with cover crop. A poorly terminated cover crop can become a weed and lessen the yield potential of the current cash crop. With the herbicide option currently available in the market, farmers should be properly able to terminate a large aray of cover crops prior to crop planting. Futhermore, some residual herbicides commonly used in row crops has the pontential to affect the establishment and development of a cover crop. However, in the Arkansas corn production system, is unlikely that residual herbicides will damage cover crop performance. In summary, these experiments show that cover crops can effectively be used in a weed management program in Arkansas agricultural system.