**Evaluation of Integrated Weed Management and Herbicide Tolerance in Peanut-Cotton Rotation**

by

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**Abstract**

As resistant weeds such as Palmer amaranth (*Amaranthus palmeri* L.) continue to spread through the Southeast, peanut-cotton producers are forced to utilize herbicides which pose a greater risk to injuring crops to control weeds. Peanut producers are further limited by the number of labeled herbicides available. Evaluating alternative non-chemical weed control methods utilizing cover crops is imperative for the future of peanut production. A series of field experiments were designed to assess peanut and cotton tolerance to select herbicides known to cause injury and to evaluate integrated weed management utilizing cover crops with residual herbicides. The first study evaluated peanut tolerance to evaluate the effect of PPO-inhibitor herbicide treatments on dryland peanut growth and yield when applied during reproduction stages: 60 (R4-R5), 75 (R6), and 90 days (R6-R7) after planting as well as combinations with different surfactants. Treatments including high surfactant oil concentrate were more likely to cause injury and yield loss than those with non-ionic surfactants. Treatments applied at 75 days after planting (DAP) were more likely to cause yield loss than those applied at 60 to 90 DAP. The second study evaluated the effect of paraquat based herbicide programs on newer peanut cultivars growth and yield. Data indicated peanut stunting may be observed following applications of paraquat tank mixes evaluated in this study, but it is unlikely these effects result in yield loss. The third study evaluated sensitive cotton stunting and yield responses resulting from 2,4-D or dicamba residues in soil after preplant burndown applications at 3 weeks prior to planting and day of planting. The data suggests stunting and stand reduction may occur if susceptible varieties are planted soon after burndown applications with 2,4-D or dicamba, but yield may not be affected after a full growing season. Dicamba showed greater potential to cause

stunting and stand reduction than 2,4-D. Incorporating cover crops has shown to help reduce weed emergence and pressure along with providing many additional agronomic benefits. However, residual herbicides can affect fall seeded cover crop establishment reducing weed suppressive qualities. The objective of the fourth trial was to investigate the responses of six cover crops (daikon radish, cereal rye, oat, crimson clover, winter wheat, and common vetch) to 12 soil residual herbicides commonly used in peanut-cotton rotation. Overall, no significant biomass reductions were observed for any cover crop species, with oats showing the most tolerance with no treatments reducing any growth parameters evaluated. Although initial injury and stunting may occur, biomass at termination of cover crops were not affected by herbicide residues evaluated in this study. As more farmers utilize no till or minimum tillage practices, previous herbicide programs need to also be evaluated to determine if they are still effective or necessary for early season weed control. Cover crop residues could prevent residual herbicides from reaching the soil surface, allowing weeds to germinate where there are gaps in the residues. The objectives of this trial were to (1) evaluate the effectiveness of residual herbicides on weed control in conventionally tilled versus high cover crop residue systems, (2) determine if weed control was greater with the combination of cover crops and residuals herbicides compared to conventionally tilled systems. Overall, combinations of heavy cover crop residue and residual herbicides provided better weed control than conventionally tilled systems. There was 75 to 89% less weed biomass with combined high residue and residual herbicides compared to conventional tilled non-treated check. These data suggest the residual is still reaching the soil surface and providing additional wed control. Finding alternative and integrated weed management programs that include agronomic practices, cover crop residues, and herbicide programs is key to the future of peanut production.

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**List of Abbreviations**

ALS- Acetolcate synthase

ACCASE- Acetyl CoA carboxylase

COC- Crop oil concentrate

CWFP-Critical Weed Free Period

DAP-Days after planting

DAT- Days after treatment

DBP- Days before planting

HSOC- High surfactant oil concentrate

NTSR- Non-target site resistance

NDVI- normalized difference vegetation index

NTC- Non-Treated Check

NT- Non-Treated

NIS- Nonionic surfactant

OM- Organic matter

PPO- Protoporphyrinogen oxidase

POST-Postemergence

PRE- Preemergence

TSR- Target site resistance

WBP- Weeks before planting

# Chapter 1: Literature Review

## 1. Peanut

### 1.1. Peanut Production

Peanut (*Arachis hypogaea*), an annual legume that is part of the Fabaceae family, is endemic to South America and is adapted to grow in tropical and subtropical climates. Several factors contributed to its growth in popularity and production in the United States at the end of the nineteenth century. First, the Civil War brought peanuts to the North, then equipment for processing and harvesting peanuts had major advancements, George Washington Carver developed additional uses for peanuts, and the U.S. government provided support programs for food crop production (American Peanut Council, 2020). Finally, the boll weevil was causing devastating losses to cotton production and peanut was encouraged as a rotation crop to reduce insect populations (Hammons et al., 2016). This crop rotation successfully helped reduce boll weevil populations and increase peanut popularity.

Peanuts are grown commercially in 13 southern states in the United States and it accounts for 5% of the world's peanut production behind China, India, and Nigeria (National Peanut Board, 2020). In 2019, the US produced 4.68 billion pounds of peanuts, with Georgia producing 50% of all peanuts in the US followed by Florida 11%, Alabama 10%, Texas 9%, North Carolina 8% and South Carolina 4% (National Peanut Board 2020). Alabama planted 155,000 acres of peanuts in 37 counties resulting in $211.4 million for the state's economy (Alabama Peanut Producers, 2020). Peanuts are primary grown for human consumption, including candy, peanut butter, salted nuts, and peanut oil. The average American consumes seven pounds of peanuts or peanut products a given year (National Peanut Board, 2020).

There are four types of peanut cultivars grown commercially: runner, Virginia, Spanish (subspecies *vulgaris*) and Valencia (subspecies *fastigiata*) (Stalker et al., 2016). Valencia and Spanish type bloom and produce pods on the upright main stem while Virginia and runners do not. In order to be considered a Virginia type rather than a standard runner, 40% of pods must ride a 34/64 inch roller standard (Anco and Thomas, 2019). Runner cultivars account for 85% of U.S. production followed by Virginia with 10%, Spanish with 2% and Valencia with 1% (National Peanut Board 2020). Runner is the most produced cultivar in the U.S. and is grown in all peanut producing states. It is a medium sized peanut mainly used for peanut butter production. Virginia type have the largest kernels of all peanuts produced, they are mainly grown as snack nuts and contain a high oleic trait. They are generally grown in Virginia, North Carolina, South Carolina and Texas. Spanish peanuts are smaller nuts that are generally used in candy bars but can also be used for peanut oil production. Generally, they are grown in Texas, Oklahoma and New Mexico. Valencia peanuts, typically grown in Texas and New Mexico are sold for roasted or boiled peanuts.

### 1.2. Peanut Growth and Development

Peanuts growth is restricted to the Southern portion of the U.S as it is a long season crop and needs 110-175 days to mature. Generally, peanuts are planted after the last frost in the first two weeks of May but can be planted as late as June 15$^{th}$ and still provide a successful yield. Peanuts are an important part of crop rotation in the southeast as the nitrogen fixing plants can improve soil fertility. Peanuts respond best to a long rotation with at least two years of cotton, corn, grain sorghum or another non-leguminous crop in between (Bolatoa, 2019; Jordan, 2020). Long rotations provide control for peanut diseases, fungus and insect issues resulting in a better peanut yield during planting years. Peanuts can be grown in conventionally tilled, no-till, strip till, and heavy cover crop residue. Peanuts are best planted at 3.8 to 7.6 cm depth on 81 to 96 cm row spacing for single row planting. Twin row planting can also be utilized in peanut production with 18 cm on 91-96 cm centers. Studies suggest twin row planting can increase overall yields and reduce tomato spotted wilt virus (Lanier et al., 2004a; Lanier et al., 2004b). Peanuts are best adapted to grow in well drained sandy loam soils, a pH range of 5.8-6.4, and temperatures between 25°C to 30°C (Jordan, 2020). Peanut prefers soil that has an application of dolomitic lime prior to planting as this also provides a source of calcium and magnesium. Higher pH soils should be avoided as it limits peanut nutrient intake, increases chances of some diseases and can increase zinc uptake. . If pH is already at optimal levels, then calcium can be applied at pegging. As a legume peanuts receive most of their nitrogen from Rhizobium bacteria through native populations or inoculation, it responds best to residual fertilization of potassium and phosphorus, but it does require calcium applications. (Bolatoa, 2019; Jordan, 2020). Inoculation is recommended when a field has not been previously planted with peanut or it has been a number of years. Additionally, peanuts need boron, magnesium and manganese in trace amounts for quality pod production.

Peanut leaves are trifoliate appearing alternatively on main stem and lateral branches (Stalker et al, 2016). Peanut plants tend to be 0.30 to 0.46 m in height with a 0.3 m canopy width (Stalker et al, 2016). Peanut have an indeterminate growth pattern, with day neutral self-pollinating flowers. Peanuts will begin flowering at 30 days after planting continuing for a 90 day period. After fertilization, at the base of the ovary, a short stalk is longed forming a peg. The peg grows down into the soil pushing the ovary down which will then develop into a pod. A normal mature peanut pod is developed 60 to 80 days after fertilization (Stalker et al., 2016). Due to the indeterminate growth habit peanuts fertilization happens over a period of few weeks therefore at harvest maturity will be a different stage. Generally, once 70-80% of the pods are at maturity harvesting is recommended (Anco and Thomas, 2019).

**1.3. Weeds in Peanut**

Peanuts require a long growing season, 135-160 days, and are slow to canopy which makes weed control vital especially early in the season. In the 2013 Southern Weed Science Society Weed survey the top ten most common weeds in peanut in Alabama were Florida beggarweed (*Desmodium tortosum* D.C), nutsedge species (*Cyperus spp)*, morningglory species (*Ipomeoa spp*.), Florida pusley (*Richardia scabra* L.), sicklepod (*Senna obtusifolia* L.), Texas millet (*Uruchloa texana* Buckl.), prickly sida (*Sida spinosa* L.), Palmer amaranth (*Amranthus palmeri* S. Wats.), bristly starbur (*Acanthospermim hispidum* D.C), and spurge species (*Euphorbia spp.*) (Webster, 2013). Of these weeds Palmer amaranth, Florida beggarweed, prickly sida, nutsedge and spurge species were also on the most troublesome weeds to control in peanut (Webster, 2013). Prickly sida and spotted spurge have also had confirmed resistance to ALS inhibitors but imazaquin and metsulfuron-methyl are not labeled in peanut (Heap, 2020). However, if weed species have shown resistance to specific modes of action it is possible to develop the resistance to other herbicides within the same group. Palmer amaranth has shown resistance to ALS inhibitors, PPO inhibitors, and long chain fatty acid inhibitors which are all utilized in peanut production (Heap, 2020).

Palmer amaranth, an annual broadleaf, is a dioecious weed with very high growth rates, large seed production and rapid seed germination (Ward et al., 2013; Steckel et al., 2004). It is a widespread weed throughout the southeast that has become economically damaging to agronomic crops. A single plant can produce up to 600,000 seed when it has no competition

(Keely et al., 1987). This large amount of seed can be extremely detrimental to agronomic fields, by adding more and more of its population to the weed seed bank and causing more competition with crops. In peanuts, the rapid growth rate and height of Palmer amaranth adds another level of competition by shading out the slow growing peanuts. Burke et al. (2007) observed as Palmer amaranth height increase peanut width decreased. The study predicted a 28% yield loss from one Palmer amaranth per meter row of peanuts with season long inference (Burke et al., 2007). Only one single plant can reduce peanut yields by 28% and potentially produce up to 600,000 seeds in a single season, it has the potential to be devastating which is why control is so important for growers. However, Palmer amaranth is quickly outpacing different chemical control methods by developing resistances to multiple modes of action. This is especially true in peanut as it is a non-GMO crop so there are limited number of herbicides that can sprayed postemergence. In the case of Palmer amaranth control in peanuts, additional methods for weed control other than just chemical need to be studied and utilized.

Sicklepod, is a summer annual is competitive in height and canopy and is difficult to control in peanut. Sicklepod has the potential to become a resistance weed as it is self-pollinating, a prolific seed producer, and producers are observing tolerance (Thompson, 2020). Dr. Eric Prostko has been monitoring and researching suspected resistant sicklepod populations in Georgia, as it is a growing concern for producers (Prostko, 2017). It is already difficult to control sicklepod in peanut as it is from the same family Fabaceae, as peanut. It is more difficult to control a weed the more closely it is related to the crop as most herbicides that would kill the weed will also kill the crop. Imazapic and paraquat have provided good postemergence control of sicklepod in peanuts but potential development of resistant to imazapic will mostly likely be at risk for control (Prostko, 2017). This would leave paraquat as the only option for growers however it is extremely toxic to humans and cannot be used on peanuts past 28 days after cracking without yield loss (Anonymous, 2016). Few studies have evaluated the effects of sicklepod competition on peanut yields and none on new peanut varieties. Hauser et al. (1982) observed 6.1-22.3 kg $ha^{-1}$ loss for each sicklepod per 10 $m^2$ when allowed to compete with peanuts over a full growing season. If resistance does develop and growers are faced with combating two resistance weeds in peanut, there could be an increase in potential yield loss.

Florida beggarweed is a summer annual that is part of the Fabaceae family that is highly competitive in peanut especially during the first 8 weeks of planting (Bucahanan et al., 1976; Hauser et al., 1982). Grey and Bridges (2005) observed consistent yield losses when Florida beggarweed was established at peanut emergence. Barbour and Bridges(1995) predicted a 20 to 40% yield loss in peanut from season long competition of Florida beggarweed using competition models. Overall, controlling Florida beggarweed during peanut establish is important to avoid yield loss.

Most weeds regardless of resistance are difficult to control once they are 4 to 6 inches in height, therefore, application timing is important. Producers need to time postemergence applications at the right stage to not only prevent weed-crop competition but to also catch the weed when they are at a height to be controlled. Herbicide applications can be applied late due to weather, field conditions, or labor shortages. If weeds are not controlled by harvest not only has it likely reduced peanut yield, it is adding seed to the seed bank that can be an issue for future growing seasons as well as cause harvest inference. Large Palmer amaranth can grow over 2 m in height and have thick stalks which can clog up harvesters (Culpepper et al. 2006), costing producers time, money and yield. The threat of resistant weeds is a constant concern for all agronomic producers, but it is even more of a concern when there are few labeled herbicides and no potential of herbicide tolerant traits being put into the plant as with peanut. The future of weed control in peanuts will have to rely on more than just chemical control as its primary choice. Integrated methods need to be evaluated in order to develop weed control programs that can effectively control not only weeds but resistant ones as well.

### 1.4. Herbicides in Peanut

Herbicides labeled in peanut are fairly limited with only 22 options including preplant, preemergence, and postemergence available. Of the 22 labeled options in peanut there are only 10 modes of action that can be utilized. Unlike corn, cotton and soybeans, peanuts do not have herbicide tolerant traits on the market. This provides less chemical control options in peanut that producers have in other crops postemergence. With limited options peanut producers must vigilant when it comes to weed control with right applications at the right time and try to protect against the development of resistant weeds or risk losing chemistries. At this time there are no new potential modes of actions on the herbicide market and there are no new herbicides about to be labelled in peanut, therefore the current chemistry must be protected. Due to resistant Palmer amaranth producers with fewer options have had to start utilizing more phytotoxic herbicides later in the season for control while risking yield. However, controlling the weeds and preventing new additions to the weed seed bank is extremely important for the following growing season.

Paraquat is commonly used in peanut for postemergent (POST) weed control of many common broadleaf weeds including sicklepod, Florida beggerweed and morningglory species (Wilcut et al., 1989; Wilcut and Swann, 1990). Paraquat is a bipyridylium that inhibits photosystem I electron transfer by creating superoxide radicals, which lead to destruction of unsaturated lipids (Shaner, 2014). It is a non-selective, foliar applied herbicide (Shaner, 2014). Paraquat requires adequate contact with actively growing green plant tissue to be effective (Anonymous, 2016). Paraquat registration in peanuts allows for up to two applications totaling in 280 g ai $ha^{-1}$ by up to 28 days after ground cracking (Anonymous, 2016). Previous research on runner type peanuts confirmed no yield loss due to paraquat applications if applied prior to pegging and fruit development and at a rate less than 280 g ai $ha^{-1}$ (Wehtje et al., 1991; Wilcut and Swann, 1990). Broadcast paraquat applications caused foliar injury to peanuts prior to the 28-day application restriction, however, it did not lead to significant yield loss (Wehtje et al., 1986; Hicks et al., 1990). While paraquat provides effective weed control producers frequently apply residual herbicides, such as chloroacetamides, in combination with it, to broaden the spectrum of weed control and to provide residual control (Jordan et al., 2011; Wilcut et al., 1995).

Bentazon can be tank mixed with paraquat to provide to protect peanuts from tissue damage and burns. Bentazon acts as ‘safener’ to paraquat as it is antagonistic and lessens injury to peanut by reducing paraquat absorption into foliage (Wehtje et al., 1992). Bentazon inhibits photosynthesis at photosystems II by binding with D1 proteins of the PSII complex in the chloroplast thylakoid membranes (Shaner, 2014). This blocks electron transport, stopping $CO_2$ fixation and energy production within the plant. Paraquat plus bentazon also controls more broadleaf weeds than if either one alone is applied (Wilcut et al., 1994).

Bentazon increases control of broadleaf weed species including bristly starbur, coffee senna (*Cassia oecidentalis* L.), prickly sida, and smallflower morningglory (*Jacquemontia tamifolia* L.) (Wehtje et al., 1992).

2,4-DB controls broadleaf weeds including sicklepod, morningglory species, smallflower morningglory and common cocklebur (*Xanthium strumarium* L.) (Buchanan et al., 1982). 2,4-DB disrupts transport systems and interferes with nucleic acid synthesis, its mode of action is not entirely understood but behaves similarly to 2,4-D (Shaner, 2014). It is generally added to tank mixes as it increases control of broadleaf weeds larger than the recommended size for treatment when used with acifluorfen, bentazon, and paraquat (Wilcut et al., 1994). 2,4-DB and bentazon are effective herbicides to tank mix with paraquat as they increase control of additional or larger weeds in peanut.

Producers frequently add chloroacetamides (Group 15 WSSA) for residual weed control both preemergence and/or postemergence. *S*-metolachlor, acetochlor, dimethenamid-P, and pyroxsulfone are labeled in peanut. These herbicides inhibit very long chain fatty acid synthesis, they effect weeds prior to emergence but will not work on weeds that have emerged (Shaner, 2014). Chloroacetamide herbicides are often used for annual grass, yellow nutsedge (*Cyperus exculentus* L.) and some broadleaf weed control in peanuts with their residual activity (Brecke and Colvin, 1991; Chambelee at al., 1982; Wilcut et al., 1994). Previous studies have observed peanut injury from chloroacetamide herbicides but rarely see yield loss (Cardina and Swan, 1988; Grichar et al., 1996; Jordan et al., 2003; Wehtje et al., 1988). One study performed under normal field circumstances saw 2% injury, 6 weeks after planting, 10% injury 11 weeks after planting and 5% at the end of the season from *S*-

metolachlor alone as a PRE, however, no yield loss occurred. (Dotray and Gilbert, 2012). Soil pH, moisture, organic matter as well as herbicide rates are factors affecting chloroacetamide injury on peanuts (Cardina and Swann, 1988; Mueller et al., 1999; Wehtje et al., 1988). Other studies have found irrigation or rainfall immediately after metolachlor or alachlor application can lead to increased injury and delayed seedling emergence (Cardina and Swan, 1988; Wehtje et al., 1988). However, none of the observed injury in these studies led to yield loss when applied at the labeled rates. It is rare to have an observable yield loss to occur, one study in observed a greater than 45% stunting with flumioxazin plus metolachlor tank mix, under cool and wet environmental conditions. This location received 74 mm of rain within 7 days after planting however another location in this study received more rainfall but had higher temperatures and no stunting at all. The stunting of greater than 45% lead to a yield loss of 48% when compared to a flumioxazin only treatment (Grichar et al., 2004). Chloroacetamides can cause injury to peanuts when environmental factors are right and only in rare cases cause yield loss therefore, they are considered safe on peanuts and make up the foundation of most peanut herbicide programs.

A frequently utilized group of herbicides utilized for preemergent weed control in peanuts are dinitroanilines, microtubule inhibitors. These herbicides inhibit the polymerization of microtubules at the assembly end of the protein-based microtubules leading to the loss of microtubule structure and function. This results in no spindle apparatus which prevents the alignment and separation of chromosomes during mitosis. Microtubules also affect cell wall formation, without them cell wall formation cannot occur (Shaner, 2014). These herbicides effect weed seeds prior to emergence and cannot control weeds after emergence. Pendimethalin and ethalfluralin are labeled for weed control in peanut with pendimethalin being the most commonly used. Ethalfluralin is a volatile herbicide and needs to be incorporated for effective weed control which means and additional pass over the field for growers. Due to incorporation it cannot be used in no-till or minimum tillage fields. Trifluralin is another dinitroaniline labeled in peanuts but it is restricted for use in Texas, Oklahoma and New Mexico only, it also needs to be incorporated for effect weed control (Anonymous, 2010). Dinitroanilines provide effect preemergent weed control of annual grasses. One study observed 85-100% control of goosegrass (*Eleusine indica*), southern crabgrass (*Digitaria cilaris*) and Florida pusley (*Richardia scabra)* when ethalfluralin was applied PRE (Brecke and Currey 1980). Prostko et al. (2001) observed greater than 85% control of southern crabgrass, greater than 93% control of crowsfoot grass (*Dactyloctenium aegyptium*) when ethalfluralin or pendimethalin was applied preplant incorporated or preemergent. Based on their findings and previous research conducted the authors suggest that ethalfluralin and pendimethalin should be the foundation of peanut weed control programs (Prostko et al., 2010).

Norflurazon, a phytoene desaturase inhibitor can be used a preemergent in peanut to control a variety of grass and broadleaf weeds. Phytoene desaturase inhibitors block carotenoid synthesis. Carotenoids are key in dissipating oxidative energy of oxygen singlets. Oxygen singlets interact with lipids causing lipid peroxidation which causes membrane leakage and eventually plant death (Shaner, 2014). Norflurazon is not commonly used as a preemergent in peanut as it has a high use rate of 2.018 kilograms per hectare and can be difficult to locate in certain areas as it is mainly marketed as an orchard herbicide (Anonymous, 2015).

For in season grass control sethoxydim or clethodim, acetyl CoA carboxylase (ACCASE) inhibitors, are often used by growers. ACCASE inhibitors herbicides inhibit fatty acid synthesis which blocks the production of phospholipids used in building new cell membranes for plant growth (Shaner, 2014). These herbicides do not provide any broadleaf weed control and cannot be tank mixed with a large number of herbicides and fungicides or they will have reduced efficacy due to antagonism (Rhodes and Coble 1984a;1984b). Therefore, utilizing these herbicides is an additional pass for growers and are an only an effective option if grass pressure is high.

Acetolcate synthase (ALS) inhibitor herbicides inhibit the synthesis of branch chain amino acids leucine, valine, and isoleucine (Shaner, 2014). ALS inhibitor herbicides are one the most diverse group of herbicides used in all major agronomic crops. They control a wide variety of broadleaf and grass weeds. Imazapic, chlorimuron, diclosulam, and imazethapyr are labeled in peanut for preemergent and postemergent application. Rimsulfuron and thifensulfuron are labeled in peanut as preplant or burndown only. Imazapic can be used as a preemergent or postemergent to control: common lambsquarters (*Chenopodium album)*, morningglory species, pigweed species, prickly sida, Flordia beggarweed, sicklepod, purple and yellow nutsedge (Grichar et al., 1994; Grichar et al., 2004; Grey et al., 2001; Wilcut et al., 1994). While imazapic provides good overall weed control in peanuts, it has strict restrictions on what can be planted after it due to soil persistence. Both imazapic and imazethapyr, members of the imidazolinone family, have an 18-month plant back restriction on cotton, the most commonly rotated crop with peanuts (Anonymous, 2014; Anonymous, 2017a). Imazapic applied preplant incorporated at 50.44 g/ha reduced cotton yield by 34% and 43% in studies in North Carolina and Georgia, respectively (York et al., 1995). A study in Mississippi showed cotton tolerated soil applied imazapic at rates of 27 to 55 g/ha with no yield reduction (Wixon and Shaw, 1992). However, Grey et al. (2005) observed a cotton yield reduction of 40% or greater at 5g/ha to 36 g/ha of imazapic. Another study observed when cotton stunting was greater than 50% due to imazapic carryover there was almost always a yield reduction (Grichar et al., 2004). One study observed different application methods of imazapic impacted carryover effects on cotton, preplant incorporated, reduced the yield by 44% while post emergent applied caused no yield reduction. (York et al., 2000). Overall, imazapic carryover can be variable and depends on a variety of field conditions that can increase soil persistence.

Cotton also has a 10-month plant back interval after using chlorimuron and diclosulam but can cause injury when environmental factors are right (Anonymous, 2017b; Anonymous, 2019). Many of the rotational crops after the use of these ALS herbicides are other legumes or field corn (Anonymous, 2014; Anonymous, 2017a; Anonymous, 2017b). As planting back to back legumes can cause disease pressure issues this leave growers with only field corn as an option for rotating after peanuts. This can be a limiting factor in its use throughout southeast and another factor growers need to consider when using ALS herbicides in peanut.

PPO inhibitor herbicides inhibit the enzyme protoporphyrinogen oxidase which is involved in chlorophyll and heme synthesis. Once inhibited there is an accumulation of protoporphyrinogen IX. The light absorbed by protoporphyrinogen IX produces a triplet state form that interactions with oxygen creating oxygen singlets. Oxygen singlets then lead to lipid peroxidation causing cellular leakage and plant death (Shaner, 2014). Carfentrazone, sulfentrazone, lactofen, flumioxazin, and acifluorfen are PPO inhibitor herbicides labeled in peanut. With the increasing spread of ALS inhibitor Palmer amaranth and many growers have had to turn to PPO inhibitor herbicides for effective postemergent mid-season weed control. PPO inhibitor herbicides are predominately post applied contact herbicides as translocation within the plant is minimal. They are generally used to control for a variety of broadleaf weeds in including sicklepod, Palmer amaranth and morningglory species.

Flumioxazin, a PPO inhibitor herbicide, be used on peanuts as preemergent only, applications after cracking or emergence will lead to severe crop injury (Anonymous, 2016b; Shaner, 2014). The introduction of flumioxazin has provided a new mode of action in peanuts when it was labeled in 2001 and provided excellent control of Florida beggarweed (Anonymous, 2016b). Flumioxazin controls a variety of broadleaf weeds but does not control grasses or nutsedge (Anonymous, 2016b). Under certain field conditions with cool wet soils, flumioxazin can cause stunting and foliar burns on emerging peanut however, in most cases peanuts will recover from this injury and there will be no yield reduction (Morichetti and Ferrell, 2010; Prostko, 2008).

PPO-inhibitor herbicides can provide effective control of many ALS-resistant weeds including Palmer amaranth, but peanut injury from these herbicides is a major concern when applied mid to late season (Boyer et al., 2011; Ferrell et al., 2013). Producers are limited on POST herbicide options in peanut, but mid to late-season weed control is important to reduce yield loss from weed inference and increase peanut harvest efficiency, therefore more are utilizing PPO even though increase crop injury is a risk (Wilcut et al., 1994; Wilcut et al., 1995). Lactofen, a PPO inhibitor herbicide plus crop oil concentrate caused up to 48% injury on peanuts when applied 4 weeks after planting but did not cause significant yield reductions

(Boyer et al., 2011). However, when applied 8 weeks after planting Boyer et al. (2011) observed up to 38% peanut injury and a 17% reduction in yields. Dotray et al. (2012) found lactofen caused 5% yield reductions when applied 70-80 DAP, at the pod filling stage. While PPO inhibitor herbicides are effective for weed control in peanuts the timing of application can increase risk for potential yield loss and need to be studied further.

Surfactants are spray solution additives that increase herbicide coverage and penetration by improving absorbing, spreading and sticking of an herbicide solution (Miller and Westra, 1998). Two main forms of surfactants used in herbicides in peanuts are non-ionic surfactants and crop oil concentrates. Nonionic surfactants are linear or nonyl phenol alcohols and/or fatty acids. They reduce surface tension and improve spreading, sticking and herbicide uptake (Miller and Westra, 1998). Crop oil concentrates are made up of surfactants blended with paraffinic based petroleum oil which reduces surface tension, improves herbicide update and spreading (Miller and Westra, 1998). Surfactants increase herbicide efficacy when environmental conditions are not ideal for herbicide activity or if they need to be applied in less than ideal conditions. They can also help with penetration on highly waxy or hairy plants where it is difficult for herbicides to reach the leaf surface. The addition of surfactants such as crop oil concentrates (COC) can lead to increased foliar injury on crops (Kapusta et al., 1986; Miller and Westra, 1998). There is a delicate balance between killing the unwanted weed but also not harming the desired crop. Surfactants are a supplementary tool growers have to help increase herbicidal efficacy. Additionally, new surfactants are coming on to the market, some have reduced rates while others are said to be more effective. High surfactant oil concentrate which is a combination of phytobland paraffinic oil, high fructose corn syrup and fatty esters that can be used at a lower rate than crop oil concentrate with the same efficacy. However, it can cause crop injury if producers use too high of a rate or if environmental conditions are right. Research is needed to determine under what conditions surfactants can cause crop injury and lead to yield loss in peanut, as well as, which ones are more crop safe at different growth stages.

Each season breeders are testing and releasing new peanuts varieties which are bred for better disease tolerance, stress tolerance, and higher oil content. As new peanut cultivars are released on the market current and past herbicide program recommendations need to be evaluated to ensure tolerance and no yield loss due to herbicide injury. Differential tolerance among crop cultivars to herbicides has been noted for years. Some soybean cultivars showed extreme sensitivity to metribuzin and it cannot be utilized in those cultivars for weed control (Monks 1992). Several older peanut cultivars, such as Early Bunch and Southern Runner, exhibited significant more sensitivity to paraquat compared to Florunner (Brecke, 1989). Another study showed reduced yields of Sunrunner, Southern Runner, and Florunner peanut cultivars by two applications of paraquat (Knauft et al., 1990). Herbicide tolerance studies on new cultivars help to determine potential rates to be utilized in the field and potential yield loss form crop injury. It can also help to determine if and how a plant will recover if it gets a higher than labeled rate whether from incorrect mixing, overlapping in the field or misapplication. It is important for producers to know if herbicide phytotoxicity can induce yield reduction or if a plant will recover.

Effective herbicide programs include a preplant burndown, preplant incorporated and/or preemergence, and postemergence applications. Withing these application timings producers should utilize more than one mode of action per application timing and try to rotate between modes of action for each timing. This helps to not only kill a wide variety of weeds but prevent the development of further resistance.

### 1.5. Additional Methods of Weed Control

In addition to broadcast spraying herbicides, peanut growers have a variety of other tools they can utilize for weed control in peanuts. First and foremost is crop rotation which allows for the introduction of new herbicides and new modes of actions that can be used on the weed population. With the introduction of 2,4-D and dicamba tolerant cotton producers can use auxin herbicides against glyphosate resistant Palmer amaranth. The use of these herbicide tolerant cotton varieties has reduced the Palmer amaranth pressure in fields not only in cotton but in the following season in peanut (personal correspondence). Early in the season mechanical cultivation can be used for weed control by uprooting small seedlings, leading to desiccation and death. However, it can disrupt residual herbicides, bring up new weed seeds and possibly damage peanut plants if done incorrectly or too late in the season. Once canopy closure occurs peanuts provide their own weed control by shading out potential germinating seedlings. There is still a chance of weed escapes to occur later in the season by then in row cultivation is not possible. A weed wiper or a wick bar can be used to control weeds when they are taller than the peanut canopy. A wiper allows producers to use non-selective herbicides, such as paraquat, that are not labeled for peanuts or at that specific growth stage. Cover crops offer a potential weed control option as high residue can suppress weeds through physical suppression and allelopathy. It is an additional crop from producers to plant but also provides a myriad of other benefits including reducing soil erosion, improved soil health, and increased water infiltration. A last resort option for producers is hand pulling to remove weeds to prevent further addition to the seed banks or interfere with harvest. This is a labor intensive and expensive method of weed control.

## 2. Cotton

### 2.1. Cotton Production

Cotton (*Gossypium hirsutum* L.) is an herbaceous annual grown in semi-arid and humid conditions. Wild cotton is a woody shrub with a perennial lifecycle. Cotton has been a staple crop grown in the United States since the 1800s, after the introduction of Eli Whitney's cotton gin. The United States is the third largest producer behind India and China and the world's largest exporter (USDA, 2021). Cotton is grown in 17 states across the southern US; Alabama, Arkansas, Arizona, California, Florida, Georgia, Kansas, Louisiana, Mississippi, Missouri, New Mexico, North Carolina, Oklahoma, South Carolina, Tennessee, Texas and Virginia (Cotton Inc, 2018). Two types of cotton are typically grown in the United States, upland cotton and pima cotton. Upland cotton makes up 95% of the cotton produced and is a short staple fiber that is used for everyday cotton items (Cotton Inc, 2018). *Gossypium barbadnense* L., pima cotton, makes up the other 5% of production in the US. Pima cotton has longer fibers and is used for higher quality products (Cotton Inc, 2018). Two other species *Gossypium herbaceum* and *Gossypium arboreum* also produce cotton fibers but are not grown within the United States.

### 2.2. Cotton Growth

Cotton has an indeterminate growth pattern, is self-pollinated, and can bloom for up to 8 weeks. Cotton grows 60 to 150 cm in height and produces a long taproot that can grow 2.5 cm a day (Martin et al., 2006). Producers utilize growth regulars to slow internode elongation and reduce vegetative growth in season due to cottons indeterminate growth pattern (Martin, 2012). Squares and flowering buds develop approximately 4-6 weeks after cotton emergence. Square development can be delayed if cotton plants are under environmental stress such as drought or pathogens. Generally, flowers are produced every 6 days once blooming has begun. Once the flower is pollinated it will develop into a cotton boll, once a boll is developed it takes approximately 50 to reach maturation (Martin, 2012). Cotton fiber development begins once the cotton flowers and growth is completed by approximately 25 days (Martin et al., 2006).  Cotton fiber lint quality is determined by length, strengthen, and fineness. Prior to harvesting, cotton plants, must be terminated due to its indeterminate growth and it can still act as a perennial under the right growing conditions (Martin et al., 2006).

### 2.3. Herbicide Resistant Traits in Cotton

Herbicide resistant traits in crops provided producers with more postemergence herbicide application options. Prior to the introduction of herbicide resistant traits growers could only utilize herbicides that crops were naturally tolerant to, which was few, or risk yield loss. In cotton the only POST options available were for grass control prior to the introduction of herbicide resistant traits. Roundup Ready® (Bayer CropScience, St. Louis, MO, 63167), glyphosate tolerant cotton was first available on the market in 1998, followed by Liberty Link® (Stoneville® BASF, Florham Park, NJ 07940), glufosinate tolerant cotton in 2004. These systems worked for several years, however, overreliance on a single mode of action lead to the development of several glyphosate resistant weeds. This has been a challenge for producers for several years, however, in 2017 dicamba resistant soybeans and cotton

(Roundup Ready® Xtend Crop System, Bayer CropScience., St. Louis, MO, 63167) were introduced to the market. They were quickly followed by 2,4-D resistant traits (Enlist® Weed Control System, Corteva Agriscience, Indianapolis, IN, 46268). These herbicide resistant traits allow for additional postemergence options that can be utilized to combat resistant weeds such as Palmer amaranth.

### 2.4. Synthetic Auxin Injury to Cotton

Synthetic auxin herbicides act like endogenous auxin (IAA) a naturally occurring auxin within a plant, however, their exact mechanism is not fully understood. These herbicides affect cell wall plasticity and nucleic acid metabolism. Auxins cause the call wall to acidify by stimulating the membrane bound ATPase proton pump which causes a reduction in apoplasmic pH. This causes cell elongation and wall loosing.  In low concentrations they can cause increases in RNA growth and protein biosynthesis which causes uncontrolled cell division and vascular tissue destruction. While in high concentrations they inhibit cell division and growth (Shaner, 2004). 2,4-D and dicamba are the two most utilized auxins, they are effective for controlling broadleaf weeds with little activity on grasses.

Prior to dicamba and 2,4-D tolerant cotton, auxins where only used in preplant burndown applications to clean up fields prior to planting in cotton. Cotton is susceptible to early season weed competition due to slow emergence, therefore, reducing any weed competition at planting is critical (Sosnoskie and Culpepper, 2014). Preplant burndown programs frequently utilized glyphosate or paraquat in the past however, including 2,4-D and dicamba in the tank mix provides additional and more effective weed control overall (Culpepper et al. 2005, Reynolds et al. 2000, York et al. 2004). Auxin injury to cotton often includes twisting or epinasty of stems, leaf strapping and/or cupping, and abnormal veins in leaves. Studies have observed cotton is more sensitive to simulated 2,4-D drift than dicamba drift at preflowering stages, 6 to 8 leaf stage (Everitt and Keeling 2009; Marple et al., 2007; 2008). A meta-analysis evaluating 30 studies of 2,4-D and dicamba drift found cotton to be more tolerant of dicamba than 2,4-D especially during the pre-flowering and squaring stages (Egan et al., 2014). One study showed cotton recovery was greater when exposed to dicamba than 2,4-D when applied at 4 leaf, 8, 14, 18 node growth (Marple et al., 2008). However, these studies do not address injury from preplant applications of 2,4-d and dicamba, only simulated drift. With preplant applications, prior to herbicide tolerant traits, growers had to meet a minimum number of requirements before they could plant cotton in auxin treated fields.

2,4-D is not persistent in soil under most environmental conditions with a half-life of 4-6 days and is generally dissipated by 20 days after application (Altom and Stritzke, 1974; Peterson et al., 2016; Wilson et al., 1997; Voos and Groffman, 1997). Dicamba is more persistent in soil than 2,4-D, with an average half-life of 31 days under aerobic conditions and 58 days under anaerobic conditions (Krueger et al. 1991). Overall, 2,4-D and dicamba are not persistent in soils, unless there is a high amount of organic carbon present, dry conditions, or there is low soil microbial activity (Paszko, 2016; Voos and Groffman, 1997; Walters, 1999). 2,4-D and dicamba degradation in soils is largely dependent on microbial activity (Burnside and Lavy, 1966; Menasseri et al., 2003; Paszko et al., 2016; Peterson et al., 2016; Walters, 1999). Previous studies have shown 2,4-D and dicamba degradation is slow or does not occur at all in sterilized or dry soils (Brown and Mitchell, 1948; Burnside and Lavy, 1966; Smith, 1974). Photodegradation does occur with 2,4-D, and it is its main degradation mechanism in dry soils; however, it has minimal impact in moist soils (Paszko et al., 2016).

$K_{oc}$ values for 2,4-D are 59 mL $g^{-1}$ in silty clay loam, 70 mL $g^{-1}$ in sandy loam, 76 mL $g^{-1}$ sand, and 117 mL $g^{-1}$ in loam soils, meaning it does not bind tightly to soil particles (Walters, 1999). 2,4-D tends to stay within the top six inches of soil, but in rare cases with low organic soils it can move 41 to 61 cm downward and as a result is less likely to leach (Wilson et al., 1997). Dicamba has low $K_d$ values of <0.7, meaning it is highly mobile in the soil and is capable of leaching (Menasseri et al., 2003, Nishimura et al., 2015). However, due to their rapid degradation and short half-lives, leaching of these two auxinic herbicides is rarely a problem (Nishimura et al., 2015; Waters, 1999). One study observed dicamba mobility increased as organic matter and clay decreased (Johnson and Sims, 1998). In addition, Voos and Groffman (1997) found through the evaluation of soils from five different land uses that there was a negative correlation between microbial biomass, soil organic content and the degradation of dicamba. Overall, 2,4-D and dicamba are not persistent in soils, unless there is a high amount of organic carbon present, dry conditions, or there is low soil microbial activity (Paszko, 2016; Voos and Groffman, 1997; Walters, 1999).

Following an application of dicamba, a minimum plant back period is 21 days and 2.54 cm of water, while 2, 4-D requires 30 days and 2.5 cm of water prior to planting of sensitive cotton (Anonymous, 2018a; Anonymous, 2018b). Baker (1993) observed cotton needed to be replanted due to poor stands when 2,4-D was applied at 2200 g ae $ha^{-1}$ as well as dicamba 300 g ai $ha^{-1}$ and 600 g ai $ha^{-1}$ 9 days prior to planting while earlier applications did not lead to significant injury. Baker (1993) also found all treatments applied 16 days before planting did not cause significant injury, stand loss or yield loss. One study observed dicamba 140 g ae $ha^{-1}$ and 280 g ae $ha^{-1}$ and 2,4-D 560 g ae $ha^{-1}$ and 1120 g ae $ha^{-1}$, 2 weeks prior to planting, caused significant stand losses (Everitt and Keeling, 2009). Another study in Texas found 2,4-D 560 g ae $ha^{-1}$ and 1120 g ae $ha^{-1}$ could be applied up to two weeks before planting without significant stand loss or yield loss (Everitt and Keeling, 2009). In the same study, dicamba at 140 g ae $ha^{-1}$ and 280 g ae $ha^{-1}$ could safely be applied 4 weeks before planting without stand or yield loss (Everitt and Keeling, 2009). York et al. (2004) found 2,4-D at 530 and 1060 g ae $ha^{-1}$ applied 3 week or earlier to planting did not have significant stand or yield losses; however, the study observed yield loss with treatments applied 2 weeks prior to planting. Overall, while dicamba and 2,4-D have minimal soil persistence they can still impact cotton health and yield if planted too soon after a burndown application.

With the new dicamba and 2,4-D herbicide tolerant traits producers can spray burndowns the day of planting without having to wait due to plant back restrictions. Even though the herbicide tolerant traits are on the market there are some situations where a grower could possibly need to replant with a different variety without the traits even if the fields have already been treated with auxins. Preplant burndown applications can be delayed due to weather conditions or labor availability. This can increase the risk of using 2,4-D and dicamba as part of burndown programs when plant back interval is too short, or the labelled amount of rainfall hasn't occurred before planting susceptible cotton varieties. With the new herbicide tolerant trait option of a preemergence application of 2,4-D and dicamba, if the stand fails due to excessive rain, herbicide injury, planter malfunctions or plant disease, a susceptible short season cotton variety could be the only option for a grower to replant. A legitimate concern is the intervals between application and replanting being too short. If a grower needs to replant a field they will want to do so immediately and cannot wait till later in the season, but this can be a risk to susceptible replant varieties. This injury could further delay maturity when the growing season is already short.

## 3. Critical Weed Free Period Cotton and Peanut

Critical weed free period (CWFP) is a period in a crop growth cycle where weeds need to be controlled to prevent (>5%) yield losses (Knezevic et al., 2002). Weeds compete against crops for light, water and nutrients. During the early growth stages this competition can reduce yield later in the season as weeds can deprive crops of needed nutrients. Controlling weeds during these periods can protect crop yields. Typically, later in the season when crops have reach canopy closure there is less risk for weed competition as larger crops can outcompete new geminating seedlings.

The CWFP produces a framework for producers to use in making decisions for timing of herbicide applications and weed control methods. CWFP can vary in different agronomic systems, tillage types, environmental factors, crop species and variety (Norsworthy and Oliveria, 2004). CWFP can be difficult to determine as they vary for crops and can vary by individual weed species. Overall, CWFP are generally presented as a set of growth stages for the crop over a period of a few weeks, it can be two weeks to 10 weeks of weed free period needed. Environmental factors can increase or decrease the CWFP, as drought condition may extend the CWFP for some crops. Timing of postemergence herbicide applications to control weeds can vary due to weed species but the generally rule of thumb is to control weeds when they are four inches or less. Weeds are easier to control when they are smaller, and they are less competitive to the crop. A twelve-inch weed is more likely to cause yield loss than a four-inch weed (Hartzler, 2021). When determining a post emergence herbicide application to control weeds, the crop stage and the weed height need to be taken into consideration. Weeds that emerge four or more weeks after crop emergence are less likely to cause crop loss unless there are high densities, however, still need to be controlled (Hartzler, 2021).

CWFP recommendations differ in research as there can be several factors that can be altered such as seeding rate, and row spacing but generally early season weed control is important to prevent yield loss. Hauser et al. (1975) found peanut yields were not reduced if the peanuts were maintained weed free for 6-10 weeks after planting. Everman et al. (2008a) observed the critical free period for peanuts to be 3 to 8 weeks after planting for mixed weed species. In another study that looked at weed population makeup, the CWFP for mixed broadleaves to be 2.6-8 weeks after planting while it was 4.3-9 weeks after planting for mixed grass species in peanut (Everman et al 2008b). This indicates even the weed population makeup can affect the CWFP as some weeds can be more competitive at different times in the growing season. Buchanan and Burns (1970) observed the CWFP for cotton to be up to 8 weeks after planting. While Tursun et al. (2014) observed the CWFP to be 8-10 weeks, however the CWFP period decrease as row spacing decreased in cotton. At 50 cm row spacing the CWFP 7.4 weeks after planting (Tursun et al., 2014). Van Acker et al. (1993) recommend producers keep fields free of weeds till R1 in conventionally tilled soybeans to prevent yield losses of greater than 2.5%. Keremati et al. (2008) also observed the CWFP in soybeans to be V2-R1, similar to Van Acker et al. (1993) results. Halford et al. (2001) also found similar results in no-till soybean with the CWFP ending at the R1 stage. Overall, it is critical to control weeds early in the season to prevent yield loss regardless of the crop.

Cover crops have the potential to shorten the critical period of weed control and possibly lessen the selection pressure for herbicide resistant weeds (Rosset and Gulden, 2020; Korres and Norsworthy, 2015). The use of cover crops residues can suppress weeds and lessen the number of postemergence herbicide applications. Ryan et al. (2011) observed reduced weed biomass with increasing rye residue biomass with complete weed suppression at 1,500 g $m^2$ of residue in soybean. One study observed a reduction in weed biomass and size of weeds when rye cover crop was utilized (Korres and Norsworthy, 2015). Weed biomass was 175 and 385 g $m^2$ in rye cover crop residue and conventional tillage, respectively (Korres and Norsworthy, 2015). While this study had variable results on determining the CWFP of cotton with a cover crop residue, one year there was a twofold reduction in weeds present when a rye cover crop was used compared to conventional tillage. Price et al. (2018) observed the presence of rye cover crop delayed the critical time to remove weeds compared to conventional tillage or winter fallow in cotton. Another study found more Palmer amaranth free days in peanut plots planted with rye cover crop compared to conventionally tilled, however, the following year no difference was observed (Dobrow et al., 2011). Overall, studies have shown the inclusion of rye cover crops can reduce weed presence and shorten the CWFP. Even in cases where it does not shorten the critical weed free period it can reduce weed biomass and likely competition with crops. Determining the CWFP for a variety of crops in different agronomic systems provides producers a tool to determine the optimal time to apply herbicides preventing a waste of money, time, and the need for additional herbicide applications.

## 4. Herbicide Resistant Weeds

Currently, weeds have evolved resistance to 23 out of the 26 known site of actions with a total of 263 herbicide resistance species (Heap, 2021). In the 1980s, herbicide resistant weed populations grew exponentially, a problem that was further compounded with the introduction of glyphosate resistant crops in 1996 (Shaner, 2014). Additionally, the development of herbicide tolerant crops shifted agricultural practices to rely heavily on postemergence herbicides only, especially in the late 1990s, which lead to further resistance growth (Shaner, 2014). Herbicide resistance can develop through two pathways: target site resistance (TSR) or non-target site resistance (NTSR). TSR is when a plant expresses additional copies of the herbicide target site proteins or causes structural changes to binding sites so herbicides cannot bind (Délye et al., 2013). Amino acid substitutions are generally thought to be responsible for structural changes to the binding sites (Délye et al., 2013). NTSR is more complex and the most common form of resistance but is not as well understood. NTSR mechanisms can include higher secondary metabolism rates, translocation alterations, reduced absorption, or any other altered pathway (Délye, 2013). Délye (2013) suggests most NTSR mechanisms are likely complex abiotic stress response pathways that are already present within the plant. Herbicides trigger the stress response pathway in all the plants in a population; however, due to genetic variation within a population some plants will be more tolerant to the stress than others (Délye et al., 2013). Unlike TSR, NTSR is likely to cause cross resistance between different chemicals, which makes weeds even harder to control. Furthermore, the develop of multiple resistance to different modes of actions is also possible as species are adapting to more and more herbicides.

Weeds are one of the few organisms that are subjected to both natural evolutionary selection pressures and artificially man-made selection pressures through agriculture. Several mechanisms are likely the cause for the origins of herbicide resistance including d*e novo* mutations, standing variation in a population, intrinsic resistance and interspecies genetic transfers (Hawkins et al., 2019). *De novo* mutations, occurs when there is an environmental change or stress placed on a population where the mutation allows the plant to have higher tolerance to that given stress. Then the more tolerant plants are likely to reproduce, selecting for a population with more of the natural tolerance. *De novo* mutations likely occur in plant populations all the time, but herbicides increase the selection pressure which in turn increases the rate of resistance in a population (Hawkins et al., 2019).

The spread of herbicide resistant genes is complex and includes many possible factors; mutation frequency, inheritance success, fitness cost, survival, degree of selection pressure, reproduction of species and gene flow within/amongst populations (Délye et al., 2013; Hawkins et al., 2019; Jasieniuk et al., 1996). Typically, the larger the weed population in an area the more genetic diversity and more likely there will be selection for resistant traits (Délye et al., 2013). Weed species that reproduce quickly and through cross pollination are more likely to spread resistance faster than weeds that self-pollinate or are slow to reproduce (Jasieniuk et al., 1996).

Overtime the continued reliance on only herbicides for weed control, no new modes of actions on the market, and increased monocropping have all lead to the production of more resistant weeds by increasing selection pressure. Producers not only need to consider the weed species behavior but also how the herbicide performs in the environment when evaluating potential selection for resistance. Herbicides that have long soil residual, are very active, control a broad spectrum of weeds, and are applied frequently to a field or ones with a single target site and specific mode of action are likely to be more selective for herbicide resistant weeds (Jasieniuk et al., 1996; Lebaron and McFarland, 1990). Weed management is ever evolving, even on the field level, once a producer manages for one weed species it can open a niche for a different species to emerge and become competitive. The same weed management program cannot be used from year to year and needs to be adjusted midseason if a late season weed emerges. Overall, best weed control management practices rely on a combination of chemical, mechanical, cultural and biological practices rather than a single control method (Norsworthy et al., 2012).

## 5. Cover Crops

Cover crops can provide many benefits to peanut and cotton rotation in terms of reducing soil erosion, conserving soil moisture for planting, increasing soil organic matter, and suppressing weeds. In recent years more and more producers are utilizing cover crop for soil health improvement, conservation, and weed control (SARE, 2020). From 2012-2017 cover crop acreage increased 50% nationally (USDA, 2017). Throughout the US producers utilize a variety of cover crop including; cereal rye, oats, winter wheat, radish species, crimson clover, hairy vetch, winter pea, cowpea, sunn hemp, annual ryegrass, winter barley and triticale (SARE, 2020). Cereal rye, radish species and oats have been the top three choices of producers since 2015 with rye being the most widely used every year (SARE, 2020). Different cover crops are chosen are determined by a producer's goals for the cover crop, the region, ease of planting, grazing needs, cost, and availability. While cover crops are not a typically harvested crop, they can be utilized for grazing needs during the winter months. Legumes are often chosen to increase fixed nitrogen in soils prior to planting corn or cotton to improve crop health and yield. Radish species and turnips are utilized for breaking up compacted soils, especially radish which grows quickly and had deep tap roots. Rye is typically considered the easiest cover to plant and grow as it needs minimal inputs and can be planted later in the season. Overall, grass species are good cover crops as they can break up soil compaction, increase water infiltration with their root system, and provide good biomass. A good stand of grass cover crops can suppress winter annuals and the residue can be utilized in the spring for weed suppression. Producers also do mixes of cover crops such as crimson clover, cereal rye and oats depending upon their needs.

Cover crops provide many benefits to growers; however, it is another crop for producers to plant and an additional cost. It is also not a program where producers will see benefits immediately and can take several years before there is return on investment. Studies and farmer correspondence have observed increased yield after several years of utilizing cover crops especially in drought years (SARE, 2019). The median cost of putting cover crops in is $37 dollars per acre but this cost can range from $15 to $78 dollars per acre depending on cover crop species chosen, planting method and termination method (SARE 2019). Once of the immediate cost benefits producers can see is a reduction in overall herbicide costs. SARE (2020) annual cover crop survey found most producers observed better overall weed control and reduced weed biomass. 38.7%, 39%, 31.9% and 70.6% of respondents to the annual survey saw reductions in herbicide costs in soybeans, corn, wheat and cotton, respectively (SARE, 2020). As cover crops increase weed control and, in some cases, reduce herbicide applications they can be utilized as a potential tool against herbicide resistant weeds.

### 5.1. Cover Crops and Weed Control

High residue cover crops have been shown to suppress weeds in no-till or strip-till cropping systems through resource competition, allelopathic affects, physical impediment and light suppression (Dabney et al., 2001; Aulakh et al., 2011; Reberg-Horton et al., 2011; Reeves et al., 2015; Price and Norsworthy, 2013). Cover crops are an additional tool in the fight against herbicide resistant weeds. SARE (2019), analyzed the economic benefit of cover crops against resistant weeds and determined a $27.00 dollar per acre savings after 2 years of use when utilizing cover crop plus herbicides than an herbicide alone program. This saving is determined by using one less postemergence spray through the season at current glyphosate ($4.50) and application costs ($7.50).

Some cover crops such as cereal rye have allelopathic abilities that can be utilized to help with weed control. Allelochemicals are biochemicals produced by the plant and released through roots, volatilization, and/or plant degradation. These chemicals prevent plant germination and growth (Weir et al., 2004). Cereal rye has allelopathic chemicals has been shown to inhibit germination of pigweed, horseweed (*Conyza canadensis*), barnyard grass (*Echinochloa crus-galli)*, lambsquarters, and foxtail species (*Diaspore species)* (Burgos and Talbert, 1996; Northsworthy, 2003; Preziorkowski and Groski, 1994). While the allelopathic affects of some covers are beneficial to producers, termination of the cover crops and planting of the commercial crop must be timed well to prevent stand reductions. If terminated too early the cover might not have reached its greatest potential biomass which would help with weed suppression (Balkcom et al., 2007; Teasdale and Mohler, 1993). However, if an earlier termination date is done it can reduce soil moisture loss and allow for soil temperature increases when it is a cool dry spring (Balkcom et al., 2007; Teasdale and Mohler, 1993). Termination timing depends on the goal of the producer and environmental field conditions to ensure a good crop stand. There are several ways to terminate cover crops including herbicide termination, rolling, mowing, and crimping.

Cereal grains tend to have a high C:N ratio which slows down plant degradation which allows for plants residue to be more persistent than legume or brassica species (SARE, 2019; Burgos and Talbert, 1996). This slow degradation of residue can provide longer in season weed control through physical suppression. Cover crops effect the light availability on the soil surface, soil temperatures and moisture levels which can reduce weed seed germination. Rolling of a cereal grain can make a mat-like residue across the field and increase weed suppression compared to terminating the stand with herbicide and leaving it to remain standing.

Studies have found cover crops suppress weeds in corn, cotton and soybeans but very few have evaluated their use in peanuts (Burgos and Talbert, 1996; Hoffman et al., 1993; Johnson et al., 1993; Reddy, 2001; Hurst, 1992). Reberg-Horton et al. (2012) observed consistent weed suppression with rye biomass exceeded 8,000 kg $ha^{-1}$ however this is not possible is some regions and climates. If weed suppression is the ultimate goal of planting cover crops, then management for the highest amount of biomass during the fall growing season is key. Ryan et al. (2011) observed reduced weed biomass with increasing rye residue biomass with complete weed suppression at 1,500 g $m^2$ of residue in soybean. Campiglia et al. (2010) observed an 85% decrease in weed density when cover crops were utilized for weed control compared to conventional systems in tomato. Burgos and Talbert (1996) observed 50% less weeds in sweet corn plots seeded with rye, wheat, and hairy vetch plus rye than hairy vetch alone or no cover indicating cereal grains provide improved weed control. Vollmer et al. (2020) observed variable weed control of summer annuals with cereal rye depending on rye biomass, and N applications.

## 6. Residual Herbicides

Residual herbicides are a key tool in controlling herbicide resistant weeds, as they tend to be resistant to postemergence herbicides. Preemergent residual herbicides extend weed control, however, this control varies from two weeks to months after application. There is a balance that has to occur between controlling weeds throughout the season but not effecting subsequent crops. Herbicide labels have plant back restrictions on when rotational crops can be planted, it can range from immediately to 24 months later. Common herbicide families with soil persistent members are: trazines, uracils, phenylureas, sulfonylureas, dinitroanlines, isoxazolidiones, imidazolinones and some pyradines (Curran, 2016). Residual herbicides break down through several pathways including microbial decomposition, photodegradation, and chemical decomposition.

The studies in the following chapters looked at several different residual herbicides, the half-lives and primary mechanisms for degradation are listed here. Herbicide half-lives is the amount of time required for half of the original chemical to dissipate. Diclosulam average half-life is 22 to 43 days, imazapic (120 days), *S*-metolachlor (90 to 150 days), pyrithobac (60 days), diuron (90 days), acetochlor (8-12 weeks), acifluorfen (14-60 days), bentazon (12 weeks), chlorimuron (40 days), flumioxazin (12-18 days), flumeturon (85 days), fluridone (90 days), fomesafen (100 days), pyroxasulfone (16-26 days), and trifloxysulfuron (6-21 days). Diclosulam is primarily degraded by microbial activity, as is *S*-metolachlor, acetochlor, pyroxasulfone, diclosulam, prometryn, flumioxazin, acifluorfen, bentazon, imazapic, chlorimuron-ethyl, pyrithobac, diuron, and acetochlor. Chlorimuron can chemically degrades through non-microbial hydrolysis and in high pH soils this is typically the primary mechanism of degradation. Trifloxysulfuron primarily degrades through chemical hydrolysis, which is temperature dependent, generally 52-20 degrees Celsius.

This dissipation rate is determined by several environmental factor and can vary greatly. Soil composition, type, soil pH, rainfall, and climatic conditions can all affect the half-life of a herbicide in the field (Colquhoun, 2006). Soils with more organic matter and clay increase soil adsorption which can lead to more potential carryover concern (Colquhoun, 2006; Curran, 2016). Soils with high pH can cause increased soil persistence in some trazines and sulfonylureas herbicides as chemical and microbial degradation are slowed down in these types of soils (Curran, 2016). Soils with low pH also increase soil persistence of the imidazolinone family. These herbicides become more bound to soil particles as the pH drops making them less available for microbial degradation (Curran, 2016).

Soil microorganisms, bacteria, fungi, protozoans, are responsible for the breakdown of most herbicides. Environmental factors such as temperature, nutrients, pH, oxygen, and moisture can affect microorganism's populations and growth. Well aerated, high in nutrients, pH near 7, warm and mist soils are ideal for microorganisms and herbicide breakdown (Curran, 2016). In cool dry years herbicide carryover will more likely be a concern the following season compared to warm wet years (Colquhoun, 2006; Curran, 2016).

Overall, if there is an environmental situation where a producer is concerned about herbicide carryover there are only a few things that can mitigate it. To reduce the risk of herbicide carryover producers can till the soil to redistribute the herbicide and increase microbial activity (Colquhoun, 2006). However, deep tillage can cause the herbicide to move to a cooler soil temperature zone increasing its persistence and placing the crops at risk if it is in their root zone (Curran, 2006). The safest option is to plant crops that are tolerant to the herbicide or have a shorter rotational period.

### 6.1. Imidazoline Herbicide Family Example

The imidazolinone herbicide family generally has increased soil persistence when there is low rainfall, low soil pH, soils with high clay content and organic matter (Curran, 2001). Many studies have suggested the main reasons for variation in carryover effects of imidazolinone herbicides is due to the clay content of soils and pH levels (Barnes et al., 1989; Grey et al., 2005; Goetz et al., 1990; Loux et al., 1989; Marchesan et al., 2010). The primary mode of imazapic degradation is through microbial activity, so decomposition is rapid in soils favoring increased microbial activity which include warm temperatures, close to a neutral pH, well aerated soil, and high moisture content. (Curran 2001; Goetz et al., 1990; Loux and Reese, 1993; Shaner and O'Connor, 1991). Photodecomposition has very little effect on imidazolinone dissipation rates (Goetz et al. 1990; Curran et al. 1992). A pH study on degradation of imadazolinones (imazamox, imazethapyr, imazaquin) in soils showed the herbicides dissipated faster at pH7 than pH5 (Aichele and Penner, 2005). Low pH has shown to increase adsorption making the herbicide unavailable for biodegradation which increases the timeframe for carryover effects (Marchesan et al., 2010, Aichele and Penner, 2005). With the optimal soil conditions known to increase imazapic dissipation, determining what actions a producer can take to ensure low carryover effects is important. While altering the soil clay content and rainfall are not options, adjusting the pH of a field though lime applications and promoting microbial activity through cover crops are options for producers. It is imperative for a producer to know the soil type and its makeup before applying members of the imidazolinone family to a field since that information will likely determine the extent of the carryover effects.

### 6.2. Cover Crops Establishment and Residual Herbicides

Regardless of the goal a producer has for planting cover crops in the fall, the cover crops need to be established. In fields where residual herbicides have been used during the growing season, establishment can be negatively affected by the herbicide residues. Very few herbicide labels have plant back restrictions for fall seeded cover crops on residual herbicides. Herbicide carryover can reduce the efficacy of a cover crop, wasting time and money for producers. In fields where residuals herbicides were used during the growing seasons several studies have shown cover crop establishment can be reduced (Curran et al., 1996; Yu et al., 2015). Limited rainfall, application rates, soil type and late in season herbicide applications can increase carryover concerns. If carryover is a concern, a tolerant cover crop should be selected for that field however few studies have been done on this tolerance in cotton-peanut rotation.

Many studies have been competed evaluating corn and soybean herbicides on fall seeded cover crops. Palhano et al. (2018) study observed pyroxasulfone caused a 12%, 16%, and 11% reduction in plant density for cereal rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* L.) and wheat (*Triticum aestivum* L.), respectively; however, the reduction in plant density did not lead to biomass reductions The same study found crimson clover (*Trifolium incarnatum* L.) biomass reductions of 13%, 12%, and 11% for atrazine, pyroxasulfone, and *S*-metolachlor, respectively, when applied during the growing season however, there were no reductions in plant density (Palhano et al., 2018). Yu et al. (2015) found imazethapyr, *S*-metolachlor + atrazine + mesotrione and saflufenacil+ dimethenamid-p did not cause any biomass reductions on oats (*Avena sativa* L.), hairy vetch, and cereal rye when planted 3 months after application at the labeled rates. A study evaluating fluometuron, MSMA, trifluralin, linuron carryover effects on hairy vetch and wheat found ground cover reductions varied greatly by soil type, with more injury found in Dundee silty clay than the silt loam soils (Rogers et al. 1986). Cornelius and Bradley (2017) observed cereal rye to be the most tolerant cover crop, while crimson clover and Austrian winter pea (*Pisum sativum* L.) were the most sensitive to herbicide carryover (Cornelius and Bradley, 2017). In addition, pyroxasulfone, imazethapyr, fomesafen and flumetsulam carryover were more likely to reduce cover crops biomass and stands (Cornelius and Bradley, 2017). Another study observed radish (*Raphanus sativus* L.) to have the most stand reductions, while cereal rye was the most tolerant (Hartzler and Anderson, 2015). Studies have found variable results on hairy vetch, with some observing it to be the most tolerant cover crop to herbicide carryover while others show it to be the most sensitive (Rogers et al., 1986; Bryan, 2014; Hartzler and Anderson, 2015; Yu et al., 2015; Stahl, 2016). Palhano et al. (2018) found clover had reduced biomass, in a field study, from residual herbicides but did not see significant emergence reductions. Another study found acetochlor and *S*-metolachlor caused significant biomass reductions of clover during one year of the study, however, saw no reductions the following year (Cornelius and Bradley, 2017). One study evaluating oilseed radish tolerance found it to be sensitive to several residual herbicides, including fomesafen, *S*-metolachlor, fomesafen, and imazethapyr, but was not affected by them the following year likely due to increased rainfall (Cornelius and Bradley, 2017). Another study, which also had varying results from year to year, did not recommend planting oilseed radish within 3 months of an imazethapyr application but did not report injury with *S*-metolachlor plus atrazine and saflufienacil plus dimethenamid-P (Yu et al., 2015). Overall, cover crop response to residual herbicide carryover can vary from year to year due to environmental factors and further studies need to be completed to ensure good stands and high biomass for weed control.

### 6.3. High Residue Cover Crops and Residual Herbicides for Weed Control

Utilizing cover crops in integrated weed management can provide weed suppression as well as increase soil organic matter, conserve additional soil moisture, and increase available nutrients (Lu et al., 2000; Danbey et al., 2001; Kasper and Singer, 2011). Cover crops are becoming more frequently used as a tool to help control against glyphosate resistant Palmer amaranth (Korres and Norstworthy, 2015). Throughout the southeast PPO and ALS inhibitor resistant Palmer amaranth are also spreading (Boyer, 2011; Webster, 2009). ALS and PPO inhibitor herbicides are the two main modes of action for postemergence control in peanut without these groups of herbicides available controlling Palmer amaranth is increasingly difficult. Therefore, the use of residuals herbicides in combination with cover crops can be vital to control weeds in peanut.

Historically, conventional tillage has been the standard practice for field preparation prior to peanuts. Cover crops have not been utilized in peanut as they were thought to be a vector for diseases including tomato spot wilt virus which would impact yield. However, a study has shown cover crops can reduce tomato spotted wilt virus compared to conventional tillage (Marois and Wright, 2003). Another study observed no difference between disease pressure of tomato spot wilt virus and white mold in several cover crop combinations evaluated compared to conventionally tilled, however, results varied from year to year (Campbell et al., 2008). Generally, utilizing cover crops in peanut will not increase disease pressure and reduce yields.

When utilizing cover crops for weed suppression in the spring the biggest goal is a high amount of biomass and slow degradation of residue through the growing season. Cover crops suppress weeds through physical suppression by effecting the light, soil surface temperature and moisture which reduces seed germination. Several cover crops such as cereal rye also have allelopathic abilities and can help with weed suppression during crop emergence even when it has been terminated (Burgos and Talbert, 1996; Northsworthy, 2003; Preziorkowski and Groski, 1994). Cover crops also can prevent the growth of winter annual weeds though competition and shading out new emerging seedlings. Cereal grains tend to have a high C:N ratio which slows down plant degradation which allows for plants residue to be more persistent than legume or brassica species (SARE, 2019; Burgos and Talbert, 1996; Pittman et al., 2020). This slow degradation of residue can provide longer in season weed control through physical suppression. Rolling of a cereal grain can make a mat-like residue across the field and increase weed suppression compared to terminating the stand with herbicide and leaving the cover to remain standing. When the cover is left standing there are more available niches and open soil surface for weeds to emerge.

As more producers utilize minimum tillage practices and cover crop residues for weed control herbicide programs need to be adjusted as weed controls changes in these agronomic systems. It is possible residual preemergent herbicides could be absorbed by the residue, preventing it from reaching the soil surface. Or the residual herbicides could make it to the soil surface in the areas where there is less residue and provide weed control. It is possible the addition of a high residue cover crops alone provides the equivalent weed control as residual herbicides in conventionally tilled fields. Residual herbicides need rainfall or irrigation to activate which could assist with washing herbicides off the cover crop residue to reach the soil surface. This can be further compounded but different amounts of cover crop residue on the soil surface as more biomass may reduce the need for residuals versus when a cover crop stand has little biomass.

Vann et al. (2018) observed cover crops in combination with preemergence herbicide saw a 99% increase in weed suppression compared to plots with no herbicide or no cover crop. The study also observed no difference in weed suppression if the cover was rolled or remained standing when no herbicides were used (Vann et al., 2018). The study observed a 67-71% control of Palmer amaranth in systems utilizing cover crops plus residual control compared to 35-57% with herbicides only at one week after planting, with similar trends till five weeks after planting (Vollmer et al., 2020). Vollmer et al. (2020) also observed the presence of rye residue alone improved weed control compared to conventionally tilled non treated check. Similar trends of weed control were observed with morningglory species and large crabgrass control as well (Vollmer et al., 2018).

Studies have observed little to no impact on late season weed biomass when cover crop residues are used (Vann et al., 2018; Moore et al., 1994). Korres and Norsworthy, (2015) observed the opposite, likely due to having more rye biomass production than the other studies. The use of high residue cover crop with residual herbicide has the potential to increase weed control and reduce the number of in season herbicide applications which can help to offset the cost of putting in cover crops (Creech, 2018). Overall, in years with less biomass a producer will likely have to increase herbicide inputs compared to years with heavy residue.

A number of studies have observed better weed control when high residue cover corps are used in conjunction with herbicides (Vann et al., 2018; Price et al., 2006; Wiggin et al., 2016; Norsworthy et al., 2011) However, few studies have been conducted to determine if preemergent herbicides are needed in high residue cover crop at planting, or if the combination of cover crop and preemergent herbicides may provide more early season weed control than cover crop alone or conventional tilled programs. No studies have been conducted in peanut cropping systems at the time of this writing. Furthermore, it is important to evaluate the residual herbicides amounts that are reaching the soil surface because if only half rates are reaching the surface this situation could increase selection pressure for resistant weeds.

## 7. Conclusion

The consistent use of one mode of action for weed control has led to the development of herbicide resistant weeds, producers then turn to a different mode of action and the cycle begin against. Currently, there are no new modes of actions on the market and herbicides chemistries need to be protected for future use. However, the problem of herbicide resistant weeds is growing, and many species have developed multiple resistance making it more difficult to control. In order to control some of these resistant weeds in season growers must utilize herbicides that are prone to causing crop injury and a risk to yield. Understanding peanut and cotton herbicide tolerance to these herbicides can assist with making informed decisions for in season post emergence herbicide applications to effectively control weeds without causing yield reductions. Another way to increase weed control, especially with herbicide resistant weeds, is to incorporate high residue cover crops into current herbicide programs. Herbicide resistant weeds are not going to disappear, and producers must incorporate different cultural practices of weed control such as cover crops, row spacing, planting populations into their current programs to give crops a competitive chance against weeds.

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## Chapter 2

## Evaluation of Peanut Tolerance to Mid-Season Applications of PPO-Inhibitor Herbicides Mixed with Different Surfactants

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## 2.1 Highlights:

- High surfactant oil concentrate caused more injury than non-ionic surfactant
- Carfentrazone caused greater injury and yield loss than acifluorfen and lactofen
- Peanuts are most sensitive to herbicide injury at 75 days after planting
- Excessive injury from herbicide and surfactant can reduce peanut yield
- Visible injury and NDVI readings are not reliable indicators of yield loss

## 2.2 Abstract

Protoporphyrinogen oxidase (PPO) inhibitor herbicides are being increasingly used to control acetolactate synthases (ALS) inhibitor-resistant weeds in peanuts (*Arachis hypogaea* L.). However, PPO-inhibitor herbicides can injure the crop under certain application conditions, especially under abiotic stress and surfactants may exacerbate this injury. The objectives of this study were to 1) investigate the effect of PPO-inhibitor based treatments on dryland peanut growth and yield when applied at three timings in mid-season, 2) evaluate the interactions of surfactants, chloroacetamide herbicides, and PPO-inhibitors, and 3) assess the level of correlation of normalized difference vegetation index (NDVI) readings to traditional visible injury rating. Field studies were conducted in Henry and Escambia counties in Alabama, U.S. during 2018, and 2019. Up to 55% of visible peanut injury was observed with acifluorfen, lactofen, and carfentrazone-ethyl treatments. In general, the NDVI readings correlated significantly with traditional visible injury ratings. A tank mixture of chloroacetamide herbicides (pyroxasulfone, *S*-metolachlor, dimethenamid-P) with lactofen did not lead to more injury or

yield loss than lactofen applied alone. Yield losses up 27% were observed with carfentrazone-ethyl plus a high surfactant oil concentrate (HSOC) at 75 and 90 days after planting (DAP) as compared to the non-treated check (NTC). Overall, treatments with HSOC and/or carfentrazone-ethyl were more likely to cause significant injury and yield loss than treatments with acifluorfen or lactofen plus nonionic surfactant (NIS). Peanuts are more sensitive to PPO-inhibitor herbicides at 75 DAP. NDVI did provide additional plant health information to subjective injury ratings, however, neither of these measurements are reliable predictors of peanut yield loss.
**KEY WORDS:** PPO-inhibitor herbicide, Surfactant, Yield loss, NDVI, Application timing, Peanut

### 2.3 Introduction

With the ever-increasing prevalence of ALS-resistant weeds including Palmer amaranth (*Amaranthus palmeri* S. Watson) and the possible development of ALS-resistant sicklepod (*Senna obtusifolia* (L.) H.S. Irwin & Barneby), peanut producers in the southeast U.S. have been challenged to find effective postemergence strategies for mid-season weed control. Peanut cultivars require a long growing season, usually 135-160 days, and are slow to close canopy which makes season-long weed control vital. However, commonly used residual herbicides do not provide season-long weed control, making mid-season postemergence (POST) applications important (Baughman et al., 2018; Wilcut et al., 1995). With ALS resistant Palmer amaranth, peanut producers have limited options for POST control and must rely on paraquat and PPO-inhibitor herbicides. Paraquat is only labeled in peanuts up to 28 days after ground cracking, any application past that risks significant yield loss (Anonymous, 2016; Knauft et al., 1990; Wehtje et al., 1986). PPO-inhibitor herbicides can provide effective control of many ALS-resistant weeds including Palmer amaranth, but peanut injury from these herbicides is a major concern when applied mid to late season (Boyer et al., 2011; Ferrell et al., 2013). The addition of surfactants such as crop oil concentrates (COC) can lead to increased foliar injury on crops (Kapusta et al., 1986). Producers are limited on POST herbicide options, but mid to late-season weed control is important to reduce yield loss from weed inference and increase peanut harvest efficiency (Wilcut et al., 1994; Wilcut et al., 1995).

Previous researchers have observed foliar injury from PPO inhibitor herbicides on peanut, but it does not always lead to significant yield reductions. Ferrell et al. (2013) observed no yield reductions when lactofen was applied with COC at 15, 30, 45 days after planting (DAP). Lactofen plus COC caused up to 48% injury when applied 4 weeks after planting but did not result in a significant yield reduction (Boyer et al., 2011). Sequential applications of lactofen to be more injurious than acifluorfen, bentazon, 2,4-DB alone, or in combination with each other when applied at 42 DAP (Sperry et al., 2017). Boyer et al. (2011) observed up to 38% peanut injury and a 17% reduction in yields when lactofen was applied 8 weeks after planting. There was a 17% and 6% yield loss when lactofen and acifluorfen were applied 70 DAP in one year but no yield loss in the next year (Boyer et al., 2011). Dotray et al. (2012) found lactofen caused 5% yield reductions when applied 70-80 DAP, at the pod filling stage but not for earlier applications in the season. Adding in a different type of surfactant can further complicate crop injury and yield loss. Overall, the relationship between PPO-inhibitors, application timings, peanut growth stage, surfactants, and yield loss needs further study.

Producers often mix chloroacetamides (WSSA group 15) with POST herbicides in early and mid-season applications to attain residual weed control and introduce another mode of action for resistance management. Grichar and Dotray (2012) observed increased stunting (up to 15%) when *S*-metolachlor was tank mixed with paraquat applied early POST; however, this did not lead to a yield loss. Jordan et al. (2003) observed more peanut stunting with metolachlor plus bentazon plus acifluorfen applied 3 weeks after emergence than without metolachlor. Eure et al. (2015) observed minor stunting of 5% with tank mixes of pyroxasulfone with lactofen, paraquat, and imazapic applied 14-20 DAP. Overall, the addition of a chloroacetamide could increase injury early in the season, however, mid-season peanut tolerance is unknown.

Visible estimates of injury can be effective for assessing foliar injury. Generally, measuring canopy width and height is the preferred method to determine crop stunting and injury from herbicide damage. However, this data does not take into account foliar burns and may not be accurate once peanuts have fully canopied. Visible injury estimates are subjective and likely vary amongst researchers. Handheld NDVI instruments could provide objective data in conjunction with visible injury estimates. Visible injury estimates are not generally an accurate predictor of yield loss and NDVI data may be more predictive. Iseave (2012) observed a positive correlation between NDVI and yield when evaluating peanut disease, however, results vary based on data collection timings. Taylor et al. (2010) evaluated dicamba injury on cotton, observed varied correlations between NDVI and yield depending on when the data was collected. The varied results indicate the relationship between NDVI, visible injury ratings and crop yield needs to be further evaluated.

Overall, there is limited published data on peanut tolerance to PPO-inhibitors herbicides applied at different growth stages and with different surfactants, especially for mid-season applications. Therefore, the objectives of this study were to: 1) investigate the effect of PPO inhibitor-based treatments with either NIS or HSOC on dryland peanut growth and yield when applied mid-season during reproductive stages at 60 (R4-R5), 75 (R6), and 90 (R6-R7) DAP, 2) evaluate peanut tolerance to tank mixes of three chloroacetamides with lactofen, and 3) assess the correlation of NDVI data to traditional visible injury ratings.

## 2.4 Materials and Methods

### *2.4.1. Field experiments.*

Field studies were conducted at the Brewton Agricultural Research Unit in Escambia County Alabama (31° 8' 29.652" N 87° 2' 52.296" W) and Wiregrass Research and Extension Center in Henry County Alabama (31°21'17.1"N 85°19'35.3"W) in 2018 and 2019. The field at each location was conventionally prepared and peanut variety Georgia 06G was planted at 112 kg $ha^{-1}$. Peanuts were planted on May 10, 2018 and April 24, 2019 in Henry County. In Escambia County, peanuts were planted on June 5, 2018 and May 16, 2019. The experimental units were arranged in a completely randomized block design with four replications. Plots were 3.6 m wide by 7.3 m long containing four rows of peanuts.

### *2.4.2. Herbicide application.*

Flumioxazin was applied at 107 g ai $ha^{-1}$ at planting and imazapic 70 g ai $ha^{-1}$ plus *S*-metolachlor 1470 g ai $ha^{-1}$ were applied early POST at each location as a blanket application to all plots including NTC to provide early season weed control. Hand-weeding was also conducted as needed to maintain the entire trial weed-free. The NTC plots did not receive any additional herbicide applications after the early post so they could be used as a comparison for the plots receiving mid-season herbicide applications. Peanut production practices recommended by Alabama Cooperative Extension were followed throughout the season to simulate on-farm production. There was no visible injury from the preemergent and early post applications before mid-season herbicide applications. Herbicide treatments were applied using a backpack sprayer with a six-nozzle boom (Teejet TT110025 wide angle flat nozzles, Teejet®, Spraying Systems Co. Wheaton, IL. 60187) propelled by compressed $CO_2$ at a spray volume of 187 L $ha^{-1}$. Herbicide treatments and rates are listed in Table 1. Three treatments contained 33% over the maximum label rates of acifluorfen, lactofen, and carfentrazone-ethyl to simulate applications by inaccurate sprayer or improper overlapping between nozzles at 75 DAP. Herbicide treatments were applied July 9 (60 DAP), July 25 (75 DAP), August 9 (90 DAP), 2018, and June 24, July 10, July 26, 2019 in Henry County. In Escambia County treatments were applied on August 6 (60 DAP), August 20 (75 DAP), September 7 (90 DAP), 2018, and July 15, July 30, and August 14, 2019.

*2.4.3. Data collection.*

Whole plot visible injury ratings of 0-100% (0% no injury, 100% complete mortality) and NDVI readings were conducted at 14, 21, and 28 DAT at each location. Five NDVI readings were randomly collected per plot from two center rows of peanut using a Trimble® GreenSeeker™ hand-held crop sensor (Trimble Inc. Sunnyvale, CA 94085). The yield was collected at peanut maturity from the two center rows of each plot.

*2.4.4. Statistical analysis.*

Yield was converted to percentage of the NTC before statistical analysis. NDVI data were averaged over each plot before statistical analysis. Yields, visible injury ratings, and NDIV data were analyzed using PROC GLIMMIX in SAS® 9.4 (SAS Institute Inc. Cary, NC. 27513). Treatment, location, year, were considered fixed effects, while block was the random effect, and all interactions were considered. If the treatment by year or treatment by location interaction was significant, data were analyzed and presented separately. All means were separated using the appropriate Tukey's Honest Significant Difference ($P \leq 0.05$) to reveal statistical difference. Injury rating data and NDVI data were also subjected to correlation analysis with PROC CORR in SAS® 9.4 (SAS Institute Inc. Cary, NC. 27513).

## 2.5 Results and Discussion

### *2.5.1 Herbicide application at 60 days after planting*

Analysis of injury rating data following 60 DAP herbicide applications revealed no year by treatment interaction, however, the location by treatment interaction was significant thus data were analyzed by location (Table 2). Tank mixes of lactofen plus *S*-metolachlor resulted in the highest visible injury (10-34%) of all applications and both locations. Treatments with chloroacetamides resulted in a similar level of injury to lactofen alone. NDVI data for 60 DAP applications did not have significant interactions and data were pooled over year and locations (Table 3). At 14 DAT lactofen plus dimethenamind-P resulted in an NDVI reduction of 0.0214 compared to the NTC; however, peanuts recovered by 28 DAT. Lactofen plus dimethenamind-P did not have the highest visible injury for either years or locations. At 28 DAT lactofen plus *S*-metolachlor had a reduction of 0.0188 from the NTC, it also had the highest visible injury (24%) in Henry County. While the herbicide treatments caused visible injury and different levels of reduction in NDVI readings, these did not result in yield loss with any of the treatments at either location (data not shown).

These results align with findings from other researchers who observed injury but no yield loss when chloroacetamides were applied POST to peanuts (Eure et al., 2015; Grichar and

Dotray, 2012: Jordan et al., 2003). Protsko et al. (2011) reported 10% or less injury and no yield loss for rates up to 480 g ai $ha^{-1}$ of pyroxasulfone applied 44-51 DAP. Grichar et al. (1996) observed less than 10% injury for *S*-metolachlor applied alone 22-35 DAP with rates up to 1.12 kg $ha^{-1}$. While many of the previous researchers applied chloroacetamides earlier in the season, the data from this study indicate peanut tolerance to these herbicides at 60 DAP. Peanut producers could expect foliar burns and some stunting from lactofen tank mixes with a HSOC applied at 60 DAP. The addition of chloroacetamides to lactofen tank mixes will increase residual control and introduce a second mode of action without likely increasing crop injury, reducing NDVI, or receiving yield loss.

### *2.5.2 Herbicide application at 75 days after planting*

For herbicide applications made 75 DAP, there was not a significant location difference in 2018. In 2019, there was a significant treatment by location difference, and data were presented by location (Table 4). In 2019, lactofen plus NIS had a 16% injury in Escambia County at 14 DAT, and this was the only time this treatment had significant injury compared to the NTC. Peanut injury in Escambia county was worse than Henry county in 2019, likely due to drought and high heat conditions. The test at Henry county received rainfall within 3 days following 75 DAP herbicide applications. The test at Escambia county did not receive any rainfall within 21 days following the 75 DAP applications which significantly delayed peanut recovery from injury. Rainfall likely allowed the peanut plants to recovery faster at the Headland site than the Escambia site from herbicide injury. Acifluorfen treatments had a similar injury rating as lactofen regardless of the surfactant used, except for Escambia county (28 DAT in 2019) when HSOC was used with the highest rate of lactofen. Sperry et al. (2017) found peanuts treated with acifluorfen had less injury than lactofen treatments when applied 6 weeks after planting. Carfentrazone-ethyl treatments caused over 43% injury at 14 DAT in 2018 and Escambia County in 2019. Dotray et al. (2010) observed injury ranging from 15-62% for carfentrazone-ethyl applied at 2.6 and 3.5 g ai $ha^{-1}$ 28-51 DAP. By 28 DAT, these treatments still had the highest overall injury rating regardless of surfactant in this study. All herbicide treatments with over the labeled rates generally resulted in higher visible injury compared to the labeled rate.

NDVI data for treatments applied at 75 DAP had no year to year differences, but location by treatment difference at 14 DAT and were assessed separately (Table 5). All treatments were significantly reduced in Escambia County 14 DAT, with carfentrazone-ethyl treatments have the largest reductions of up to 0.049 in 2018-2019 from the NTC. None of the treatments were reduced in Henry County at 14 DAT which correlates to visible injury as shown in Table 4. By 28 DAT, only carfentrazone-ethyl plus 2,4-DB plus HSOC at the highest labeled rate (35 g ai $ha^{-1}$) had a reduction of 0.0337 compared to the NTC over both locations. However, more differences of visible injury were observed than NDVI reading reductions at 28 DAT, which indicates a divergence between these two types of measurements. These NDVI results indicate most treatments had some recovery from the foliar burn at 28 DAT as new foliage likely grew on top of the peanut plant by this time. However, during visible injury ratings, leaf burns on older foliage under these new leaves were still taken into consideration which resulted in more treatment differences. NDVI readings provide additional data points to be used with visible injury rating especially immediately after crop injury to herbicides until the plant produces new vegetative growth.

Peanut yields did have a significant year by treatment interaction and were analyzed separately year (Table 6). There was also a location by treatment difference in 2019 data. In 2018, all treatment yields were reduced compared to the NTC except for acifluorfen plus 2,4-DB plus NIS. Aciflurofen and lactofen with HSOC had reductions of 16% and 13% respectively, in 2018, regardless of rates. In 2018, all lactofen and acifluorfen treatments caused yield reductions of 5-13% and 2-16% regardless of surfactant. When NIS was used, only lactofen and acifluorfen caused minimal yield loss of 5% and 2% respectively, in 2018. While minimal yield loss was observed regardless of surfactant, NIS is a safer surfactant than HSOC with less potential to cause foliage burn and yield loss. Dotray et al. (2012) observed the highest yield loss when lactofen was applied at 70-80 DAP compared to any other timing studied. Jordan et al. (2003) observed that acifluorfen 0.28 kg ai $ha^{-1}$ plus bentazon 0.56 kg ai $ha^{-1}$ reduced peanut yields by 150 to 200 kg $ha^{-1}$ when applied at 42-56 DAP compared to the NTC. No yield reductions were observed for the lactofen or acifluorfen treatments in 2019 at either location even though there was significant injury, suggesting favorable environmental factors allowed for more peanut recovery with a full growing season. Carfentrazone-ethyl plus 2,4-DB plus HSOC at over the label rate (52 g ai $ha^{-1}$) caused a 31% yield loss compared to the NTC in 2018, which was the greatest yield loss of all treatments. In Escambia County, carfentrazone-ethyl 52 g ai $ha^{-1}$ plus 2,4-DB plus HSOC, and carfentrazone-ethyl 35 g ai $ha^{-1}$ plus 2,4-DB plus NIS caused yield reductions of 20% and 18% respectively in 2019. Dotray et al. (2010) observed yield loss at two of six locations when carfentrazone-ethyl was applied at 26 and 35 g ai $ha^{-1}$ 28-51 DAP. Overall, carfentrazone-ethyl over the label rate (52 g ai $ha^{-1}$) lead to the worst yield loss trend in 2018 and Escambia County in 2019 compared to other treatments evaluated. Overall, PPO-inhibitor herbicides applied at 75 days after planting were more likely to cause foliar injury, reduced

NDVI readings, and yield loss if HSOC was used rather than NIS. Of the three PPO-inhibitors evaluated in this study, crop damage and yield loss potential follow the sequence of carfentrazone-ethyl > lactofen ≥ acifluorfen. Peanut producers should avoid applying PPO-inhibitor herbicides with HSOC at this timing and refrain from using carfentrazone-ethyl.

There was less injury, higher NDVI readings, and no yield loss observed for all treatments conducted at Henry County in 2019 compared to Escambia County. This possibly was due to rainfall (1 cm) that occurred within 48 hours of application at this location in 2019 which did not occur at the other site. This suggests environmental factors could alter the injury potential of PPO inhibitor herbicides regardless of surfactant used. However, this needs to be studied further to determine what conditions can mitigate injury and provide effective weed control.

#### *2.5.3. Herbicide application at 90 days after planting*

For injury ratings of herbicide applications made 90 DAP, there was a significant year by treatment interaction, data was separated accordingly (Table 7). In 2019 at 14 DAT, there was a significant location by treatment interaction thus data was analyzed by location. Regardless of the surfactant used, treatments with carfentrazone-ethyl had more injury than lactofen treatments at both 14 and 21 DAT at either location. In 2018, lactofen plus NIS was not significantly different from the NTC by 21 DAT; this was the only treatment not different from the NTC at 14 DAT in 2019 at Escambia county. Lactofen plus NIS showed an overall trend of having the least amount of injury compared to other treatments evaluated in both years. The addition of HSOC with lactofen increased foliar burn and peanut injury compared to NIS at this application timing. Dotray et al (2010) 3-13% injury 14 DAT from carfentrazone-ethyl applied 93-121 DAP which is lower than what was observed in this study; however, surfactants were not utilized. If a producer needs to spray weeds at 90 DAP, lactofen with NIS is the least likely to cause visible injury, or using lower than maximum label rates of carfentrazone-ethyl is recommended.

For NDVI data, there was not a treatment by year interaction or treatment by location interaction and were analyzed together (Table 8). At 14 DAT, all treatments significantly reduced NDVI readings by 0.0117-0.0418 compared to the NTC. At 14 DAT, carfentrazone-ethyl plus NIS had the highest reduction of 0.0418 compared to the NTC, it also had the highest injury rating of 55% in 2018. At 21 DAT lactofen plus NIS did not have a significant reduction from the NTC while all other treatments did, which aligned with injury ratings. Carfentrazone-ethyl plus NIS had the highest reduction of 0.035 while carfentrazone-ethyl plus HSOC had a similar reduction of 0.0325 compared to NTC at 21 DAT, which corresponded to visible injury rating. Overall, regardless of the surfactant, carfentrazone-ethyl caused a greater reduction in NDVI and higher visible injury than lactofen.

There was not a treatment by year interaction or treatment by location interaction; therefore, results were analyzed together for yields (Table 9). The only treatment to cause a significant yield loss of 16% was carfentrazone-ethyl plus HSOC. While carfentrazone-ethyl plus NIS had the highest NDVI reductions and some of the highest injury ratings, overall, it only resulted in a 9% yield reduction which was not significantly different from the NTC. Similarly, Dotray et al. (2010) observed an 8% yield loss with carfentrazone-ethyl 35 g ai $ha^{-1}$ when applied 93-121 DAP. However, this yield loss was only observed at one location while 5 other locations did not have yield losses. Lactofen plus HSOC resulted in injury and lower NDVI compared to the NTC but this treatment did not result in yield loss. Overall, treatments with HSOC and carfentrazone-ethyl generated the highest injury rating, lowest NDVI readings, and more yield reductions when applied at 90 DAP.

*2.5.4 NDVI data vs visible injury data*

Generally, NDVI and visible injury had a negative correlation with a varying agreement for each application timing. When injury ratings were higher, NDVI was lower but significance varied (Table 10). Injury ratings for herbicides applied 60 DAP taken at 14 DAT were not significantly correlated with NDVI data. This is likely due to visible injury ratings considering general stunting that NDVI data could not account for. A nonsignificant correlation was observed for injury and NDVI data taken at 28 DAT for herbicide applications applied 75 DAP. This nonsignificant correlation likely was caused by the new foliage growth on the top portion of the peanut plants hiding the foliar burn observed on older leaves. All of the correlations were significant for herbicide applications applied 90 DAP. This was probably due to the lack of new foliage growth, so injury was visible. NDVI was not able to take into account observed stunting, twisting, curled, or flipped leaves which may explain the lack of correlations in two cases here. Similar to visible injury ratings, a significantly reduced NDVI did not often result in a predicted yield loss. Overall, NDVI data are a useful tool to add to visible injury ratings that provide objective measurements, but it is not a replacement for injury ratings. The relationship with NDVI to injury ratings and yields needs further evaluation.

## 2.6 Conclusion

PPO-inhibitor herbicides applied at 60 and 90 DAP with NIS will likely not result in significant yield losses. Additionally, chloroacetamide treatments in this study did not increase foliar injury or yield loss when applied with lactofen at 60 DAP. Applications of PPO-inhibitor herbicides should be avoided past 60 DAP if possible, as it can result in unpredictable yield loss which is also environmentally dependent. Carfentrazone-ethyl treatments regardless of the surfactant may lead to more frequent yield loss if applied 75 or 90 DAP at full label rate or over full label rate. The addition of HSOC with PPO-inhibitor herbicides will result in more overall injury, lower NDVI, and yield loss than NIS, especially at 75 DAP. NDVI did provide an additional growth measurement to compare to subjective injury ratings. However, both of these measurements do not adequately predict yield loss. PPO-inhibitor herbicides can be an effective option for ALS-inhibitor resistant weed control for peanut producers; however, caution needs to be taken to avoid applying these herbicides during the pod filling stage under adverse weather conditions as it will likely result in yield loss.

### 2.7 Conflict of Interest

The authors of this study do not have conflict of interest to declare.

### 2.8 Acknowledgments

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| Table 1: Herbicide tank mix treatments evaluated | |
|---|---|
| Herbicide | Rates evaluated<br>g ai ha$^{-1}$ |
| 60 DAP | |
| Lactofen[a] + 2,4DB[b] + HSOC[c] | 219 + 420 + 0.75% v/v |
| Lactofen + 2,4DB + Pyroxasulfone[d] + HSOC | 219 + 420 + 39 + 0.75% v/v |
| Lactofen + 2,4DB + S-metolachlor[e] +HSOC | 219 + 420 + 1,700 + 0.75% v/v |
| Lactofen + 2,4DB + Dimethenamind-P[f] + HSOC | 219 + 420 + 1,102 +0.75% v/v |
| 75 DAP | |
| Lactofen + 2,4DB + HSOC | 219 + 280 + 0.75% v/v |
| Lactofen + 2,4DB + NIS[g] | 219 + 280 + 0.25% v/v |
| Lactofen + 2,4DB + HSOC | 328 + 420 + 0.9% v/v |
| Carfentrazone-ethyl[h]+ 2,4DB + HSOC | 35 + 280 + 0.75% v/v |
| Carfentrazone-ethyl+ 2,4DB + NIS | 35 + 280 + 0.25% v/v |
| Carfentrazone-ethyl+ 2,4DB + HSOC | 52 + 420 + 0.9% v/v |
| Aciflurofen[i] + 2,4DB + HSOC | 420 + 280 + 0.75% v/v |
| Aciflurofen + 2,4DB + NIS | 420 + 280 + 0.25% v/v |
| Aciflurofen + 2,4DB + HSOC | 630 + 420 +0.9% v/v |
| 90 DAP | |
| Lactofen + 2,4DB + HSOC | 219 + 420 + 0.75% v/v |
| Carfentrazone-ethyl+ 2,4DB + HSOC | 35 + 280 + 0.75% v/v |
| Lactofen + 2,4DB + NIS | 219 + 420 + 0.25% v/v |
| Carfentrazone-ethyl+ 2,4DB + NIS | 35 + 280 + 0.25% v/v |
| Non-treated check | --- |

[a] Cobra® Valent USA. Walnut Creek, CA
[b]Butyrac® Albaugh Inc. Ankeny, IA
[c]Superb HC® Windfield Solutions LLC St. Paul, MN
[d]Zidua® BASF Corporation Research Triangle Park, NC
[e]Dual Magnum® Syngenta Corporation Greensboro, NC
[f]Outlook® BASF Corporation Research Triangle Park, NC
[g]TopSurf® Winfield Solutions LLC St. Paul, MN
[h]Aim® FMC Corporation Philadelphia, PA

Table 2: Peanut injury as affected by lactofen and chloroacetamides applied 60 days after planting 2018-2019[ab]

| Treatment[c] | Active ingredient g ai ha$^{-1}$ | Peanut injury % | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 14 DAT | | | | 28 DAT | | | |
| | | Henry | | Escambia | | Henry | | Escambia | |
| Lactofen<br>HSOC | 219<br>0.75 % v/v | 21 | ab | 31 | a | 19 | a | 9 | a |
| Lactofen<br>Pyroxasulfone<br>HSOC | 219<br>39<br>0.75 % v/v | 18 | b | 34 | a | 14 | a | 14 | a |
| Lactofen<br>*S*-Metolachlor<br>HSOC | 219<br>1,700<br>0.75 % v/v | 26 | a | 34 | a | 24 | a | 10 | a |
| Lactofen<br>Dimethenamind-P<br>HSOC | 219<br>1,102<br>0.75 % v/v | 20 | ab | 32 | a | 15 | a | 11 | a |
| Non-Treated Check | | 0 | c | 0 | b | 0 | b | 0 | b |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate

[c] All treatments included 2,4-DB 420 g ai ha$^{-1}$

Table 3: Peanut NDVI as affected by lactofen and chloroacetamides applied 60 days after planting in 2018-2019 over both locations[ab]

| Treatment[c] | Active ingredient g ai $ha^{-1}$ | Peanut NDVI reading | | | |
|---|---|---|---|---|---|
| | | 14 DAT | | 28 DAT | |
| Lactofen<br>HSOC | 219<br>0.75 % v/v | 0.8671 | ab | 0.9001 | ab |
| Lactofen<br>Pyroxasulfone<br>HSOC | 219<br>39<br>0.75 % v/v | 0.8724 | ab | 0.8994 | ab |
| Lactofen<br>*S*-Metolachlor<br>HSOC | 219<br>1,700<br>0.75 % v/v | 0.8671 | ab | 0.8892 | b |
| Lactofen<br>Dimethenamind-P<br>HSOC | 219<br>1,102<br>0.75 % v/v | 0.8645 | b | 0.8949 | ab |
| Non-Treated Check | | 0.8859 | a | 0.9080 | a |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

[c] All treatments included 2,4-DB 420 g ai $ha^{-1}$

Table 4: Peanut injury as affected by PPO-inhibitor herbicides and surfactants applied at 75 days after planting [ab]

| Treatment | Active ingredient g ai ha$^{-1}$ | Peanut injury (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 14 DAT | | | 28 DAT | | |
| | | 2018 | 2019 | | 2018 | 2019 | |
| | | Both Locations | Henry | Escambia | Both Locations | Henry | Escambia |
| Lactofen<br>2,4-DB<br>HSOC | 219<br>280<br>0.75 % v/v | 26 c | 9 ab | 25 cd | 21 de | 5 a | 14 bc |
| Lactofen<br>2,4-DB<br>NIS | 219<br>280<br>0.25 % v/v | 17 cd | 9 ab | 16 cd | 11 ef | 4 a | 6 cd |
| Lactofen<br>2,4-DB<br>HSOC | 328<br>420<br>0.9%v/v | 23 c | 15 a | 30 bc | 18 de | 5 a | 25 ab |
| Carfentrazone-ethyl<br>2,4-DB<br>HSOC | 35<br>280<br>0.75 % v/v | 50 ab | 9 ab | 43 ab | 41 ab | 3 a | 25 ab |
| Carfentrazone-ethyl<br>2,4-DB<br>NIS | 35<br>280<br>0.25 % v/v | 46 ab | 14 a | 43 ba | 36 abc | 6 a | 26 a |
| Carfentrazone-ethyl<br>2,4-DB<br>HSOC | 52<br>420<br>0.9%v/v | 54 a | 8 ab | 53 a | 44 a | 5 a | 35 a |
| Acifluorfen<br>2,4-DB<br>HSOC | 420<br>280<br>0.75 % v/v | 33 bc | 11 a | 15 d | 26 bcd | 5 a | 6 cd |
| Acifluorfen<br>2,4-DB<br>NIS | 420<br>280<br>0.25 % v/v | 25 c | 9 ab | 15 d | 23 cde | 4 a | 6 cd |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Acifluorfen<br>2,4-DB<br>HSOC | 630<br>420<br>0.9%v/v | 27 c | 8 ab | 18 cd | 23 cde | 5 a | 11 cd |
| Non-Treated Check | | 0 d | 0 b | 0 e | 0 f | 0 a | 0 d |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

Table 5: Peanut NDVI readings as affected by PPO-inhibitor herbicides and surfactants applied at 75 days after planting[ab]

| Treatment | Active ingredient g ai ha$^{-1}$ | Peanut NDVI reading | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2018-2019 | | | | | |
| | | 14 DAT | | | | 28 DAT | |
| | | Henry | | Escambia | | Both Locations | |
| Lactofen<br>2,4-DB<br>HSOC | 219<br>280<br>0.75 % v/v | 0.9025 | a | 0.8943 | b | 0.9002 | a |
| Lactofen<br>2,4-DB<br>NIS | 219<br>280<br>0.25 % v/v | 0.9135 | a | 0.9040 | b | 0.9106 | a |
| Lactofen<br>2,4-DB<br>HSOC | 328<br>420<br>0.9%v/v | 0.8965 | a | 0.8900 | b | 0.8941 | a |
| Carfentrazone-ethyl<br>2,4-DB<br>HSOC | 35<br>280<br>0.75 % v/v | 0.8645 | a | 0.8740 | c | 0.8637 | b |
| Carfentrazone-ethyl<br>2,4-DB<br>NIS | 35<br>280<br>0.25 % v/v | 0.8915 | a | 0.8720 | c | 0.8847 | ab |
| Carfentrazone-ethyl<br>2,4-DB<br>HSOC | 52<br>420<br>0.9%v/v | 0.88925 | a | 0.8728 | c | 0.8835 | ab |
| Acifluorfen<br>2,4-DB<br>HSOC | 420<br>280<br>0.75 % v/v | 0.905 | a | 0.8963 | b | 0.9015 | a |
| Acifluorfen<br>2,4-DB<br>NIS | 420<br>280<br>0.25 % v/v | 0.906 | a | 0.8993 | b | 0.9030 | a |
| Acifluorfen<br>2,4-DB<br>HSOC | 630<br>420<br>0.9%v/v | 0.9075 | a | 0.8940 | b | 0.9019 | a |
| Non-Treated Check | | 0.898 | a | 0.9210 | a | 0.8974 | a |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

Table 6: Peanut yield as affected by PPO-inhibitor herbicides and surfactants at 75 days after planting[ab]

| Treatment | Active ingredient g ai $ha^{-1}$ | Peanut yield (%NTC) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2018 | | 2019 | | | |
| | | Both Locations | | Henry | | Escambia | |
| Lactofen<br>2,4-DB<br>HSOC | 219<br>280<br>0.75 % v/v | 87 | c | 101 | a | 96 | abc |
| Lactofen<br>2,4-DB<br>NIS | 219<br>280<br>0.25 % v/v | 95 | b | 104 | a | 101 | ab |
| Lactofen<br>2,4-DB<br>HSOC | 328<br>420<br>0.9%v/v | 87 | c | 102 | a | 97 | abc |
| Carfentrazone-ethyl<br>2,4-DB<br>HSOC | 35<br>280<br>0.75 % v/v | 73 | ef | 94 | a | 90 | bcd |
| Carfentrazone-ethyl<br>2,4-DB<br>NIS | 35<br>280<br>0.25 % v/v | 74 | def | 104 | a | 82 | cd |
| Carfentrazone-ethyl<br>2,4-DB<br>HSOC | 52<br>420<br>0.9%v/v | 69 | f | 108 | a | 80 | d |
| Acifluorfen<br>2,4-DB<br>HSOC | 420<br>280<br>0.75 % v/v | 84 | cde | 97 | a | 102 | ab |
| Acifluorfen<br>2,4-DB<br>NIS | 420<br>280<br>0.25 % v/v | 98 | a | 107 | a | 107 | a |
| Acifluorfen<br>2,4-DB<br>HSOC | 630<br>420<br>0.9%v/v | 84 | bcd | 99 | a | 98 | ab |
| Non-Treated Check | | 100 | a | 100 | a | 100 | ab |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

Table 7: Peanut injury as affected by lactofen tank mixes and different surfactants applied 90 days after planting[a]

| Treatment[c] | Active ingredient g ai $ha^{-1}$ | Peanut injury % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 14DAT | | | | | | 21 DAT | | | |
| | | 2018 | | 2019 | | | | 2018 | | 2019 | |
| | | Both Locations | | Henry | | Escambia | | Both Locations | | Both Locations | |
| Lactofen<br>HSOC | 219<br>0.75 % v/v | 24 | b | 33 | bc | 18 | bc | 19 | b | 12 | b |
| Carfentrazone-ethyl<br>HSOC | 35<br>0.75 % v/v | 49 | a | 43 | ab | 31 | a | 38 | a | 17 | a |
| Lactofen<br>NIS | 219<br>0.25 % v/v | 12 | c | 18 | c | 10 | cd | 9 | c | 6 | c |
| Carfentrazone-ethyl<br>NIS | 35<br>0.25 % v/v | 55 | a | 53 | a | 28 | ab | 46 | a | 16 | a |
| Non-Treated Check | | 0 | d | 0 | d | 0 | d | 0 | c | 0 | d |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

[c] All treatments included 2,4-DB 420 g ai $ha^{-1}$

Table 8: Peanut NDVI readings as affected by lactofen tank mixes and different surfactants applied 90 days after planting in 2018-2019 over both locations[ab]

| Treatment[c] | Active ingredient g ai ha$^{-1}$ | Peanut NDVI reading | |
|---|---|---|---|
| | | 14 DAT | 21 DAT |
| Lactofen<br>HSOC | 219<br>0.75 % v/v | 0.8993 b | 0.8902 b |
| Carfentrazone-ethyl<br>HSOC | 35<br>0.75 % v/v | 0.8802 c | 0.8719 c |
| Lactofen<br>NIS | 219<br>0.25 % v/v | 0.9071 b | 0.8989 a |
| Carfentrazone-ethyl<br>NIS | 35<br>0.25 % v/v | 0.8770 c | 0.8694 c |
| Non-Treated Check | | 0.9188 a | 0.9044 a |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of the non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

[c] All treatments included 2,4-DB 420 g ai ha$^{-1}$

Table 9: Peanut yields as affected by lactofen tank mixes and different surfactants applied 90 days after planting in 2018-2019[ab]

| Treatment[c] | Active ingredient g ai $ha^{-1}$ | Peanut yield (%NTC) |
|---|---|---|
| | | Both locations |
| Lactofen<br>HSOC | 219<br>0.75 % v/v | 98 ab |
| Carfentrazone-ethyl<br>HSOC | 35<br>0.75 % v/v | 84 c |
| Lactofen<br>NIS | 219<br>0.25 % v/v | 106 a |
| Carfentrazone-ethyl<br>NIS | 35<br>0.25 % v/v | 91 bc |
| Non-Treated Check | | 100 ab |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as a percentage of non-treated check.

[b] Abbreviations: DAT, days after treatment; HSOC, high surfactant oil concentrate; NIS, non-ionic surfactant

[c] All treatments included 2,4-DB 420 g ai $ha^{-1}$

Table 10: Pearson correlation of NDVI and injury ratings over both locations in 2018 and 2019

| Application Date DAP[a] | Rating Date DAT[a] | r | P-value |
|---|---|---|---|
| 60 | 14 | 0.02758 | 0.7729 |
| 60 | 28 | -0.49927 | <0.0001 |
| 60 | All data points | -0.22446 | 0.0007 |
| 75[b] | 14 | -0.68996 | <0.0001 |
| 75 | 28 | -0.00410 | 0.9595 |
| 75 | All data points | -0.33597 | <0.001 |
| 90 | 14 | -0.70399 | <0.0001 |
| 90 | 21 | -0.60803 | <0.0001 |
| 90 | All data points | -0.57211 | <0.0001 |
| All | All data points | -0.29031 | <0.0001 |

[a] Abbreviations: days after planting DAP, days after treatment DAT

[b] 6 points were removed from the 75 days after planting application due to being outliers. These were likely caused by the sensor reading soil surface along with the plant surface.

Chapter 3

# Evaluation of Runner-Type Peanut Cultivar Tolerance to Paraquat Tank Mixes

Running Title: Peanut tolerance to paraquat

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## 3.1 Abstract

Herbicide tank mixes are often used to reduce peanut injury caused by paraquat and broaden the weed control spectrum. New peanut cultivars are continuously being introduced therefore determining tolerance to paraquat based herbicide programs is essential to provide growers with appropriate recommendations. The objective of this trial was to evaluate effect of paraquat based herbicide programs on newer peanut cultivars growth and yield. Field trials were conducted in Macon, Henry and Baldwin counties in Alabama in 2016 and 2017 and the peanut cultivars 'Georgia 06G', 'Georgia 12Y', 'Georgia 14N', and 'TufRunner 511' were evaluated. Paraquat was applied alone (210, 280, 420 g ai/ha), in tank mixes with either bentazon plus acifluorfen or 2,4-DB and one of the following, *S*-metolachlor, pyroxasulfone, acetochlor, or pyroxasulfone plus carfentrazone at the highest labeled rates 3 to 4 wk after peanut planting. No cultivar by treatment interactions were observed for any growth parameters evaluated for any location. In 2017, paraquat either applied at 280 g ai/ha alone, tank mixed with *S*-metolachlor plus 2,4-DB, or with *S*-metolachlor plus bentazon plus acifluorfen significantly reduced canopy widths of 22 to 30%, 12 to 22%, and 20 to 37% respectively at 45 to 48 DAP when compared to the non-treated check (NTC). Yield reductions compared to the NTC were rare, paraquat plus bentazon plus acifluorfen plus pyroxasulfone plus carfentrazone had a 13% yield loss in Henry County and a 7% yield loss with paraquat 280 g ai/ha at Baldwin County in 2016 only. Data indicates peanut stunting may be observed following applications of paraquat tank mixes evaluated in this study, but it is unlikely these effects result in yield loss.

**Key Words:** bentazon; height; stunting; widths; yield loss

### 3.2 Introduction

Paraquat is often used in peanut for postemergence (POST) broadleaf weed control of sicklepod (*Senna obtusifolia* L.), Florida beggerweed (*Desmodium tortosum* D.C) and morningglory species (*Ipomoea* spp.) in the southern US (Wilcut et al. 1990; Wilcut et al. 1989; Wilcut and Swann 1990). Paraquat is labeled in peanuts up to 28 d after ground cracking with up to two applications at a total of 280 g ai/ha (Anonymous 2016). Broadcast applications of paraquat, prior to 28-day restriction, causes foliar injury to peanuts, however, it does not lead to yield loss (Wehtje et al. 1986). Other research has also confirmed runner type and virginia market-type peanuts are tolerant to paraquat if applied prior to pegging and fruit development at a rate less than 280 g ai/ha (Grichar and Dotray 2012; Wehtje et al. 1991; Wilcut and Swann 1990).

Paraquat tank mixed with 2,4-DB and/or bentazon is a frequently utilized POST program in peanut (Brecke and Colvin 1991; Wilcut et al. 1989, 1994b). Paraquat plus bentazon tank mixes control more broadleaf weeds including bristly starbur (*Aeanthospermum hispidum* DC.), coffee senna (*Cassia oecidentalis* L.), prickly sida (*Sida spinosa* L.), and smallflower morningglory (*Jacquemontia tamifolia* L.) than either herbicide applied alone (Wehtje et al. 1992; Wilcut et al. 1994a). Using 2,4-DB in combination with acifluorfen, bentazon, and paraquat will improve control of broadleaf weeds larger than the recommended size for treatment (Wilcut et al. 1994b). Additionally, bentazon acts as an antagonist to paraquat reducing paraquat efficacy on weed control; however, it reduces peanut injury. Bentazon, a photosynthetic inhibitor, inhibits the Hill reaction in photosystem II and reduces the flow of electrons into photosystem I (Mine and Matsunaka 1975; Shaner 2014). Paraquat inhibits photosynthesis at photosystem I by diverting electrons creating oxygen singlets (Shaner, 2014). It has been shown that herbicides that inhibit photosystems II, such as bentazon, can cause herbicides that inhibit efficacy of photosystem I, such as paraquat. (Hogue and Warren 1970; Moore and Banks 1991). Another study reported bentazon interferes and reduces the absorption of paraquat on the leaf surface (Wehtje et al. 1992).

Lack of residual activity and a short window for application are the two main drawbacks for paraquat (Wilcut et al. 1995). Therefore, producers frequently apply residual herbicides in combination with paraquat to broaden the spectrum of weed control, provide residual control and to prevent the development of herbicide resistant weeds (Jordan et al. 2011; Wilcut et al. 1995). Chloroacetamides are residual herbicides that are often used to control annual grasses, yellow nutsedge (*Cyperus exculentus* L.) and broadleaf weeds in peanuts (Brecke and Colvin 1991; Wilcut et al. 1994). Previous studies in Virginia, Texas, North Carolina, and Alabama have observed peanut injury from the application of chloroacetamide herbicides (Cardina and Swan 1988; Grichar et al. 1996; Jordan et al. 2003; Wehtje et al. 1988). Soil pH, moisture, organic matter, as well as, herbicide rates can affect chloroacetamide injury on peanuts (Cardina and Swann 1988; Wehtje et al. 1988). However, none of the observed injury in these studies led to yield loss when applied at the labeled rates. Therefore, tank mixing a chloroacetamide herbicide with paraquat and 2,4-DB or bentazon may increase peanut injury under certain environmental conditions, but it will provide longer weed control and should not decrease peanut yield.

Previous studies have determined runner-type peanut tolerance to paraquat is neither cultivar dependent nor influenced by seed size (Johnson et al. 1993; Wehtje et al. 1991; 1994). New runner-type peanut cultivars with different growth characteristics and greater yield potential are being released; however, they have not been sufficiently evaluated for tolerance to frequently used paraquat based herbicide programs in the southeastern US. Therefore, the objective of this study was to evaluate the tolerance runner-type peanut cultivars (Georgia 06G, Georgia 12Y, Georgia 14N, and TufRunner 511) to paraquat based programs and determine if these programs may result in growth suppression and yield losses in peanut.

**3.3 Materials and Methods**

Field trials were conducted in Macon County (32°29'45.6"N 85°53'25.2"W), Baldwin County (30°32'45.7"N 87°52'52.2"W), and Henry County (31°21'17.1"N 85°19'35.3"W), Alabama in 2016 and 2017. Soils at the Macon County location were kalmia sandy loam (fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludult), soils at the Henry County location were Dothan fine sandy loam, (fine-loamy, kaolinitic, thermic Plinthic Kandiudult), while soils at the Baldwin County location were a red bay fine sandy loam (fine-loamy, kaolinitic, thermic Rhodic Kandiudult).  Soils at the Macon County location had a pH of 6.1 and organic matter (OM) of 0.9%, Henry County Location had a pH of 6.2 and OM 1.2% and the Baldwin County location had a pH of 5.6 and OM of 1.6%.

Fields were conventional tilled and experiments were set up as a split plot design with four replications. The main plot was herbicide treatment and the subplot was peanut cultivar. Each subplot contained two rows while a whole plot had eight rows of peanut. Peanut cultivars evaluated were Georgia 06G (Branch 2007), Georgia 12Y (Branch 2013), Georgia 14N (Branch and Brenneman 2015), and TufRunner 511 (Tillman and Gobert 2017). Subplots were 7.6 m long in Headland in 2016 and at all locations in 2017. Subplots in Macon and Baldwin counties in 2016 were 9.1m long. Peanuts were planted on 0.9 m wide rows at all locations. Henry, Macon, and Baldwin County trials were planted on May 25, May 27, and May 16, 2016, respectively, while in 2017, Henry, Macon, and Baldwin County trials were planted on May 9, June 9, and May 10 respectively. Flumioxazin at 107 g ai/ha was applied at planting and imazapic at 70 g ai/ha plus 2,4-DB 280 at g ai/ha plus *S*-metolachlor at 1470 g ai/ha were applied POST as needed to all treatments including non-treated check to provide season-long weed control. Hand-weeding was used whenever needed to maintain a weed-free trial.

Treatments were applied using a backpack sprayer with a six-nozzle boom (Teejet TT110025 wide angle flat nozzles, Teejet®, Spraying Systems Co. Wheaton, IL. 60187) using compressed $CO_2$ at a spray volume of 187 L/ha. POST treatments were applied June 17, June 22, and June 13, 2016 in Henry, Macon and Baldwin County respectively; May 31, July 3, and June 2, 2017 in Henry, Macon and Baldwin County respectively. Henry and Macon County trials were planted dryland while Baldwin County trials were under irrigation. Table 1 includes rainfall and irrigation amounts for each location in 2016 and 2017. Although similar herbicide treatments were used each year, the paraquat rate was higher in 2017 since peanut varieties demonstrated sufficient tolerance, with little to no foliar burn, to paraquat at the recommended rate of 210 g ai/ha in 2016. While paraquat rates were different in 2016 (210 g ai/ha) and 2017 (280 g ai/ha), they fall within the labeled registration (Anonymous 2016). Additionally, several herbicide rates that were utilized in tank mixes with paraquat were changed from 2016 to 2017. In 2016, pyroxasulfone was applied at a higher than label rate of 179 g ai/ha, because at the time of the application it was not registered in peanuts so an estimated rate was used. In 2017, the newly registered labeled rate of 125 g ai/ha for peanut on sandy soils was used. Pre-mixture of pyroxasulfone plus carfentrazone (Anthem Flex®, FMC Corporation, Philadelphia, PA) was only used in 2016 study. Treatments can be found in Table 2 for 2016 and Table 3 for 2017. All treatments included a nonionic surfactant at 0.25 % v/v (Top Surf®, Winfield Solutions LLC. St. Paul, MN. 55164). Stand counts were recorded prior to POST treatment applications to ensure consistency between cultivars. In 2016, ten plant heights were randomly recorded in each subplot at 50 to 55 days after planting (DAP) and 72 to 78 DAP. In 2017, ten plant heights and canopy widths were randomly recorded in each subplot at 45 to 48 DAP and 66 to 68 DAP. Heights were measured from base of the plant at soil line to the highest growing point. Canopy widths were measured from furthest leaf tips horizontally across the peanut canopy at a spot randomly selected in the row. Based on peanut pod maturity (Williams and Drexler 1981) peanuts were dug October 3, October 6, October 24 in Henry, Baldwin, and Macon respectively in 2016. In 2017, peanuts were dug September 21, October 20, and November 8 in Henry, Baldwin, and Macon respectively. Pod yield was determined 4 to 7 days after digging utilizing a combine for each subplot.

*3.3.1Statistical analysis.* All data was converted to a percentage of NTC prior to statistical analysis. Then, converted data was processed with PROC GLIMMIX procedure in SAS® 9.4 (SAS Institute Inc. Cary, NC. 27513). Cultivar, treatment, location and block were subjected to analyses of variance for a split plot treatment arrangement. Combined analysis over years was not conducted due to herbicide treatment differences among year. Treatment, location, and cultivar were considered fixed effects, while block was a random effect. If treatment by location was not significant, then location was used as a random effect and data was combined over location for analysis. If the interaction was significant, data was analyzed and presented by location. All means were separated using the Fisher's Protected LSD ($P \leq 0.05$) to reveal statistical differences.

## 3.4 Results and Discussion

Data was combined over peanut cultivars, as there was no significant cultivar by treatment interaction ($P \leq 0.05$) for any of the parameters evaluated during 2016 and 2017. Therefore, the results of this study indicate response of four cultivars to paraquat is not cultivar specific. This agrees with previous research that concluded paraquat tolerance in peanut was not cultivar dependent (Johnson et al. 1993; Wehtje et al. 1991; Wehtje et al.1994). Irrigation and dryland effects were considered a part of the location effects and not considered for analysis due to irrigation only being located at Baldwin County. Peanut stands prior to application were not significantly different at any location over both years; the stands were healthy and consistent and did not influence the results.

In 2016, there was a significant treatment by location interaction ($P=0.03$) for heights therefore, locations were analyzed separately. Paraquat 420 g ai/ha reduced plant height by 10 to 20% at 50 to 55 DAP, and 5 to 16% at 72 to 78 DAP, and it was the only treatment that reduced plant height at both timings across all locations in 2016 (Table 2). The greatest overall height reductions of 10%, 14%, 20% were observed for paraquat at 420 g ai/ha in Baldwin, Macon and Henry County, respectively at 50-55 DAP. At 72 to 78 DAP, paraquat tank mixed with bentazon plus acifluorfen was the only treatment that did not generate reduced heights compared to the NTC across all locations. In 2017, there was no location by treatment interaction ($P=0.22$) for peanut heights therefore, this data was pooled over all locations (Table 3). Paraquat alone at 280 g ai/ha and paraquat plus 2,4-DB plus acetochlor were the only treatments evaluated at 45 to 48 DAP which did not have height reductions compared to the NTC over all locations. Paraquat plus bentazon plus acifluorfen plus either pyroxasulfone or acetochlor had the highest height reduction of 8% over all locations in 2017. Peanuts with early season height reductions recovered and no reductions were observed when evaluated 66 to 68 DAP (data not shown).

Peanut canopy widths, collected only in 2017, showed a significant treatment by location interaction (P=0.032) and were analyzed separately (Table 4). The Henry and Macon County locations showed reduced widths of 12 to 37% and 15 to 26% respectively, for all treatments evaluated 45 to 48 DAP. At the Baldwin County location, width reductions of 22%, 12%, and 20% with paraquat at 280 g ai/ha, paraquat plus bentazon plus acifluorfen plus *S*-metolachlor, and paraquat plus 2,4-DB plus *S*-metolachlor, respectively, were noted 45-48 DAP. At the Henry County location, paraquat plus 2,4-DB plus *S*-metolachlor showed the largest width reduction of 37% 45-48 DAP. Paraquat at 280 g ai/ha alone resulted in width reductions at the Baldwin and Macon County locations by 22% and 28%, respectively, 45 to 48 DAP.

At 66 to 68 DAP, the Macon County location no width reductions with any treatments were noted. At the Henry County location, paraquat plus bentazon plus acifluorfen, paraquat plus bentazon plus acifluorfen plus acetochlor, paraquat plus bentazon plus acifluorfen plus pyroxasulfone and paraquat plus 2,4-DB plus acetochlor all recovered from early season stunting and were no longer different from NTC. Paraquat plus 2,4-DB plus *S*-metolachlor showed a 12% width reduction 66 to 68 DAP while paraquat plus bentazon plus acifluorfen plus *S*-metolachlor showed a 9% reduction. At the Baldwin County location, more treatments had width reductions 66 to 68 DAP than 45 to 48 DAP with the exception of paraquat plus bentazon plus acifluorfen. Paraquat plus 2,4-DB plus *S*-metolachlor had the largest width reduction of 28% in Baldwin County at 66-68. It is likely an environmental factor, such as higher soil moisture and wetter conditions, may have prolonged herbicide injury and crop stunting at Baldwin County that did not occur in Macon and Henry County.

Yield losses were rare and did not occur over multiple locations or years. In 2016, there was a treatment by location interaction for yield (P=0.023) therefore, locations were analyzed separately (Table 5). In Henry and Baldwin County trials, paraquat at 420 g ai/ha resulted in a yield loss of 11% and 9% respectively. Paraquat at 420 g ai/ha, was included for research purpose only, but data does show that paraquat does not always have a 1.5 times safety margin; therefore, applications of higher than labeled rates will could result in height and up to 11% yield reductions as it did in 2016. Peanut producers should use caution when spraying paraquat to avoid spraying errors, miscalculations, or overlapping, as peanuts in this study showed sensitivity to paraquat over the labeled rate. In Henry County, a 13% yield loss was observed with paraquat plus bentazon plus acifluorfen plus pyroxasulfone plus carfentrazone, which also had the highest height reduction among all of the tank mixes evaluated. The Baldwin County location also had a 7% yield reduction for paraquat at 210 g ai/ha; however, this treatment did not have any height reductions at either evaluation timing. It is rare for paraquat to have caused a yield loss at a labeled rate of 210 g ai/ha as was observed in the Baldwin County trial. Other studies have not reported yield loss with labeled rate of paraquat on previous peanuts evaluated (Carley et al. 2009; Johnson et al. 1993; Wehtje et al. 1991). It is possible the herbicide application may have been applied too late in the peanut growth stage even though it was 28 DAP or an environmental factor influenced the herbicide injury in this rare case.

In 2017, there was no treatment by location interaction for yield (P=0.49), therefore data was analyzed together (Table 6). There were no significant yield reductions for any of the treatments evaluated in 2017. Based on these data, significant height and width reductions are not always indicative of a yield loss and peanuts can recover from initial stunting. Overall, these data and previous research indicates paraquat is safe to use on the peanuts and it is extremely rare to observe yield losses.

Treatments that included chloroacetamides were more likely to result in height and width reductions than those without. Jordan et al. (2003) observed more peanut injury with POST tank mixes of acifluorfen plus bentazon or acifluorfen plus bentazon plus 2,4-DB which included metolachlor compared to tank mixes including diclosulam, dimethenamid, and flumioxazin. This increased injury, however, did not lead to a significant yield loss (Jordan et al. 2003). Another study reported that the highest amount of stunting when *S*-metolachlor and paraquat were combined in a tank mix rather than either herbicide applied alone, however, this injury was only observed in one year (Grichar and Dotray 2012). Other studies have shown that chloroacetamide herbicides applied POST did not cause significant peanut injury (Grichar et al. 1996; Jordan et al. 2003). In 2017, it is possible that rainfall following application increased peanut injury when using *S*-metolachlor. During the first 7 d after application in 2016, Henry, Macon and Baldwin County trials had 3.5 cm, 0.03 cm, and 1 cm of rainfall respectively. In 2017, Henry, Macon and Baldwin County trials had 1.6 cm, 4.6 cm, and 7.3 cm respectively in that period. Therefore, it is likely that during our multi-location study, some field conditions, possibly rainfall, resulted in increased chloroacetamide injury and peanut stunting.

Overall, peanut in Henry County showed most sensitivity to paraquat tank mix treatments with greater height and width reductions than any other location for both years, while peanut in Baldwin County showed the most tolerance to the tank mix treatments evaluated in 2016. However, Baldwin County had more height and width reductions observed with paraquat alone than with any tank mix treatments in 2017. No treatment using labeled rates caused a significant yield loss compared to NTC over all locations in 2017. Meanwhile, for both years, we observed 10-20% less foliar injury to peanuts when bentazon was tank mixed with paraquat (data not shown). While the addition of bentazon increases broadleaf weed control and reduces injury to peanuts, it also increases herbicide cost per acre. Previous studies have shown bentazon combined with paraquat reduces peanut injury, however, this reduction in injury does not often result in a greater yield (Wehtje et al.1986; Wilcut et al. 1989). Therefore, unless a producer is trying to broaden their weed control spectrum and increase efficacy on certain weeds such as smallflower morningglory, the use of bentazon only for safening effect with paraquat may not be cost effective.

Different crop cultivar tolerance to herbicides has been noted for years. Several older peanut cultivars, such as ‘Early Bunch’ and ‘Southern Runner’, exhibited significant more sensitivity to paraquat compared to ‘Florunner’ (Brecke 1989). Another study showed reduced yields of ‘Sunrunner’, ‘Southern Runner’, and ‘Florunner’ peanut cultivars from two applications of paraquat (Knauft et al. 1990). As new cultivars are introduced herbicide programs need to be continually evaluated. In this study, ‘Georgia 06G’, ‘Georgia 12Y’, ‘Georgia 14N’, and ‘TufRunner 511’ were equivalently tolerant to labeled rates of paraquat and paraquat tank mixes evaluated. Overall, paraquat based tank mixes can be safely applied on the peanut cultivars tested in this study when using labeled rates. However, producers should expect some early season stunting, especially when tank mixing paraquat and chloroacetamides herbicides. These situations warrant further investigation to determining the environmental factors, such as rainfall, that contribute to increased chloroacetamide injury on peanuts when tank mixed with paraquat.

### 3.5 Conflict of Interest

The authors of this study do not have conflict of interest to declare.

### 3.6 Acknowledgements

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Table 1: Rainfall and irrigation amounts for all locations in 2016 and 2017[a]

| Rainfall | 2016 Henry | 2016 Baldwin | 2016 Macon | 2017 Henry | 2017 Baldwin | 2017 Macon | Irrigation | 2016 Baldwin |
|---|---|---|---|---|---|---|---|---|
| | cm[b] | | | | | | | cm[c] |
| May | 0 | 7.52 | 0 | 8.33 | 13.08 | 0 | May | 0 |
| June | 9.3 | 11.2 | 7.16 | 10.95 | 24.54 | 11.56 | June | 0 |
| July | 12.73 | 13 | 7.47 | 9 | 14.78 | 13 | July | 1.27 |
| August | 16.33 | 21.75 | 10.46 | 11.15 | 29 | 1.04 | August | 1.27 |
| September | 5.36 | 10.8 | 2.4 | 9.37 | 1.24 | 0 | September | 0 |
| October | 0 | 0 | 0.58 | 0 | 21.23 | 5.77 | October | 0 |
| November | 0 | 0 | 0 | 0 | 0 | 0.03 | November | 0 |
| Total | 43.72 | 64.27 | 28.07 | 48.8 | 103.87 | 31.4 | Total | 2.54 |

[a]Weather data provided by Alabama Mesonet Weather Data in cooperation with Agricultural Weather Services and Alabama Agricultural Experiment Stations

[b]Rainfall amounts were included from planting date to digging date

[c]Baldwin County was the only site that was under irrigation. Irrigation amounts were included from planting date to digging date. Irrigation was not needed in 2017 due to adequate rainfall.

Table 2: Peanut height as affected by POST herbicides in 2016 in Alabama[a]

| Treatment | Rate (g ai/ha) | Plant height 50-55 DAP[b] Henry | | Baldwin | | Macon | | Plant height 72-78 DAP[c] Henry | | Baldwin | | Macon | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ——% (NTC)—— | | | | | | | | | | | |
| Paraquat | 210 | 87 | d[d] | 99 | c | 93 | c | 91 | dc | 106 | a | 100 | a |
| Paraquat | 420 | 80 | e | 90 | d | 86 | d | 84 | e | 95 | d | 93 | b |
| Paraquat plus bentazon plus acifluorfen | 210 + 560 + 280 | 93 | bc | 104 | ab | 99 | ab | 97 | ab | 105 | ab | 99 | a |
| Paraquat plus bentazon plus acifluorfen plus *S*-metolachlor | 210 + 560 + 280 + 1,466 | 91 | dc | 103 | abc | 94 | bc | 90 | dc | 106 | ab | 99 | a |
| Paraquat plus bentazon plus acifluorfen plus acetochlor | 210 + 560 + 280 + 1,259 | 96 | ab | 106 | a | 94 | bc | 97 | bc | 105 | ab | 99 | a |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone | 210 + 560 + 280 + 179 | 95 | bc | 103 | abc | 95 | abc | 93 | bc | 103 | abc | 97 | ab |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone plus carfentrazone | 210 + 560 + 280 + 122 + 9 | 88 | d | 100 | bc | 91 | c | 89 | d | 102 | bc | 93 | b |
| Non-treated check[ef] | 0 | 100 | a | 100 | bc | 100 | a | 100 | a | 100 | c | 100 | a |

[a]Abbreviations: Non-treated check, NTC; d after planting, DAP

[b] Data was collected 52 DAP in Henry County, 55 DAP in Macon County and 50 DAP in Baldwin County.

[c] Data was collected 72 DAP in Henry County, 74 DAP in Macon County and 78 DAP in Baldwin County.

[d]Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of non-treated control. Data was

combined for all four cultivars since there was no significant cultivar by treatment interaction.
[e]NTC height = 31, 23.5, 42.41 cm for Henry, Baldwin and Macon Counties at 50 to 55 DAP, respectively
[f]NTC height = 41.66, 40.64, 42.41 cm for Henry, Baldwin and Macon Counties at 72 to 78 DAP, respectively

Table 3: Peanut height as affected by POST herbicide tank mixes in 2017[a]

| Treatment | Rate | Plant height 45-48 DAP[b] | |
|---|---|---|---|
| | (g ai/ha) | ———% (NTC)——— | |
| Paraquat | 280 | 97 | abc[c] |
| Paraquat plus bentazon plus acifluorfen | 280 + 560 + 280 | 95 | bcd |
| Paraquat plus bentazon plus acifluorfen plus *S*-metolachlor | 280 + 560 + 280 + 1,466 | 93 | dc |
| Paraquat plus bentazon plus acifluorfen plus acetochlor | 280 + 560 + 280 + 1680 | 92 | d |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone | 280 +560 + 280 + 125 | 92 | d |
| Paraquat plus 2, 4-DB plus *S*-metolachlor | 280 + 280 + 1,466 | 94 | bcd |
| Paraquat plus 2, 4-DB plus acetochlor | 280 +280 + 1680 | 97 | ab |
| Non-Treated Check[d] | 0 | 100 | a |

[a]Abbreviations: Non-treated check, NTC; d after planting, DAP
[b]Data was collected 45 DAP in Henry County, 46 DAP in Macon County and 48 DAP in Baldwin County.
[c]Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of NTC
[d]NTC height = 26.65 cm at 45to 48 DAP averaged over all locations

Table 4: Peanut canopy widths as affected by POST herbicide tank mixes in 2017 in Alabama[a]

| | | Canopy width[b] | | | | | |
|---|---|---|---|---|---|---|---|
| | | 45-48 DAP | | | 66-68 DAP | | |
| Treatment | Rate | Henry | Baldwin | Macon | Henry | Baldwin | Macon |
| | (g ai/ha) | % (NTC) | | | | | |
| Paraquat | 280 | 70 e[c] | 78 c | 74 b | 91 cd | 74 c | 102 a |
| Paraquat plus bentazon plus acifluorfen | 280 +560 + 280 | 88 B | 93 ab | 85 b | 100 abc | 88 ab | 99 a |
| Paraquat bentazon plus acifluorfen + *S*-metolachlor | 280 + 560 + 280 + 1,466 | 81 cd | 88 b | 78 b | 91 d | 76 bc | 102 a |
| Paraquat bentazon plus acifluorfen plus acetochlor | 280 + 560 + 280 + 1680 | 85 bc | 89 ab | 79 b | 104 a | 76 bc | 102 a |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone | 280 + 560 + 280 + 125 | 81 cd | 93 ab | 79 b | 94 bcd | 76 bc | 99 a |
| Paraquat plus 2, 4-DB plus *S*-metolachlor | 280 + 280 + 1,466 | 63 F | 80 c | 79 b | 88 d | 72 c | 102 a |
| Paraquat plus 2, 4-DB plus acetochlor | 280 + 280 + 1680 | 77 d | 93 ab | 78 b | 95 bcd | 74 bc | 102 a |
| Non-Treated Check[de] | 0 | 100 a | 100 a | 100 a | 100 ab | 100 a | 100 a |

[a]Abbreviations: Non-treated check, NTC; d after planting, DAP
[b]Data was collected 45 and 66 DAP in Henry County, 46 and 68 DAP in Macon County and 48 and 68 DAP in Baldwin County.
[c]Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of non-treated control. Data was combined for all four cultivars since there was no significant cultivar by treatment interaction.

[d]NTC width = 48.55, 41.58, 38.45 cm for Henry, Baldwin, and Macon Counties at 45 to 48 DAP, respectively
[e]NTC width= 70.07, 42.67, 73.8 cm for Henry, Baldwin, and Macon at 66 to 68 DAP respectively

Table 5: Peanut pod yield as affected by POST herbicide tank mixes in 2016 in Alabama[a]

| | | Yield[b] | | |
|---|---|---|---|---|
| Treatment | Rate | Henry | Baldwin | Macon |
| | g ai/ha | %(NTC) | | |
| Paraquat | 210 | 93 ab[c] | 93 b | 106 a |
| Paraquat | 420 | 89 b | 91 b | 94 ab |
| Paraquat plus bentazon plus acifluorfen | 210 +560 + 280 | 96 ab | 98 ab | 105 a |
| Paraquat plus bentazon plus acifluorfen plus *S*-metolachlor | 210 + 560 + 280 + 1,466 | 93 ab | 102 a | 106 a |
| Paraquat plus bentazon plus acifluorfen plus acetochlor | 210 + 560 + 280 + 1,259 | 96 ab | 101 a | 89 ab |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone | 210 + 560 + 280 + 179 | 96 ab | 102 a | 85 b |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone plus carfentrazone | 210 + 560 + 280 +122 + 9 | 87 b | 103 a | 92 ab |
| Non-treated check[d] | 0 | 100 a | 100 a | 100 ab |

[a]Abbreviations: Non-treated check, NTC; days after planting, DAP

[b]Data was collected 131 DAP in Henry County, 150 DAP in Macon County and 143 DAP in Baldwin County.

[c]Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of non-treated control. Data was combined for all four cultivars since there was no significant cultivar by treatment interaction.

[d]NTC yield= 5,318, 5,981, 4,075 kg/ha for Henry, Baldwin and Macon Counties at 131 to 150 DAP, respectively

Table 6: Peanut pod yield as affected by POST herbicide tank mixes in 2017 in Alabama[a]

| Herbicide treatment | Rate | Yield[b] | |
|---|---|---|---|
| | (g ai/ha) | ——%(NTC)—— | |
| Paraquat | 280 | 99 | a[c] |
| Paraquat bentazon plus acifluorfen | 280 + 560 + 280 | 98 | A |
| Paraquat plus bentazon plus acifluorfen plus *S*-metolachlor | 280 + 560 + 280 + 1,466 | 101 | A |
| Paraquat plus bentazon plus acifluorfen plus acetochlor | 280 + 560 + 280 + 1680 | 93 | A |
| Paraquat plus bentazon plus acifluorfen plus pyroxasulfone | 280 + 560 + 280 + 125 | 95 | A |
| Paraquat plus 2, 4-DB plus *S*-metolachlor | 280 + 280 + 1,466 | 99 | A |
| Paraquat plus 2, 4-DB plus acetochlor | 280 + 280 + 1680 | 103 | A |
| Non Treated Check[d] | 0 | 100 | A |

[a]Abbreviations: Non-treated check, NTC; days after planting, DAP
[b]Data was collected 135 DAP in Henry County, 152 DAP in Macon County and 163 DAP in Baldwin County.
[c]Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of non-treated control. Data was combined for all four cultivars since there was no significant cultivar by treatment interaction.
[d]NTC yield= 2,751, 3,848, 1,336 kg/ha for Henry, Baldwin and Macon Counties at 131 to 150 DAP, respectively

# Chapter 4

# Cotton Response to Preplant Applications of 2,4-D or Dicamba

**Short Title: Cotton 2,4-D or Dicamba**

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### 4.1 Abstract

Sensitive cotton varieties planted into soil treated with 2,4-D or dicamba utilized in burndowns can result in stunting and stand loss if use rate is too high and the plant-back interval is too short. The objective of this study was to evaluate cotton stunting and yield responses resulting from 2,4-D or dicamba residues in soil after preplant burndown applications at three locations in 2016 and 2017. Treatments with 2,4-D included 532 and 1,063 g ae $ha^{-1}$ applied 3 wk before planting (WBP) and 53, 160, 266, 532, 1,063 g ae $ha^{-1}$ applied at planting. Dicamba treatments included 560 and 1,120 g ae $h^{-1}$ applied 3 WBP and 56, 168, 280, 560, 1,120 g ae $ha^{-1}$ applied at planting. Dicamba or 2,4-D treatments applied 3 WBP resulted in no adverse effects on cotton stand, plant height, or yield. Dicamba 560 g ae $h^{-1}$ applied at planting reduced cotton stand by 36% at 21 to 24 d after planting (DAP) over all locations in 2016. In 2017, stands were reduced by dicamba at 168, 280, 560, and 1,120 g ae $ha^{-1}$ by 17% to 25% at 20 to 23 DAP. Moreover, cotton stands were not affected by 2,4-D in 2016, and only 266, 532, and 1,063 g ae $ha^{-1}$ of 2,4-D caused stand reductions of 26% to 36% at 20 to 23 DAP over all locations in 2017. Dicamba at 560 g ae $ha^{-1}$ at planting was the only treatment in this study that reduced plant height. Although stand losses were observed in both years, no yield loss occurred. The data suggest that stunting and stand reduction may occur if susceptible varieties are planted soon after burndown applications with 2,4-D or dicamba, but yield may not be affected after a full growing season. Dicamba showed greater potential to cause stunting and stand reduction than 2,4-D.

**Nomenclature:** 2,4-D; dicamba; cotton, *Gossypium hirsutum* L.

**Key words:** Stunting, stand reduction, plant height, yield loss.

## 4.2 Introduction

A preplant burndown program is a crucial component of managing weeds in cotton production throughout the southern United States. Cotton is susceptible to early-season weed competition because of its slow emergence and growth (Sosnoskie and Culpepper 2014). As a result, cotton fields need to be weed-free at the time of emergence for a successful crop. Preplant burndown programs have frequently utilized glyphosate or paraquat in the past; however, more effective weed control burndown programs include 2,4-D or dicamba in the tank mix (Culpepper et al. 2005, Reynolds et al. 2000, York et al. 2004). With the introduction of 2,4-D- or dicamba-tolerant cotton varieties, producers can apply new formulations of 2,4-D or dicamba in burndown applications very close to planting or use them in PRE applications (Anonymous 2018a, 2018b). This new use pattern allows cotton producers more flexibility to control weeds and plant their crop.

Many cotton varieties are sensitive to synthetic auxin herbicides such as 2,4-D or dicamba; these injure cotton by disrupting the plant hormone systems, causing twisting or epinasty of stems, leaf strapping and/or cupping, and abnormal veins in leaves. Previous research has observed that cotton is more sensitive to 2,4-D drift than to dicamba drift, especially at the preflowering and squaring stages (Egan et al. 2014, Everitt and Keeling 2009; Marple et al. 2007). However, these studies do not address preplant application effects on cotton. 2,4-D is not persistent in soil under most environmental conditions, with a half-life of 4 to 6 d, and is generally dissipated by 20 d after application (Altom and Stritzke 1973; Peterson et al. 2016; Wilson et al. 1997; Voos and Groffman 1997). Dicamba is more persistent in soil than 2,4-D, with an average half-life of 31 d under aerobic conditions and 58 d under anaerobic conditions (Krueger et al. 1991). Overall, 2,4-D and dicamba are not persistent in soils, unless a high amount of organic carbon is present, conditions are dry, or soil microbial activity is low (Paszko et al. 2016; Voos and Groffman 1997; Walters 1999).

Following an application of dicamba, a minimal waiting period according to the label is 21 d between application and planting, with at least 2.5 cm of water from either rainfall or irrigation, whereas 2, 4-D requires 30 d and 2.5 cm of water prior to planting of sensitive cotton (Anonymous 2018a, 2018b). Baker (1993) observed that cotton needed to be replanted because of poor stands when 2,4-D was applied at 2,200 g ae $ha^{-1}$ or dicamba at 300 g ai $ha^{-1}$ and 600 g ai $ha^{-1}$ 9 d before planting (DBP), whereas earlier applications did not lead to significant injury. In another study, dicamba 140 g ae $ha^{-1}$ and 280 g ae $ha^{-1}$ and 2,4-D at 560 g ae $ha^{-1}$ and 1,120 g ae $ha^{-1}$ applied 2 WBP caused significant stand losses (Everitt and Keeling 2009). York et al. (2004) found that 2,4-D at 530 and 1,060 g ae $ha^{-1}$ applied 3 wk or more prior to planting did not cause significant stand or yield losses.

The use of 2,4-D or dicamba in preplant burndowns can be very important to a successful weed control program, but producers need to plan for a sufficient plant-back interval and be very cautious with the use of 2,4-D or dicamba on resistant cotton varieties. With the PRE application option available for 2,4-D- or dicamba-resistant cotton, if an acceptable stand of a resistant variety is not achieved as a result of excessive rain, plant disease, planter malfunction, or soil herbicide injury, a short-season variety may be the best replant option. A legitimate concern is whether the intervals between application and replanting are long enough to prevent injury to susceptible varieties. This injury could further delay maturity when the remaining growing season is already short. Minimal data have been published evaluating sensitive cotton responses to 2,4-D or dicamba residuals in soil if they are not degraded completely. Therefore, a field study was needed to determine whether cotton injury and yield loss may occur in these situations. The objective of this trial was to evaluate cotton establishment and yield in response to various rates of 2,4-D or dicamba residues in soil applied 3 WBP and at planting.

### 4.3 Materials and Methods

Six field trials were conducted in Macon (32.4939° N 85.8903° W) and Baldwin (30.5477°"N 87.8598°"W) counties, AL, and Santa Rosa County (30.7765°"N 87.1432°"W), FL, in 2016, and in Macon, Baldwin, and Henry counties (31.3512°"N 85.3146"W) AL, in 2017. These trials were set up as a completely randomized block design with four replications at each location. Plots at all locations were 7.62 m long, except for Macon County in 2016, where plot lengths were 6.1 m. Cotton was planted in rows 0.9 m wide, and all locations had four rows per plot. All trials were irrigated as needed throughout the season. The cotton variety planted in Santa Rosa and Macon counties was PHY 499 (PhytoGen®, Dow AgroSciences. Indianapolis, IN). PHY 444 was planted in Henry and Baldwin counties. All fields were conventionally tilled prior to herbicide application. Treatments were applied either 3 WBP or within 1 h after planting (at planting) with an ATV sprayer (Teejet TTI 110025 at Alabama locations and 11003VK flat-fan nozzles at Florida location) (Teejet®, Spraying Systems Co., Wheaton, IL) propelled by compressed air at a spray volume of 187 L $ha^{-1}$. Treatments of 2,4-D included 532 and 1,063 g ae $ha^{-1}$ applied 3 WBP and 53, 160, 266, 532, and 1,063 g ae $ha^{-1}$ applied at planting. Dicamba treatments included 560 and 1,120 g ae $ha^{-1}$ applied 3 WBP and 56, 168, 280, 560, and 1,120 g ae $ha^{-1}$ applied at planting. In 2016, 2,4-D at 53 g ae $ha^{-1}$ and dicamba 56 g ae $ha^{-1}$ were evaluated at planting; however, they were removed from the treatment list in 2017 as a result of lack of cotton responses, and two higher rates at planting were included at all locations (1,063 g ae $ha^{-1}$ of 2,4-D or 1,120 g ae $ha^{-1}$ of dicamba). Clarity® (BASF®, Research Triangle Park, NC), a diglycolamine salt formulation, was used for all dicamba treatments. 2,4-D Amine (Alligare

LLC®, Opelika, AL), a dimethylamine salt formulation, was used for all 2,4-D treatments. Soil texture, planting, harvesting dates, and rainfall are listed in Tables 1 and 2. The Baldwin County location did not receive treatments applied 3 WBP in 2017 because of a prolonged rainfall period prior to cotton planting and field inaccessibility.

All treatments, including the nontreated control (NTC), were maintained weed-free throughout the growing season with standard cotton POST herbicide treatments (glyphosate or glufosinate + *S*-metolachlor), layby (flumeturon or diuron + MSMA), and hand weeding as needed. Overall, there was very little visual cupping and leaf strapping present on the cotton plants; therefore, stand counts and height measurements were chosen as the growth parameters to determine the effect of 2,4-D or dicamba on cotton. At approximately 3 and 7 wk after planting, cotton stands were evaluated by counting all plants in 1-m-long stands from each of the two center rows, and cotton heights were recorded for 10 randomly selected plants in the two center rows of the plots. Seed cotton yield was collected at each location from the two center rows and averaged for statistical analysis. Only yield data were collected from the Santa Rosa County site.

All data collected were converted to a percentage of NTC prior to statistical analysis, then processed with PROC GLIMMIX procedure in SAS® 9.4 (SAS Institute Inc, Cary, NC). All means were separated with Fisher's protected LSD ($P \leq 0.05$) to reveal statistical differences. Treatment and location were considered fixed effects, whereas block was treated as a random effect. If treatment-by-location interaction was significant ($P \leq 0.05$), results were separated and analyzed by location and presented by each location individually in the results. If treatment-by-location interaction was not significant, then location was used as a random effect and data were averaged over all locations.

### 4.4 Results and Discussion

None of the treatments applied 3 WBP affected cotton stands, heights, or yield ($P \leq 0.05$) in 2016 and 2017 at any location (Tables 3 and 4). Therefore, only treatments applied at planting are discussed in this section. Treatment-by-location interaction was not significant ($P \leq 0.05$) for stand counts, so data from all locations were pooled in 2016 and 2017. Dicamba at 280 and 560 g ae $ha^{-1}$ applied at planting were the only treatments that lowered cotton stands by 36% and 37% in 2016. In 2017, 160 g ae $ha^{-1}$ of 2,4-D at planting was the only rate of either herbicide evaluated that did not reduce cotton stand at 20 to 23 DAP. Cotton stands were not affected by 2,4-D rates of 266 g ae $ha^{-1}$ and lower at 47 to 48 DAP. 2,4-D at 266 to 1,063 g ae $ha^{-1}$ caused stand losses of 26% to 36% at 20 to 23 DAP. All rates of dicamba reduced cotton stands at 20 to 23 DAP, whereas only the 168 g ae $ha^{-1}$ rate did not exhibit a stand loss at 47 to 48 DAP. Dicamba caused more cotton stand loss than 2,4-D in 2016 and 2017, most likely a result of its longer soil residual activity than 2,4-D. Therefore, dicamba mistakenly applied to sensitive cotton may cause more damage early on cotton seedlings than 2,4-D.

Treatment-by-location interactions were significant ($P \leq 0.05$) for cotton plant heights, so they were evaluated and presented by location in 2016 (Table 4). Cotton plant heights were not affected by any treatment at Baldwin County in 2016 at 24 DAP. Dicamba at 560 g ae $ha^{-1}$ applied at planting was the only treatment that reduced cotton plant heights at the other three locations. Interestingly 2,4-D applied at 532 g ae $ha^{-1}$ increased plant height in 2016 at Baldwin County when applied 3 WBP. Cotton plant heights were not affected by any treatments in 2017 (data not shown).

Seed cotton yield at each location in both years was not affected by any of the treatments evaluated in this study (data not shown), even though stand losses were documented with multiple treatments. Overall, cotton stands should have two to four plants per row foot for optimum yield (Boman and Lemon 2007). Cotton stand losses can cause significant yield reductions when there are large gaps within the row and stand variability throughout a field (Boman and Lemon 2007). A study from Texas documented a 13% yield loss with a 25% stand loss (Supak and Boman 1999). However, as apparently occurred in this study, cotton can compensate for significant stand losses and still produce an acceptable yield.

Overall, these results align with previous studies by Everitt and Keeling (2007), York et al. (2004), and Baker (1993), which reported that dicamba caused more cotton stand and yield loss than 2,4-D when applied preplant. These earlier reported results are similar to the conclusion drawn from our study that 2,4-D or dicamba can be safely applied 3 WBP without significant stand or yield. At the time this study was conducted, no previous studies could be found evaluating the effect of full preplant rates of 2,4-D or dicamba applied at planting on sensitive cotton varieties. It should be noted that our studies received at least 2 cm of rainfall prior to planting and that a period of drought could increase injury and potential stand loss. Our study and all aforementioned studies demonstrated that if 2,4-D or dicamba is applied close to the planting date, especially with high rates, or if preplant applications do not have a long enough plant-back interval, a producer can expect to see more stand reductions with the potential for yield losses on sensitive cotton varieties.

Although cotton stand losses were observed in both years over all locations, no yield losses were observed. Thus, damage to cotton foliage and stand loss from 2,4-D or dicamba preplant applications should not be used as a yield loss predictor based on these data. Baker (1993) found that yield loss occurred when 600, 1,100, 2,200 g ae $ha^{-1}$ 2,4-D and 300, 600 g ae $ha^{-1}$ dicamba were applied 3 DBP. Another study observed a 23% yield loss in 1 out of 3 yr for dicamba applied 1 WBP at 280 g ae $ha^{-1}$ (Everitt and Keeling 2007). Similar to the findings of our study, Everitt and Keeling (2007) did not find a consistent correlation between yield reductions and visual injury or stand reductions. York et al. (2004) observed significant yield loss when 2,4-D at 1,060 g ae $ha^{-1}$ and dicamba at 560 g ae $ha^{-1}$ were applied 1 WBP at several, but not all, locations in their study. Although we did not find any significant yield losses, it is possible that different soil and environmental conditions from the ones in this study could result in yield losses after 2,4-D or dicamba preplant applications. Overall, based on this and previous studies, it is difficult to predict yield outcome from stand loss and visual injury in cotton, especially when it is early in the growing season.

Rainfall and temperature are factors needing more in-depth research to elucidate their impact on cotton yield loss when there is a short plant-back interval after a 2,4-D or dicamba preplant burndown program. Previous research has shown that cotton injury and stand loss due to dicamba were more severe when there was little rain between application timing and cotton planting (Ferguson 1996; Guy and Ashcraft 1996; York et al. 2004). However, we observed more injury and stand loss with 2,4-D or dicamba treatments in 2017 at locations that received more rainfall than 2016, the opposite of what other studies have reported (Table 2). Everitt and Keeling (2009) saw more stand reductions during one year of their study compared to the other year because of cooler temperatures leading to slower germination. It is possible that cooler and wetter weather conditions in 2017 slowed cotton germination and allowed more herbicide injury, which reduced stands to a greater extent than 2016. The combination of these field conditions and herbicide residues in the soil should be evaluated further.

Overall, more negative effects were observed with dicamba treatments in this study in terms of stand loss and plant height reductions than with 2,4-D treatments. Higher rates of dicamba or 2,4-D caused more cotton stand loss than lower rates. Treatments applied at planting caused more stand loss than applications made 3 WBP. The early-season stand loss did not result in significant yield loss when cotton had a full growing season to recover. Therefore, without a full growing season to recover, it is possible that stand and yield losses could be observed for the higher rates of 2,4-D or dicamba if accidentally applied close to planting or at planting. According to results of this study and previous studies, if cotton producers want to plant a sensitive cotton variety after utilizing 2,4-D or dicamba as part of a preplant burndown program, they should allow  a minimal 3-wk plant-back interval to prevent stand loss and cotton injury.

### 4.5 Conflict of Interest

The authors of this study do not have conflict of interest to declare.

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**Table 1.** Locations, application, planting, and harvesting dates and soil information of field trials conducted in 2016 and 2017[a,b]

| Location (county) | City, state | Pre-plant application date: 3 WBP | Planting and application date[c] | Harvesting date | Soil texture | pH | OM% | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|---|---|---|
| Santa Rosa | Jay, FL | May, 4, 2016 | May 25, 2016 | October, 17, 2016 | Red Bay fine sandy loam[d] | 6.1 | 1.55 | 69 | 16 | 15 |
| Henry | Headland, AL | April 11, 2017 | May 3, 2017 | October 18, 2017 | Dothan fine sandy loam[e] | 6.2 | 1.2 | 81.88 | 1.25 | 16.88 |
| Macon | Shorter, AL | April 21,2016 | May 11, 2016 | November 7, 2016 | Kalmia sandy loam[f] | 6.1 | 0.9 | 71.9 | 10.6 | 17.5 |
| | | May 15, 2017 | June 9, 2017 | December 5, 2017 | | | | | | |
| Baldwin | Fairhope, AL | April 26, 2016 | May 16, 2016 | October 24, 2016 | Red Bay fine sandy loam[d] | 5.6 | 1.6 | 60 | 15.0 | 25.0 |

| | | | |
|---|---|---|---|
| | – | June 15, 2017 | November 15, 2017 |

[a] Soil information was provided by Auburn University Soil Testing Laboratory (Auburn, AL) and Waters Agricultural Laboratories, Inc. (Camilla, GA).

[b]Abbreviations: OM, organic matter; WBP, weeks before planting.

[c] Treatments applied immediately after planting within the same day.

[d] Fine-loamy, kaolinitic, thermic Rhodic Kandiudults.

[e] Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.

[f] Fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults.

**Table 2.** Rainfall amounts for each field location in 2016 and 2017.[a]

| Location | Soil type | Rainfall 2016 0–21 DBP[b] | Rainfall 2016 0–14 DAP | Rainfall 2017 0–21 DBP | Rainfall 2017 0–14 DAP |
|---|---|---|---|---|---|
| Macon County, AL | Kalmia sandy loam | 6.3 cm | 2.7 cm | 20 cm | 10.8 cm |
| Baldwin County, AL | Red Bay fine sandy loam | 2.6 cm | 3.4 cm | – | 15 cm |
| Henry County, AL | Dothan fine sandy loam | – | – | 2.4 cm | 3.2 cm |
| Santa Rosa County, FL | Orangeburg sandy loam | 6.6 cm | 4.9 cm | – | – |

[a] Cells containing a dash indicate that the study or applications were not conducted at that location that year.

[b] Abbreviations: DAP, days after planting; DBP, days before planting.

**Table 3.** Cotton stand as affected by residual 2,4-D and dicamba in soil.[a]

| Herbicide | Rate | Application timing | Cotton stand 2016 24 DAP[c] | 2016 51 DAP | 2017[b] 23 DAP | 2017[b] 48 DAP |
|---|---|---|---|---|---|---|
| | g ae ha$^{-1}$ | | —% of NTC[d] — | | | |
| 2,4-D | 532 | 3 WBP | 125 a | 116 a | 90 a | 92 a |
| 2,4-D | 1,063 | 3 WBP | 102 ab | 99 abc | 85 a | 101 a |
| Dicamba | 560 | 3 WBP | 98 ab | 95 abc | 95 a | 104 a |
| Dicamba | 1,120 | 3 WBP | 101 ab | 86 abcd | 99 a | 102 a |
| 2,4-D | 53 | At planting | 102 ab | 108 ab | –[e] | –[e] |
| 2,4-D | 160 | At planting | 104 ab | 90 abcd | 89 ab | 90 ab |
| 2,4-D | 266 | At planting | 122 a | 110 ab | 74 cd | 86 abc |
| 2,4-D | 532 | At planting | 101 ab | 94 abc | 71 cd | 66 e |
| 2,4-D | 1,063 | At planting | –[e] | –[e] | 64 d | 70 cde |
| Dicamba | 56 | At planting | 117a | 105 ab | –[e] | –[e] |
| Dicamba | 168 | At planting | 102 ab | 105 ab | 82 bc | 85 abcd |
| Dicamba | 280 | At planting | 89 bc | 75 dc | 83 bc | 80 bcde |
| Dicamba | 560 | At planting | 64 c | 63 d | 81 bc | 82 bcde |
| Dicamba | 1,120 | At planting | –[f] | –[f] | 75 bcd | 68 de |
| NTC | | | 100 ab | 100 abc | 100 a | 100 a |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model ANOVA of a randomized complete block (P = 0.05). Data are expressed as percentage of nontreated control (NTC). Blank cells with dash indicate treatments not tested that year.

ata collected in Macon County May 31 and June 30, 2016; Baldwin County June 9 and July 5, 2016; Henry County May 26 and June 20, 2017; Macon County June 30 and July 18, 2017; Baldwin County July 5 and July 27, 2017.

[b] Treatments applied 3 wk before planting were only evaluated in Henry County and Macon County in 2017.

[c] Abbreviations: DAP, days after planting; WBP, weeks before planting.

[d] Data collected in Macon County May 31 and June 30, 2016; Baldwin County June 9 and July 5, 2016; Henry County May 26 and June 20, 2017; Macon County June 30 and July 18, 2017; Baldwin County July 5 and July 27, 2017.

[e] These two rates were not evaluated in 2017 because of lack of cotton response.

These two rates were not evaluated in 2017 due to lack of cotton response.

[f] These two rates were not evaluated in 2016.

**Table 4.** Cotton plant height as affected by residual 2,4-D and dicamba in soil in 2016.[a]

| Treatment | Rate | Application timing | Cotton height | | | |
|---|---|---|---|---|---|---|
| | | | 24 DAP | | 51 DAP[b] | |
| | | | Macon | Baldwin | Macon | Baldwin |
| | g ae ha$^{-1}$ | | ——% of NTC[c] —— | | | |
| 2,4-D | 532 | 3 WBP[c] | 103 ab | 100 a | 101 ab | 115 a |
| 2,4-D | 1,063 | 3 WBP | 101 abc | 105 a | 110 a | 110 ab |
| Dicamba | 560 | 3 WBP | 108 a | 90 a | 104 ab | 92 cd |
| Dicamba | 1,120 | 3 WBP | 108 a | 88 a | 120 a | 101 bcd |
| 2,4-D | 53 | At planting | 106 a | 102 a | 110 a | 104 ab |
| 2,4-D | 160 | At planting | 94 bc | 103 a | 102 ab | 104 ab |
| 2,4-D | 266 | At planting | 100 abc | 103 a | 100 ab | 106 ab |
| 2,4-D | 532 | At planting | 110 a | 90 a | 108 ab | 103 bc |
| Dicamba | 56 | At planting | 100 abc | 96 a | 107 ab | 99 bcd |
| Dicamba | 168 | At planting | 10 abc | 96 a | 99 ab | 103 bc |

| | | | | | | |
|---|---|---|---|---|---|---|
| Dicamba | 280 | At planting | 90 c | 91 a | 95 b | 92 cd |
| Dicamba | 560 | At planting | 73 d | 88 a | 62 c | 91 d |
| NTC[c] | | | 100 abc | 100 a | 100 ab | 100 bcd |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model ANOVA of a randomized complete block (P = 0.05). Data are expressed as percentage of nontreated control (NTC). Plant heights were not affected by treatments in 2017.

[b]Abbreviations: DAP, days after planting; WBP, weeks before planting.

[c] Data collected in Macon County May 31 and June 30, 2016 . Baldwin County June 9 and July 5, 2016.

## Chapter 5

## Cover crop response to residual herbicides in peanut-cotton rotation

Short Title: Cover Crop Residual Herbicides

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## 5.1 Abstract

Cover crops can provide many benefits to peanut and cotton crops planted in rotation including suppressing weeds, conserving soil moisture after termination, increasing soil organic matter, and reducing soil erosion. However, herbicide carryover can affect cover crop establishment. The objective of this study was to investigate the responses of 6 cover crops (daikon radish, cereal rye, oat, crimson clover, winter wheat, and common vetch) to 12 soil residual herbicides. A multiyear (2016–2018), multilocation study was conducted in Macon and Henry counties, Alabama. Herbicide treatments included *S*-metolachlor, acetochlor, pyroxasulfone, diclosulam, imazapic, chlorimuron-ethyl, bentazon plus acifluorfen, pyrithiobac-sodium, trifloxysulfuron-sodium, diuron, prometryn, and flumioxazin, each applied at 10% of the full-labeled rate. At 42 to 52 and 145 to 149 d after planting (DAP), cover crop plant heights and stand counts were evaluated, as was biomass at 145 to 149 DAP. Treatments varied from year to year but not locations. In 2016, significant stand reductions ($P \leq 0.10$) of 36% to 43% in rye and 44% to 75% in wheat were observed at 48 to 52 DAP for *S*-metolachlor, acetochlor, pyroxasulfone, imazapic, and bentazon plus acifluorfen compared with nontreated plants. Vetch had stand reductions ranging from 14% to 80% for all treatments 50 DAP except for plants treated with prometryn. *S*-metolachlor, pyroxasulfone, and acetochlor reduced stands of rye, wheat, and vetch more than any other herbicides. In 2017, at 147 to 149 DAP, clover stands were reduced by 29% with diclosulam and by 38% with trifloxysulfuron-sodium. Similarly, radish stands were reduced by 64% with diclosulam treatment. No significant biomass reductions were observed for any cover crop species either year. Oat showed the most tolerance with no treatments reducing any growth parameters either year. Although initial injury and stunting may occur, biomass at termination of cover crops were not affected by herbicide residues evaluated in this study.

**Nomenclature:** Acetochlor; acifluorfen; bentazon; chlorimuron-ethyl; diclosulam; diuron; flumioxazin; imazapic; prometryn; pyroxasulfone; pyrithiobac-sodium; *S*-metolachlor; trifloxysulfuron-sodium; cereal rye, *Secale cereal* L.; common vetch, *Vicia villosa* L.; cotton, *Gossypium hirsutum* L.; crimson clover, *Trifolium incarnatum* L.; daikon radish, *Raphanus sativis* L.; oat, *Avena sativa* L.; peanut, *Arachis hypogaea* L.; winter wheat, *Triticum aestivum* L.

**Keywords:** Biomass, establishment, herbicide carryover, stand reduction

## 5.2 Introduction

Cover crops can provide many benefits to a peanut and cotton rotation including suppressing weeds, conserving soil moisture after termination, increasing soil organic matter, and reducing soil erosion (Clark 2007; Dabney et al. 2001; Kasper and Singer 2011; Lu et al. 2000). High-residue cover crops have been shown to suppress weeds in no-till or strip-till cropping systems through resource competition, alleopathic affects, physical impediment, and light suppression (Aulakh et al. 2011; Dabney et al. 2001; Price and Norsworthy 2013; Reberg-Horton et al. 2011; Reeves et al. 2005). In recent years, throughout the Southeastern United States there has been an increasing practice of using cover crops and conservation tillage (Claassen et al. 2018; SARE CTIC 2017). Producers often use residual herbicides during the growing season to extend the period of weed control and provide another control method to herbicide programs especially to manage herbicide-resistant weeds. However, residual herbicides can prevent the successful establishment of fall-seeded cover crops, thus reducing biomass and subsequent weed suppression and achieving longer-term benefits provided by cover crops (Curran et al. 2006; Rogers et al. 1986; Yu et al. 2015).

Previous studies have evaluated soybean and corn herbicide carryover onto fall-seeded cover crops with varied results. One study observed pyroxasulfone caused a 12%, 16%, and 11% reduction in plant density for cereal rye, hairy vetch, and wheat, respectively; however, the reduction in plant density did not lead to significant biomass reductions (Palhano et al. 2018). The same study found crimson clover biomass reductions of 13%, 12%, and 11% for atrazine, pyroxasulfone, and *S*-metolachlor, respectively, when applied during the growing season; however, there were no significant reductions in plant density (Palhano et al. 2018). Yu et al. (2015) found imazethapyr, *S*-metolachlor + atrazine + mesotrione, and saflufenacil + dimethenamid-p did not cause any significant injury or biomass reductions to oat, hairy vetch, and cereal rye when planted 3 mo after application at the labeled rates. One study evaluating the carryover effects of cotton herbicides (fluometuron, MSMA, trifluralin, linuron) on hairy vetch and wheat found ground cover reductions varied greatly by soil type, with more injury found in Dundee silty clay than the silt loam soils (Rogers et al. 1986). Cornelius and Bradley (2017) found cereal rye to be the most tolerant cover crop to all of the corn and soybean herbicides evaluated, with cloransulam-methyl, flumioxazin, fomesafen + *S*-metolachlor, and metribuzin causing reductions in cover crop stands or biomass. The study also found that crimson clover and Austrian winter pea (*Pisum sativum* L.) were the most sensitive to herbicide carryover (Cornelius and Bradley 2017). In addition, pyroxasulfone, imazethapyr, fomesafen, and flumetsulam carryover reduced stand and cover crop biomass more than other herbicides evaluated (Cornelius and Bradley 2017). A greenhouse study in Iowa showed radish was the most sensitive to corn and soybean herbicide carryover, whereas cereal rye was the most tolerant (Hartzler and Anderson 2015). All of these previous studies have shown there are cases in which herbicide carryover can affect the establishment and biomass of fall-seeded cover crops; however, there is not a comprehensive understanding of the effects of cotton and peanut herbicides on

Southeastern and mid-South cover crops.

Herbicide carryover can reduce cover crop biomass and subsequent weed suppressive qualities. It can increase expenses associated with cover crop establishment if replanting is needed in the fall or more herbicide applications the following season are needed for weeds. Herbicide chemistry and soil properties including pH, texture, organic matter, clay content, temperature, and moisture determine herbicide persistence in the soil. Overall, few of the previous studies evaluated commonly used peanut and cotton residual herbicides and limited research has been conducted in the Southeast, which has different environmental conditions and soil compared with other regions. Therefore, the objective of this study was to investigate the responses of 6 cover crops (daikon radish, cereal rye, oat, crimson clover, winter wheat, and common vetch) to simulated carryover from 12 common soil residual herbicides used in peanut and cotton.

### 5.3 Materials and Methods

Field trials were conducted in Macon County (32.4939°N 85.8903°W), and Henry County (31.3512° N 85.3146°W), Alabama, in 2016–17 and 2017–18. The Macon County trial had a Kalmia sandy loam soil (fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults) and the Henry County trial had a Dothan fine sandy loam soil (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). Soil composition and pH for each location are listed in Table 1. At each location, soil was conventionally tilled 1 wk prior to herbicide application to provide ideal soil seeding conditions and prevent previous crop residue interference with herbicide application. The study was set up as a completely randomized block design with herbicide treatments in each block applied in strips, and the cover crops planted in perpendicular strips across the herbicide treatment. Plots were 1.8 m by 3.7 m with four replications in Henry County and three replications in Macon County each year. Herbicide rates were set at 10% of full-labeled rate and all treatments were applied prior to cover crop planting (Table 2). The treatment rate of 10% of the full-labeled rate was selected to simulate high concentrations of herbicide residue carryover beyond cotton or peanut harvest. Herbicide treatments were applied November 18, 2016 and October 30, 2017 in Macon County and November 3, 2016 and October 30, 2017 in Henry County. Herbicide treatments were applied using a backpack sprayer with a six-nozzle boom (Teejet TT110025 flat-fan nozzles in Henry County and Teejet XR11002VS extended-range flat-fan spray tips in Macon County; Teejet®, Spraying Systems Co., Wheaton, IL 60187) propelled by compressed $CO_2$ at a spray volume of 187 L $ha^{-1}$. Plots were immediately irrigated with 1.3 cm after herbicide applications to ensure activation. Six cover crops were planted: Daikon radish, Wrens Abruzzi cereal rye, Coker 227 oat, crimson clover, Pembroke 2017 winter wheat, and AU Olympic vetch. Cover crops were drill-seeded with a Hege plot grain drill November 21, 2016 and November 7, 2017 in Macon County, and November 7, 2016 and November 3, 2017 in Henry County with a Great Plains 1205 no-till drill. Rye, oat, and wheat were planted at 100 kg $ha^{-1}$. Clover and vetch were planted at 22 kg $ha^{-1}$. Radish was planted at 11 kg $ha^{-1}$. No rain was received for 7 d after planting (DAP) either year at either location.

Plant stands and heights for 10 random plants were collected for each herbicide-by-cover crop treatment at 42 to 52 DAP and 145 to 149 DAP. Stand counts were taken in two linear 1-m rows in broadleaf cover crops and three 30-cm linear row stand counts were collected from the cereal grain cover crops. Heights were measured from the base of the plants at the soil to the highest growing point. A fresh weight biomass was recorded for each plot at 146 to 149 and 148 to 150 DAP in 2017 and 2018, respectively. In Henry County, cover crops were harvested with a hay cutter then two 1-$m^2$ quadrats were raked and weighed onsite. In Macon County, a Carter® flail forage harvester was utilized to harvest and weigh the center 1.5-m by 3-m of the plot.

All data were converted to a percentage of the nontreated (NT) prior to statistical analysis for each individual cover crop. Then, converted data were processed with the PROC GLIMMIX procedure in SAS® 9.4 (SAS Institute Inc., Cary, NC 27513). Year, treatment, location, and block were subjected to ANOVA for a randomized complete block design. Each cover crop species was analyzed separately because the objective of the study was not to compare the different cover crops to each other but to evaluate the effects of different residual herbicides on each species individually. Treatment and location were considered fixed effects, while block was a random effect. If treatment by location was not significant, then location was used as a random effect and data were combined over location for analysis. If the interaction was significant, data were analyzed and presented by location. All means were separated using Tukey's honestly significant difference test with $P < 0.10$ to reveal statistical difference. This significance level was used because differences in cover crop injury and growth are difficult to distinguish, and $P < 0.10$ will, without question, reveal biologically significant differences among treatments.

## 5.4 Results and Discussion

There was a year-by-treatment interaction ($P < 0.10$) for each cover crop species; therefore, 2016–17 and 2017–18 were analyzed separately for stand counts and plant heights. Data were combined over both locations for stand counts because there were no location-by-treatment differences for each year. Stand counts were evaluated at 48 to 52 DAP and 145 to 148 DAP at each location in 2016–17 (Table 3). Stand reductions of 43%–52% in rye and 44%–75% in wheat, respectively, were observed at 48 to 52 DAP for *S*-metolachlor, acetochlor, pyroxasulfone, imazapic, and bentazon plus acifluorfen over both locations. Wheat also had stand reductions of 36% with chlorimuron-ethyl use and 52% with diclosulam use at both locations. Vetch had significant stand reductions for all herbicide treatments, except for prometryn, at 48 to 52 DAP, ranging from 14% to 80% over both locations. The sensitivity of vetch to residual herbicides was not observed in two previous studies that evaluated corn and soybean herbicides (Bradley et al. 2016; Yu et al. 2015). However, two other studies found significant vetch injury or biomass reductions, indicating that environmental or soil composition factors are likely playing a role in herbicide carryover effecting vetch establishment (Bryan 2014; Palhano et al. 2018). *S*-metolachlor, pyroxasulfone, and acetochlor had the largest negative impacts on stand counts for rye (52%, 45%, 44%), wheat (75%, 59%, 67%), and vetch (80%, 66%, 74%) at 48 to 52 DAP. Similarly, Palhano et al. (2018) saw stand reductions 14 DAP of 12% and 11% with pyroxasulfone used with rye and wheat, respectively. Clover, radish, and oat were not affected by any herbicide treatment at 48 to 52 DAP. By 145 to 148 DAP, there were no stand reductions for any of the cover crops evaluated in 2016–17. The stand recovery was due to late-season germination of the affected cover crops. In 2017–18, stand counts were evaluated at 42 to 45 DAP and 147 to 149 DAP at each location (Table 4). At 147 to 149 DAP, diclosulam and trioxysulfuron-sodium reduced clover stand by 29% and 38%, respectively. Diclosulam reduced radish stand by 64% at 147 to 149 DAP. Chlorosis and stunting were observed for clover and radish plants following herbicide treatments that had stand reductions at 147 to 149 DAP. Oat, rye, and vetch did not have any stand reductions at either 42 to 45 DAP or 147 to 149 DAP. Overall, more stand reductions were observed at 147 to 149 DAP than at 42 to 45 DAP, which was different from 2016–17, when by 145 to 148 DAP there were no observed stand reductions. Conditions in 2016–17 favored more stand reductions by herbicides than in 2017–18. In 2016–17 there was more rainfall and lower soil temperatures than 2017–18 (Table 5). These environmental factors may have slowed cover crop germination and emergence allowing the seedling to be exposed to herbicide for a longer period compared with 2017–18, especially for herbicides that are not very water-soluble.

Location by treatment was different for radish height and was analyzed by each location in 2016–17 (Table 6). Treatments applied in Henry County did not result in any height reductions for radish at 48 or 145 DAP. In Macon County, height reductions of radish were reduced by 31% at 52 DAP when imazapic was used. This was the only time and location to show radish plant height reduction. Radish sensitivity was also observed in other studies in which radish had more injury from herbicide carryover than any other cover crop evaluated (Anderson 2014; Bradley et al. 2016; Bryan 2014; Hartzler and Anderson 2015). By 147 DAP, radish had recovered and there was no height differences compared with NT plants. Radish did not have height reductions at either timing in 2017–18. Again, no other cover crop had height reductions in either year or location of this study. Previous studies have not considered height as a potential growth parameter to evaluate for herbicide carryover onto fall-seeded cover crops. Based on the results of this study, plant height reductions are not a good visual indicator of herbicide carryover. Because radish was the only cover crop to have a plant height reduction, this was likely due to radish being sensitive to environmental factors or, possibly, to higher clay content in the soil in Macon County in 2016–17. Overall, based on these data, stand reductions are a better indicator of herbicide carryover compared to height reductions. Although stand losses were observed for some cover crops each year, this did not lead to biomass reduction at the end of the growing season either year. Also, the average biomass of all treated plots was not different from the average NT plots for each cover crop. Oat had the largest average biomass of the evaluated grass species in both treated and NT plots both years (Table 7). Although vetch had stand reductions for all but one herbicide in 2016–17 at the beginning of the season, it had the greatest average amount of biomass of the broadleaf species evaluated in the treated and NT plots. Even though clover did not exhibit any reductions, it did not have the largest amount of biomass of the broadleaf plants in 2016–17. Therefore, if a producer is growing a cover crop for biomass, then species selection and herbicide carryover need to be considered. Clover did not show any stand reductions but did not have the greatest amount of biomass at the end of the growing season in 2016–17 of the broadleaf plants evaluated. In 2017–18 radish exhibited the largest average biomass of the broadleaf species in the treated and NT plots. Overall, some cover crops had stand reductions; however, the new plants that did emerge were able to compensate for the reduced population and produce a biomass similar to that of the NT plots with a full growing season for each cover crop evaluated in this study. Cover crop response to herbicides varied from year to year, even though the same amount of herbicides were applied each year they did not vary between locations, suggesting environmental factors favored certain herbicide persistence each year and not soil composition. Although this study applied low rates of herbicides prior to planting to simulate carryover, in field settings, these herbicides would be applied weeks to months before planting fall-seeded cover crops. Environmental factors including soil pH, soil composition, microbial activity, soil temperatures, air temperatures, and other conditions can extend soil herbicide residual persistence, thus increasing carryover chances on to fall-seeded cover crops (Curran 2016). In addition to herbicide chemistry, how it degrades, and its half-life can affect how long an herbicide will be persistent in a soil. Overall in this study, diclosulam caused more stand reductions than any other herbicide by affecting all cover crops with the exception of oat and rye. Trifloxysulfuron-sodium, diuron, flumioxazin, pyrithiobac, and prometryn did not affect the establishment of any grass cover crop stands either year. Prometryn was the only herbicide to not affect broadleaf cover crops. Although injury and/or stand reduction is possible with residual herbicide use, producers should likely expect cover crops to recover and produce full biomass potential.

Overall, oat showed the most herbicide tolerance with no treatments reducing stands, heights, or biomass in either year. This aligns with other studies that found oat to be tolerant to many corn and soybean herbicides, including *S*-metolachlor, imazethapyr, atrazine, and mesotrione (Hartzler and Anderson 2015; Yu et al. 2015). Previous studies have shown rye to be more tolerant than oat to residual herbicides (Bryan 2014; Cornelius and Bradley 2017). One study found cereal rye had the most tolerance out of all the cover crops tested, with stand and biomass reductions caused by only a few herbicides, including by flumioxazin, cloransulam, sulfentrazone, metribuzin, and fomesafen + *S*-metolachlor (Cornelius and Bradley 2017). Another study also found rye to be the most tolerant to commonly used corn herbicides including *S*-metolachlor (Bryan 2014). However, this study did observe rye stand losses with a number of herbicides including *S*-metolachlor in 2016–17. Wheat exhibited the most sensitivity to herbicide carryover out of the grasses evaluated as more stands were reduced compared with other grasses. Rogers et al. (1986) observed significant cover reductions of wheat to cotton herbicides (fluometuron, MSMA, trifluralin) in three different soil types. Broadleaf cover crops showed more sensitivity to herbicide carryover compared to grass species. Vetch response was variable in that it had the most sensitivity to herbicide carryover of all the broadleaf plants with all but one herbicide effecting stand establishment in 2016–17; however, it did not exhibit a stand reduction the following year. Some studies have shown hairy vetch to be the most tolerant cover crop to herbicide carryover, whereas other studies showed it to be the most sensitive (Bryan 2014; Hartzler and Anderson 2015; Rogers et al. 1986; Stahl 2016; Yu et al. 2015). Palhano et al. (2018) found clover had reduced biomass in a field study from residual herbicides but emergence reductions were not observed, whereas the opposite occurred in this study. Another study found acetochlor and *S*-metolachlor caused biomass reductions of clover during one year of the study; however, neither herbicide caused injury in this study (Cornelius and Bradley 2017). Previous studies indicated radish, similar to clover and vetch, had both tolerance and susceptibility to carryover (Cornelius and Bradley 2017; Yu et al. 2015). One study evaluating oilseed radish tolerance found it to be sensitive to a number of residual herbicides, including fomesafen, *S*-metolachlor/fomesafen, and imazethapyr but was not affected by them the following year, likely due to increased rainfall (Cornelius and Bradley 2017). Another study that also had varying results from year to year did not recommend planting oilseed radish within 3 mo of an imazethapyr application but did not report injury with *S*-metolachlaor + atrazine and saflufienacil + dimethenamid-P (Yu et al. 2015). The results of this study and all previous studies indicate that residual herbicides have the potential to reduce fall-seeded cover crop establishment; however, weather conditions, soil textures, application timings, and other environmental factors affect the severity of damage observed.

Overall, cover crop stand establishment varied over the years but not locations, similar to previous studies with other row crop residual herbicides, likely due to environmental factors affecting herbicide persistence (Cornelius and Bradley 2017; Tharp and Kells 2000; Yu et al. 2015). Fall-seeded cover crop should be planted based on the residual herbicides applied to row crops the previous season, when the last application of residuals occurred and based on the biomass goal and nutrient needs of the field. Although initial injury and stunting may occur, cover crop biomass was not affected by the residual herbicides evaluated in this study and producers can still expect the full benefits offered by cover crops. Further research needs to be conducted to determine the minimum plant-back interval needed for fall-seeded cover crops after herbicide applications in the previous crop, especially as the utilization of cover crops increases in the Southeast.

### 5.5 Conflict of Interest

The authors of this study do not have conflict of interest to declare.

### 5.6 Acknowledgments

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**Table 1.** Locations and soil information of field trials conducted in 2016–17 and 2017–18.[a]

| Location (county) | City, State | Soil texture | pH | OM%[b] | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|
| Henry | Headland, AL | Dothan fine sandy loam[b] | 6.2 | 1.2 | 82 | 1 | 17 |
| Macon | Shorter, AL | Kalmia sandy loam[c] | 6.1 | 0.9 | 72 | 11 | 18 |

[a]Soil information was provided by Auburn University Soil Testing Laboratory (Auburn AL).

[b]Abbreviation: OM, organic matter.

[c]Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.

[d]Fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults.

**Table 2.** Herbicide treatments and rates.

| Common name | Trade name | Manufacturer | City, State; website | Rate[a] (g ai $ha^{-1}$) |
|---|---|---|---|---|
| Acetochlor | Warrant | Monsanto Company | St. Louis, MO; www.monsanto.com | 126 |
| Aciflurofen + Bentazon | Storm | United Phosphorus, Inc. | King of Prussia, PA; http://www.upi-usa.com | 28 +56 |
| Chlorimuron-Ethyl | Classic | DuPont Crop Protection | Wilmington, DE; www.corteva.us.com | 0.88 |
| Diclosulam | Strongarm | Dow AgroSciences, LLC | Indianapolis, IN; www.corteva.us.com | 0.33 |
| Diuron | Direx | Drexel Chemical Company | Memphis, TN; www.drexchem.com | 84 |
| Flumioxazin | Valor | DuPont Crop Protection | Wilmington, DE; www.corteva.us.com | 11 |
| Imazapic | Cadre | BASF Corporation | Research Triangle Park, NC; www.BASF.com/us | 7 |

| | | | | |
|---|---|---|---|---|
| Prometryn | Caparol | Syngenta Crop Protection, LLC | Greensboro, NC; www.syngenta-us.com | 224 |
| Pyrithiobac | Staple LX | DuPont Crop Protection | Wilmington, DE; www.corteva.us.com | 11 |
| Pyroxasulfone | Zidua | BASF Corporation | Research Triangle Park, NC; www.BASF.com/us | 2.2 |
| *S*-metolachlor | Dual Magnum | Syngenta Crop Protection, LLC | Greensboro, NC; www.syngenta-us.com | 207 |
| Trifloxysulfuron-sodium | Envoke | Syngenta Crop Protection, LLC | Greensboro, NC; www.syngenta-us.com | 2.4 |
| Nontreated | | | | |

[a]All treatments are 10% of the full-labeled rate to simulate carryover.

**Table 3.** Plant stand response to residual herbicides in peanut and cotton rotation in 2016–2017.[a]

| Herbicide treatment | Rate (g ai ha$^{-1}$) | Plant stands[bcd] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Rye | | | | Wheat | | | | Vetch | | | |
| | | 48–52 DAP | | 145–148 DAP | | 48–52 DAP | | 145–148 DAP | | 48–52 DAP | | 145–148 DAP | |
| | | ——% (NT)—— | | | | | | | | | | | |
| Acetochlor | 126 | 56 | d | 78 | a | 33 | fg | 73 | a | 26 | jk | 85 | a |
| Aciflurofen + Bentazon | 28 +56 | 69 | abcd | 87 | a | 72 | abcde | 98 | a | 61 | ef | 93 | a |
| Chlorimuron-Ethyl | 0.88 | 70 | abcd | 101 | a | 64 | bcdef | 102 | a | 54 | fg | 81 | a |
| Diclosulam | 0.33 | 65 | abcd | 76 | a | 49 | defg | 109 | a | 41 | hi | 90 | a |
| Diuron | 84 | 93 | ab | 127 | a | 95 | ab | 91 | a | 81 | bc | 87 | a |
| Flumioxazin | 11 | 87 | abc | 100 | a | 103 | a | 82 | a | 86 | bc | 107 | a |
| Imazapic | 7 | 57 | bcd | 86 | a | 56 | cdefg | 81 | a | 47 | hg | 76 | a |
| Prometryn | 224 | 87 | abc | 109 | a | 103 | a | 110 | a | 87 | ab | 98 | a |
| Pyrithiobac | 11 | 80 | abcd | 82 | a | 80 | abcd | 99 | a | 67 | de | 79 | a |
| Pyroxasulfone | 1.8 | 55 | bc | 80 | a | 41 | efg | 93 | a | 34 | ij | 86 | a |
| *S*-metolachlor | 138 | 48 | d | 75 | a | 25 | g | 87 | a | 20 | k | 101 | a |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trifloxysulfuron-sodium | 2.4 | 84 | abcd | 77 | a | 87 | abc | 106 | a | 74 | dc | 72 | a |
| Nontreated | | 100 | a | 100 | a | 100 | a | 100 | a | 100 | a | 100 | a |

[a]Abbreviations: NT, nontreated; DAP, days after planting.

[b]Data collected in Henry County December 12, 2016 and March 20, 2017. Collected in Macon County January 12, 2017 and April 18, 2017.

[c]Clover, radish, and oat did not have any significant stand reductions, and therefore were not included in this table.

[d]Means followed by the same letter in the same column do not differ based on a mixed model analysis of variance of a randomized complete block (P = 0.1). Data are expressed as percentage of nontreated.

**Table 4.** Plant stand response to residual herbicides in peanut and cotton rotation in 2017–2018.[a]

| Herbicide treatment | Rate (g ai ha$^{-1}$) | Plant stands[bcd] | | | |
|---|---|---|---|---|---|
| | | Clover | | Radish | |
| | | 42–45 DAP | 147–149 DAP | 42–45 DAP | 147–149 DAP |
| | | ——% (NT)—— | | | |
| Acetochlor | 126 | 95 a | 93 ab | 106 a | 111 a |
| Aciflurofen + Bentazon | 28 + 56 | 92 a | 85 ab | 97 a | 113 a |
| Chlorimuron-Ethyl | 0.88 | 87 a | 87 ab | 96 a | 87 ab |
| Diclosulam | 0.33 | 80 a | 71 bc | 109 a | 36 b |
| Diuron | 84 | 95 a | 93 ab | 99 a | 83 ab |
| Flumioxazin | 11 | 92 a | 99 ab | 95 a | 123 a |
| Imazapic | 7 | 89 a | 106 a | 89 a | 67 ab |
| Prometryn | 224 | 84 a | 94 ab | 97 a | 115 a |
| Pyrithiobac | 11 | 89 a | 91 ab | 99 a | 102 a |
| Pyroxasulfone | 1.8 | 94 a | 93 ab | 101 a | 120 a |
| *S*-metolachlor | 138 | 95 a | 94 ab | 109 a | 126 a |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Trifloxysulfuron-sodium | 2.4 | 76 | a | 62 | c | 109 | a | 86 | ab |
| Nontreated | | 100 | a | 100 | a | 100 | a | 100 | a |

[a]Abbreviations: NT, nontreated; DAP, days after planting.

[b]Data collected in Henry County on December 18, 2017 and March 29, 2018. Collected in Macon County on December 19, 2017 and April 5, 2018.

[c]Rye, vetch, and oat did not have any significant stand reductions, and therefore were not included in this table.

[d]Means followed by the same letter in the same column do not differ based on a mixed model analysis of variance of a randomized complete block (P = 0.01). Data are expressed as percentage of nontreated.

**Table 5.** Average monthly rainfall, temperature, and soil temperatures

| Month | 2016–2017 | | | | | | 2017–2018 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Henry | | | Macon | | | Henry | | | Macon [b] | | |
| | Rainfall (cm) | Temperature (C) | Soil Temperature[a] (C) | Rainfall (cm) | Temperature (C) | Soil temperature (C) | Rainfall (cm) | Temperature (C) | Soil Temperature (C) | Rainfall (cm) | Temperature (C) | Soil temperature C |
| November | 0.03 | 16 | 19 | 5 | 14 | 16 | 1 | 15 | 27 | 3 | 13 | 17 |
| December | 21 | 13 | 19 | 16 | 10 | 12 | 5 | 11 | 24 | 7 | 9 | 12 |
| January | 30 | 13 | 18 | 20 | 11 | 11 | 3 | 6 | 19 | 12 | 5 | 9 |
| February | 11 | 15 | 18 | 9 | 12 | 12 | 18 | 16 | 22 | 10 | 16 | 15 |
| March | 4 | 16 | 20 | 6 | 14 | 13 | 10 | 14 | 24 | 12 | 13 | 15 |
| April | -- | -- | -- | 8 | 19.2 | 17 | -- | -- | -- | 9 | 16 | 18 |

[a]Soil temperatures were taken at 10-cm depth.

[b]Soil temperature data was missing from November 25, 2017 to December 14, 2017 because the Macon County weather station soil sensor was down for repairs. Soil temperature data for the missing days came from Natural Resources Conservation Service Weather Station on Morris Farms, an Alabama SCAN site, approximately 10 miles away.

**Table 6.** Radish plant height response to residual herbicides in peanut and cotton rotation in Macon County in 2016–17.[a]

| Herbicide treatment | Rate (g ai ha$^{-1}$) | Radish[bc] 52 DAP | | Radish[bc] 148 DAP | |
|---|---|---|---|---|---|
| | | % (NT) | | | |
| Acetochlor | 126 | 93 | def | 105 | a |
| Aciflurofen + Bentazon | 28 + 56 | 120 | ab | 81 | a |
| Chlorimuron-Ethyl | 0.88 | 85 | fg | 105 | a |
| Diclosulam | 0.33 | 106 | abcdef | 91 | a |
| Diuron | 84 | 91 | ef | 105 | a |
| Flumioxazin | 11 | 118 | abc | 82 | a |
| Imazapic | 7 | 69 | g | 97 | a |
| Prometryn | 224 | 125 | a | 91 | a |
| Pyrithiobac | 11 | 108 | abcde | 82 | a |
| Pyroxasulfone | 1.8 | 95 | edf | 112 | a |
| *S*-metolachlor | 138 | 113 | abcd | 106 | a |
| Trifloxysulfuron-sodium | 2.4 | 99 | cdef | 108 | a |
| Nontreated | | 100 | bcdef | 100 | a |

[a]Abbreviations: NT, nontreated; DAP, days after planting.

[b]Data collected in Macon County on January 12, 2017 and April 18, 2017.

[c]Means followed by the same letter in the same column do not differ based on a mixed model analysis of variance of a randomized complete block (P = 0.1). Data are expressed as percentage of nontreated.

**Table 7.** Average wet weight cover crop biomass in nontreated and all treated plots.[a]

| Cover crop | Wet weight of biomass | | | |
|---|---|---|---|---|
| | Treated plots[b] | NT[c] | Treated plots | NT |
| | 2016–17 | 2016–17 | 2017–18 | 2017–18 |
| | ----------------------- kg ha$^{-1}$ ------------------------- | | | |
| Clover | 16,660 | 14,020 | 6,480 | 7,050 |
| Oat | 11,590 | 10,500 | 6,550 | 6,440 |
| Radish | 11,400 | 13,840 | 8,630 | 10,290 |
| Rye | 4,930 | 6,080 | 4,350 | 5,110 |
| Vetch | 17,760 | 16,950 | 7,280 | 7,920 |
| Wheat | 4,040 | 4,900 | 3,000 | 4,440 |

[a]Data collected in Henry County March 31, 2017 and March 30, 2018. Collected in Macon County April 19, 2017 and April 6, 2018.

[b]Treated plots are the average of all plots treated with herbicides across both locations.

[c]Abbreviation: NT, nontreated.

## Chapter 6

## Efficacy of Residual Herbicide and Cover Crop Residue Integration for Early Season Weed Control in Peanut

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## 6.1 Abstract

As herbicide resistant weeds continue to evolve and spread, alternative non-chemical control methods integrated into current control programs need to be evaluated. Few studies have been conducted to determine the effectiveness of residual herbicides sprayed onto cover crop residues compared to conventionally tilled systems in peanut. The objectives were twofold for this trial, first to evaluate the effectiveness of residual herbicides on weed control in conventionally tilled versus cover crop residue system. Second, was to determine if weed control was greater with combination of cover crop residues and residual herbicides compared to conventionally tilled system by measuring weed population counts and weed biomass. Field trials were conducted in Henry County in 2019, as well as Henry and Macon County in Alabama in 2020. Treatments in both systems included: acetochlor 1,260, flumioxazin 107, diclosulam 26, *S*-metolachlor 1,700 g ai $ha^{-1}$, and a non-treated check (NTC) in each production system. Weed species counts were collected every 7 days until 56 days after planting when weed biomass was quantified. Herbicide treatments + a rye residue cover had significantly better control (>80%) of *Ipomoea spp.* and *Senna obtusfolia* compared to the conventionally tilled non-treated check (CTNTC) over 2019-2020. *Amaranthus palmeri* control was variable from year to year, in 2019, rye residue alone provides significant control while the same was not observed in 2020. Overall, total weed biomass in plots with rye residue cover and soil residual herbicides had significantly reduced weed biomass of 75-89% compared to CTNTC in 2019-2020. Flumioxazin and diclosulam with rye residue had the highest amount of weed biomass reductions of 86% and 89% respectively, compared to the conventionally tilled NTC in peanut in 2019. Overall, the combination of residual herbicides with cover crop residue provided more effective weed control than residual herbicides in conventionally tilled systems.

Keywords: Residual herbicides, peanut, rye residue, Palmer amaranth

## 6.2 Introduction

With increasing prevalence of multiple herbicide resistant weeds and limited modes of action in postemergence weed control, peanut producers are increasingly interested in nonchemical control options. Inclusion of high residue cover crops into peanut production is a potential technique to control weeds. Utilizing cover crops as part of the integrated weed management can provide additional benefits including increasing soil organic matter, conserving soil moisture, and preventing erosion (Lu et al., 2000; Danbey et al., 2001; Kasper and Singer, 2011). Cover crop residue aids in early season weed control through physical suppression of weed seed germination and allelopathy (Price et al. 2006). Cereal rye's (S*ecale cereale*) allelopathic chemicals have been shown to inhibit germination of Palmer amaranth *(Amaranthus palmeri)*, horseweed (*Conyza canadensis*), barnyard grass (*Echinochloa crus-galli)*, lambsquarters (*Chenopodium album)*, and foxtail species (*Diaspore species)* (Burgos and Talbert, 1996; Northsworthy, 2003; Przepiorkowski and Groski, 1994). Cover crops effect the light availability on the soil surface, soil temperatures, and moisture levels which can reduce weed seed germination (Teasdale and Mohler, 1993). Germinating seedlings must penetrate the cover crop residue, which can use all its energy reserves prior to reaching the surface and can lead to death before the seedling surfaces especially in heavy residue (Teasdale and Mohler, 1993). Cereal grains tend to have a high C:N ratio which slows down plant degradation and allows for plants residue to be more persistent than legume or brassica species (SARE, 2019; Burgos and Talbert, 1996; Pittman et al., 2020). This slow degradation of residue can provide longer in season weed control through physical suppression.

With the ongoing spread of glyphosate, PPO and ALS inhibitor resistant Palmer amaranth, peanut producers are limited in postemergence weed control, making early season control critical. Historically, conventional tillage has been the standard practice for field preparation prior to peanuts. Cover crops have not been utilized in peanut because they were thought to be a vector for diseases; however, studies have observed similar rates of reductions of tomato spotted wilt virus and white mold in high residue cover crops versus conventional tillage (Campbell et al., 2008; Marois and Wright, 2003). The use of high residue cover crop with residual herbicides has the potential to increase weed control and reduce the number of in season herbicide applications which can help to offset the cost of putting in cover crops (Creech, 2018). It is possible cover crop residue can interfere with residual herbicides reaching the soil surface decreasing efficacy in high residue cover cropping systems and has yet evaluated in peanut production.

Several studies have observed better weed control in soybeans and cotton when cover crops residue are used in conjunction with herbicides but few in peanut (Vann et al., 2018; Price et al., 2006; Wiggins et al., 2016; Norsworthy et al., 2011). Vann et al. (2018) observed cover crops in combination with preemergence herbicide had a 99% increase in weed suppression compared to plots with no herbicide or no cover crop in cotton. A study observed a 67-71% control of Palmer amaranth in systems utilizing cover crops plus residual control compared to 35-57% with herbicides in conventional tillage at one week after planting, with similar trends until five weeks after planting in soybean (Vollmer et al., 2020). Akulakh et al. (2015) observed better weed control of strip tilled systems with rye cover crop compared to conventionally tilled when residual herbicides were used in peanut, however, results were variable by weed species. Another study observed greater and extended weed control with all rates of rye residue (low, medium, high) with pendimethalin compared to winter fallow with pendimethalin (Kelton et al., 2015). Vollmer et al. (2020) found variable weed control dependent on weed species when high residue plus preemergent herbicides were used. Dobrow et al (2011) reported more Palmer amaranth free days when rye residue was included in the weed control program one year but did not observe a difference the following year. These studies indicate weed control results can be variable when programs include cover crops residues and residual herbicides and need to be evaluated further.

Few studies have been conducted to determine if preemergent herbicides are needed in cover crop residue at planting or if the combination of cover crop and preemergent herbicides may provide additional early season weed control than cover crop alone or conventional tilled programs. Therefore, the objectives of this trial were to (1) evaluate the effectiveness of residual herbicides on weed control in conventionally tilled versus cover crop residue systems, (2) determine if weed control was greater with the combination of cover crops and residuals herbicides compared to conventionally tilled systems in peanut production.

## 6.3 Materials and Methods

Field trials were conducted under irrigation in Macon County (32.4939°N 85.8903°W) Alabama in 2020, and Henry County (31.3512° N 85.3146°W) Alabama in 2019 and 2020. The Macon County trial had a Kalmia sandy loam soil (fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults) and the Henry County trial had a Dothan fine sandy loam soil (fine-loamy, kaolinitic, thermic Plinthic Kandiudults). Soil composition and pH for each location are listed in Table 1. Conventionally tilled plots were placed next to the cover crop residue so weed populations were similar and plots were comparable.

### *6.3.1 Cover Crop Management*

Cereal rye (Wrens Abruzzi) was planted in early November prior to the growing season at 112 kg $ha^{-1}$ by no-till grain drill. 33 kg $ha^{-1}$ of nitrogen was applied at jointing in the spring to increase biomass of the rye. Rye was terminated with 1.125 kg ae $ha^{-1}$ of glyphosate two weeks prior to planting and rolled after termination to create a mat of residue. Four 61 by 61 cm quadrats of rye residues were randomly clipped weekly from buffers and additional border rows of these trials. These samples were dried for a week then weighed to monitor degradation of rye residues throughout the growing season.

*6.3.2 Peanut Management and Treatment Description*

Peanuts (GA-06G variety) were planted in single row and 91 cm row spacing with a no-till planter into rye residue and conventionally tilled areas. GA-06G is a high yielding runner type cultivar with a medium maturity pattern. It has indeterminate and decumbent growth pattern. Peanuts were planted in Henry County on May 17, 2019 and May 29, 2020, and in Macon County on June 2, 2020. Peanut management practices recommended by Alabama Cooperative Extension were followed throughout the season to simulate on-farm production. The experimental units were arranged in a completely randomized block design with four replications within the conventionally tilled and the rye residue areas. Plots were 3.6 m wide by 7.3 m long containing four rows of peanuts. Herbicides were applied the day of planting and activated by rainfall or with 1.27 cm of irrigation within 3 days of application. Herbicide treatments were applied using a backpack sprayer with a four-nozzle boom (Teejet TT110025 wide angle flat nozzles, Teejet®, Spraying Systems Co. Wheaton, IL. 60187) propelled by compressed $CO_2$ at a spray volume of 187 L $ha^{-1}$. Treatments included 1) acetochlor (Warrant®, Bayer CropScience LP, Research Triangle Park, NC, 27709) 1,260 g ai $ha^{-1}$, 2) flumioxazin (Valor® Herbicide Valent, Walnut Creek, CA, 94596) 107 g ai $ha^{-1}$, 3) diclosulam (Strongarm®, Corteva

Agriscience, Indianapolis, IN, 46268) 26 g ai ha$^{-1}$, 4) *S*-metolachlor (Dual Magnum®, Syngenta Crop Protection, Greensboro, NC, 27419) 1,466 g ai ha$^{-1}$, as well as a rye residue non-treated check and a conventionally tilled non-treated check. Herbicide treatments were applied to both rye residue plots and conventionally tilled plots immediately after planting at all locations.

*6.3.3 Data Collection*

All data was collected from the middle two rows of each plot. Peanut stand counts, canopy widths and heights were collected at 21 days after planting in conventionally tilled and rye residue plots. Plant heights were counted from one-meter sections randomly from the two middle rows of the plots four times. Ten heights were randomly measured from base of the plant at soil line to the highest growing point for each plot. Ten canopy widths were randomly measured from furthest leaf tips horizontally across the peanut canopy. Weed species present in the plots included sicklepod (*Senna obtusifolia),* Palmer amaranth (*Amaranthus palmeri),* morningglory species (*Ipomoea species),* crabgrass species (*Digitaria species),* goosegrass (*Eleusine indica),* and crowsfoot grass (*Dactyloectenium aegyptium)*. Macon County did not have any Palmer amaranth or sicklepod present at the site. In 2019, weed counts and wet weight biomass were collect by randomly placing two 61 by 61 cm quadrats in between two middle rows. In 2020, to further understand the weed population in each system, weed counts and wet weight weed biomass were taken from the whole middle of two center rows (0.91 by 7.62 meters). Weed counts for each species were recorded at 14, 21, 35, 48, and 56 days after planting at each location.

*6.3.4 Statistical Analysis*

All data was converted to percentage of conventionally tilled non-treated check (CTNTC) prior to data analysis. Peanut growth measurements and weed counts were analyzed using PROC GLIMMIX in SAS® 9.4 (SAS Institute Inc. Cary, NC. 27513). Treatment, and site-year, were considered fixed effects, while block was the random effect, and all interactions were considered. If the treatment by site-year interaction was significant, data were analyzed and presented separately by location and collection timing. All means were separated using Tukey's Honest Significant Difference ($P \leq 0.05$) to reveal statistical difference. Microsoft Excel® (Microsoft, Redmond, Washington, 98052) exponential decay non-linear regression was used to graph the rye biomass decomposition over the season.

**6.4 Results and Discussion**

Henry County had >6,000 kg $ha^{-1}$ in rye residue at planting in both 2019 and 2020 (Figure 1). At 56 DAP, when weed biomass was collected, Henry County had >4,000 kg $ha^{-1}$ and >1,000 kg $ha^{-1}$ in 2019 and 2020, respectively. Macon County had >3,000 kg $ha^{-1}$ of rye residue at planting. In Henry County 2020, there was a higher rate of decomposition likely due to increased rainfall compared to 2019 which was a drier hotter year. The increased biomass decomposition could have led to the emergence of weeds later in the season, but further study needs to be done to evaluate this. Previous studies have observed as rye residue increases weed control increases (Reddy 2001; 2003; Ryan et al., 2011; Mirksy et al. 2011; Vollmer et al. 2020). Ryan et al. (2011) observed reduced weed biomass with increasing rye residue biomass with complete weed suppression at 1,500 g $m^2$ of residue in soybean. Mirksy et al. (2011) also observed reduced weed densities as cover crop biomass increased. Vollmer et al. (2020) observed greater control of morningglory species and Palmer amaranth with as cereal rye biomass increased with N applications. While Macon County had less rye biomass than desired at the time of planting it is reflective of producers who may not get rye planted on time or have a poorer stand. This allowed for various levels of rye residue at planting to be evaluated in this study.

There were no stand reductions at any of the sites at 19-21 DAP indicating emergence was successful even in the cover crop residue plots. Overall, peanut heights and widths were comparable between the two systems (data not shown). Nutsedge counts were also collected throughout the growing season, however, results were variable, and no differences were observed in either system (data not shown). Other studies have observed no additional control of nutsedge with the addition of rye residue (Mirsky et al. 2011; Reddy, 2001). As nutsedge is a perennial weed with larger energy reserves it is likely unaffected by cover crops (Mirsky et al. 2011; 2013). In 2020, additional weed counts were taken later in that season at 47-49 DAP to further evaluate weed species populations at a later timing.

There were no site-year by treatment ($p<0.05$) differences for morningglory species, therefore, data was combined over site-years (Table 2). There were no treatment differences at 19-23 DAP but flumioxazin (72-77%) and diclosulam (85-92%) did provide the greatest morningglory control regardless of system it was used in. At 34-36 DAP all the conventionally tilled treatments had more morningglory present than the cover crop residue treatments. All treatments with residue including the cover crop residue non-treated check had > 87% morningglory control compared to the CTNTC. Flumioxazin was the only treatment in the conventionally tilled plots to have a significant reduction of 94% compared to the CTNTC. In 2020, flumioxazin and diclosulam regardless of system had greater weed control than other treatments compared to the CTNTC at 47-49 DAP. Similarly, Vollmer et al. (2020) observed greater morningglory control of rye with N applications compared to no rye and increased control when residual herbicides were added in soybean. Overall, while not always significantly different rye residue did reduce the number of morningglory present compared to the same residual herbicide treatments in conventionally tilled system.

There were no site-year by treatment ($P<0.05$) differences for Palmer amaranth, therefore, data was combined over site-years (Table 3). Palmer amaranth control was variable from year to year and only present at the Henry County location (Table 3). In 2019, rye residue on its own provided greater weed control of than all conventionally tilled treatments except for acetochlor, although it was not always significant at 19-21 DAP.  Rye reside alone provided 78% greater weed control compared to CTNTC. Flumioxazin with rye residue had 100% control of Palmer amaranth while all other treatments had some plants present at 19-21 DAP. Similar trends were observed at 35-34 DAP in 2019 for Palmer amaranth counts. In 2020, the presence of a rye residue did not increase Palmer amaranth control compared to conventionally tilled systems. There was more germination of Palmer amaranth in ryeresidue non-treated check than any other treatments including CTNTC in 2020 at both timings. Suggesting the rye residue provided the right microclimate for Palmer amaranth germination. By 47-49 DAP in 2020, Palmer amaranth control was variable, and no differences were observed in either system (data not shown). Palmer amaranth control varied from year to year and the presence of a rye residue did not always lead to greater control.

Several studies have observed similar results where the combination of residual herbicides plus cover crop residue increased Palmer amaranth control at one site-year and then observed no differences the following year (Dobrow et al., 2011; Hand et al. 2019; Price et al. 2012; Vann et al. 2018). A study observed Palmer amaranth free days in peanut plots planted with rye cover crop compared to conventionally tilled, however, the following year no difference was observed (Dubrow et al. 2011). While other studies observed consistent Palmer amaranth control with the addition of cover crop residue in cotton (Culpepper et al. 2010; Price et al. 2006; Vollmer et al. 2020). Culpepper et al. (2010) observed a 94% reduction in Palmer amaranth emergence in row middles when a cover crop residue was utilized in cotton. Vollmer et al. (2020) observed 67-71% control of Palmer amaranth with the combination of cereal rye and residual herbicides. Further research is needed to determine the cause of variability in Palmer amaranth control.

There was a site-year by treatment ($p<0.05$) for sicklepod at 19-21 DAP, therefore, data was analyzed separately (Table 4). At 34-35 DAP, there were no site-year by treatment ($P<0.05$) differences so data was combined over site-years. Sicklepod was only present at the Henry County location. By 47-49 DAP in 2020, sicklepod control was variable, and no differences were observed in either system (data not shown). In 2019, all treatments with the rye residue including the rye residue alone had greater control of sicklepod than the conventionally tilled treatments. In 2020, flumioxazin and *S*-Metolachlor with cover crop residue provide the best sicklepod control with 82-91% reduction compared to the CTNTC. By 34-35 DAP all herbicide treatments with the cover crop residue had better control than the conventionally tilled treatments. Overall, the rye residue alone did provide greater large seeded broadleaf weed control than the conventionally tilled treatments and control increased when residuals were included.

There were no site-year by treatment ($p<0.05$) differences for annual grass species, therefore, data was combined over site-years (Table 5). All treatments regardless of system had grass reductions compared to the CTNTC at all timings. At 19-21 DAP and 47-49 DAP treatments with cover crop residue tended to have more grasses present than the conventionally tilled treatments with herbicides although it was not significant. The rye residue alone did not have more grasses present than the CTNTC, but several of treatments with residue did. This trend was observed in the field with more grass species being present in rye residue while more broadleaf weeds were observed in the conventionally tilled treatments. It is possible the rye residue created a microenvironment that allowed for grasses to readily germinate compared to the conventionally tilled system. Whether it was the cooler soil temperature or increase soil moisture in the rye residue caused more germination is unknown. Similarly, Reddy (2001) did not see an increase of barnyardgrass (*Echinochloa crus- galli)* when rye residue was added to the weed control program. Other studies have observed improved grass control with the integration of cover crop residue (Hand et al. 2019; Vollmer et al 2020; Dobrow et al. 2011). Further research needs to be conducted to determine what is allowing more grasses to emerge in the cover crop residue**.**

Fresh weight weed biomass, collected at 56 DAP, was separated out by monocots, dicots, total biomass and then analyzed. There were no site-year by treatment ($p<0.05$) differences for monocots and total weed biomass, therefore, data was combined over site-years (Table 6). There was a site-year by treatment ($p<0.05$) differences for dicots so data was analyzed separately for each site-year. For monocot biomass all treatments were different from the CTNTC, however, there were no statistical differences between the remaining treatments. This result aligns with the grass counts observed throughout the season. Dicot biomass was variable across all three site years but the combination of flumioxazin plus rye residue tended to provide the best overall control with 90-99% reduced dicot biomass compared to CTNTC.  Further study needs to be conducted to determine if the increased monocot pressure in the rye residue prevented the emergence of dicots. While conventionally tilled flumioxazin treatments had 0-68% reduction in dicot biomass compared to the CTNTC. Treatments with rye residue had less total weed biomass than the conventionally tilled systems, although not always statistically different. Flumioxazin plus cover crop residue had 42% less total weed biomass than flumioxazin in conventionally tilled system. Diclosulam plus residue had 34% less weed biomass than diclosulam in conventionally tilled system. Overall, treatments with residual herbicides and cover crop residue combined had 75 to 89% less weed biomass than the CTNTC.

All these results indicate some of the residual herbicides is making it to the soil surface in a cover crop residue system and the combination provides greater weed control than herbicides applied in conventionally tilled systems. While these locations had less rye residue than previous studies have shown to control weeds, these results show >6,000 kg $ha^{-1}$ and >3,000 kg $ha^{-1}$ of rye residue can provide additional weed control compared to conventionally tilled systems. Results did vary from year to year especially with Palmer amaranth control. One year it provides an effective tool while the next year the addition of the cover crop did not help with Palmer amaranth control. Additional, non-chemical control methods will likely be needed to control resistant Palmer amaranth, but the cover crop residue does increase control. Flumioxazin and diclosulam provided greater weed control when combined with rye residue and are viable options for peanut producers. Overall, these results suggest the residual herbicide is reaching the soil surface through the rye residue additional studies need to be complete to determine the amount of herbicide reaching the surface. If reduced rates are reaching the surface through the rye, even with irrigation, this could cause increased selection pressure for herbicide resistant weeds. In this study fields were irrigated after application, ensuring application, however it is possible in situations where a grower must wait for rain the results could be different. The results of this study suggest the inclusion of a rye cover crop residue with residual herbicides may extend weed control further into the growing season helping, potentially help reduce herbicide resistant weeds, and reduce early season postemergence herbicide applications.

**6.5 Conflict of Interest**

The authors of this study do not have conflict of interest to declare.

**6.6 Acknowledgements**

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**Table 1: Locations and soil information of field trials[a]**

| Location (county) | City, State | Soil texture | pH | OM%[b] | Sand | Silt | Clay |
|---|---|---|---|---|---|---|---|
| Henry | Headland, AL | Dothan fine sandy loam[c] | 6.2 | 1.2 | 82 | 1 | 17 |
| Macon | Shorter, AL | Kalmia sandy loam[d] | 6.1 | 0.9 | 72 | 11 | 18 |

[a] Soil information was provided by Auburn University Soil Testing Laboratory (Auburn AL).

[b]Abbreviation: OM, organic matter.

[c]Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.

[d] Fine-loamy over sandy or sandy-skeletal, siliceous, semiactive, thermic Typic Hapludults.

**Figure 1: Rye biomass decomposition over each location**

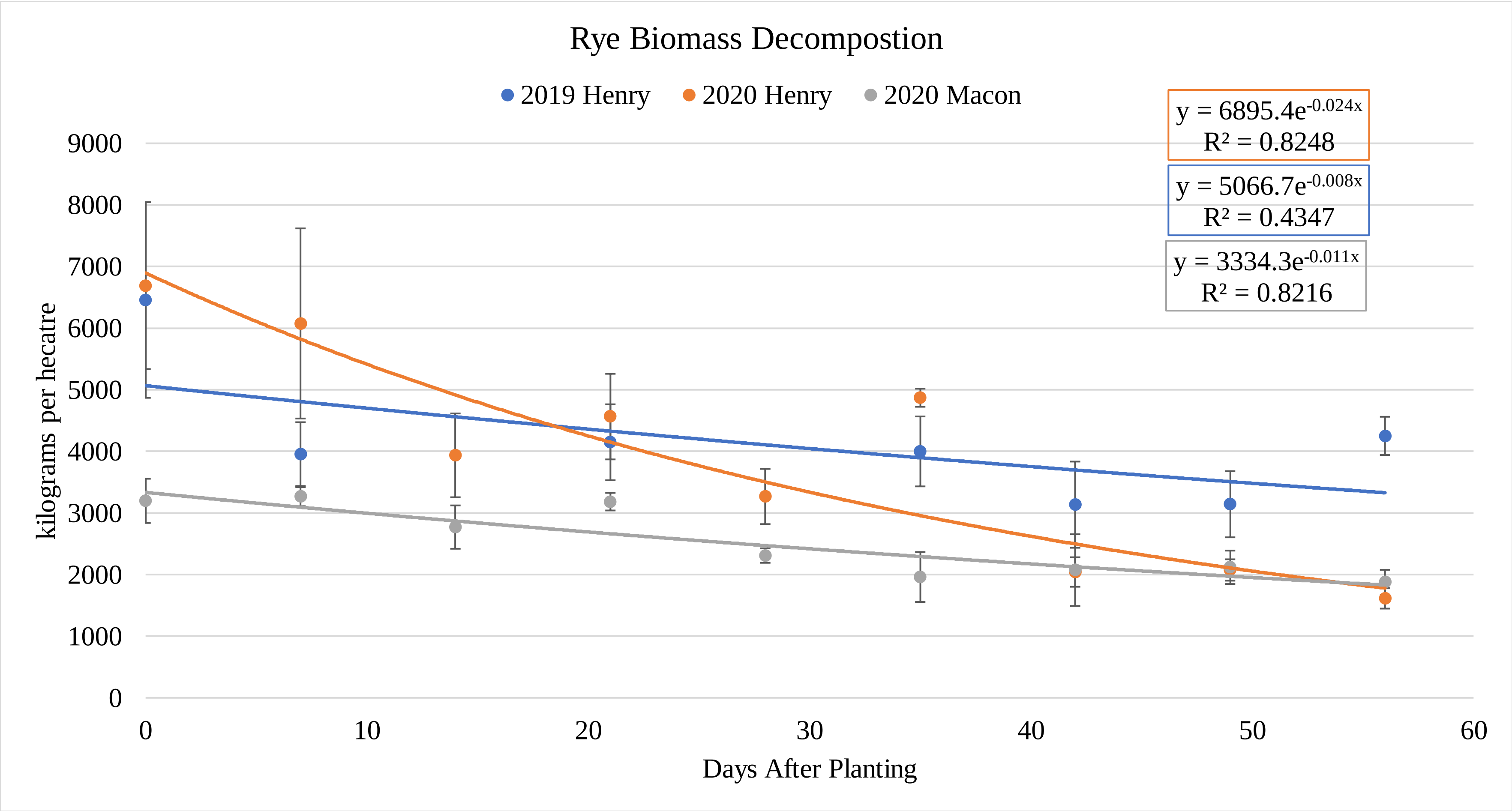

**Table 2: Morningglory spp. counts across all locations in 2019-2020[a]**

| System | Herbicide | Active Ingredient g ai ha$^{-1}$ | Morningglory counts (% of CTNTC)[b] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 19-23 DAP | | 34-36 DAP | | 47-49 DAP | |
| | | | All location | | All locations | | 2020 Locations only[c] | |
| Rye Residue | Acetochlor | 1,260 | 77 | a | 13 | bc | 34 | abcd |
| | Flumioxazin | 107 | 28 | a | 5 | c | 12 | bcd |
| | Diclosulam | 26 | 8 | a | 1 | c | 5 | d |
| | *S*-Metolachlor | 1,466 | 19 | a | 8 | bc | 36 | abcd |
| | Non-Treated Check[d] | 0 | 33 | a | 12 | bc | 38 | abcd |
| Conventionally Tilled | Acetochlor | 1,260 | 111 | a | 75 | a | 89 | ab |
| | Flumioxazin | 107 | 23 | a | 6 | bc | 11 | bcd |
| | Diclosulam | 26 | 15 | a | 10 | ab | 9 | cd |
| | *S*-Metolachlor | 1,466 | 65 | a | 63 | ab | 85 | abc |
| | Non-Treated Check[d] | 0 | 100 | a | 100 | a | 100 | a |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of the conventionally tilled non-treated check

[b] Abbreviations: DAP- days after planting; CTNTC – conventionally tilled non-treated check

[c] 2020 additional weed counts were taken at 47-49 to further determine the weed pressure present

[d] Rye residue non-treated check: 19-23 DAP 6 plants, 34-36 DAP 7 plants, 47-49 DAP 2 plants. Conventional tilled non-treated check: 19-23 DAP 24 plants, 34-36 DAP 73 plants, 47-49 DAP 5 plants

**Table 3: Palmer amaranth counts at Henry County locations only in 2019 and 2020[ab]**

| System | Herbicide | Active Ingredient g ai ha$^{-1}$ | Palmer amaranth counts (% of CTNTC)[c] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2019 | | | | 2020 | | | |
| | | | 21 DAP | | 35 DAP | | 21 DAP | | 34 DAP | |
| Rye Residue | Acetochlor | 1,260 | 11 | b | 0 | b | 0 | b | 20 | ab |
| | Flumioxazin | 107 | 0 | b | 0 | b | 0 | b | 0 | b |
| | Diclosulam | 26 | 17 | b | 5 | b | 100 | b | 60 | ab |
| | *S*-Metolachlor | 1,466 | 17 | b | 0 | b | 500 | b | 0 | b |
| | Non-Treated Check[d] | 0 | 22 | b | 0 | b | 1800 | a | 280 | a |
| Conventionally Tilled | Acetochlor | 1,260 | 6 | b | 10 | b | 100 | b | 40 | ab |
| | Flumioxazin | 107 | 56 | ab | 10 | b | 0 | b | 0 | b |
| | Diclosulam | 26 | 150 | a | 100 | a | 100 | b | 60 | ab |
| | *S*-Metolachlor | 1,466 | 22 | b | 14 | b | 300 | b | 80 | ab |
| | Non-Treated Check[d] | 0 | 100 | ab | 100 | a | 100 | b | 100 | ab |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of the conventionally tilled non-treated check
[b] No *Amaranthus palmeri* were present at the Macon County location in 2020
[c] Abbreviations: DAP- days after planting; CTNTC – conventionally tilled non-treated check
[d] 2019 Rye residue non treated check 21 DAP- 9 plants, 35 DAP-0 plants; Conventional tilled non-treated check 21 DAP-42 plants, 35 DAP-49 plants; 2020 Rye residue non treated check 21 DAP- 4.5 plants, 34 DAP-3.5 plants; Conventional tilled non-treated check actual counts 21 DAP-0.25 plants, 34 DAP-1.25 plants

**Table 4: Sicklepod counts at Henry County locations only in 2019 and 2020[ab]**

| System | Herbicide | Active Ingredient g ai ha$^{-1}$ | Sicklepod counts (% of CTNTC)[c] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 21 DAP | | | | 34-35 DAP | |
| | | | 2019 | | 2020 | | Both locations | |
| Rye Residue | Acetochlor | 1,260 | 5 | b | 36 | ab | 6 | d |
| | Flumioxazin | 107 | 0 | b | 9 | b | 6 | d |
| | Diclosulam | 26 | 10 | b | 36 | ab | 19 | bcd |
| | *S*-Metolachlor | 1,466 | 0 | b | 18 | b | 6 | d |
| | Non-Treated Check[d] | 0 | 0 | b | 82 | ab | 13 | cd |
| Conventionally Tilled | Acetochlor | 1,260 | 70 | ab | 36 | ab | 78 | abcd |
| | Flumioxazin | 107 | 100 | ab | 27 | ab | 91 | abc |
| | Diclosulam | 26 | 165 | a | 45 | ab | 100 | ab |
| | *S*-Metolachlor | 1,466 | 100 | b | 172 | a | 103 | a |
| | Non-Treated Check[d] | 0 | 100 | ab | 100 | ab | 100 | ab |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of the conventionally tilled non-treated check
[b] No *Senna obtusifolia* were present at the Macon County location in 2020
[c] Abbreviations: DAP- days after planting; CTNTC – conventionally tilled non-treated check
[d] Rye residue non treated check actual counts 21 DAP- 0 plants, 2020 21 DAP- 2.25 plants;34-35 DAP-0.33 plants; Conventional tilled non-treated check 21 DAP-47 plants, 2019-21 DAP 2.75 plants, 34-35 DAP-14 plants;

**Table 5: Annual grass species counts over all locations in 2019-2020[ab]**

| System | Herbicide | Active Ingredient g ai ha$^{-1}$ | Annual Grass species counts (% of CTNTC)[c] | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 19-21 DAP | | 34-35 DAP | | 47-49 DAP | |
| | | | All locations | | All locations | | 2020 locations [d] | |
| Rye Residue | Acetochlor | 1,260 | 15 | b | 9 | b | 18 | bc |
| | Flumioxazin | 107 | 7 | b | 6 | b | 45 | b |
| | Diclosulam | 26 | 8 | b | 4 | b | 11 | bc |
| | *S*-Metolachlor | 1,466 | 13 | b | 13 | b | 24 | bc |
| | Non-Treated Check[e] | 0 | 28 | b | 21 | b | 17 | bc |
| Conventionally Tilled | Acetochlor | 1,260 | 4 | b | 15 | b | 2 | c |
| | Flumioxazin | 107 | 10 | b | 21 | b | 7 | bc |
| | Diclosulam | 26 | 12 | b | 25 | b | 17 | bc |
| | *S*-Metolachlor | 1,466 | 2 | b | 11 | b | 8 | bc |
| | Non-Treated Check[e] | 0 | 100 | a | 100 | a | 100 | a |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of the conventionally tilled non-treated check

[b] Species included: *Digitaria sp*, *Eleusine indicia*, and *Dactyloctenium aegyptium*

[c] Abbreviations: DAP- days after planting; CTNTC – conventionally tilled non-treated check

[d] 2020 additional weed counts were taken at 47-49 DAP to further determine the weed pressure present

[e] Rye residue nontreated check actual counts 19-21 DAP-84 plants, 34-35 DAP-62 plants, 47-49-11 plants, Conventional tilled non-treated check 19-21 DAP-167 plants, 34-35 DAP-296 plants, 47-49-51 plants,

**Table 6: Fresh weight biomass at 56-59 days after planting across all locations in 2019 - 2020[ab]**

| System | Herbicide | Active Ingredient g ai ha$^{-1}$ | Fresh wet biomass (% of CTNTC)[c] Monocot Biomass | | Dicot Biomass | | | | | | Total Biomass | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | All Locations | | Henry Co 2019 | | Henry Co 2020 | | Macon 2020 | | All Locations | |
| Rye Residue | Acetochlor | 1,260 | 24 | bc | 31 | bc | 27 | b | 13 | ab | 25 | bc |
| | Flumioxazin | 107 | 18 | bc | 10 | c | 7 | b | 1 | b | 14 | c |
| | Diclosulam | 26 | 6 | c | 27 | bc | 95 | b | 0 | b | 11 | c |
| | *S*-Metolachlor | 1,466 | 18 | bc | 50 | bc | 47 | b | 24 | ab | 25 | bc |
| | Non-Treated Check | 0 | 48 | bc | 12 | c | 72 | b | 28 | b | 40 | bc |
| | Actual Weight[d] g | | 1,743 | | 276 | | 586 | | 210 | | 11,835 | |
| Conventionally Tilled | Acetochlor | 1,260 | 36 | bc | 65 | abc | 65 | b | 106 | a | 58 | b |
| | Flumioxazin | 107 | 54 | b | 114 | abc | 34 | b | 32 | ab | 56 | b |
| | Diclosulam | 26 | 19 | bc | 194 | a | 109 | b | 0 | b | 45 | bc |
| | *S*-Metolachlor | 1,466 | 24 | bc | 135 | ab | 288 | a | 40 | ab | 46 | bc |
| | Non-Treated Check | 0 | 100 | a | 100 | abc | 100 | b | 100 | a | 100 | a |
| | Actual Weight[d] g | | 3,385 | | 2,275 | | 813 | | 740 | | 19,381 | |

[a] Means followed by the same letter in the same column do not differ significantly based on a mixed model analysis of variance of a randomized complete block (p=0.05). Data are expressed as percentage of the conventionally tilled non-treated check
[b]All weeds regardless of species were included in weed biomass
[c]Abbreviations: CTNTC – conventionally tilled non-treated check
[d] Actual weights of in grams of heavy cover crops residue and conventionally tilled non-treated check