ADDRESSING THE CURRENT CHEMICAL WEED CONTROL CHALLENGES IN GEORGIA PEANUT PRODUCTION

by

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(Under the Direction of ERIC P. PROSTKO)

ABSTRACT

Research was conducted to address several current weed science issues that Georgia peanut growers are facing. These issues include the potential evolution of ALS-resistant (imazapic) sicklepod, peanut tolerance to picloram + 2,4-D, peanut tolerance to terbacil, and time of day effects on peanut weed control programs.

Peanut response to picloram + 2,4-D was investigated by applying 1/10th, 1/100th, 1/300th X labeled rates at planting, 30 days after planting (DAP), 60 DAP, and 90 DAP. Peanuts yields were reduced by 11% with the $1/10^{th}$ X rate. Peanut fields unintentionally exposed to picloram + 2,4-D rates $\geq 1/100^{th}$X (0.018 + 0.067 kg ai/ha) exhibited typical injury symptoms (leaf roll) but yields were not reduced.

Peanut response to terbacil was investigated by applying 0.03 to 0.22 kg ai/ha of terbacil after planting. Peanut yields were significantly reduced by terbacil at 0.12 and 0.22 kg ai/ha. Yield losses at these rates were 37% and 79%, respectively. Consequently, these results suggest that peanut could be planted following terbacil applications after approximately two field half-lives.

Time of day (TOD) effects were investigated by applying standard peanut weed control programs at 7:00 h, 12:00 h, 17:00 h, and 22:00 h. Peanut injury was significantly lower at 7:00 h and 22:00 h. Lactofen was more injurious to peanut than imazapic. Palmer amaranth control was not influenced by TOD or herbicide program. Annual grass control was significantly lower at the 7:00 h application timing and with the lactofen program. A significant reduction in sicklepod control was observed at the 22:00 h timing and with the lactofen program. While TOD influenced peanut injury and weed control, peanut yield was not affected.

Seed from 22 populations of sicklepod were collected from Georgia production fields during 2014 and were screened for potential resistance to imazapic in greenhouse studies. Plants grown from the seed were subjected to a discriminatory dose of 70 g ai/A of imazapic. Suspect populations were then subjected to dose response assays to determine I_{50} values. Results of these greenhouse studies suggest that these specific sicklepod populations were not resistant to imazapic.

INDEX WORDS: Peanuts, Picloram, Terbacil, Imazapic, Time of day, Sicklepod

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BS, ABRAHAM BALDWIN AGRICULTURAL COLLEGE, 2013

MS, UNIVERSITY OF GEORGIA, 2016

A DISSERTATION Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2018

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August 2018

DEDICATION

I would like to dedicate this dissertation to my parents. Without their constant love and support, nothing that I have accomplished would have been possible.

ACKNOWLEDGEMENTS

I would like to thank all of the members of my committee who have helped make this possible. Their direction and guidance throughout this process has been invaluable. Thank you all for showing me how to be a professional and the value of a strong work ethic. Dr. Prostko, thank you for allowing me to come work for you and be an unneeded extra cause of stress in your life. Thank you to all of the graduate students who have each helped make this possible. Our exchanges and conversations made the difficulties of graduate school a little bit easier. Also, a special thanks to Dr. Tim Grey for always being willing to help with any question I might have had throughout my lengthy time at UGA.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Peanut (*Arachis hypogaea* L.) is a self-pollinating, herbaceous legume, native to South America. Peanut production is concentrated in three distinct geographic areas in the U.S.: the southeast (Alabama, Florida, Georgia, Mississippi, and South Carolina), the southwest/mid-south (Arkansas, New Mexico, Oklahoma, and Texas) and mid-Atlantic (North Carolina and Virginia) (NASS, 2018). Total peanut production for the U.S. has varied in recent years with a low of 4.2 billion pounds in 2013, to a high of 7.2 billion pounds in 2017. Peanut production in the U.S. had a total value in excess of 1.5 billion dollars in 2017. Georgia consistently contributes half of all peanut production in the U.S. Peanut production in Georgia was valued at greater than $684,000,000 in 2015, which made up 31% of the total row and forage crop value for the state (Wolfe and Stubbs, 2016).

Peanut is a slow-growing, short statue crop that is not considered to be as competitive as other crops such as field corn (*Zea mays* L.) and soybean (*Glycine max* L.)(Buchanan *et al.*, 1982; Brecke and Colvin, 1991; Wilcut *et al.*, 1994). The slow growth habit and thus slow shading of row middles makes peanut a poor competitor with some weed species. Depending on the cultivar and growing region, peanut grown in the southeast typically has a growing season of approximately 135-160 days (Wilcut *et al.*, 1994; Anonymous, 2017). The long growing season and slow growth habit of peanut allow for multiple flushes of weeds that must be controlled season-long in order to obtain a harvestable and profitable crop.

Successful weed control is vital for a sustainable agricultural production system. Weeds can compete with crops for valuable nutrients, light, and water. Crop losses approaching 100% due to weeds have been noted (Lacey, 1985). Not only can weeds reduce yield and crop quality due to direct competition, they can interfere with a variety of other agricultural practices. Weeds present in crops can interfere with pesticide applications, harbor insects and diseases, and impact harvest efficiency (Wilcut *et al.,* 1995; Royal *et al.,* 1997).

Palmer amaranth (*Amaranthus palmeri* S. Watson) has been reported to be the most difficult weed to control in Georgia peanut production (Webster, 2013). Its rapid growth rate, high seed production, and extended germination period make it a strong competitor with the peanut crop (Horak and Loughin, 2000; Steckel *et al.*, 2004). It has been reported that 1 Palmer amaranth plant/row meter can cause peanut yield losses up to 28% (Burke *et al.*, 2007). Along with direct yield losses, the fast growth rate of Palmer amaranth enables it to stand above the peanut canopy for the majority of the growing season if early season control is not achieved (Burke *et al.*, 2007). The fact that Palmer amaranth would be above the peanut canopy could also lead to less efficacious pesticide applications and harvestability. Florida beggarweed (*Desmodium tortuosum* Sw.), is the second most difficult to control weed in Georgia and populations as low as 1 plant/row meter have been shown to reduce peanut yield by 20-40% (Buchanan *et al.*, 1982). Research has also shown that reduced control of Florida beggarweed will allow the weed to grow above the crop canopy and reduce the efficacy of pesticides (Hauser *et al.*, 1975; Royal *et al.*, 1997). Sicklepod (*Senna obtusifolia* L.) can also reduce pesticide efficacy, as well as reducing yield by 70% due to season long competition (Buchanan *et al.*, 1982; Royal *et al.*, 1997). Nutsedge species (*Cyperus* spp.) also ranks in the top ten most difficult weeds to control in Georgia peanut production (Webster, 2013). Yield reductions due to nutsedge competition for resources have been reported to reach as high as 32% (Keeley, 1987; Wilcut *et al.*, 1994; Johnson and Mullinix, 2003). Johnson and Mullinix reported that one yellow nutsedge plant/m^2 can reduce yields by as much as 13 kg/ha. Along with competing with the peanut crop for valuable resources, nutsedge is important to control due to harvest interference and potential contamination of the harvested peanuts with nutsedge tubers (Wilcut *et al.*, 1995). Considerable efforts by the peanut producer must be made throughout the growing season in order to effectively control a diverse infestation of weeds.

Weed control in peanut, as with other row crops, involves a multi-faceted approach. A combination of cultural, mechanical, and chemical control tactics are necessary for sustainable weed control. Three of the most influential cultural control methods are seeding rate, row pattern, and uniformity of crop stand (Johnson and Davis, 2016). Peanuts planted in narrow row patterns (< 91 cm) have increased yields over wide row (>91 cm) patterns due to the increased competitiveness of the crop (Buchanan and Hauser, 1980; Johnson *et al.*, 2005). Stand uniformity also helps to contribute to weed control in peanut. Large "skips", or areas without peanut plants, have resulted in reduced crop competitiveness and lower yields (Johnson and Davis, 2016). Sound crop rotation allows for the peanut crop to be healthier, due to reduced instances of diseases, as well as, enables the use of multiple herbicide modes of action to control difficult species (Buhler, 2003; Sanyal *et* al., 2008; Ferrell *et al.*, 2015).

Deep tillage, before the growing season, can also be a viable means of burying weed seeds to prevent germination and destroy seeds (Buhler *et al.*, 1997; Buhler, 2002; Davis and Renner, 2007). Mechanical cultivation can be an important component of a sustainable weed control program. However, cultivation in peanut is limited to the early portion of the growing season due to the peanut plant's lateral growth habit. Late season cultivations can damage the peanut vines and increase the instance of soil borne diseases such as southern stem blight or white mold (*Sclerotina sclerotiorum* Lib.) (Buchanan *et al.*, 1982; Bridges *et al.*, 1984; Ferrell *et al*, 2015). Chemical weed management programs in Georgia usually include a combination of a preplant incorporated (PPI), preemergence (PRE), early-postemergence (EPOST), and postemergence (POST) applications (Horton, 2018). A combination of soil residual, contact, and systemic herbicides are recommended for use in order to achieve optimum weed control in peanut (Horton, 2018).

While chemical weed management is one of the most effective tools that a peanut grower can use, it does not come without challenges. Issues that can arise from chemical weed management in any row crop may include the following: reduced efficacy due to misapplication of the herbicide (i.e. incorrect rate and improper timing of application); reduced efficacy due to environmental factors (i.e. drought stress); resistance to the herbicide mode of action (MOA); poor coverage of the target weed; off-target movement; and antagonistic effects of herbicide tank-mixtures (Mckinlay *et al.*, 1974; Lake, 1977; Grichar, 1991; Hart *et al.*, 1992; Zhou *et al.*, 2007; Vencill *et al.*, 2012; Sosnoskie and Culpepper, 2014). Use of herbicides to control weed species also comes with the risk of crop injury. Injury can be caused by a variety of factors such as misapplication of herbicide (i.e. wrong rate, applying herbicides at an inappropriate crop growth stage), off-target of movement of the herbicide from the target area to susceptible plants, and herbicide residues remaining in the soil or water and damaging sensitive rotational crops (Wehjte *et al.*, 1986; Leonard, 1990; Coffman *et al.*, 1993; Barbash and Resek, 1996; Grichar, 1998; Zhang *et al.*, 2000; Etheridge *et al.*, 2001; Mohsen and Doohan, 2015;).

Herbicides are the primary means of weed control in peanut. However, achieving consistent weed control without crop injury is complex. The goal of this research was to better understand several of the most current herbicide and weed control challenges in Georgia peanut.

Project 1: Peanut Response to Picloram + 2,4-D

Picloram. Picloram is a systemic, persistent, auxin-type herbicide that is a member of the pyridine carboxylic acid family (Fast *et al.,* 2010). Picloram controls sensitive broadleaf weed species due to uncontrolled cellular division and growth, which leads to cell wall destruction (Shaner, 2014). Picloram was first introduced in 1963 for the control of broadleaf weeds and woody brush species (Hamaker *et al.*, 1963). The relatively long half-life of picloram (average of 90 d with a range from 20 to 300 d) and high sensitivity of broadleaf plant species to the herbicide can make it potentially damaging to rotational crops (Shaner, 2014). Picloram is also highly water soluble and can readily move from the treated area through ground and surface water (Lym and Messersmith, 1988; Fast *et al.*, 2010). This mobility allows picloram to move into nearby water reservoirs, which could potentially be used for irrigation on agronomic crops (Lym and Messersmith, 1988; Fast *et al.*, 2010).

Picloram has been reported to increase the movement of 2,4-D in weed species and thus they are commonly sold together as a pre-mixed herbicide combination (Agbakoba and Goodin, 1970; Anonymous, 2018). The combination of picloram+ 2,4-D, sold as Grazon® P+D, is used on approximately 20% of all permanent pasture and grassland in Georgia (P.E. McCullough, University of Georgia, pers. commun., 2017). Every year, peanut growers have consistently, 5-10 times per year for ~20 years, experienced injury due to picloram in their peanut crop (E.P. Prostko, The University of Georgia, pers. commun., 2018). Research has been conducted previously to determine the effect of picloram on peanut, however no yield data was recorded

(Banks *et al.,* 1977; Ketchersid *et al.,* 1995). Additional research is needed to determine the effects of various rates of picloram on the growth and yield of peanut.

Project 2: Peanut Response to Terbacil

Terbacil. Terbacil, a substituted uracil, is a selective herbicide sold under the trade name Sinbar® and is used for the control of broadleaf and grass weeds in apples, alfalfa, peaches, mint, strawberry, sugarcane, watermelon and several other crops (Anonymous, 2018). Terbacil is a photosystem II (PSII) inhibitor. The herbicide is readily absorbed by roots and translocated acropetally into leaves. Absorption by the leaves and stems occurs but is less than that of the roots (Gardiner *et al.*, 1969). Plants are controlled due to lipid peroxidation that results in a loss of chlorophyll and carotenoids and a leaky membrane (Shaner, 2014). Considered to be a long soil residual herbicide, terbacil has an average field half-life of 120 d, with reports of persistence as high as five to six months on a silt loam soil (Gardiner *et al.*, 1969; Wauchope *et al.*, 1992; Shaner, 2014).

Watermelon is an important high-value crop for Georgia growers. Georgia consistently ranks in the top 4 producing states in the country and accounts for 13% of the total U.S. watermelon production (USDA, 2017). In 2015, Georgia watermelon production was valued at $81,500,000 (NASS, 2015). Weed control is critical for producing a high-value and quality yielding watermelon crop. Weeds can be a serious problem in watermelon because of initial slow plant growth, low plant densities, and limited ability for cultivation once plants are established (Elmstrom and Locascio, 1974; Larson *et al.*, 2004). Crop rotation, tillage, and a sound herbicide program are all critical components for long-term weed control success in watermelon (Culpepper and Smith, 2018). An herbicide with long soil residual properties to control emerging weeds for the entire watermelon growing season is necessary (Elmstrom, 1972). Several University of Georgia recommended watermelon weed control programs include terbacil for the control of broadleaf weeds and it is currently being utilized on 70-75% of watermelon hectares (A.S. Culpepper, The University of Georgia, pers. commun., 2017; Culpepper and Smith, 2018).

Maximizing yields is essential to maintaining a productive farming operation. One tool that growers use to maximize yield is crop rotation (Higgs *et al*., 1990). Georgia peanut growers commonly rotate the fields in which they plant their peanut crops to more successfully manage weeds, insects, and disease pressure (Higgs *et al.*, 1990; Vencill *et al.*, 2012). Rotating crops can be a difficult task with the multitude of crop tolerances to the variety of herbicides that could potentially be used in Georgia. Currently the Sinbar® herbicide label restricts the planting of peanut, along with all other row crops, for 2 years following the last application of terbacil. The ability to plant peanut 12 months or earlier after a terbacil application would greatly increase the rotational crop options for Georgia growers. Research is needed to determine if this two year rotational restriction from peanut is justifiable.

Project 3: Time of day effects on peanut herbicide programs

Time of Day (TOD) Effects on Herbicides. Changes in farming practices and technology have led to the application of pesticides over a broader time period in a given day (Mohr *et al.*, 2007). In recent years, average farm size in the U.S. has continued to increase while number of farms has decreased (Hoppe and MaCdonald, 2016). Due to this increase in farm size, growers must now manage more land area in a given time period in order to be timely with pesticide applications. Covering more land area means that work days begin earlier in the morning and can sometimes extend into the night. The addition of global positioning systems (GPS) technology on most pesticide application equipment has allowed for the accurate application of pesticides under all light conditions (Tillet, 1991; Klassen *et al.*, 1993; Mohr *et al.*, 2007).

The extended hours that pesticides are applied does not come without concerns. One such concern that can arise from applying pesticides early in the morning or late into the evening is variations in herbicide efficacy. Reduced weed control due to variable application timing has previously been reported for several herbicides including acifluorfen, bentazon, fomesafen, glyphosate, and glufosinate (Doran and Andersen 1976; Lee and Oliver 1982; Martinson *et al.* 2002; Miller *et al.* 2003; Mohr *et al.* 2007). While there have been reductions in herbicide efficacy due to herbicide applications at varying times during the day, weed control is still largely species dependent. Species specific TOD effects for atrazine, bromoxynil, dicamba, glyphosate, glufosinate, and nicosulfuron have been observed when applied to barnyardgrass (*Echinochloa crus-galli* L.), common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), redroot pigweed (*Amaranthus retroflexus* L.) and velvetleaf (*Abutilon theophrasti* Medik.) (Stewart *et al.* 2009). For these species, control was generally reduced when applications occurred at 6:00 h, 21:00 h, and 24:00 h. Velvetleaf was the most sensitive to TOD effects, followed by common ragweed, common lambsquarters, and redroot pigweed (Stewart *et al.*, 2009). Annual grasses are not as sensitive to TOD, however control was reduced in some environments when applications occurred at 6:00 h and after 21:00 h (Stewart *et al.*, 2009). Acifluorfen applied at night (21:00 h) resulted in better control of hemp sesbania (*Sesbania herbacea* P. Mill.), pitted morningglory (*Ipomoea lacunose* L.*)* and smooth pigweed (*Amaranthus hybridus* L.*)*, while no TOD effect was observed for common cocklebur (*Xanthium strumarium* L.) or prickly sida (*Sida spinose* L.) (Lee and Oliver, 1982). Bentazon efficacy was reduced when applied before daybreak in the morning and after sunset in the evening (Doran and Andersen, 1976). However, more recent studies indicated that TOD had no effect on the efficacy of bentazon when applied to common ragweed, common lambsquarters, pigweed, and velvetleaf (Stopps *et al.*, 2013).

Environmental and plant physiological factors may also contribute to the varying degrees of control that can be evident when herbicides are applied at different TOD. Environmental factors such as dew, temperature, and relative humidity (RH) can influence herbicide performance. Typically dew can be present on leaf surfaces in early morning (6:00 h) and late evening (19:00 h to 24:00 h). It is hypothesized that dew can intercept herbicide spray droplets potentially diluting the herbicide and increasing herbicide runoff from the leaf surface (Fausey and Renner, 2001; Kogan and Zuniga, 2001; Stewart *et al.*, 2009). Others have reported an increase in herbicide efficacy when dew or rainwater is present on plant foliage (Nalewaja *et al*., 1975; Caseley, 1989). This increase in efficacy could be due to enhanced retention of the herbicide, or redistribution of the active ingredient to locations on the leaf where entry and systemic action are greater (Caseley, 1989). Increased air temperature and RH have also been shown to increase herbicide efficacy (Sharma and Singh 2001). Lower air temperatures (below 25 C) have reduced control regardless of the time of day when the herbicide was applied (Friesen and Wall, 1991). Daytime air temperatures above 25 C have increased control of pitted morningglory, common cocklebur, and velvetleaf when compared to temperatures below 25 C (Doran and Andersen, 1976; Lee and Oliver 1982). Increases in RH have increased herbicide efficacy over a range of herbicides and species (Wills, 1978; Wills and McWhorter, 1981; Johnson and Young, 2002). Increases in RH may result in greater absorption, resulting in more translocation of the herbicide (Willis, 1978). Increasing RH increases cuticle hydration and stomatal opening, which eases the diffusion of water soluble herbicides into the leaf surface (Hull, 1970; Johnson and Young, 2002).

Plant morphological and physiological factors at different TOD also influence the efficacy of the herbicide applied (Hess and Falk, 1990). Factors such as leaf position, exposed leaf surface area, thickness of epicuticular wax, and plant metabolic rate may all affect plant absorption and translocation of herbicides (Doran and Andersen, 1976; Mohr *et al.*, 2007; Hess and Falk, 1990; Waltz *et al.*, 2004; Stewart *et al.*, 2009). The factors listed above can also vary largely depending on weed species (Hess and Falk 1990).

The previously mentioned TOD studies have evaluated effects on a range of herbicides, however the herbicides were evaluated when applied alone and not in tank-mixtures. Additional information is needed to determine TOD effects on herbicides when multiple active ingredients are used in a tank-mixture. Also, growers do not typically make one herbicide application per growing season. Multiple herbicide applications (i.e. programs) are part of all effective weed control strategies. More information is needed to determine how a peanut weed control program could be influenced by variations in TOD.

Project 4: Imazapic and Sicklepod

Imazapic. Imazapic, formerly known as AC 263,222, was registered for use in peanut in 1996 for the control of annual broadleaf weeds, nutsedge species, and annual/perennial grasses (Richburg *et al.*, 1994; Wilcut *et al.*, 1996; Burke *et al.*, 2004; Shaner, 2014). Imazapic is a member of the imidazolinone herbicide family and controls plants by inhibiting the formation of branched chain amino acids due to the inhibition of acetolactate synthase (ALS) enzyme. Imazapic is a systemic herbicide that is mobile in both the xylem and phloem, with the majority of translocation occurring in the phloem. Symptomology and resulting death occurs 1-2 weeks after application of imazapic, however cessation of growth typically occurs within several hours after the application of the herbicide. Peanut tolerance to imazapic is due to the ability of the crop to rapidly metabolize the herbicide. Susceptible weed species either do not metabolize the herbicide at all, or do so slowly enough that symptomology and death occurs (Shaner, 2014). A recent survey on the chemical use in six states (AL, FL, GA, NC, SC, and TX) reported that 47% of peanut acres received an application of imazapic, making imazapic the third most commonly used herbicide in U.S. peanut production systems (NASS, 2014). Imazapic is estimated to have been used on approximately 63% of peanut acres in Georgia in 2013 (NASS, 2014). One particularly troublesome weed in peanut that is controlled through the use of imazapic is sicklepod. Imazapic will provide approximately 90% control of sicklepod when applied at the correct rate and stage of growth (Grey *et al.*, 2003; Grey and Wehjte, 2005).

Sicklepod. Sicklepod is an annual, non-nodulating legume native to tropical America (Irwin and Barneby, 1982). Sicklepod is widely distributed throughout temperate and tropical regions (Holm *et al.,* 1979). In the U.S., sicklepod distribution continues to grow, with it spanning the entire southeastern peanut production area (Isley, 1990). A prolific seed producer, sicklepod seed coats are hard and can remain viable in the soil for upwards of 5 years (Creel *et al.*, 1968; Senseman and Oliver, 1993). Sicklepod germination can occur over a wide range of temperatures and depths. Germination temperatures range from 15 to 50 C, with and optimum temperature range of 15 to 30 C. Mean emergence depth is reported to be between 3.3 and 4.6 cm in a highly disturbed sand and sandy loam soil, respectively. A maximum emergence depth of 10 cm has also been reported in a sandy loam soil (Norsworthy and Oliveira, 2006). Sicklepod ranks in the top 5 most troublesome weeds in Georgia peanut (Webster, 2013).

Season long competition from sicklepod can reduce peanut yield by up to 70% (Buchanan *et al.* 1982).

A ten year, comprehensive study of peanut weed control conducted across the southeastern peanut production area has shown that imazapic is one of the most effective herbicides used for sicklepod control (> 90%) (Grey *et al.*, 2003). Recently, reduced control of sicklepod with imazapic has been reported by Georgia peanut growers. A heightened awareness of herbicide resistance has led growers to suspect that potential resistance to imazapic may be the cause of the perceived reductions in control. Results from preliminary tests of two sicklepod populations suggested that resistance to imazapic may have evolved (W.K. Vencill, The University of Georgia, pers. Commun., 2016). Additional research is needed to confirm imazapic resistance in sicklepod and the potential geographic distribution of resistance.

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CHAPTER 2

THE EFFECT OF PICLORAM + 2,4-D ON PEANUT GROWTH AND YIELD[1]

[1] Carter, Oliver. To be submitted to *Peanut Science.*

Abstract

Picloram + 2,4-D is used on approximately 20% of the pastures in Georgia. Picloram injury, in the form of leaf roll, is frequently observed in peanut fields due to short crop rotations, contaminated irrigation water, treated hay, and contaminated livestock urine/feces. Limited data on peanut response to picloram is available. In 2015, 2016, and 2017, small-plot field trials were conducted near Tifton GA to determine the effects of picloram + 2,4-D on peanut growth and yield. Picloram + 2,4-D was applied to 'GA-06G' peanut at four different timings: preemergence (PRE); 30 days after planting (DAP); 60 DAP; and 90 DAP. At each timing, three rates of picloram + 2,4-D were applied including the following: $1/10^{th}$X (0.18 + 0.67 kg ai/ha); $1/100^{th}$X (0.018 + 0.067 kg ai/ha); and $1/300^{th}$X (0.006 + 0.023 kg ai/ha). A non-treated control (NTC) or 0 rate was included for comparison. Peanut plant density was not affected by any rate or timing of picloram + 2,4-D. For peanut injury (leaf roll), a significant rate X timing interaction was observed. At 120 DAP, leaf roll was significant for the $1/10^{th}$X rate applied at 30, 60, and 90 DAP, the $1/100^{th}$X rate applied at 60 and 90 DAP, and for the $1/300^{th}$X rate applied at 90 DAP. When averaged over timing, peanut height at 120 DAP was significantly reduced by the $1/10^{th}$X and $1/100^{th}$X rates. When averaged over rate, peanut height reductions were greatest when picloram + 2,4-D was applied at 60 DAP. When averaged over timing, only the $1/10^{th}$X rate caused significant yield reductions (11%). When averaged over rate, timing had no effect on yield (P=0.5403). Peanut fields unintentionally exposed to picloram + 2,4-D rates ≥ $1/100^{th}$X can exhibit typical injury symptoms but should not experience yield losses.

Introduction

Picloram is an auxin-type herbicide that is a member of the pyridineocarboxylic acid family. Picloram controls plants by mimicking indoleacetic acid (IAA) in the new growth of the plant and inhibiting protein synthesis (Shaner, 2014). It was first introduced in 1963 for the control of broadleaf weed species and woody brush species (Hamaker *et al.*, 1963). Picloram is commonly mixed with 2,4-D to control broadleaf weeds because of the increased spectrum of weed control and the ability to lower use rates of the herbicides when used together (Agabakoba and Goodin, 1970). This mixture is currently formulated and sold as Grazon® P+D and is labeled for use in grasslands, permanent pastures, and non-crop land (Anonymous, 2018). While picloram and 2,4-D have relatively low mammalian toxicity, picloram is a restricted use pesticide because of its long persistence, high water solubility with potential to contaminate surface/groundwater, and its high phytotoxicity to broadleaf plants (Lym and Messersmith, 1988; Ketchersid *et al.*, 1994).

The soil half-life of picloram has been reported to be from 1 month to 4 years depending on soil and climate (Hunter and Strobe 1972; Shaner, 2014). However, phytotoxic levels of picloram residues can remain in the soil for up to five years depending on soil type and dose (Lym and Messersmith, 1988). The high water solubility that allows picloram to move readily through the soil profile contaminating groundwater and surface water can lead to a contamination of irrigation water (Lym and Messersmith 1988). The extreme sensitivity of broadleaf crops to picloram would allow for irrigation water to damage non-labeled crops. The combination of picloram+ 2,4-D is used on approximately 20% of all permanent pasture and grassland in Georgia (P. E. McCullough, The University of Georgia, personal communication 2017).

Peanut (*Arachis hypogaea* L.) is a self-pollinating, herbaceous legume, native to South America. Peanut is an extremely important agricultural crop for the southeastern United States and the state of Georgia. Georgia consistently contributes half of all peanut production in the US (NASS, 2018), with a value in 2015 of $684,000,000; which made up 31 percent of the total row and forage crop value for the state (Wolfe and Stubbs, 2016). In 2018, it is projected that peanut will be planted on ~291,498 hectares (NASS, 2018).

Georgia peanut growers have consistently, 5-10 times per year for ~20 years, reported injury due to picloram (E.P. Prostko, The University of Georgia, personal communication, 2018). Previous research has been conducted to determine picloram's potential effects on peanut. In Texas, picloram at 1 ppb caused visual injury, however no yield data was recorded (Ketchersid *et al.*, 1995). In Georgia, subsurface applied picloram at rates ranging from 0.56 to 1.12 kg ai/ha caused complete peanut death (Banks *et al.*, 1977). Consequently, research was conducted to determine the effect of several rates and timings of picloram + 2,4-D on peanut growth and yield.

Materials and Methods

Small plot field trials were conducted in 2015, 2016, and 2017 at the Ponder Research Farm near Ty Ty, Georgia (31.507654^{0}N, -83.658395^{0}W). The soil type was a Fuquay sand with 96% sand, 0% silt, 4% clay, 0.57% organic matter, and a pH of 6.6. Conventional tillage practices were used and 'GA-06G' (Branch, 2007) peanut was planted using a vacuum planter calibrated to deliver 18 peanut seed/m at a depth of 5 cm (Monosem Precision Planters, 1001 Blake St., Edwardsville, KS). Peanuts were planted in 2 twin rows (90 cm X 22 cm spacing) with a plot size of 7.6 m X 0.9 m.

Treatments were arranged in a randomized complete block design with a 4 (application timings) by 4 (picloram + 2,4-D rates) factorial arrangement of treatments. Application timings were preemergence (PRE), 30, 60, and 90 days after planting (DAP) and rates of picloram + 2,4-D were 0, 0.2 + 0.7, 0.02 + 0.07, and 0.006 + 0.02 kg ai/ha. It is important to note that previous research has shown that peanut exposure to 2,4-D at these lower rates does negatively impact peanut growth and yield (Johnson *et al.,* 2012; Leon *et al.*, 2014; Merchant *et al.,* 2014). The typical use of rate of picloram + 2,4-D in pastures/grassland is 1.8 + 6.7 kg ai/ha. Treatment rates were based on 1/10th, 1/100th, and 1/300th of the labeled use rate. Treatments were replicated 3 or 4 times depending on field size for each year. Treatments were applied using a CO_2 pressurized backpack sprayer calibrated to deliver 140 L/ha at 4.8 km/hr. Peanut plant height, width, and stage of growth at the time of application are presented in Table 1. Plots were maintained weed-free throughout the season using a combination of herbicides (pendimethalin, diclosulam, flumioxazin, imazapic, and 2,4-DB) and hand-weeding. Peanut yield data were obtained by mechanical harvesting at maturity.

Data collected included plant density (14 and 30 DAP), visual injury (leaf roll) approximately every 14 days throughout season, plant height (120 DAP), and yield. Leaf roll ratings were based on a subjective visual scale of 1-4; with 1 = none and 4 = severe. Leaf roll symptoms were considered severe when greater than 75% of peanut leaves exhibited symptomology. All data were analyzed using the PROC GLM procedure in SAS (SAS, 2017). Data was combined over years and was pooled over rate and timing when no significant interaction was present. Means were separated using Tukey's HSD (P=0.10).

Results and Discussion

Peanut Density: Peanut density was recorded 14 DAP by counting peanut plants/ 1 m of row. Rate did not affect peanut plants/m at the PRE application timing (data not reported and P

> 0.5467). Previously it was reported that peanut plant density was not negatively affected by 2,4-D applications PRE of up to 1066 g ai/ha (Blanchett *et al.*, 2017).

Peanut Injury (Leaf Roll): Data presented in Table 2 present leaf roll ratings taken 14 days after each treatment was applied for each application timing. At 14 days after application, each treatment exhibited significantly more leaf roll than the NTC. Data are also presented from leaf roll ratings at 120 DAP, to show the peanut plant's ability to recover throughout the season. Data were unable to be pooled over rate and timing due to a significant interaction. Thus, data are presented by rate for each application timing (Table 3). At the PRE application timing, rate had no effect on peanut leaf roll and injury was minor. At the 30 DAP timing, only the 1/10th labeled rate cause significant leaf roll. At the 60 DAP timing, both the 1/10th and 1/100th rates caused significant leaf roll rate. At the 90 DAP timing, all three rates of picloram + 2,4-D caused significantly more leaf roll injury when compared to the non-treated control (0 kg/ha rate). In earlier research, picloram at rates as low as 1 ppb caused visual injury (leaf roll) symptoms (Ketchersid *et al.*, 1995). Visual injury, such as leaf cupping and epinasty, from other auxin herbicides has been observed on peanut from dicamba at rates as low as 35 g ai/ha (Leon *et al.*, 2014). Generally, dicamba was more injurious than 2,4-D on peanut. Only 2,4-D rates >560 g ai/ha caused significant peanut injury (Leon *et al.*, 2014).

Peanut Height and Yield: There was no interaction between rate and timing, therefore data were pooled over the 2 factors and 3 years (Tables 4 & 5). At 120 DAP, the 1/10th rate and the 1/100th reduced plant height by 9 and 4%, respectively. When data were pooled over timing, only the 60 DAP timing had a negative effect on plant height. This timing effect is likely due to the peanut stage of growth at the time of application. The approximate growth stages of the peanut crop were V6 (last vegetative stage), R5 (beginning seed), and R6 (full seed) at 30, 60, and 90 DAP timings, respectively (Boote, 1982). Increased injury from herbicide applications at the R5 growth stage have been reported with applications of dicamba and lactofen (Prostko *et al.*, 2011; Dotray *et al.*, 2012).

For peanut yield there was no significant interaction between rate and timing. When averaged over timing, the 1/10th rate (0.18 + 0.67 kg ai/ha) caused significant yield reductions. Yield loss with the 1/10th X rate was 11%. Previous research indicated that peanuts exposed to picloram at 0.56 to 1.12 kg ai/ha caused complete peanut death, thus no yield data was recorded (Banks, 1977). Yield losses up to 29% have been reported from dicamba at rates as low as 40 g ai/ha (0.14X of normal use rate) (Prostko *et al.*, 2011). When averaged over rates, timing had no effect on yield. While the 60 DAP timing significantly reduced peanut plant height, it did not negatively impact yield.

Summary and Conclusions

Significant peanut yield loss was only observed for the highest rate of picloram + 2,4-D (1/10th X rate). While peanuts appeared to be more sensitive to the 60 DAP timing, timing did not have an influence on yield. Peanut growers need to be aware of the fact that picloram is a persistent herbicide and injury can occur long after the initial application. Also, while injury symptoms may appear severe, injury does not always result in yield losses. If picloram injury occurs, peanut growers should continue to manage their peanut crop as planned with the goal of minimizing potential yield losses.

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Table 2.1. Peanut stage of growth[a] at the time of picloram + 2,4-D applications in Georgia, 2015-2017.

	Time of Application			
	PRE	**30 DAP[b]**	**60 DAP**	**90 DAP**
Height	---	8 cm	28 cm	43 cm
Width	---	15 cm	43 cm	60 cm
Growth Stage	---	R5	R5	R6

[a]Peanut stages of growth as defined by Boote 1982.
[b]PRE = preemergence at planting.
[c]DAP= days after planting.

Table 2.2. Peanut visual injury ratings at 14 DAT[ab] from picloram + 2,4-D in Georgia, 2015-2017[c].

	Time of Application			
Picloram + 2,4-D rate[d]	**PRE[e]**	**30 DAP[f]**	**60 DAP**	**90 DAP**
NTC	1.0d[g]	1.0d	1.0d	1.0c
1/300th	1.6c	1.2c	2.0c	1.6ab
1/100th	2.1b	2.5b	2.7b	1.7ab
1/10th	3.9a	3.7a	3.3a	2.0a

[a]DAT= days after treatment
[b]Ratings are based on a visual scale of 1-4; with 1= no leaf roll and 4 = all peanut leaves exhibiting leaf roll.
[c]Data pooled over 3 site-years.
[d]Picloram + 2,4-D rates as follows (kg ai/ha): 1/300th = 0.006 + 0.02; 1/100th = 0.02 + 0.07; 1/10th = 0.2 + 0.7.
[e]PRE= preemergence.
[f]DAP= days after planting.
[g]Means in the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10).

Table 2.3. Peanut visual injury ratings at 120 DAP[ab] from picloram + 2,4-D in Georgia, 2015-2017[c].

	Time of Application			
Picloram + 2,4-D rate[d]	**PRE[e]**	**30 DAP**	**60 DAP**	**90 DAP**
NTC	1.0a[f]	1.0a	1.0a	1.0a
1/300th	1.1a	1.1a	1.3a	1.5b
1/100th	1.1a	1.1a	2.6b	1.6bc
1/10th	1.1a	2.0b	3.5c	2.0c

[a]DAP= days after planting
[b]Ratings are based on a visual scale of 1-4; with 1= no leaf roll and 4 = all peanut leaves exhibiting leaf roll.
[c]Data pooled over 3 site-years.
[d]Picloram + 2,4-D rates as follows (kg ai/ha): 1/300th = 0.006 + 0.02; 1/100th = 0.02 + 0.07; 1/10th = 0.2 + 0.7.
[e]PRE= preemergence after planting.
[f]Means in the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10).

Table 2.4. Peanut plant height at 120 DAP[a] and yield response to picloram + 2,4-D rate in Georgia, 2015-2017[b].

Picloram + 2,4-D rate[c]	**Height**	**Yield**
	- cm -	- kg/ha -
NTC	40.4a[d]	5630a
1/300th	39.4ab	5520a
1/100th	38.9b	5335a
1/10th	37.3c	4996b

[a]DAP = days after planting
[b]No interaction was observed for application time X rate, therefore date are pooled over 4 timings and 3 site-years.
[c]Picloram + 2,4-D rates as follows (kg ai/ha): 1/300th = 0.006 + 0.02; 1/100th = 0.02 + 0.07; 1/10th = 0.2 + 0.7.
[d]Means in the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10).

Table 2.5. Peanut plant height at 120 DAP[a] and yield response to picloram + 2,4-D time of application in Georgia 2015-2017[b].

Time of Application	**Height**	**Yield**
	-cm-	-kg/ha-
PRE[c]	40.1a[d]	5398a
30 DAP	39.9a	5464a
60 DAP	37.3b	5196a
90 DAP	38.9a	5426a

[a]DAP= days after planting
[b]No interaction was observed for application time X rate, therefore date are pooled over 4 rates and 3 site-years.
[c]PRE = preemergence after peanut planting.
[d]Means in the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10).

CHAPTER 3

PEANUT RESPONSE TO TERBACIL[2]

[2] Carter, Oliver. To be submitted to *Peanut Science.*

Abstract

Current label restrictions prohibit the planting of peanut for 2 years after an application of terbacil in watermelons. Thus, research was conducted in 2016 and 2017 to determine peanut response to terbacil with the ultimate goal of reducing the current rotation restriction. Small-plot replicated field trials were conducted during 2016 and 2017 in Ty Ty, Georgia. Terbacil was applied preemergence (PRE) to 'Georgia 06G' peanut at: 0.03, 0.06, 0.12 and 0.22 kg ai/ha. Terbacil use rates in watermelon range from 0.12 kg ai/ha to 0.22 kg ai/ha. A non-treated control (NTC) or 0 rate was included for comparison. The only rate of terbacil that caused a significant reduction in peanut plant density was 0.22 kg ai/ha. Peanut density at this rate was reduced by 60%, when compared to the NTC. At 28 DAP the 0.06, 0.12, and 0.22, kg ai/ha rates caused significantly more visual injury than the NTC. However, at the final injury rating 100 DAP, only the 0.12 and 0.22 kg ai/ha rates continued to cause crop injury. The last visual injury rating reflects the peanut plant's ability to recover from early-season terbacil injury. Peanut yields were reduced 37 and 79% by terbacil at 0.12 and 0.22 kg ai/ha, respectively. Consequently, these results suggest that peanut could be planted following terbacil after approximately two field half-lives have occurred.

Introduction

Watermelon is an important high-value crop in Georgia. Georgia consistently ranks in the top 4 producing states and accounts for 13% of the total U.S. watermelon production (NASS, 2017). In 2017, the production value of watermelons in Georgia exceeded $74,000,000 (NASS, 2017). Weed control is critical for producing a high yielding, quality, and profitable watermelon crop. Weeds can be a serious problem in watermelon because of initial slow plant growth, low plant populations, and limited ability for cultivation once plants are established (Elmstrom, 1973; Larson *et al.*, 2004). Crop rotation, tillage, and a sound herbicide program are all critical components for long-term weed control success in watermelon (Culpepper and Vance, 2018). An herbicide with long residual activity to control emerging weeds for the entire watermelon growing season is necessary (Elmstrom, 1973). Several University of Georgia recommended watermelon weed control programs include terbacil for control of broadleaf weeds and it is currently being utilized on 70-75% of watermelon hectares (Culpepper, Personal Communication 2017, Culpepper and Vance 2018). Terbacil is registered for use in watermelon, caneberries, mint, peach and several other specialty crops and is sold under the trade name of Sinbar® (Anonymous, 2018).

Terbacil is a photosystem II inhibiting herbicide that is a member of the substituted uracil family. It is absorbed by the crop roots and transported to its site of action in the mesophyll chloroplasts via the xylem, however it can also penetrate foliar tissue to reach the site of action (Barrentine and Warren, 1970; Ashton and Monaco, 1991). Its soil residual activity provides control of germinating weeds and germinated weed seedlings (Hu *et al.*, 2017). The average field half-life for terbacil is 120 days (Shaner, 2014). However, a half-life of up to 6 months was reported in a Butlertown silt loam (Gardiner *et al.*, 1969). Another study noted that 5-7 months was needed for the amount of soil surface terbacil to be reduced by 50% (Marriage *et al.*, 1977). Visual injury symptomology was observed on soybean six months following an application of 1 kg ai/ha (Rahman, 1977). Soil organic matter and clay content greatly influence persistence of terbacil in the soil (Rahman, 1977).

Maximizing yields is essential for crop production. One tool that growers use to maximize yield is crop rotation (Higgs *et al.* 1990). Georgia peanut growers commonly use crop rotation as a method to help successfully manage weeds, insects, and disease pressure (Higgs *et al.*, 1990; Vencill *et al.*, 2012). Rotating crops can be a difficult task with the variability in crop tolerances to the numerous herbicides that could potentially be used in agronomic and vegetable crop rotations. Currently, the terbacil herbicide label restricts the planting of peanut, along with all other row crops, for 2 years following the last application of terbacil (Anonymous, 2018). The ability to plant peanut 12 months or earlier after a terbacil application would greatly increase the options that a Georgia watermelon grower has for rotational crops. Research was conducted to determine peanut response to terbacil with the ultimate goal of reducing this two year rotational restriction.

Materials and Methods

Small-plot replicated field trials were conducted at the Ponder Research Farm in Ty Ty, Georgia in 2016 and 2017 (31.507654^{0}N, -83.658395^{0}W) to determine the effects of direct terbacil applications to peanut. The soil type was a Fuquay sand with 96% sand, 0% silt, 4% clay, 0.57% organic matter, and a pH of 6.6. Conventional tillage practices were used and 'GA-06G' (Branch 2007) peanut was planted using a vacuum planter calibrated to deliver 18 peanut seed m^{-1} at a depth of 5 cm. (Monosem Precision Planters, 1001 Blake St., Edwardsville, KS). Peanuts were planted in 2 twin rows (90 cm X 22 cm spacing) with a plot size of 7.6 m X 0.9 m.

Treatments were arranged in a randomized complete block design and replicated four times. Terbacil was applied preemergence immediately after peanut planting at the following rates: 0.03, 0.06, 0.12 and 0.22 kg ai/ha. Immediately following application, the plot area received 1.25 cm of overhead irrigation for soil incorporation. Additional rainfall in the first 14 DAP was 8 cm in 2016 and 10 cm in 2017. Terbacil use rates in watermelon range from 0.12 kg ai/ha to 0.22 kg ai/ha, with a maximum use rate per year of 0.22 kg ai/ha (Anonymous, 2018). Treatments were applied using a CO_2 – pressurized backpack sprayer calibrated to deliver 140 L/ha at 4.8 km/hr. Plots were maintained weed-free throughout the season using a combination of herbicides (pendimethalin, diclosulam, flumioxazin, imazapic, and 2,4-DB) and hand-weeding.

Data collected included peanut density at approximately 30 DAP, visual estimates of crop injury, and peanut yield. Peanut density was obtained by counting the number of emerged plants per 1 row meter. Visual estimates of crop injury were obtained 14, 28, 50, and 100 DAP, using a subjective scale of 0 to 100 (0= no injury; 100= plant death). Peanut yield data was obtained using commercial harvesting equipment. All data were subjected to analysis of variance using the mixed procedure in SAS (SAS 2017). Means were separated using Tukey's HSD (P=0.10).

Results and Discussion

Visual Injury: Visual injury ratings were collected 14, 28, 50, and 100 DAP (Table 1). At 14 DAP, all rates of terbacil caused visual injury symptoms. Typical terbacil injury symptoms include stunting, veinal chlorosis, and eventual necrosis of the leaf (Figure 1). At 28 DAP the 0.06, 0.12, and 0.22, kg ai/ha rates caused significantly more visual injury than the non-treated check. Visual injury at these rates was anticipated based on previous soybean research

(Rahman 1977). At the 50 DAP observation, the same three treatments continued to cause significantly more visual injury than the non-treated check. However, at the final injury rating 100 DAP, only the 0.12 and 0.22 kg ai/ha rates caused visual damage greater than the control. The last visual injury rating reflects the peanut plant's ability to recover from early-season terbacil injury.

Peanut Density and Yield: The only rate of terbacil that caused a significant reduction in peanut density was 0.22 kg ai/ha (Table 2). Peanut density at this rate was reduced by 60%, when compared to the non-treated check. Peanut yields were significantly reduced by terbacil at 0.12 and 0.22 kg ai/ha. Yield losses at these rates were 37% and 79% respectively. Soybean yield has been reported to be reduced 81% from applications of 0.5 kg ai/ha of terbacil on a sandy loam soil (Rahman *et al.* 1976). Thus, yield losses were only observed from the typical range of field use rates in watermelon.

Summary and Conclusions

All rates of terbacil caused visual peanut injury. However, only the 2 highest rates (0.12 and 0.22 kg ai/ha) resulted in significant peanut yield losses. Consequently, these data suggest that peanut could be planted following terbacil after approximately 2 field half-lives. With additional research on other soil types, the labeled peanut crop rotation restriction could be reduced. Typically watermelon is planted earlier in the spring (March to Mid-April) than peanut (Late-April to Early-June) and this would allow for the planting of peanut the following growing season approximately 365 days after an application of terbacil. If labeled rotation restrictions could be reduced, Georgia growers would be able to increase their potential crop rotation options.

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Figure 3.1. Injury from 0.22 kg ai/ha of terbacil on peanut

Table 3.1. Peanut injury caused by preemergence applications of terbacil in Georgia, 2016-2017[a].

Terbacil Rate	Time after application (DAP[b])			
	14	28	50	100
-kg ai/ha-	--%--			
NTC[c]	0d[d]	0d	0d	0c
0.03	9c	9d	5dc	4c
0.06	13c	24c	14c	7c
0.11	45b	51b	45b	27b
0.22	86a	86a	86a	83a

[a]Ratings are visual estimates of injury based on percent of non-treated control (0 = no crop injury, 100 = complete crop death) and are averaged over 2 site-years.
[b]DAP= days after planting.
[c]NTC= non-treated control (0 rate).
[d]Means of the same letter in the same column with the same letter are not significantly different according to Tukey’s HSD (p=0.10).

Table 3.2. Peanut density and yield in response to preemergence applications of terbacil in Georgia, 2016-2017.

Terbacil Rate	**Density[a]**	**Yield**
-g ai/ha-	-plants/row m-	-kg/ha-
NTC[b]	15ab[c]	5239a
0.03	15ab	5348a
0.06	16a	5095a
0.12	13b	3373b
0.22	6c	1110c

[a]Peanut density data collected 14 days after planting .
[b]NTC= non-treated control (0 rate).
[c]Means in the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10). All data averaged over 2 site-years.

CHAPTER 4

TIME OF DAY EFFECTS ON PEANUT HERBICIDE PROGRAMS[3]

[3] Carter, Oliver. To be submitted to *Peanut Science.*

Abstract

Recent research on the effects of time of day (TOD) on glufosinate in cotton and several PPO-inhibiting herbicides in soybean has growers concerned about potential TOD effects on peanut weed control programs. Consequently, research was conducted in 2015, 2016, and 2017 to determine if TOD influences the performance of peanut weed control programs. Both a non-crop (bare-ground) study and in-crop (peanut) study were conducted. In the non-crop study, paraquat (0.21 kg ai/ha) plus bentazon (0.37 kg ai/ha) plus acifluorfen (0.19 kg ai/ha) plus *S*-metolachlor (1.23 kg ai/ha); imazapic (0.07 kg ai/ha) plus *S*-metolachlor (1.23 kg ai/ha) plus 2,4-DB (0.25 kg ai/ha); or lactofen (0.22 kg ai/ha) plus *S*-metolachlor (1.23 kg ai/ha) plus 2,4-DB (0.25 kg ai/ha) were applied to Palmer amaranth and a mixture of annual grasses at 7:00 h, 12:00 h, 17:00 h, and 22:00 h. For the in-crop studies, two recommended peanut weed control programs were chosen and the entire herbicide program was applied at the same TOD. The herbicide programs consisted of the following treatments: paraquat (0.21 kg ai/ha) + acifluorfen (0.19 kg ai/ha) + bentazon (0.37 kg ai/ha) + *s*-metolachlor (1.23 kg ai/ha) (EPOST) followed by either imazapic (0.07 kg ai/ha) + *s*-metolachlor (1.23 kg ai/ha) + 2,4-DB (0.25 kg ai/ha) or lactofen (0.22 kg ai/ha) + *s*-metolachlor (1.23 kg ai/ha) + 2,4-DB (0.25 kg ai/ha) (POST). For the non-crop studies, a significant interaction between TOD and herbicide program was observed for the 7 DAT rating of Palmer amaranth control. Control was reduced with the imazapic treatment applied at 22:00 h. At 14 DAT, there was no TOD effect and control was reduced with all imazapic treatments due to ALS resistance. There was no interaction between TOD and herbicide program for annual grass control. Annual grass control was unacceptable (< 50%) for the lactofen treatment. For the in-crop studies, there was no interaction between TOD or herbicide program, for peanut injury. Peanut injury was significantly lower at 7:00 h and 22:00 h

when compared to the other timings. Generally, lactofen was more injurious to peanut than imazapic. Palmer amaranth control was not influenced by TOD or program. When averaged over programs, annual grass control was significantly lower at the 7:00 h application timing when compared to the other timings. When averaged over TOD, annual grass control was also significantly reduced with the lactofen program. A significant reduction in sicklepod control was observed at 22:00 h and with the lactofen program. While TOD influenced peanut injury and weed control, peanut yield was not affected.

Introduction

Changes in farming practices and technology have led to the application of pesticides over a broader time period in a given day (Mohr *et al.*, 2007). In recent years, average farm size in the U.S. has continued to increase while number of farms has decreased (Hoppe and Macdonald, 2015). Due to this increase in farm size, growers must manage more land area in a given time period in order to be timely with pesticide applications. Managing more land area results in work days beginning earlier in the morning and extending later in the evening. The desire to control herbicide drift may also lead to applications early in the morning or late in the evening, when wind speed is generally lower. The addition of global positioning technology (GPS) to most modern application equipment has allowed for the accurate application of pesticides under all light conditions (Tillet, 1991; Klassen *et al.*, 1993; Mohr *et al.*, 2007). The increased occurrence of these practices is validating the well-researched fact that the efficacy of many herbicides is directly related to sunlight (Stewart *et al.*, 2009; Stopps *et al.*, 2013; Montgomery *et al.*, 2017).

Reduced weed control due to variable application timing has previously been reported for several herbicides including; bentazon, acifluorfen, fomesafen, glufosinate, and glyphosate (Doran and Andersen, 1976; Lee and Oliver, 1982; Martinson *et al.*, 2002; Miller *et al.*, 2003; Mohr *et al.*, 2007). While there have been reported reductions in herbicide efficacy due to herbicide applications at varying times during the day, weed control is still largely species dependent. Species specific TOD effects for atrazine, bromoxynil, dicamba, glufosinate, glyphosate, and nicosulfuron were observed when applied to barnyardgrass (*Echinochloa crus-galli* L), common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), redroot pigweed (*Amaranthus retroflexus* L.) and velvetleaf (*Abutilon* *theophrasti* L.) (Stewart *et al.,* 2009). Acifluorfen applied at night (21:00 h) resulted in better control of hemp sesbania (*Sesbania herbacea* Mill.), pitted morningglory (*Ipomoea lacunose* L.*)* and smooth pigweed (*Amaranthus hybridus* L.*),* while no TOD effect was observed for several other species (Lee and Oliver, 1982). Bentazon was less efficacious when applied before daybreak in the morning (6:00 h) and after sunset in the evening (21:00 h) (Doran and Andersen, 1976). However, another study reported no statistical difference in bentazon efficacy when applied at various times to common ragweed, common lambsquarters, pigweed, and velvetleaf (Stopps *et al.,* 2013).

Environmental and plant physiological factors can contribute to the varying degrees of control observed when herbicides are applied at different times of day. Environmental factors such as dew, temperature, and relative humidity (RH) can all influence herbicide performance. Typically dew can be present on leaf surfaces in early morning (6:00 h) and late evening (19:00 to 24:00 h). It is hypothesized that the dew can intercept herbicide spray droplets potentially diluting the herbicide and increasing herbicide run-off from the leaf surface (Fausey and Renner, 2001; Kogan and Zuniga, 2001; Stewart *et al.,* 2009). Other research suggests that dew could potentially increase herbicide absorption, thus increasing efficacy (Nalewaja *et al.,* 1975; Caseley, 1989). Increased air temperature and RH have also been shown to increase herbicide efficacy (Sharma and Singh, 2001). Lower air temperatures (< 25 C) have reduced control regardless of the TOD when the herbicide was applied (Friesen and Wall, 1991). Daytime air temperatures > 25 C increased control of pitted morningglory, common cocklebur, and velvetleaf when compared to temperatures < 25 C (Doran and Andersen, 1976; Lee and Oliver, 1982). Increases in RH have also been reported to increase herbicide efficacy over a range of herbicides and species, due to increased absorption and translocation of the herbicide (Willis, 1978; Willis and McWhorter, 1981; Johnson and Young, 2001).

Plant morphological and physiological factors at different TOD also influence the efficacy of the herbicide applied (Hess and Falk, 1990). Factors such as leaf orientation, exposed leaf surface area, thickness of epicuticular wax, and plant metabolic rate may all affect plant absorption and translocation of herbicides (Doran and Andersen, 1976; Hess and Falk, 1990; Waltz *et al.,* 2004; Mohr *et al.,* 2007; Stewart *et al.,* 2009). These factors can also vary largely depending on weed species (Hess and Falk, 1990).

Additional information is needed to determine TOD effects on herbicides when multiple active ingredients are used in a tank-mixture. Most previous studies on TOD effects only evaluated treatments consisting of a single mode of action. Also, growers do not typically make one herbicide application per growing season. Multiple applications (i.e. programs) are made in order to have an effective season-long weed control program. Research was conducted to determine the effects of TOD on the performance of peanut weed control programs.

Materials and Methods

Non-crop study (bare-ground). A non-crop study was conducted during 2015 and 2017 at the Ponder Research Farm located near Ty Ty, Georgia (31.507654^{0}N, -83.658395^{0}W) on a Tifton loamy sand soil with 93% sand 3% silt, 4 % clay, 1% organic matter, and pH of 6.0. The trial was arranged in a randomized complete block design with a 3 by 4 factorial arrangement of treatments. Three herbicide treatments were applied at four different times during the day. The herbicide treatments were as follows: paraquat (0.21 kg ai/ha) plus bentazon (0.37 kg ai/ha) plus acifluorfen (0.19 kg ai/ha) plus *S*-metolachlor (1.23 kg ai/ha); imazapic (0.07 kg ai/ha) plus *S*-

metolachlor (1.23 kg ai/ha) plus 2,4-DB (0.25 kg ai/ha); and lactofen (0.22 kg ai/ha) plus *S*-metolachlor (1.23 kg ai/ha) plus 2,4-DB (0.25 kg ai/ha); a non-treated control (NTC) was included for comparison. Times of application were as follows: 7:00 h, 12:00 h, 17:00 h, and 22:00 h. Temperature, relative humidity (RH), and weed height for each application are presented in Table 1.

Plot size was 7.6 m by 0.9 m. Each treatment was replicated 3 or 4 times depending upon field size. Palmer amaranth and a non-uniform mixture of annual grasses including, Texas millet (*Brachiaria texana,* Buckley), crowfootgrass (*Dactyloctenium aegyptium,* L. Wild), goosegrass (*Eleusine indica*, L. Gaertn.), and crabgrass (*Digitaria* spp.) were present in the non-treated check plots at densities of 50 – 100 plants/m^2 and 20 – 40 plants/m^2, respectively. The treatments were applied when weeds were 5 to 8 cm tall using a CO_2-pressurized backpack sprayer calibrated to deliver 141 L/ha at 262 kPa and 4.83 km/ha. An 11002DG flat fan nozzle was used for all applications (TeeJet, Springfield, IL 62701). Visual estimates of percent weed control were obtained at 7 and 14 days after treatment (DAT) using a scale of 0% = no control; 100% = complete control or plant death. Plant stunting, chlorosis, and necrosis were considered when making the visual estimates.

In-Crop study. An in-crop trial was also conducted at the Ponder Research Farm and the Attapulgus Research and Education Center (30.763629^{0}N, -84.479938^{0}W) on a Faceville loamy sand with 84% sand, 10% clay, 6% silt, 1.6% organic matter, and pH of 6.0 during 2015, 2016, and only at the Ponder Research Farm in 2017 (5 site-years). Weed control ratings are based on 4 site-years. Conventional tillage practices were used and ‘Georgia-06G’ (Branch, 2007) peanut was planted at both locations. A vacuum planter (Monosem Precision Planters, 1001 Blake St., Edwardsville, KS 66111) was calibrated to deliver 18 peanut seed/m at a depth of 5 cm. Peanut was planted in 2 twin rows (90 cm by 22 cm spacing) at Ponder and 2 single rows (90 cm spacing) in Attapulgus. Plot size was 7.6 m by 0.9 m.

The trial was arranged in a randomized complete block design with a 2 by 4 factorial design (2 herbicide programs and 4 TOD) with 4 replications. The herbicide programs used are presented in Table 2. Each herbicide program was applied at each TOD throughout the entire season (7:00 h, 12:00 h, 17:00 h, and 22:00 h). Temperature, RH, and weed size at each treatment are presented in Table 3.   Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 141 L/ ha at 262 kPa and 4.83 km/h. Visual estimates of peanut crop injury were obtained 7 to 14 and 50 days after the EPOST and POST treatments. Visual estimates of crop injury consisted of a combination of leaf burn and stunting (0%= no crop injury; 100%= no crop present). Visual estimates of weed control were collected 7 and 14 days after the EPOST treatment. Visual estimates of weed control were also collected 7 to 14 and 50 days after the POST treatment. Various weed species were rated including Palmer amaranth, sicklepod, and a non-uniform mixture of annual grasses including, Texas millet, crowfootgrass, goosegrass, and crabgrass. Peanuts were inverted, allowed to air dry, and harvested 4 days later using commercial equipment. Peanut yields were adjusted to 10% moisture.

University of Georgia Extension peanut production recommendations were used and supplemental irrigation was applied to maximize peanut growth and development (Anonymous 2017). Soil types, planting date, peanut stages of growth at application, weed heights, and harvest dates are presented in Table 4.

Data for all parameters in both the non-crop and in-crop studies were analyzed as factorial plot designs and subjected to ANOVA using the PROC MIXED procedure in SAS (SAS Institute 107 Inc., Cary, NC 27511). TOD and herbicide treatment/program were considered fixed effects and locations and replications (nested within year) were considered random effects. Least square means of significant main effects were separated using Tukey's HSD test (p=0.10).

Results and Discussion

Non-crop study. For the non-crop study there was a significant interaction between TOD and herbicide treatment for the 7 DAT rating for Palmer amaranth control. Thus, data for this rating date are presented by treatment for each TOD (Table 5) Palmer amaranth control was lower when imazapic + s-metolachlor + 2,4-DB were applied at 22:00 h, when compared to applications made during daylight hours. Generally, Palmer amaranth control was unacceptable (<70%) with imazapic because the population at this location is known to be ALS-resistant. At 14 DAT, there was no interaction between treatment and TOD. Palmer amaranth control was reduced with the combination of imazapic + s-metolachlor + 2,4-DB (Table 6) and no TOD effects were observed (Table 7).

There was no significant interaction between TOD and treatment for the 7 and 14 DAT rating timing for annual grass control. At 7 DAT, annual grass control was reduced with the imazapic + S-metolachlor + 2,4-DB and lactofen + s-metolachlor + 2,4DB treatments. At 14 DAT, only the lactofen + S-metolachlor + 2,4-DB treatment provided unacceptable control of annual grasses (< 35%) (Table 8). Lactofen is a broadleaf herbicide and has little efficacy on grass weed species (Minton *et al.*, 1989; Grichar, 1991). TOD had no effect on annual grass control (Table 9). This is contrary to previous research where a TOD effect was observed for barnyardgrass control with nicosulfuron (Stewart *et al.*, 2009).

Crop Injury. Peanut crop injury was evaluated 1 week after the EPOST and POST applications. Significant differences in injury were observed at both times. Generally, herbicide programs were less injurious when applied at 7:00 h and 22:00 h (Tables 10 and 11). When averaged over TOD, the lactofen program was more injurious than the imazapic program (Table 11). Peanut injury from lactofen has been observed in other research ranging from 20 to 48%, with no observed yield losses (Ferrell *et al.*, 2013; Boyer *et al.*, 2011). However, yield losses of 5**%** were observed from applications of lactofen applied approximately 60 days after planting (Dotray *et al.*, 2012).

Palmer amaranth. Palmer amaranth was completely controlled by a combination of the PRE and EPOST herbicide applications both 1 and 2 weeks after the EPOST application was made (data not reported). For Palmer amaranth control after the POST herbicide applications, there was no significant interaction for any rating. There were also no significant differences between programs or TOD (Tables 11 and 12). Reduced control of Palmer amaranth when applying 2,4-D, imazethapyr, dicamba, glufosinate, and bentazon late in the evening or at night, has been observed in other research (Doran and Andersen, 1976; Stopps *et al.*, 2013; Montgomery *et al.*, 2017; Johnston *et al.*, 2017). However, these studies differ from ours in that a single herbicide was used, not a tank-mixture with multiple active ingredients. TOD does not appear to influence Palmer amaranth control when a complete peanut herbicide program is used consisting of multiple active ingredients at a single application timing.

Annual grass. After the EPOST applications, annual grass control at 7 to 14 DAT was significantly lower at 7:00 h. (Table 10). Paraquat has been reported to be more efficacious when applied at night or later in the evening for weed control due to minor intercellular translocation occurring (Brian, 1967; Putnam and Ries, 1968; Montgomery *et al.*, 2017). It has been reported that annual grasses are not as sensitive as broadleaf weeds to a TOD effect with herbicides (Stewart *et al.*, 2009). One possible explanation for the reduction in control observed at 7:00 h is that dew was present on the weeds and on the crop. Dew presence has been reported to both increase or decrease herbicide efficacy depending on the herbicide and weed species involved (Nalewaja *et al.,* 1975; Caseley, 1989; Wanamarta and Penner, 1989; Fausey and Renner, 2001). There was no significant TOD X herbicide program interaction for grass control after the POST applications, thus data is averaged over TOD and program. At 1 week after the POST application there was no difference in herbicide program for annual grass control (Table 11). However, at the end of season rating (50 DAT) there was a significant difference in control. Annual grass control with the lactofen program was significantly lower than the imazapic program. Although primarily used for nutsedge (*Cyperus* spp.) and broadleaf weed control in peanut, imazapic provides various levels of annual grass control depending upon the species and stage of growth (Monks *et al.,* 1996; Wilcut *et al.,* 1999; Jordan *et al.*, 2009). Also, lactofen is not a grass herbicide (Minton *et al.,* 1989; Grichar, 1991).

At 7 to 14 days after the POST application, reduced control of annual grass was observed at 7:00 h and 22:00 h (Table 12). However, at the end of season control rating, there was no significant difference in TOD for annual grass control. As previously mentioned grass species are less sensitive to TOD effects when compared to broadleaf weed species (Stewart *et al.,* 2009). Additionally, the dense canopy and spreading growth habit of the peanut crop likely resulted in the peanut plants out-competing the few grasses that were present at the earlier application timing (Leon *et al.*, 2016).

Sicklepod. There was a significant TOD of day effect for control of sicklepod at 7 to 14 days after the EPOST application with less control, observed at 22:00 h (Table 10). The diurnal leaf movement of sicklepod has been reported to reduce herbicide interception and control (Norsworthy *et al.* 1999). There was no interaction between herbicide program and TOD for the visual control ratings of sicklepod after the POST application was made, data presented are pooled over herbicide treatment and TOD. Significant differences for sicklepod control were observed for both program and TOD at 7 to 14 and 50 days following the POST application. The application made at 22:00 h resulted in significant reductions in sicklepod control when compared to all other application timings. The imazapic program was more effective than the lactofen program for the control of sicklepod (Table 11). Sicklepod control with imazapic has been well documented (Grey *et al.*, 2003; Grey and Wehjte, 2005).

Peanut Yield. There was no interaction between TOD and herbicide program for peanut yield, data are pooled over TOD, herbicide program, and site-year. Herbicide program had a significant effect on peanut yield. The imazapic program resulted in higher yields than the lactofen program. The reduction in yield observed between the two programs is potentially due to the reduction in annual grass and sicklepod control that was observed between the two treatments. Control of annual grass species for 8 to10 weeks after peanut emergence has been shown to be critical in maintaining a high yielding peanut crop (Everman *et al.*, 2008; Grichar, 1991; Johnson and Mullinix, 2006). Peanut injury from lactofen has been observed in other research ranging from 20 to 48%, with no observed yield losses (Ferrell *et al.* 2013; Boyer *et al.* 2011). But other research has reported a yield loss of 5% from lactofen treatments occurring after 60 DAP (Dotray et al. 2012). TOD of did not affect peanut yield. While reductions in sicklepod control were observed from applications made at 22:00 h those reductions did not result in yield loss.

In summary, TOD influenced peanut injury and weed control, but did not affect peanut yield. Peanut growers who choose to spray early in the morning or late in the evening should be aware of the possibility of reduced control of certain weed species, especially sicklepod, that exhibit diurnal leaf movements. The diurnal leaf movements of sicklepod and several other weed species can greatly reduce herbicide interception (Norsworthy *et al.* 1999). The use of a complete herbicide program, i.e. multiple active ingredients in a tank-mix and multiple applications, has been shown to reduce TOD effects on herbicide efficacy (Sellers *et al.* 2003).

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Table 4.1. Sunrise, sunset, weed heights, temperature, and relative humidity at the time of application for non-crop time of day studies in Ty Ty, Georgia, 2015 and 2017[a].

	Year	
	2015	2017
	June 23	May 15
Sunrise	6:29	6:37
Sunset	8:41	8:23
Weed Stage of growth		
Annual grass	4-8 cm	4-8 cm
Palmer amaranth	5-7 cm	5-7 cm
7:00 h		
Temp.	74	62
RH	99	96
Soil Temp.	81	71
12:00 h		
Temp.	76	80
RH	88	53
Soil Temp.	84	78
17:00 h		
Temp.	96	86
RH	51	38
Soil Temp.	89	91
22:00 h		
Temp.	73	73
RH	92	73
Soil Temp.	81	84

Table 4.2. Herbicide program, active ingredient, rate, and timings for in-crop/peanut time of day studies in Georgia, 2015, 2016, and 2017[a].

	Herbicide Program	Rate	Timing[b]
		kg ai/ha	
	paraquat	0.21	EPOST
	acifluorfen	0.19	EPOST
	S-metolachlor	1.23	EPOST
	imazapic	0.07	POST
	s-metolachlor	1.23	POST
	2,4-DB	0.25	POST
	paraquat	0.21	EPOST
	acifluorfen	0.19	EPOST
	s-metolachlor	1.23	EPOST
	lactofen	0.23	POST
	s-metolachlor	1.23	POST
	2,4-DB	0.25	POST
NTC			

[a]Pendimethalin applied PRE with all treatments at 0.84 kg ai/ha
[b]PRE= Preemergence, EPOST= early-postemergence, POST= postemergence

Table 4.3. Sunrise, sunset, temperature, and relative humidity at time of application for in-crop/peanut time of day studies in Georgia, 2015, 2016, and 2017[a].

	Ty Ty			Attapulgus
	2015	2016	2017	2016
EPOST	May 12	May 12	May 15	May 23
Sunrise	6:39	6:39	6:37	6:38
Sunset	8:20	8:21	8:23	8:30
7:00 h				
Temp.	72	69	62	59
RH	99	64	96	85
Soil Temp.	78	68	71	63
12:00 h				
Temp.	86	82	80	82
RH	61	52	53	37
Soil Temp.	86	89	78	80
17:00 h				
Temp.	92	88	86	85
RH	40	38	38	26
Soil Temp.	92	95	91	94
22:00 h				
Temp.	83	81	73	67
RH	53	51	73	76
Soil Temp.	86	84	84	83
POST	June 3	June 9	June 23	June 13
Sunrise	6:34	6:28	6:30	6:34
Sunset	8:41	8:37	8:43	8:41
7:00 h				
Temp.	68	66	75	76
RH	99	86	98	83
Soil Temp.	77	70	77	77
12:00 h				
Temp.	89	90	90	91
RH	50	35	67	55
Soil Temp.	80	85	85	86
17:00 h				
Temp.	85	91	90	95
RH	60	30	64	47
Soil Temp.	93	94	90	92
22:00 h				
Temp.	74	77	81	82
RH	94	65	83	74
Soil Temp.	87	82	86	87

Table 4.4. Soil type, planting dates, application dates, sunrise and sunset times, peanut stages of growth, weed heights, and harvest dates for in-crop/peanut TOD studies in Georgia, 2015, 2016, and 2017[a].

	Ty Ty			Attapulgus
	2015	2016	2017	2016
Soil Type	Dothan ls	Tifton ls	Dothan ls	Faceville sl
Planting Date	Apr. 27	Apr. 25	April 24	May 2
EPOST	May 12	May 12	May 15	May 23
Peanut Stage[b]	V3	V3	V3	V4
Palmer amaranth	5-7 cm	5-7cm	5-7cm	5-7 cm
Annual grass	4-8 cm	4-8 cm	4-8 cm	4-8 cm
Sunrise	6:39	6:39	6:37	6:38 am
Sunset	8:20	8:21	8:23	8:20 pm
POST	June 3	June 9	June 23	June 3
Peanut Stage	R1	R1	R1	R2
Palmer amaranth	5-7 cm	5-7 cm	5-7cm	5-7 cm
Annual grass	4-8 cm	4-8 cm	4-8 cm	4-8 cm
Sunrise	6:34	6:28	6:30	6:34
Sunset	8:41	8:37	8:43	8:41
Inverting	Sept. 14	Sept. 8	Sept. 12	Sept. 22
Harvesting	Sept. 18	Sept. 12	Sept. 18	Sept. 26

[a]Abbreviations: ls = loamy sand, sl = sandy loam, PRE= preemergence, EPOST= early-postemergence, POST= postemergence.

[b]Peanut stages according to Boote 1982.

Table 4.5. Herbicide treatment and time of day (TOD) effects on Palmer amaranth control 7 DAT[a] in the non-crop study, Ty Ty, Georgia 2015 and 2017.

Treatment	7:00 h	TOD 12:00 h	 17:00 h	22:00 h
	--% Control--------------------------------			
paraquat acifluorfen bentazon *s*-metolachlor	99a[b]	99a	99a	99a
imazapic *s*-metolachlor 2,4-DB	60a	60a	60a	51b
lactofen *s*-metolachlor 2,4-DB	99a	99a	99a	98a

[a]DAT= days after treatment.
[b]Least square means the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10). Data are averaged over two site-years.

Table 4.6. Herbicide treatment effects on Palmer amaranth control 14 DAT[a] for the non-crop study, Ty Ty, Georgia 2015 and 2017[b].

Treatment	Control (%)
paraquat acifluorfen bentazon *s*-metolachlor	99a
imazapic *s*-metolachlor 2,4-DB	61b
lactofen s-metolachlor 2,4-DB	99a

[a]DAT= Days after treatment.

[b]Least square means the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10). Data are averaged over 4 timings and 2 site-years.

Table 4.7. Time of day (TOD) effects on Palmer amaranth control 14 DAT[a] for the non-crop study, Ty Ty Georgia 2016 and 2017[b].

TOD	14 DAT
	------%------
7:00 h	84a
12:00 h	87a
17:00 h	89a
22:00 h	85a

[a]DAT= days after treatment
[b]Least square means the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10). Data are averaged over 4 herbicide treatments and 2 site-years.

Table 4.8. Annual grass control 7 and 14 DAT[a] in the non-crop study, Ty Ty, Georgia 2015 and 2017

Treatment	7 DAT	14 DAT
	----------%----------	
paraquat acifluorfen bentazon *s*-metolachlor	86a	85a
imazapic *s*-metolachlor 2,4-DB	69b	81a
lactofen *s*-metolachlor 2,4-DB	46c	32b

[a]DAT= days after treatment
[b]Least square means the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10). Data are averaged over 4 timings and 2 site years.

Table 4.9. Time of day (TOD) effects on annual grass control 7 and 14 DAT[a] in the non-crop study, Ty Ty, Georgia 2015 and 2017[b].

TOD	7 DAT	14 DAT
	----------%----------	
7:00 h	69a	68a
12:00 h	67a	66a
17:00 h	67a	64a
22:00 h	66a	67a

[a]DAT= days after treatment

[b]Least square means the same column with the same letter are not significantly different according to Tukey's HSD (p=0.10). Data are averaged over 4 herbicide programs and 2 site-years.

Table 4.10. Influence of time of (TOD) on peanut injury and weed control after EPOST application in Georgia, 2015, 2016, and 2017[a].

TOD	Peanut injury[b]	Annual grass control[c] Days after EPOST treatment		Sicklepod control[d] Days after EPOST treatment
		7 to 14	50	7 to 14
	--------------------------------	---%---	--------------------------------	
7:00 h	18b	95b	94b	93a
12:00 h	19a	98a	98a	94a
17:00 h	20a	98a	98a	96a
22:00 h	12c	97a	97a	89b

[a] Least square means in the same column with the same letter are not significantly different according Tukey's HSD (alpha=0.10). Data combined over 2 herbicide programs and 4 site-years.
[b]7 days after early-postemergence application. Herbicides applied were paraquat +, acifluorfen + bentazon + S-metolachlor.
[c]A non-uniform mixture of *Urochloa texana, Dactyloctenium aegyptium, Eleusine indica,* and *Digitaria spp.*
[d]Data comprised of 3 site-years

Table 4.11. Influence of herbicide program on peanut injury, weed control, and yield after treatments in Georgia, 2015-2017[a].

Program[b]	Rates	Peanut injury[c]	Palmer amaranth control: Days after POST treatment		Annual grass control[d]: Days after POST treatment		Sicklepod control[e]: Days after POST treatment		Peanut Yield
			7-14	50	7-14	50	7-14	50	
	kg ai/ha	------------------	------------------	------------------	------------------	%	------------------	------------------	kg/ha
imazapic	0.07	26b	98 a	98 a	90a	98a	92a	92a	6787a
2,4-DB	1.23								
s-metolachlor	0.25								
lactofen	0.23	37a	96 a	97 a	89a	88b	89a	75b	6537b
2,4-DB	1.23								
s-metolachlor	0.25								

[a] Least square means in the same column with the same letter are not significantly different according Tukey's HSD (alpha=0.10). Data combined over 4 times of day and 4 site-years.
[b]Programs also included pendimethalin (PRE), paraquat + acifluorfen + bentazon + S-metolachlor (EPOST).
[c]7 days after postemergence application.
[d]A non-uniform mixture of *Urochloa texana*, *Dactyloctenium aegyptium*, *Eleusine indica*, and *Digitaria spp.*
[e]Data from of 3 site-years

0

Table 4.12. Influence of time of day (TOD) on peanut injury, weed, and yield after all treatments in Georgia, 2015-2017[a].

TOD	Peanut injury[b]	Palmer amaranth control		Annual grass control[c]		Sicklepod control[d]		Peanut Yield
		Days after POST treatment		Days after POST treatment		Days after POST treatment		
		7-14	50	7-14	50	7-14	50	
	------------------------------------%------------------------------------							kg/ha
7:00h	30bc	98 a	98 a	89b	92a	90a	91a	6875a
12:00 h	33a	98 a	98 a	94a	94a	90a	90a	6853a
17:00 h	32ab	99 a	98 a	93a	92a	88ab	88a	6646a
22:00 h	29c	98a	97a	89b	93a	86b	66b	6597a

[a] Least square means in the same column with the same letter are not significantly different according Tukey's HSD (alpha=0.10). Data combined over 2 herbicide programs and 4 site-years.
[b]7 days after postemergence application.
[c]A non-uniform mixture of *Urochloa texana, Dactyloctenium aegyptium, Eleusine indica,* and *Digitaria spp.*
[d]Data comprised of 3 site-years

CHAPTER 5

EVALUATING SICKLEPOD RESISTANCE TO IMAZAPIC IN GEORGIA[4]

[4] Carter, Oliver. To be submitted to *Peanut Science.*

Abstract

Imazapic has a mechanism of action (ALS-inhibitor) to which weeds have previously developed resistance to in Georgia. As a result, a perceived reduction in the performance of imazapic on sicklepod has led some peanut growers to suspect that sicklepod may have evolved resistance. Thus, 22 populations of sicklepod seed were collected from peanut fields during 2014 and were screened for potential imazapic resistance in greenhouse studies. An imazapic-susceptible population, with no prior history of peanut production or imazapic use was acquired from Azlin Seed Company in Leland, Mississippi (AZ1). For comparison, AZ1 plants were treated with seven rates (0, 18, 35, 70, 140, 280, 560, and 1120 g ai/ha) of imazapic. The registered use rate of imazapic is 70 g ai/ha. At 21 days after treatment, all plants were harvested at the soil surface, fresh weight measured, and a biomass reduction calculated as a percent of the non-treated control. Data were fit to a log-logistic regression model, where one of the parameters is the I_{50}, which is the herbicide dose that provides 50% reduction in biomass. The I_{50} of the AZ1 population was estimated to be 44 g ai/ha. The 22 populations collected in Georgia were evaluated for their response to 70 g ai/ha imazapic and compared to the non-treated control for each population. Three populations (B4, DC1, E6) had significantly less biomass reduction than the AZ1 population. These three populations were subjected to a similar dose response study (0 to 1120 g ai) to determine their corresponding I_{50} values. None of the suspect populations had I_{50} values greater than the AZ1 population. I_{50} values were 24, 9, and 29 g ai/ha for the B4, DC1, and E6 populations, respectively. These results indicate that imazapic resistant sicklepod were not present at these 22 locations in Georgia.

Introduction

Sicklepod (*Senna obtusifolia* [(L.) Irwin & Barneby]) is an annual, non-nodulating legume native to tropical America (Irwin and Barneby, 1982). Sicklepod is widely distributed throughout temperate and tropical regions (Holm *et al.*, 1979). In the United States, sicklepod distribution continues to grow, with it spanning the entire southeastern peanut production area (Isley, 1990). A prolific seed producer (~8000 seeds/plant), sicklepod seed coats are hard and can remain viable in the soil for upwards of 5 years (Creel *et al.,* 1968; Senseman and Oliver, 1993). Sicklepod ranks among the top 5 most troublesome weeds to control in Georgia peanut (Webster, 2013). Season long competition from sicklepod (2 plants/ 1m row) has been reported to reduce peanut yield by up to 70% (Buchanan *et al.,* 1982). Due to increased crop competition twin row patterns have been shown to improve sicklepod control by 7% when compared to single row patterns. Tillage practices (conventional vs. strip-tillage) do not influence sicklepod control (Brecke and Stephenson IV, 2006).

Imazapic was registered for use in peanut in 1996 for the control of annual broadleaf weeds, nutsedge species, and annual/perennial grasses (Richburg *et al.,* 1994; Wilcut *et al.,* 1996; Burke *et al.,* 2004; Shaner, 2014). Imazapic is a member of the imidazolinone herbicide family and controls plants by inhibiting the formation of branched chain amino acids due to the inhibition of the acetolactate synthase (ALS) enzyme. A recent survey on chemical use in Georgia peanut reported that 63% of peanut hectares were treated with imazapic (NASS, 2014). A 10 year, comprehensive study of peanut weed control conducted across the southeastern peanut production area concluded that imazapic is one of the most effective herbicides for the control of sicklepod (Grey *et al.,* 2003). When applied at the correct rate and stage of growth, imazapic can provide 90% control of emerged sicklepod (Grey *et al.*, 2003; Grey and Wehjte, 2005).

Due to recent problems with herbicide resistance in Georgia, growers are more conscious of potential issues involving weed escapes. Georgia growers have brought to the attention of county extension agents and extension specialists that they have observed reduced efficacy of imazapic on sicklepod. Results from preliminary studies have suggested that populations of sicklepod from three counties in Georgia have evolved resistance to imazapic (W. K. Vencill, The University of Georgia, personal communication, 2015). The objective of this study was to determine if sicklepod seeds collected from Georgia peanut fields were resistant to imazapic.

Materials and Methods

Seed Collection: Sicklepod seeds were collected from peanut fields in ten Georgia counties during the late summer-fall of 2014 and 2015. Thirty populations were obtained and fields identified using Global Positioning System (GPS) coordinates. Of the 30 populations collected, only 22 had viable seed in sufficient quantity for testing. Those populations are presented in Table 1 and locations illustrated in Figure 1. Samples were harvested by randomly collecting seeds from several plants. Seeds were removed from mature pods and then placed in paper bags and stored at room temperature. Seed from a susceptible sicklepod population was obtained from a field with no previous history of ALS herbicide use or peanut production (Azlin Seed Service, Leland, MS).

Dose Response of Susceptible Population: Susceptible sicklepod seeds (AZ1) were sown in 28 X 54 X 6 cm flats containing commercial potting mix (Miracle Gro Potting Lawn Products Inc., Marysville, OH). Prior to seeding, 15 g lots of seed were scarified for 10 sec using a mechanical drum scarifier (40 grit sandpaper). Fifteen seeds per flat were sown and then placed inside the greenhouse. The greenhouse was maintained at 32 ± 5 C and natural light was supplemented for 12 h each day by metal halide lamps. After 7 days, the plants were thinned to 10 plants per flat.

Herbicide treatments were applied when the sicklepod plants were in the 2-3 leaf stage and 5 to 10 cm tall (approximately 2 weeks after planting). Imazapic (Cadre 2AS, BASF Corporation, Research Triangle Park, NC) was applied at 0, 18, 35, 70, 140, 280, 560, and 1120 g ai/ha in combination with a crop oil concentrate at 1% v/v. The normal field use rate of imazapic in peanut is 70 g ai/ha. Treatments were applied using a stationary spray chamber calibrated to deliver 140 L/ha at 193 kPa using a single XR11002 nozzle tip (TeeJet Technologies, Springfield, IL). After treatment, the flats were immediately returned to the greenhouse. At 21 DAT, plants were harvested at the soil surface and above-ground fresh weight biomass was determined. Treatments were arranged in a randomized complete block design with 3 replications and the study was repeated (60 plants/ treatment total). I_{50} values were determined using a three parameter log-logistic equation (Ritz *et al.* 2015). The equation used was: $y = C + \left[\frac{D-C}{1+\left(\frac{X}{I50}\right)^{b}}\right]$; where C is the lower limit, D is the upper limit, b is the slope, and I_{50} is the dose giving 50% response (Seefeldt *et al.* 1995). An approximate $R^2_{nonlinear}$ value was calculated as: $R^2_{nonlinear}$ = 1 - (residual sum of squares ÷ corrected total sum of squares) and is used to determine goodness of fit for nonlinear models (Askew and Wilcut, 2001; Webster *et al.*, 2017).

Screening of Georgia Populations: Using the same greenhouse methods as described above, the 22 Georgia sicklepod populations, as well as the known susceptible population (AZ1), were treated with the labeled use rate of 70 g ai/ha of imazapic. The treated plants were compared to a non-treated check of the same population to determine percent fresh weight biomass reduction. Populations that exhibited significantly less reductions in biomass in comparison to the AZ1 population were then subjected to the dose response test to determine the I_{50} value.

Statistical Analysis. All data in the initial screening of Georgia populations using 70 g ai/ha of imazapic were subjected to ANOVA. Treatment means of each population were compared to the AZ1 population that was treated at the same time. A Dunnett's test using a p-value= 0.05 was used to determine significant differences. All populations that were significantly different than the AZ1 population were then subjected to the dose response study. Data (fresh weight, plant biomass) from the dose response test was subjected to the log-logistic regression that was performed using Sigma Plot (Systat Software, San Jose, CA). The log-logistic regression was used to determine that rate of imazapic that provided 50% reduction in plant biomass.

Results and Discussion

Dose Response of Susceptible Population. The dose response of sicklepod to imazapic has not been previously reported. The imazapic I_{50} value for the known susceptible population (AZ1) in this study was 44 g ai/ha (Table 2, Figure 2).

Screening of Georgia Populations. Georgia populations collected were treated with imazapic at 70 g ai/ha (1X rate) and fresh weight biomass reduction based on percentage of non-treated controls. Biomass reduction of the Georgia populations ranged from 50-97% (Table 1). Biomass reduction of the susceptible population (AZ1) ranged between 47 to 96 %. Previously, it was reported that sicklepod biomass reduction was 67% at 70 g ai/ha of imazapic (Newsome and Shaw, 1994). Visual imazapic injury symptoms included plant stunting, chlorosis, and eventually necrosis of the individual plants. Individual populations exhibited varying degrees of control which might explain commercial field observations. Three sicklepod populations (B4, DC1, E6,) exhibited significantly less biomass reduction when compared to the known susceptible and were subjected to the dose response assay.

Dose Response Suspect Georgia Populations. Three Georgia populations that exhibited lower biomass reductions when compared to the AZ1 population were subjected to the dose response assay (Figures 3, 4, 5). None of these populations had I_{50} values that were greater than the AZ1 population (Table 2). $R^2_{nonlinear}$ values were greater than >0.94 for all three populations. Consequently, sicklepod populations collected in the study were not considered to be resistant to imazapic. These results are contrary to those previously reported (W.K. Vencill, The University of Georgia, personal communication, 2015). Worldwide, herbicide resistance in sicklepod has not been officially reported (Heap, 2018).

In summary, 22 populations of sicklepod collected from the peanut-growing region in Georgia were not resistant to imazapic. Other possible causes of the perceived reductions in sicklepod control recently observed in commercial peanut fields could be due to an herbicide application made either too early in the morning or late in the evening. Sicklepod exhibits diurnal leaf movements that can reduce herbicide interception, thus reducing control (Norsworthy *et al.*, 1999). Sicklepod size/height at time of application could also be a reason for reduced control being evident. Large weeds, especially sicklepod, are often times more difficult to control (Jonhson *et al.*, 1999). Another possible explanation is the variability of control that has been observed for different populations of sicklepod in the greenhouse.

Imazapic is used on approximately 63% of the peanut hectares in Georgia (NASS, 2014). It is the only herbicide that provides adequate control of sickelpod in peanut (Grey *et al.*, 2003). Because of this importance, the development of resistance to imazapic could be potentially devastating. Growers need to be aware of the potential for resistance development with sicklepod partly because varying levels of resistance have been documented in the state (W.K. Vencill, University of Georgia, personal commun., 2015). A diverse weed management program consisting of tillage, row spacing, multiple herbicide modes of action, and multiple timing of herbicide applications should be used to ensure effective sicklepod control in peanut.

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Table 5.1. Sicklepod populations collected in Georgia and fresh weight biomass reductions caused by imazapic at 70 g ai/ha in the greenhouse.

Population	County	Latitude (N)	Longitude (W)	Biomass Reduction (%)
B3	Berrien	31.32641	083.15154	97
B4	Berrien	31.24611	083.05128	57*
B5	Berrien	31.25325	083.05433	80
C1	Colquitt	31.26259	083.94089	72
DC1	Decatur	30.79286	084.48690	63*
DC2	Decatur	30.76269	084.47968	96
DC3	Decatur	30.99376	084.73146	82
DC4	Decatur	30.99489	084.70725	91
DL1	Dooly	32.18721	083.76782	94
E1	Early	31.37575	084.95801	93
E3	Early	31.40267	085.03100	94
E5	Early	31.42773	084.92450	93
E6	Early	31.49039	084.78944	76*
P1	Pierce	31.41792	082.31400	77
S1	Sumter	31.95656	084.30818	97
S2	Sumter	31.99940	084.34608	97
TN1	Tattnall	32.16226	082.16087	82
TN/EV2	Tattnall/Evans	32.24205	081.99572	76
TR2	Terrell	31.66658	084.48003	96
T1	Tift	31.50416	083.45520	94
T2	Tift	31.51063	083.56462	92
W1	Worth	31.50664	083.65919	92

*Populations that had significantly lower biomass reductions when compared to the known susceptible population (AZ1). AZ1 fresh weight biomass reductions ranged between 47-96% depending on greenhouse run.

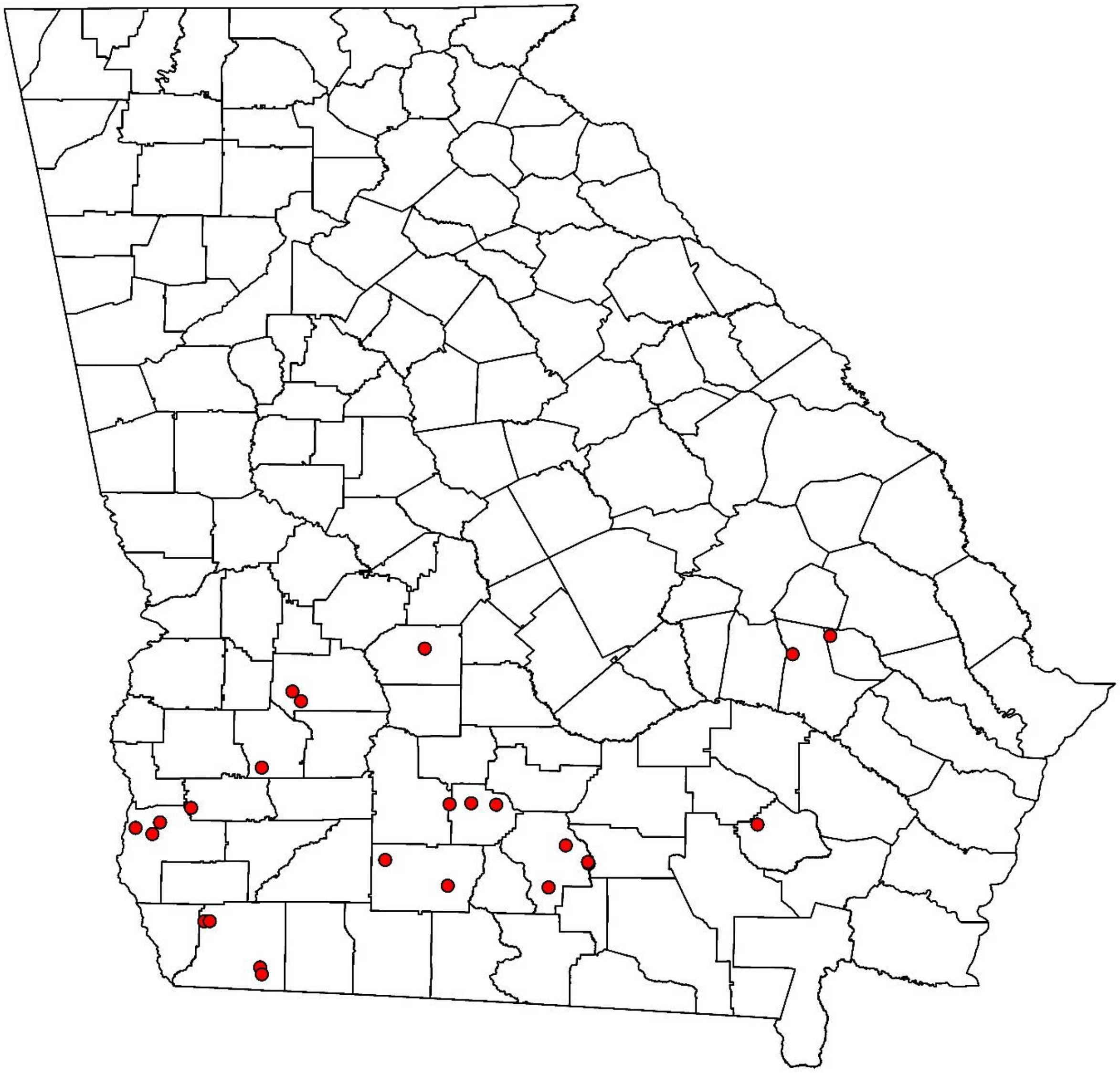

Figure 5.1. Georgia sicklepod seed collection sites (2014-2015).

Table 5.2. Parameter estimates and their standard errors for log-logistic equation of biomass reduction to various rates of imazapic on potential resistant populations in Georgia.

Accession	I_{50}	SE	b	SE	d	SE	R_2 nonlinear
AZ1	44	8.8	2.9	0.77	90	6.3	0.78
B4	24	1.1	19.5	2.8	95	1.1	0.98
DC1	9	2.2	2.2	0.60	96	3.1	0.94
E6	29	2.5	2.9	0.38	97	2.7	0.95

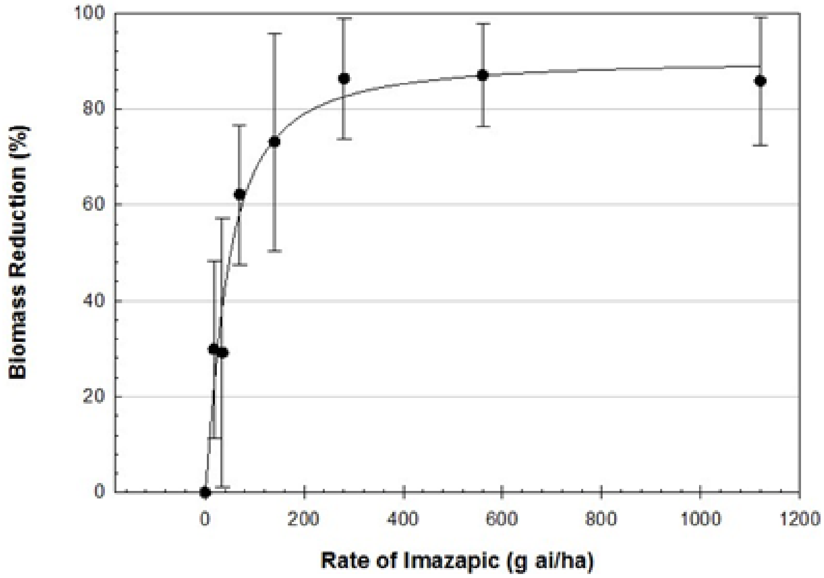

Figure 5.2. AZ1 sicklepod population (known susceptible) response to imazapic rates (I_{50} = 44 g ai/ha)

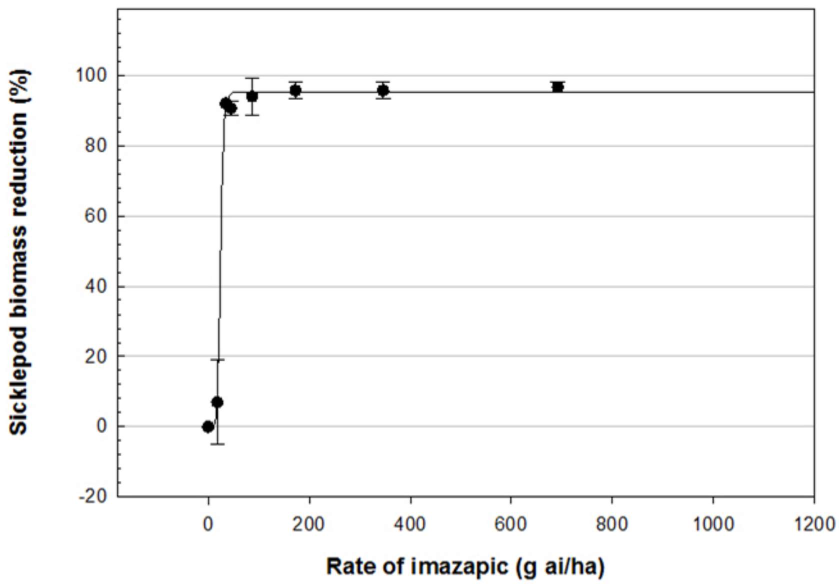

Figure 5.3. B4 sicklepod population response to imazapic rates (I_{50} = 24 g ai/ha)

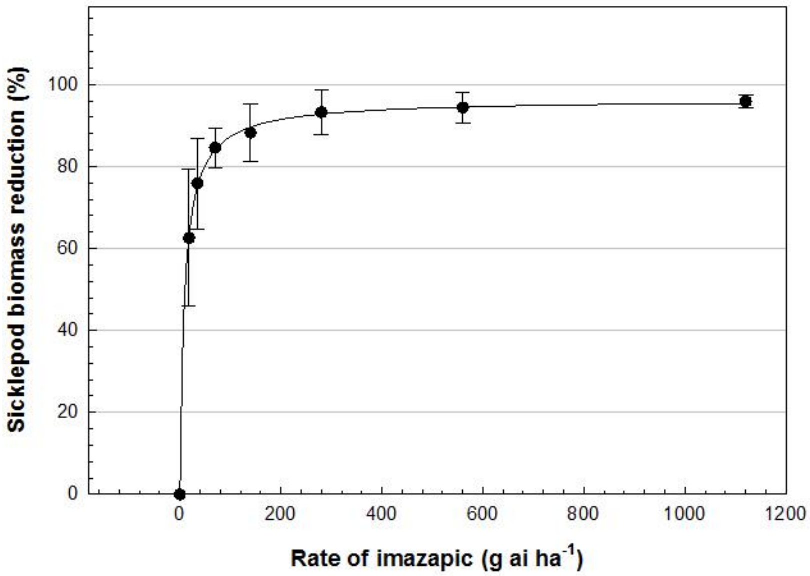

Figure 5.4. DC1 sicklepod population response to imazapic rates (I_{50} = 9 g ai/ha).

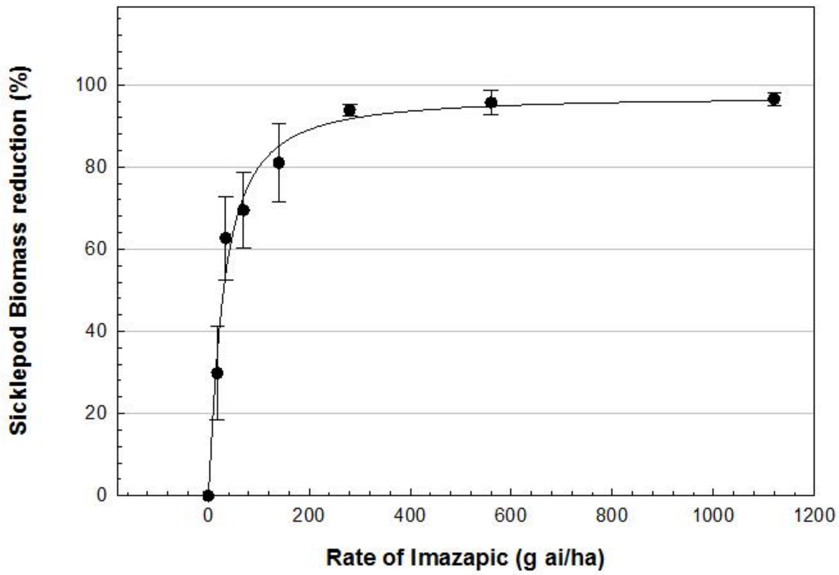

Figure 5.5. E6 sicklepod population response to imazapic rates (I_{50} = 29 g ai/ha).

CHAPTER 6

CONCLUSION

Herbicides are a vital component of a sound weed control program in Georgia peanut production. However, use of chemicals for weed control can lead to challenges that a grower must be aware of. Injury from herbicides, poor weed control from misapplication, and weed resistance to herbicides are just some of the challenges that can arise. Issues regarding such challenges that have been frequent problems for Georgia growers have been addressed herein.

Due to the persistence of picloram, peanut injury from the herbicide can occur in a variety of ways. While the injury may seem severe, visible injury does not always result in a significant yield loss. Peanut fields unintentionally exposed to picloram + 2,4-D rates $\geq 1/100^{th}$X (0.018 + 0.067 kg ai/ha) exhibited typical injury symptoms (leaf roll) but yields were not reduced.

Terbacil is an important herbicide for the control of weeds in watermelon and planting peanuts within two years of a terbacil application is currently restricted by the label. The ability to rotate crops is a valuable component of effective and profitable crop production. Terbacil is typically applied for weed control in watermelon at rates ranging from 0.12 to 0.22 kg ai/ha. Peanut yields were significantly reduced by terbacil at 0.12 and 0.22 kg ai/ha. Yield losses at these rates were 37% and 79%, respectively. Ratesa lower than these had no effect on yield. Consequently, these results suggest that peanut could be planted following terbacil applications after approximately two field half-lives.

Time of day (TOD) effects were investigated by applying standard peanut weed control programs at 7:00 h, 12:00 h, 17:00 h, and 22:00 h. Peanut injury was significantly lower at 7:00 h and 22:00 h. Lactofen was more injurious to peanut than imazapic. Palmer amaranth control was not influenced by TOD or herbicide program. Annual grass control was significantly lower at the 7:00 h application timing and with the lactofen program. A significant reduction in sicklepod control was observed at the 22:00 h timing and with the lactofen program. While TOD influenced peanut injury and weed control, peanut yield was not affected. Georgia peanut growers need to be aware of the fact that certain herbicides and certain weed species are more susceptible to TOD effects.

Seed from 22 populations of sicklepod were collected from Georgia production fields during 2014 and were screened for potential resistance to imazapic in greenhouse studies. Plants grown from the seed were subjected to a discriminatory dose of 70 g ai/A of imazapic. Suspect populations were then subjected to a full dose response assays to determine I_{50} values. Results of these greenhouse studies suggest that these specific sicklepod populations were not resistant to imazapic.

Imazapic is used on approximately 63% of the peanut hectares in Georgia. It is the only herbicide that provides adequate control of sickelpod in peanut. Growers need to be aware of the potential for resistance development with sicklepod partly because varying levels of resistance have been documented in the state. A diverse weed management program consisting of tillage, row spacing, multiple herbicide modes of action, and multiple timing of herbicide applications should be used to ensure effective sicklepod control in peanut.