

Comparison of Single and Double Drip Tapes for PRE Herbicide Application for Control of Nutsedge spp. in Plasticulture Tomato (*Solanum lycopersicum*)

by

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Key words: Nutsedge, fomesafen, halosulfuron, S-metolachlor, chemigation, drip tape

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Abstract

Field studies were conducted in 2015 and 2016 in Auburn and Shorter, Alabama, to evaluate single and double drip tapes for PRE application of herbicides under polyethylene mulch beds for yellow and purple nutsedge (*C. esculentus* & *C. rotundus*, respectively) control as well to monitor tomato crop response (height and yield). Three PRE-applied herbicides [fomesafen (280 g ai ha⁻¹), halosulfuron (54 g ai ha⁻¹), *S*-metolachlor (1.4 kg ai ha⁻¹)] were applied using either a single drip tape running down the center of the bed, or two drip tapes spaced equidistantly in the bed. A no-herbicide control was also included. Treatments were applied after drip tapes were purged of air and beds were pre-wetted. Drip tape treatment had no influence on yellow nutsedge punctures. However, purple nutsedge punctures were reduced by double drip tape treatments compared to single drip tape treatments, regardless of herbicide injected. Comparisons among herbicide treatments revealed that *S*-metolachlor provided the greatest reduction in yellow nutsedge punctures, while fomesafen provided the greatest reduction in purple nutsedge punctures.

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Table of Contents

Abstract	ii
Acknowledgments	iii
Table of Contents	vi
List of Figures	vii
List of Abbreviations	viii
Chapter I: Introduction and Literature Review	1
Chapter II: An evaluation of the effect of single or double drip tapes at time of PRE herbicide application on control of yellow nutsedge (<i>Cyperus esculentus</i>)	11
Introduction.....	11
Literature Review	11
Materials and Methods.....	19
Results and Discussion	21
Chapter III: An evaluation of the effect of single or double drip tapes at time of PRE herbicide application on control of purple nutsedge (<i>Cyperus rotundus</i>)	26

Introduction.....	26
Literature Review.....	27
Materials and Methods.....	34
Results and Discussion	37
Chapter IV: Final Discussion	41
References	45

Table of Contents

Chapter II:

Table 1: Yellow nutsedge puncture-count response, tomato plant height response, and tomato plant yield response following treatment with herbicides using single and double drip tapes at Auburn in 2015 and 2016	25
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Chapter III:

Table 2: Purple nutsedge puncture-count response, tomato plant height response, and tomato plant yield response following treatment with herbicides using single and double drip tapes at E.V. Smith in 2015 and 2016	40
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List of Figures

Figure 1	43
Figure 2	45

List of Abbreviations

OAF	Old Agronomy Farm
EVS	E.V. Smith Research Station
PSRC	Plant Sciences Research Center
PRE	Pre emergence
DAP	Days after Planting
DAT	Days after Treatment
SU	Sulfonylurea
MBr	Methyl Bromide
EPA	Environmental Protection Agency
USDA	United States Department of Agriculture

Chapter 1

Introduction and Literature Review

Weed control is one of the most difficult aspects of vegetable production, and a problem which producers all over the world are facing (Gilreath and Santos, 2004). If left unchecked, excessive weed competition can result in substantial yield reduction. Many vegetable crops do not possess the competitive capabilities to outcompete weeds for resources like light, water, nutrients, and space (Gilreath and Santos, 2004). Two problematic weed species include *Cyperus esculentus* (yellow nutsedge) and *Cyperus rotundus* (purple nutsedge). In the Southeastern United States, these two weeds are commonly found together, are considered major weeds of vegetable production, and are widespread in almost all areas where commercial vegetable production takes place (Webster, 2006). Yellow nutsedge was once listed as the number one weed to cause agronomic losses worldwide and purple nutsedge has been called the world's costliest agricultural weed (Holm et al., 1991). Competition from nutsedge can reduce crop yield and quality substantially, with some reported reductions in agronomic crops of 79 to 87% (Earl et al., 2004).

Nutsedge

Nutsedge is an herbaceous C4 perennial that is a member of the family *Cyperaceae* and is in the genus *Cyperus*. Nutsedge has three ranked basal leaves with triangular stems, and is one of the world's most problematic weed species (Earl et al., 2004). This perennial reproduces by both seed and vegetative structures. The seedhead can range in color from yellowish-brown to purple to reddish-brown. Seeds from yellow and purple nutsedge have low germination rates of 1-2% (Hoffmann et al., 2006), and are not the main method for reproduction. Nutsedge reproduce by tubers, which are edible (Colvin et al., 1992). These tubers vary in shape from round to oblong,

are generally whitish, and may or may not contain hair depending on the species of nutsedge. The prolific vegetative reproduction by means of tubers and rhizomes has helped nutsedge become one of the most widespread and aggressively competitive weed species that we face today. In 1961, Tumbleson and Komedahl reported that a single nutsedge tuber has the capability of producing up to 1900 shoots and 6900 tubers in a single year. These tubers, and their longevity, have caused *Cyperus* species to become a major problem in the Southeastern United States (Troxler et al., 2003). Webster and Coble published a survey in Southern Weed Science Society in 1997 that listed yellow nutsedge and purple nutsedge among the top 3 problematic weeds in the United States. This was attributed to the fact that they are so well established and difficult to control (Warren et al., 1999). Purple and yellow nutsedge can also serve as alternate hosts for plant parasitic nematodes such as the Southern root-knot nematode [*Meloidogyne incognita*] (Hogger et al., 1974). Even plastic mulch is ineffective at controlling nutsedge as the plant can easily puncture the mulch, allowing competition with crops (Branenberger et al., 2005). However, Webster did report in 2005 that plastic mulch, either clear or black, reduced shoot and tuber production compared to unmulched controls. In peppers, losses of 31% were reported from nutsedge populations as small as 1.64 plants per square meter at fruit-set, with losses of at least 70% being reported from populations of approximately 30 plants per square meter. Trends were similar in tomato production (Motis et al., 2003). A study by Gilreath and Santos in 2004 reported tomato yield reduction of 51% from season long nutsedge populations of 113 plants per square meter. Likewise, a study in 2003 (Morales-Payan et al., 1997), reported that marketable tomato yield reductions of 25, 55, and 65% were observed when yellow nutsedge emerged at densities of 25, 50, and 100 plants per square meter, respectively. It was also reported that for

lower nutsedge populations (25-50 plants per square meter), suppression in the first 8 weeks after transplant was required to prevent yield reductions greater than 5%.

Methyl bromide

In years prior to the 1997 Montreal Protocol, nutsedge and many other pests were controlled by the use of the fumigant Methyl bromide (MBr). Since the early 1900s, MBr has been an integral part of pest management programs in the commercial production of many vegetable crops (Webster et al., 2005). Insects, soil borne pathogens, and a list of weed species were controlled successfully by the use of MBr. Webster et al. reported in 2005, that roughly 85% of MBr applications were taking place in the United States as a pre-plant soil fumigant. However, due to its consideration as an ozone depleting agent (Gilreath and Santos, 2004), MBr has now been phased out of use in all agricultural applications. This phase out is in accordance with the United States Clean Air Act as well as provisions of the Montreal Protocol Agreement. With MBr now off the market, producers face a challenge to find effective chemicals or combinations to control pests which had previously been managed with MBr. (Webster et al., 2005). Many such chemicals and combinations are being researched as replacements and the list of such replacements includes sulfonylureas, chloroacetamides, diphenyl ethers, metam-sodium, methyl iodine, steam, fumigants, solarization, and even ozone gas.

Herbicides

Sulfonylurea (SU) herbicides have some characteristics that make them prime candidates to be an MBr replacement. These characteristics include: comparatively low application rates, insignificantly adverse environmental effects, and a high degree of crop selectivity (Burker et al., 2004). The mode of action of sulfonylurea herbicides as a group, is characterized by the inhibition of the synthesis of certain branched-chain amino acids like valine, leucine, and

isoleucine. Sulfonylurea's first target the enzyme acetolactate synthase (ALS) (Burker et al., 2004). The first SU, chlorosulfuron, was produced in 1975 and was intended to be used as an insecticide for spider mites (Flogel, 1998). It wasn't until 1978 that chlorosulfuron was patented as an herbicide after testing revealed it was detrimental to some plants. Flogel found in 1998, that SU's are 100 times more lethal in weed control than the herbicides that were in use prior to 1982. SU's are used for their selectivity in controlling perennial sedges, such as yellow and purple nutsedge, kyllingas, and a selection of broadleaf weeds in horticultural and agronomic crops (Burker et al., 2004). Some SU's have short persistence in the soil, and their selectivity allows them to be used in many different weed control situations (Askew et al., 2004). Tomatoes have exhibited excellent tolerance to SU's (Troxler et al., 2003).

Halosulfuron is one such SU herbicide that is being considered as an MBr replacement. This ALS inhibitor is produced by Gowan (Yuma, Arizona) under the label name Sandea. Halosulfuron is a systemic herbicide (Branenberger et al., 2005) that can be applied as a preemergence (PRE) or postemergence (POST) application in many situations (McElroy et al., 2004). It has both PRE and POST activity on yellow nutsedge (Senseman, 2007). Halosulfuron is currently registered for use on many vegetable crops, including tomatoes

Chloroacetamides are a class of herbicides also being considered as MBr replacements. Chloroacetamides are soil applied herbicides that have PRE or pre plant incorporations use, though they are not volatile enough to require incorporation. As a class, the chloroacetamides have very low acute toxicity. These herbicides act by inhibiting production of long chain lipids which are needed for production of plant waxes. Although absorption of chloroacetamides occurs in both the roots and shoots of young seedlings, shoot tissues are both more sorptive, as

well as the site of herbicide action. These herbicides are broken down mainly by microbial action, and dissipate within 6-10 weeks on average. (Senseman, 2007).

S-metolachlor is an herbicide belonging to the chloroacetamide class of herbicides. *S*-metolachlor is produced by Syngenta Crop Protection Inc. (Greensboro, North Carolina) under the label name of Dual Magnum, and is a biosynthesis inhibitor with multi-site, nonspecific mode of action. It is labeled for control of annual grasses, yellow nutsedge, and broadleaf weeds in many different crops (Syngenta, 2005). *S*-metolachlor has been used for both PRE and POST weed control since 1952 (Feigenbrugel et al., 2004). Though the ability of *S*-metolachlor to control sedges has been established in some crops (Grichar, 1992; Obrigawitch et al., 1980), little has been published on the use of *S*-metolachlor alone in tomato production. Increased nutsedge control has been achieved with the addition of metolachlor and other herbicides to fumigant applications (Santos et al. 2006, Gilreath and Santos, 2004).

Diphenyl ethers are a family of herbicides which are characterized by two rings linked by an ether bridge. These herbicides are generally considered POST active but all have some amount of PRE activity. Of these, fomesafen has the most PRE activity. This family of herbicides has seen increased use in transgenic crop production where herbicide resistant weeds are becoming more of a problem. This family inhibits protoporphyrin oxidase or PROTOX. Inhibition of PROTOX results in lipid peroxidation, disruption of cell membranes, and ultimately plant death (Ensminger and Hess, 1985). After treatment, leaves of susceptible plants become chlorotic, and then desiccated and necrotic within one to three days. (Senseman, 2007). Diphenyl ethers mode of action, PROTOX inhibition, differs from other modes of action commonly used in GMO crops; therefore, herbicide resistance is presumed to be much less likely (Senseman, 2007).

Fomesafen is a systemic-active herbicide belonging to the diphenyl ether family of herbicides. Fomesafen is currently labeled for control of a number of broadleaf weeds and sedges in soy, cotton, and potatoes (Anonymous, 2013), and has recently been evaluated for use in a number of vegetable crops and has received labels for use in tomato and pepper production in Georgia, Florida, and North Carolina (Culpepper, 2012). Fairly long soil persistence and moderate mobility in the soil have led to some restrictions to crops following fomesafen use. A recent study showed fomesafen to have similar levels of control over a similar spectrum of weed species as the chloroacetamide *S*-metolachlor; however, fomesafen provides an important tool for rotation of herbicide mode of action.

Tomato Production

Tomato (*Lycopersicon esculentum* Mill.) is members of the *Solanaceae* family, which also includes nightshade, peppers, eggplants, and Irish potatoes (Kemble et al., 2004). In Alabama, tomatoes are an annual crop grown for its fruit, a berry. Tomato leaves are compound, deeply pinnately lobed, and have a strong odor when crushed. Tomatoes have perfect flowers which are yellow in color. Initial uses of tomatoes were for herbal remedies and their ornamental value (Peralta and Spooner, 2007). The tomato fruit would not become popular in Europe until the eighteenth century, largely due to the fact that they were first believed to be poisonous as they are closely related to the nightshade (Kemble et al., 2004). In the twentieth century, the botanist George Washington Carver played a large role in promoting tomato as an excellent source of vitamins and nutrients for the poor (Jones, 1998). Since 2004, Alabama has produced approximately \$10 million in fresh market tomatoes annually, and in 2015 Alabama ranked 13th in fresh market tomato production. In 2015, the total value for fresh market tomatoes produced in

the U.S. was over \$1.2 billion which was an increase of over \$100 million from the previous year.

Tomatoes perform best in a well-drained, sandy-loam to clay-loam soil with a slightly acidic p.H., 6.0 - 6.8. Tomatoes fall into the nutritional requirement category of moderate to heavy feeders. Per hectare, tomatoes require between 168 – 202 kg of nitrogen (N) and 224 – 280 kg of phosphorus (P_2O_5) and potassium (K_2O) (Kemble et al., 2004b). Generally, fifty percent of the N and K_2O and one hundred percent of P_2O_5 are applied pre-plant, while the remaining N and K_2O are injected through the irrigation system on a set schedule. The most common practice in commercial tomato production is to plant on raised beds 15 cm tall and between 74-91cm in width. These beds are covered with either black or white on black polyethylene mulch depending on the growing season. For spring grown tomatoes, black polyethylene mulch is utilized for its soil warming ability; conversely in the summer when increasing soil temperature could damage plant roots, white polyethylene mulch is used (Konsler and Gardner, 2010).

Tomatoes, which are comprised of 85-95% water, need 1-4 cm of water per week for proper development (Kemble et al., 2004b). Commercial production generally involves drip irrigation laid along with or prior to application of polyethylene mulch. This system has led to improvement in overall tomato quality and yield. Transplants are spaced 46-61 cm apart within rows with rows spaced 1.2 – 1.8 m apart (Kemble et al., 2004b). Staking and tying tomatoes is required for successful tomato production. Wooden stakes, 1.2 – 1.5 m in length, are placed between every other plant and driven into the ground until secure. Tomatoes are tied 3-4 times during the growing season depending on plant height and variety selection (Kemble et al., 2004b). Following the first tying, initial pruning of the plant occurs. Pruning of suckers, or

axillary shoots on the main stem, helps maintain the desired balance between vegetative growth and fruit production (Konsler and Gardner, 2010). Fresh market tomatoes are hand harvested with or without harvest aid. Machine harvesting is usually reserved for processing tomatoes. Once harvested, immediate and thorough postharvest cooling to remove excess field heat aids greatly in maintaining quality and substantially lengthens shelf life (Konsler and Gardner, 2010).

Chemigation

Chemigation, or the process of applying an agricultural chemical to the soil or plant surface through irrigation systems, is achieved by introducing the chemical into the irrigation water with the use of an injector. Though initially designed to deliver fertilizers that had previously required soil incorporation, this system has shown promise in its ability to also inject other agricultural chemicals such as herbicides, insecticides, or fungicides (Wang et al., 2009). While chemigation systems can vary in their design, the basic components include: an irrigation pump, a backflow preventer, a chemical injection pump, and a chemical reservoir. Since most vegetable production systems utilize drip irrigation under polyethylene mulch, they are an ideal choice for using chemigation. To achieve optimal results an initial wetting period is used to get any air out of the irrigation lines and to ensure initial water movement into the soil. The desired chemical is injected after this wetting period, and after injection the system is flushed with fresh water to expel any remaining chemicals from the drip irrigation lines. There are a few possible disadvantages to drip application of agricultural chemicals such as the need for additional equipment (injection pump) and increased application times. However, these disadvantages are generally offset by the many advantages of chemigation which can include increased applicator safety and chemical movement to desired zone, as well as decreased compaction and damage from chemical drift (Thomas et al., 2003; Wang et al., 2009). Along with these advantages, weed

control through drip-applied herbicides can increase production efficiency of crops through lowering application cost, labor, and fuel costs (Johnson et al., 1986). While many studies exist reporting the potential of using drip-application systems in vegetable production for fumigant application (Ajwa et al., 2002, Candole et al., 2007, Chase et al., 2006, Locascio et al., 1997), fewer studies have been conducted on herbicide injection. Recent studies have shown drip-application of *S*-metolachlor and halosulfuron to be competitive with spray applications in controlling yellow nutsedge under polyethylene mulch when no crop was present (Adcock, 2007). These two herbicides were also found to be safe for tomatoes as well as effective in controlling yellow nutsedge in polyethylene-mulched tomato production systems (Santos et al., 2008, Dittmar et al., 2012a, Dittmar et al., 2012b).

A limiting factor in the acceptance of drip application of herbicides has been herbicide movement. It has been reported in recent studies (Dittmar et al., 2012b, Monday et al., 2015) that yellow nutsedge control is observed to be reduced as distance from the drip tape emitters increases, and that two drip tapes were required for uniform application of herbicides across the bed surface. These same trends have also been noted in studies examining drip-tape application of fumigants in polyethylene-mulched beds (Fennimore et al., 2003, Candole et al., 2007, and Chase et al., 2006). Keeping this in mind, it is necessary to improve lateral movement of drip-applied herbicides in polyethylene-mulched beds for the optimization of nutsedge control as well as to allow for multi-cropping of a single application of polyethylene mulch.

Conclusion

Weed control is an important and difficult task for vegetable producers. With the EPA phase out of methyl bromide, some farmers have been left searching for viable alternatives for

hard to control weeds such as nutsedge. The ability of nutsedge species to puncture polyethylene plastic has led to them being declared some of the world's worst weed species (Earl et al., 2004). Recent work has shown promise in methyl bromide replacements with certain herbicides, fumigants, and combinations of both. Previous work at Auburn University (Adcock et al., 2007; Monday et al., 2015) has shown that drip applied herbicides can offer competitive control to sprayed applications. While this work was promising, the large volume of water used at time of application seemed to leach herbicides lower into the soil profile out of their target zone and possibly into the crop root zone. Therefore, a need exists in drip application of agricultural chemicals for increased lateral movement of the wetting zone and herbicides without leaching herbicides. With this in mind we conducted studies evaluating the use of either a single drip tape centered in the bed or two drip tapes spaced equidistant across the bed width to determine if the second drip tape increased lateral movement of herbicides, decreased nutsedge punctures, and influenced tomato yield. Based on previous research (Adcock et al., 2007; Monday et al., 2015), the author does expect to see some initial stunting in certain herbicide treatments but does not expect this to result in loss of yield. The double drip tape system, if proven effective in controlling nutsedge punctures, could extend the life of polyethylene mulch to allow for a multi cropping system and therefore extend the increased cost of drip tape over multiple crops. Additionally, this could reduce costs to farmers and increase overall production.

Chapter II

An Evaluation of Single and Double Drip Tapes for Applying PRE Herbicides for Control of Yellow Nutsedge (*Cyperus esculentus*) in Plasticulture Tomato (*Solanum lycopersicum*)

Introduction

Field studies were conducted in 2015 and 2016 at the Old Agronomy Farm (OAF) in Auburn, Alabama, to evaluate the effect of single and double drip tapes for the application of PRE herbicides under polyethylene mulched beds for yellow nutsedge (*Cyperus esculentus*) control in plasticulture tomato. Tomato crop response was also monitored. Three herbicides [fomesafen (280 g ai ha⁻¹), halosulfuron (54 g ai ha⁻¹), *S*-metolachlor (1.4 gk ai ha⁻¹)] were PRE-applied using either a single drip tape running down the center of the bed, or two drip tapes spaced equidistantly within the bed. Treatments were applied after drip tape lines were purged of air and beds were pre-wetted. A no herbicide control, with a single drip tape, was included. The addition of a second drip tape did not reduce yellow nutsedge punctures. Reduced yellow nutsedge punctures were obtained with *S*-metolachlor treatments. Tomato plant heights and yield were reduced in single drip tape treatments compared to double drip tape treatments.

Literature Review

Weed control is one of the most difficult aspects of vegetable production, and a problem which producers all over the world are facing (Gilreath and Santos, 2004). If left unchecked, excessive weed competition can result in substantial crop yield reduction. Most vegetable crops do not possess the competitive capabilities to outcompete weeds for resources like light, water, nutrients, and space (Gilreath and Santos, 2004). One such competitive weed species is yellow nutsedge (*Cyperus esculentus*). In the Southeastern United States, yellow nutsedge is considered

a major weed of vegetable production and is widespread in almost all areas where commercial vegetable production takes place (Webster, 2006). Competition from nutsedge can reduce crop yield and quality substantially, with some reported reductions in agronomic crops of 79 to 87% (Earl et al., 2004).

Nutsedge

Nutsedge is an herbaceous C4 perennial that is a member of the family *Cyperaceae* and is in the genus *Cyperus*. Nutsedge has three ranked basal leaves with triangular stems, and is one of the world's most problematic weed species (Earl et al., 2004). This perennial reproduces by both seed and vegetative structures. The seedhead can range in color from yellowish-brown to golden. Seeds from yellow nutsedge have low germination rates of 1-2% (Hoffmann et al., 2006), and are not the main method for reproduction. The main method of reproduction for nutsedge is by tubers, which are edible (Colvin et al., 1992). These tubers vary in shape from round to oblong, are generally whitish, and may or may not contain hair depending on the species of nutsedge. The prolific vegetative reproduction by means of tubers and rhizomes has helped nutsedge become the widespread and aggressively competitive weed species that we are fighting today. In 1961, Tumbleson and Komedahl reported that a single nutsedge tuber has the capability of producing up to 1900 shoots and 6900 tubers in a single year. These tubers, and their longevity, have caused *Cyperus* species to become a major problem in the southeastern United States (Troxler et al., 2003). Webster and Coble published a survey in Southern Weed Science Society in 1997 that listed yellow nutsedge (*Cyperus esculentus*) among the top 3 problematic weeds in the United States. This was attributed to the fact that it is so well established and difficult to control (Warren et al., 1999). Yellow nutsedge can also serve as alternate hosts for plant parasitic nematodes such as the Southern root-knot nematode (*Meloidogyne incognita*) (Hogger et al.,

1974). Plastic mulch is even ineffective at controlling nutsedge as the plant can easily puncture the plastic mulch, allowing competition with crops (Branenberger et al., 2005). However, plastic mulch, either clear or black, can reduce shoot and tuber production compared to unmulched controls (Webster, 2005). In peppers, losses of 10% were reported from nutsedge populations as small as five plants per square meter with losses up to 74% from populations of 30 plants per square meter. The case is similar in tomato production (Motis et al., 2003). A study by Gilreath and Santos in 2004 reported yield reductions of 51% from season long nutsedge populations of 113 plants per square meter. Likewise, a study in 2003 (Morales-Payan et al., 1997), reported that marketable yield reductions of 25, 55, and 65% were observed when yellow nutsedge emerged at densities of 25, 50, and 100 plants per square meter, respectively. It was also reported that for lower nutsedge populations (25-50 plants per square meter), suppression in the first 8 weeks after transplant was required to prevent yield reductions greater than 5%.

Methyl bromide

In years prior to the 1997 Montreal Protocol, nutsedge and many other pests were controlled by the use of the fumigant methyl bromide (MBr). However, due to its consideration as an environmental concern (Gilreath and Santos, 2004), MBr has now been phased out of use in all agricultural applications. With MBr now off the market, producers face a challenge to find effective chemicals or combinations to control pests which had previously been managed with MBr. (Webster et al., 2005). Many such chemicals and combinations are being researched as replacements and the list of such replacements includes sulfonylureas, chloroacetamides, diphenyl ethers, metam-sodium, methyl iodine, steam, fumigants, solarization, and even ozone gas.

Herbicides

Sulfonylurea (SU) herbicides have some characteristics that make them prime candidates to be an MBr replacement. These characteristics include: comparatively low application rates, insignificantly adverse environmental effects, and a high degree of crop selectivity (Burker et al., 2004). The mode of action of sulfonylurea herbicides as a group, is characterized by the inhibition of the synthesis of certain branched-chain amino acids like valine, leucine, and isoleucine. SU's first target the enzyme acetolactate synthase (ALS) (Burker et al., 2004). Floegel found in 1998, that SU's are 100 times more lethal in weed control than the herbicides that were in use prior to 1982. SU's are used for their selectivity in controlling perennial sedges, like yellow and purple nutsedge, kyllingas, and a selection of broadleaf weeds in horticultural and agronomic crops (Burker et al., 2004). SU's have short persistence in the soil, and their selectivity allows them to be used in many different weed control situations (Askew et al., 2004). Tomatoes have exhibited excellent tolerance to SU's (Troxler et al., 2003).

Halosulfuron is a sulfonylurea herbicide that is being considered as an MBr replacement. It is an ALS inhibitor. Halosulfuron is produced by Gowan (Yuma, AZ) under the label name Sandea. Halosulfuron is a systemic herbicide that can be applied as a preemergence (PRE) or postemergence (POST) herbicide in many situations (McElroy et al., 2004). It has both PRE and POST activity on yellow nutsedge. Currently, Halosulfuron is used for weed control in vegetable crops (Senseman, 2007) including tomatoes (*Lycopersicon esculentum*).

Chloroacetamides are soil applied chemistries that have PRE or pre plant incorporation use, though they are not volatile enough to require incorporation. These herbicides act by inhibiting production of long chain lipids which are needed for production of plant waxes. As a class, the chloroacetamides have very low acute toxicity. Although absorption of

chloroacetamides occurs in both the roots and shoots of young seedlings, shoot tissues are both more sorptive, as well as the site of herbicide action. Translocation through the xylem is not considered relevant since death occurs at seedling growth stage. These herbicides dissipate fairly quickly due to microbial action, with the group averaging 6-10 weeks. (Seneseman, 2007).

S-metolachlor is soil active herbicide in the chloroacetamide family of herbicides. *S*-metolachlor is produced by Syngenta Crop Protection Inc. (Greensboro, NC) under the label name of Dual Magnum, and is a biosynthesis inhibitor with multiple site, nonspecific mode of action. It is labeled for control of annual grasses, yellow nutsedge, and broadleaf weeds in many different crops (Syngenta, 2005). *S*-metolachlor has been used for both PRE and POST control since 1952 (Feigenbrugel et al., 2004). Though the ability of *S*-metolachlor to control sedges has been established in some crops (Grichar, 1992; Obrigawitch et al., 1980), little has been published on the use of *S*-metolachlor alone in tomato production. Despite this, Santos et al. (2006) and Gilreath and Santos (2004) have published results of combining *S*-metolachlor and other MBr replacements showing increased yellow nutsedge control.

Diphenyl ethers are a family of herbicides which are characterized by two rings linked by an ether bridge, and are generally considered POST active but all have some amount of PRE activity. Of these, fomesafen has the most PRE activity. This family has been of growing interest in transgenic crop production where herbicide resistant weeds are becoming more of a problem. Diphenyl ethers mode of action, PROTOX inhibition, differs from those modes of action used in GMO crops. These diphenyl ethers have been used to control escapes, and resistance to this mode of action is presumed to be much less likely. (Senseman, 2007)

Fomesafen is a systemic-active herbicide from the diphenyl ether family of herbicides. This family inhibits protoporphyrinogen oxidase or PROTOX. Inhibition of PROTOX results in

lipid peroxidation, disruption of cell membranes, and ultimately plant death (Ensminger and Hess, 1985). After treatment, leaves of susceptible plants become chlorotic, and then desiccated and necrotic within one to three days. (Senseman, 2007). Fomesafen, which is currently labeled for control numerous broadleaf weeds as well as sedges in soy, cotton, and potatoes (Anonymous, 2013), has recently been evaluated for use in some vegetable crops and has received Section 24C labels for use in tomato and pepper production in Georgia, Florida, and North Carolina (Culpepper, 2012). Fairly long soil persistence and moderate mobility in the soil have led to some restrictions in crops that can follow fomesafen use. A recent study showed fomesafen to have similar levels of control over a similar spectrum of weed species as the chloroacetamide *S*-metolachlor; however, fomesafen provides an important tool for rotation of herbicide mode of action.

Chemigation

Chemigation, or the process of applying an agricultural chemical to the soil or plant surface through irrigation systems, is achieved by introducing the chemical into the irrigation water with the use of an injector. Though initially designed to deliver fertilizers that required soil incorporation, this system has shown promise in its ability to also inject other agricultural chemicals such as herbicides, insecticides, or fungicides (Wang et al., 2009). While chemigation systems can vary in their design, the basic components include: An irrigation pump, a backflow preventer, a chemical injection pump, and a chemical reservoir. Since most vegetable production systems utilize drip irrigation under polyethylene mulch, they are an ideal choice for using chemigation. To achieve optimal results an initial wetting period is used to get any air out of the irrigation lines and to ensure initial water movement into the soil. The desired chemical is injected after this wetting period, and after injection the system is flushed with fresh water to

expel any remaining chemicals from the drip irrigation lines. There are a few possible disadvantages to drip application of agricultural chemicals such as the need for additional equipment (injection pump) and increased application times. However, these disadvantages are generally offset by the many advantages of chemigation which can include increased applicator safety and chemical movement to desired zone, as well as decreased compaction and damage from chemical drift (Thomas et al., 2003; Wang et al., 2009). Along with these advantages, weed control through drip-applied herbicides can increase production efficiency of crops through lowering application, labor, and fuel costs (Johnson et al., 1986). While many studies exist reporting the potential of using drip-application systems in vegetable production for fumigant application (Ajwa et al., 2002; Candole et al., 2007; Chase et al., 2006; Locascio et al., 1997), fewer studies have been conducted on herbicide injection. Recent studies have shown drip-application of *S*-metolachlor and halosulfuron to be competitive with spray applications in controlling yellow nutsedge under polyethylene mulch when no crop was present (Adcock et al., 2007). These two herbicides were also found to be safe for tomatoes as well as effective in controlling yellow nutsedge in polyethylene-mulched tomato production systems (Santos et al., 2008; Dittmar et al., 2012a; Dittmar et al., 2012b).

A limiting factor in the acceptance of drip application of herbicides has been herbicide movement. It has been reported in recent studies (Dittmar et al., 2012b; Monday et al., 2015) that yellow nutsedge control is observed to be reduced as distance from the drip tape emitters increases, and that two drip tapes were required for uniform application of herbicides across the bed surface. These same trends have also been noted in studies examining drip-tape application of fumigants in polyethylene-mulched beds (Fennimore et al., 2003; Candole et al., 2007; and Chase et al. 2006). Keeping this in mind, it is necessary to improve lateral movement of drip-

applied herbicides in polyethylene-mulched beds for the optimization of nutsedge control as well as to allow for multi-cropping of a single application of polyethylene mulch. Monday et al. (2015) reported that for Marvyn sandy loam comprised of after 7 hours of irrigation using a single drip tape on a polyethylene mulched bed, emitter-to-emitter coverage was achieved and approximately 70% of the bed surface had been wetted. Additional irrigation did not result in an increase in lateral movement of the moisture field across the bed surface. It should be noted that different soil types can affect lateral movement of the moisture field in polyethylene-mulched beds and therefore herbicide movement.

Conclusion

Weed control is an important and difficult task for vegetable producers. With the EPA phase out of methyl bromide, a soil fumigant that had been used extensively in agriculture as a soil sterilant, some farmers have been left searching for effective alternatives for hard to control weeds such as nutsedge. The ability of nutsedge species to punctures polyethylene plastic has led to them being declared some of the world's worst weed species. Some recent work has shown promise in Methyl bromide replacements with certain herbicides, fumigants, and combinations of both. Previous work at Auburn has shown that drip applied herbicides can offer competitive control to a sprayed application (Monday et al., 2015). While this work was promising, the large volume of water used at time of application leached herbicides lower into the soil profile out of their target zone and possibly into the crop root zone. A need exists in drip application of agricultural chemicals for increased lateral movement of the wetting zone and herbicides with minimal herbicide leaching. In this study, the use of either a single drip tape centered in the bed or two drip tapes spaced equidistance across the bed width was evaluated to determine if the second drip tape increased lateral movement of herbicides, if the use of a second

drip tape decreased nutsedge punctures, and if the use of a second drip tape would cause injury to a tomato crop. The double drip tape system, if proven effective in controlling nutsedge punctures, could extend the life of polyethylene mulch to allow for a multi cropping system and therefore extend the increased cost of drip tape over multiple crops.

Materials and Methods

Field studies were conducted in the summer of 2015 and 2016 at the Old Agronomy Farm (OAF) located at Auburn University, Auburn, AL. The soil type was a Marvyn sandy loam (fine-loamy, kaolinitic, thermic type Kanhadpludults) comprised of 76.3, 5.0, and 18.8% sand, silt, and clay respectively, with pH 6.2. Fields used in the experiment had a history of heavy yellow nutsedge infestation. In both years, soil was prepared and formed using a bedder (Reddick fumigants, Williamson, NC) into four raised beds 61 m long, 91 cm wide, 13 cm high, and covered with white polyethylene mulch (1.25 mil, white on black, embossed; Berry Plastics Corp., Evansville, IN). Each of the four rows (spaced 2 meters apart) contained 8 4.57-m plots with a 3-m buffer between plots. In both years, experimental units contained 8 tomato plants (cv. Red Bounty) spaced 0.4-m apart. Transplants were started on April 14 & March 28 in 2015 and 2016, respectively. Transplants were grown at Auburn University's Plant Sciences Research Center. Transplants received fertilization of 200 ppm N once per week, beginning two weeks after germination. Tomatoes were transplanted on May 20 & May 18 in 2015 and 2016, respectively. Fertility and management of tomatoes followed commercial growing standards (Kemble, 2013). Prior to mulch application, drip tapes (Toro Ag., Bloomington, MN) were placed in the beds. Drip tape emitters were spaced 30.5 cm apart delivering 1.02 L h⁻¹.

The experiment was conducted in a completely randomized design with four replications. Treatments were arranged in an augmented factorial consisting of two drip tape arrangements and three PRE-applied herbicide treatments [halosulfuron (54 g ai ha⁻¹), *S*-metolachlor (1.4 kg

ha⁻¹), and fomesafen (280 g ha⁻¹)]. The two drip tape arrangement methods were either a single drip tape placed in the middle of the bed or two drip tapes placed equidistance from bed shoulders. All drip tapes were buried 5 cm deep. An additional no-herbicide control with single drip tape was included. Drip treatments were applied along with approximately 14,000 L ha⁻¹ of water with Dosatron® D14MZ2 injectors (Dosatron International Inc., Clearwater, FL) and a custom injection manifold. Length of application time (wetting period plus herbicide application plus flush) and the large quantity of water used was based on Csinos et al. (2002) dye injection test for tracing water and pesticide movement in polyethylene mulched beds. From each port on the manifold, a section of 1.27-cm plastic tubing was connected to the front of each corresponding plot. Plots of the same treatments were then connected together by splicing into the drip tape and capped where needed.

Quantity of herbicide applied to each treatment was based on the combined area of the four individual plots utilized per treatment. Single drip tape treatments required 3.5 hours to inject while the double drip tape treatments required half that, at 1.75 hours. Treatments were applied on 13 May and 24 May in 2015 and 2016, respectively. Treatments were applied 7 d prior to transplanting tomatoes, per herbicide label recommendations. Nutsedge punctures were counted 30 and 60 days after treatment (DAT) from a 1.0 m² section of the plot. Tomato height was measured from the base of plant to the top of the growing point 30 and 60 days after planting (DAP) to evaluate potential herbicide injury. Additionally, tomato fruit was harvested when fruit were 5 cm or larger in diameter, in breaker to red stage, and were graded as marketable or nonmarketable according to U.S. Department of Agriculture standards (USDA, 1991). Fruit were harvested from the middle four plants of each plot in both years. In 2015,

intense disease pressure resulted in rapid plant decline beginning at fruit set which resulted in a single harvest. Plants were harvested three times in 2016.

Data were analyzed with generalized linear models with the use of GLMMIX procedure of SAS (version 9.2; SAS Institute, Cary, NC) with the normal distribution and identity link function for plant height and yield and negative binomial distribution and log link function for puncture counts. Tomato height, nutsedge punctures, marketable yield, and unmarketable yield were included in the models as random factors. Herbicide by application method interactions were not significant for all variables; therefore, levels within main effects were examined. Least-squares means for tomato height were compared to those for the control and other plots with the use of lower-tailed *t* tests. In addition, least-squares means for nutsedge puncture and marketable and unmarketable yield were compared to those for the commercial standard by two-tailed *t* tests. All P values for tests of differences between least-squares means were adjusted with the use of the Shaffer-Simulated method ($\alpha=0.10$).

Results and Discussion

Yellow Nutsedge Punctures. Yellow nutsedge punctures at both 30 and 60 DAT were influenced only by the main effect of herbicides; main effect of drip tape and interaction of herbicide and drip tape were both nonsignificant ($\alpha=0.10$; Table 1)

30 DAT. Treatments containing *S*-metolachlor had less punctures (1.8 m⁻²) than those containing fomesafen or halosulfuron (3.7 and 3.3 m⁻², respectively). Comparisons among individual treatments revealed no differences in punctures counts (Table 1).

60 DAT. Treatments containing *S*-metolachlor had less punctures (9.1 m⁻²) than those containing fomesafen or halosulfuron (16.3 and 13.7 m⁻², respectively). Comparisons of individual treatments revealed that *S*-metolachlor applied by single drip tape had less punctures (8.1 m⁻²) than halosulfuron applied by single drip tape, fomesafen applied by double drip tape, and the nontreated control (15.8, 18.0, and 16.3 m⁻², respectively) (Table 1).

Tomato Response. Tomato plant height at both 30 and 60 DAT was influenced only by the main effect of drip tape treatment; main effect of herbicide and interaction of herbicide and drip tape were both nonsignificant ($\alpha=0.10$; Table 1).

30 DAP. Plant height was reduced across single drip tape treatments compared to double drip tape treatments (53.1 and 47.7 cm, respectively) (Table 1). Moreover, comparisons among individual treatments revealed significant differences (Table 1). Plant height in single drip tape treatments of halosulfuron and *S*-metolachlor were reduced (46.0 and 48.3 cm, respectively) (Table 1) compared to double drip tape treatments of fomesafen, *S*-metolachlor, and the nontreated control (52.9, 54.1, and 53.4 cm, respectively) (Table 1).

60 DAP. Plant height was reduced across single drip tape treatments compared to double drip tape treatments (105.4 and 108.3 cm, respectively) (Table 1). Comparison of individual treatments revealed a reduction in plant heights in single drip tape fomesafen treatments (75.5 cm) compared to double drip tape halosulfuron and control treatments (83.3 and 84.3 cm, respectively) (Table 1).

Yield: Tomato marketable yield was only influenced by the main effect of drip tape treatment; main effect of herbicide and interaction of drip tape and herbicide were both nonsignificant

($\alpha=0.10$; Table 1). Marketable yield was reduced across single drip tape treatments compared to double drip tape treatments (4.5, and 6.1 kg, respectively).

Discussion

Across all collected data, yellow nutsedge punctures were lowest in plots receiving *S*-metolachlor when compared to other herbicide treatments and the control (9.1, 13.7, 16.3, and 16.3 punctures, for *S*-metolachlor, halosulfuron, fomesafen, and the control, respectively).

Previous research has shown drip-applied herbicides in polyethylene-mulched tomato provided similar results when compared to the commercial standard of *S*-metolachlor spray-applied to the bedded surface prior to polyethylene mulch application (Adcock, 2007; Monday et al., 2015). Use of two drip tapes in the application of these herbicides failed to provide better control of yellow nutsedge punctures when compared to applications with a single drip tape. However, the use of two drip tapes in the application of herbicides produced greater yields, and failed to result in any negative growth responses (quantified by plant height and yield) when compared to the use of a single drip tape for herbicide application. Plots receiving herbicides from single drip tape treatments showed stunting in plant height compared to double drip tape treatments, possibly from the herbicides being leached more directly to the root zone. This stunting could explain the differences in yield between single and double drip tape treatments as well. It is important to note that these studies were conducted on a sandy loam soil and studies conducted on soils containing higher amounts of sand or clay could yield different results. Additional research on those soil types is needed to determine possible outcomes and recommendations.

Overall, the data shows that double drip tape treated plots had higher yields than single drip tape treated plots. A cost-benefit analysis would be required to make any cost saving claim, and that was not part of this research project. Without further research it would be unwise to make definite claims, but in some settings a second drip tape at the time of PRE herbicide treatment could indeed prove beneficial.

In our situation of light to moderate yellow nutsedge infestation, drip tape number at time of treatment had no effect on puncture incident. However, herbicide treatment did effect yellow nutsedge control. Plots receiving *S*-metolachlor had reduced punctures compared to other herbicide treatments. Tomato height and yield were reduced in single drip tape treatments when compared to double drip tape treatments, likely due to injury by herbicide leached into the crop root zone. Although the use of a second drip tape could not be recommended on the basis of improved nutsedge control, it could be recommended as beneficial but not cost-saving. Growers dealing with yellow nutsedge populations could find drip application of *S*-metolachlor beneficial in their weed management programs.

The main goal of this research was to examine one versus two drip tapes to improve herbicide efficacy and herbicide lateral movement throughout the bed. Use of two drip tapes would reduce the length of application times and therefore the amount of time pumps would need to run to reach adequate irrigation levels. With concerns over water conservation growing, the increase in water use needed for drip application of herbicides could limit its use. Future studies to examine the use of surfactants in drip-applied herbicide application in attempts to lower water use are needed. Future research towards yellow nutsedge control could also benefit by looking at the combination of double drip tape application of *S*-metolachlor with different

types of polyethylene mulch, as well as combinations of *S*-metolachlor and other PRE herbicides.

Table 1. Yellow nutsedge puncture count following treatment with herbicides using single and double drip tapes; Old Agronomy Farm, Auburn, AL. 2015 and 16 pooled data.

Treatment		Nutsedge Punctures		Tomato Height ^b		Tomato Yield	
Drip Tape ^a	Herbicide	30 DAT ^b	60 DAT	30 DAT ^c	60 DAT	Marketable	Nonmarketable
<i>Comparisons among main effects:</i>							
		no./m ²		cm		kg	
Single	-	3.6 ns ^b	12.8 ns	47.7 b ^d	78.2 b	4.5 a ^b	3.6 ns ^c
Double	-	2.5	13.2	53.1 a	81.2 a	6.1 b	4.1
-	Fomesafen	3.7 a ^c	16.3 a	50.8 ns	77.9 ns	5.6 ns	3.7 ns
-	Halosulfuron	3.3 a	13.7 a	49.1	81.1	5.4	4.1
-	<i>S</i> -metolachlor	1.8 b	9.1 b	51.2	80.2	4.9	4.2
<i>Comparisons among individual treatments:</i>							
Single	Fomesafen	4.5 ns	14.6 ab ^c	48.7 bc ^d	75.5 b	4.4 ns	3.2 ns
-	Halosulfuron	4.5	15.8 a	46.0 c	78.9 ab	4.7	3.8
-	<i>S</i> -metolachlor	1.8	8.1 b	48.3 c	80.2 ab	4.3	3.8
Double	Fomesafen	3.0	18.0 a	52.9 a	80.3 ab	6.8	3.2
-	Halosulfuron	2.5	11.6 ab	52.2 ab	83.3 a	6.1	4.5
-	<i>S</i> -metolachlor	1.9	10.0 ab	54.1 a	80.1 ab	5.5	4.6
	Nontreated ^d	4.1	16.3 a	53.4 a	84.3 a	5.6	5.1
^a Single: single drip tape laid in the center of each plastic mulched bed; Double: two drip tapes laid equidistantly down each plastic mulched bed. Herbicide rates: fomesafen = 280 g ai ha ⁻¹ , halosulfuron = 54 g ai ha ⁻¹ , <i>S</i> -metolachlor = 1,400 g ai ha ⁻¹ ^b Abbreviations: DAT, days after treatment; ns, no significant difference. ^c Means followed by the same letter do not differ according to the Shaffer-Simulated test ($\alpha = 0.10$). ^d Nontreated = no herbicide and with single drip tape.							

Chapter III

Evaluation of Single and Double Drip Tapes in PRE Herbicide Application for Control of Purple Nutsedge (*Cyperus rotundus*) in Plasticsulture Tomato

Introduction

Field studies were conducted in 2015 and 2016 at the E.V. Smith Research Station in Shorter, Alabama, to evaluate the effect of single and double drip tapes for the application of PRE herbicides under polyethylene mulched beds for purple nutsedge (*Cyperus rotundus*) control in plasticsulture tomato. Tomato crop response was also monitored (plant height and yield). Three PRE-applied herbicides [fomesafen (280 g ai ha⁻¹), halosulfuron (54 g ai ha⁻¹), S-metolachlor (1.4 gk ai ha⁻¹)] were applied using either a single drip tape running down the center of the bed, or two drip tapes spaced equidistantly within the bed. Treatments were applied after drip tape lines were purged of air and beds were pre-wetted. A control treatment of a single drip tape with no herbicide was also included. The addition of a second drip tape reduced purple nutsedge punctures (44 and 47% at 30 and 60 DAT, respectively) compared to single drip tape treatments. Purple nutsedge punctures were also reduced in plots receiving fomesafen compared to plots receiving halosulfuron or S-metolachlor. Plant heights measured 30 DAT were reduced in plots receiving fomesafen and by single drip tape treatments; however, no height differences were found 60 DAT. Tomato yield was higher in double drip tape treatments compared to single drip tape treatments. These results suggest producers facing heavy purple nutsedge populations could benefit from using a second drip tape at time of herbicide application.

Literature Review

Weed control is one of the most difficult aspects of vegetable production, and a problem which producers all over the world are facing (Gilreath and Santos, 2004). If left unchecked, excessive weed competition can result in substantial crop yield reduction. Most vegetable crops do not possess the competitive capabilities to outcompete weeds for resources like light, water, nutrients, and space (Gilreath and Santos, 2004). One such competitor would be purple nutsedge (*Cyperus rotundus*) which has been called the world's costliest agricultural weed (Holm et al., 1991). In the Southeastern United States, this weed is considered a major weed of vegetable production and is widespread in almost all areas where commercial vegetable production takes place (Webster, 2006). Competition from nutsedge can reduce crop yield and quality substantially, with some reported reductions in agronomic crops of 79 to 87% (Earl et al., 2004).

Nutsedge

Nutsedge is an herbaceous C4 perennial that is a member of the family *Cyperaceae* and is in the genus *Cyprus*. Nutsedge has three ranked basal leaves with triangular stems, and is one of the world's most problematic weed species (Earl et al., 2004). This perennial reproduces by both seed and vegetative structures. The seedhead can range in color from purple to reddish-brown. Seeds from purple nutsedge have low germination rates of 1-2% (Hoffmann et al. 2006), and are not the main method for reproduction. The main method of reproduction for nutsedge is by tubers, which are edible (Colvin et al., 1992). These tubers vary in shape from round to oblong, are generally whitish, and may or may not contain hair depending on the species of nutsedge. The prolific vegetative reproduction by means of tubers and rhizomes has helped nutsedge become the widespread and aggressively competitive weed species that we are fighting today. In 1961, Tumbleson and Komedahl reported that a single nutsedge tuber has the capability of

producing up to 1900 shoots and 6900 tubers in a single year. These tubers, and their longevity, have caused *Cyperus* species to become a major problem in the southeastern United States (Troxler et al., 2003). Webster and Coble published a survey in Southern Weed Science Society in 1997 that listed purple nutsedge among the top 3 problematic weeds everywhere in the United States. This was attributed to the fact that it is so well established and difficult to control (Warren et al., 1999). Purple nutsedge can also serve as alternate hosts for plant parasitic nematodes such as the Southern root-knot nematode (*Meloidogyne incognita*) (Hogger et al., 1974). Plastic mulch is even ineffective at controlling nutsedge as the plant can easily puncture the plastic mulch, allowing competition with crops (Branenberger et al., 2005). However, Webster did report in 2005 that plastic mulch, either clear or black, reduced shoot and tuber production compared to unmulched controls. In peppers, losses of 10% were reported from nutsedge populations as small as five tubers per square meter and losses up to 74% being reported from populations of 30 tubers per square meter. The case is similar in tomato production (Motis et al., 2003). A study by Gilreath and Santos in 2004 reported yield reduction of 51% from season long nutsedge populations of 113 plants per square meter. Likewise, a study in 2003 (Morales-Payan et al., 1997), reported that marketable yield reductions of 25, 55, and 65% were observed when yellow nutsedge emerged at densities of 25, 50, and 100 plants per square meter, respectively. It was also reported that for lower nutsedge populations (25-50 plants per square meter), suppression in the first 8 weeks after transplant was required to prevent yield reductions greater than 5%.

Methyl bromide

In years prior to the 1997 Montreal Protocol, nutsedge and many other pests were controlled by the use of the fumigant Methyl bromide (MBr). However, due to its consideration as an environmental concern (Gilreath and Santos, 2004), MBr has now been phased out of use in all agricultural applications. With MBr now off the market, producers face a challenge to find

effective chemicals or combinations to control pests which had previously been managed with MBr. (Webster et al., 2005). Many such chemicals and combinations are being researched as replacements and the list of such replacements includes Sulfonylureas, Chloroacetamides, diphenyl ethers, metam-sodium, methyl iodine, steam, fumigants, solarization, and even ozone gas.

Herbicides

Sulfonylurea (SU) herbicides have some characteristics that make them prime candidates to be an MBr replacement. These characteristics include: comparatively low application rates, insignificantly adverse environmental effects, and a high degree of crop selectivity (Burker et al., 2004). The mode of action of sulfonylurea herbicides as a group, is characterized by the inhibition of the synthesis of certain branched-chain amino acids like valine, leucine, and isoleucine. SU's first target the enzyme acetolactate synthase (ALS) (Burker et al., 2004). Fogel found in 1998, that SU's are 100 times more lethal in weed control than the herbicides that were in use prior to 1982. SU's are used for their selectivity in controlling perennial sedges, like yellow and purple nutsedge, kyllingas, and a selection of broadleaf weeds in horticultural and agronomic crops (Burker et al., 2004). SU's have short persistence in the soil, and their selectivity allows them to be used in many different weed control situations (Askew et al., 2004). Tomatoes have exhibited excellent tolerance to SU's (Troxler et al., 2003).

Halosulfuron is a sulfonylurea herbicide that is being considered as an MBr replacement. It is an ALS inhibitor. Halosulfuron is produced by Gowan (Yuma, AZ) under the label name Sandea. Halosulfuron is a systemic herbicide that can be applied as a preemergence (PRE) or postemergence (POST) herbicide in many situations (McElroy et al., 2004). It has both PRE and

POST activity on yellow nutsedge. Currently, Halosulfuron is used for weed control in vegetable crops (Senseman, 2007) including tomatoes (*Lycopersicon esculentum*).

Chloroacetamides are soil applied chemistries that have PRE or pre plant incorporation use, though they are not volatile enough to require incorporation. These herbicides act by inhibiting production of long chain lipids which are needed for production of plant waxes. As a class, the chloroacetamides have very low acute toxicity. Although absorption of chloroacetamides occurs in both the roots and shoots of young seedlings, shoot tissues are both more sorptive, as well as the site of herbicide action. Translocation through the xylem is not considered relevant since death occurs at seedling growth stage. These herbicides dissipate fairly quickly due to microbial action, with the group averaging 6-10 weeks (Senseman, 2007).

S-metolachlor is soil active herbicide in the chloroacetamide family of herbicides. *S*-metolachlor is produced by Syngenta Crop Protection Inc. (Greensboro, NC) under the label name of Dual Magnum, and is a biosynthesis inhibitor with multiple site, nonspecific mode of action. It is labeled for control of annual grasses, yellow nutsedge, and broadleaf weeds in many different crops (Syngenta, 2005). *S*-metolachlor has been used for both PRE and POST control since 1952 (Feigenbrugel et al., 2004). Though the ability of *S*-metolachlor to control sedges has been established in some crops (Grichar, 1992; Odrigawitch et al., 1980), little has been published on the use of *S*-metolachlor alone in tomato production. Despite this, Santos et al. (2006) and Gilreath and Santos (2004) have published results of combining *S*-metolachlor and other MBr replacements showing increased yellow nutsedge control.

Diphenyl ethers are a family of herbicides characterized by two rings linked by an ether bridge, are generally considered POST active but all have some amount of PRE activity. Of these, fomesafen has the most PRE activity. This family has been of growing interest in

transgenic crop production where herbicide resistant weeds are becoming more of a problem. Diphenyl ethers mode of action, PROTOX inhibition, differs from those modes of action used in GMO crops. These diphenyl ethers have been used to control escapes, and resistance to this mode of action is presumed to be much less likely (Senseman, 2007).

Fomesafen is a systemic-active herbicide from this diphenyl ether family of herbicides. This family inhibits protoporphyrin oxidase or PROTOX. Inhibition of PROTOX results in lipid peroxidation, disruption of cell membranes, and ultimately plant death (Ensminger and Hess, 1985). After treatment, leaves of susceptible plants become chlorotic, and then desiccated and necrotic within one to three days (Senseman, 2007). Fomesafen, which is currently labeled for control a list of broadleaf weeds as well as sedges in soy, cotton, and potatoes (Anonymous, 2013), has recently been evaluated for use in a number of vegetable crops and has received Section 24C labels for use in tomato and pepper production in Georgia, Florida, and North Carolina (Culpepper, 2012). Fairly long soil persistence and moderate mobility in the soil have led to some restrictions in crops that can follow fomesafen use. A recent study showed fomesafen to have similar levels of control over a similar spectrum of weed species as the chloroacetamide *S*-metolachlor; however, fomesafen provides an important tool for rotation of herbicide mode of action.

Chemigation

Chemigation, or the process of applying an agricultural chemical to the soil or plant surface through irrigation systems, is achieved by introducing the chemical into the irrigation water with the use of an injector. Though initially designed to deliver fertilizers that required soil incorporation, this system has shown promise in its ability to also inject other agricultural chemicals such as herbicides, insecticides, or fungicides (Wang et al., 2009). While chemigation

systems can vary in their design, the basic components include: An irrigation pump, a backflow preventer, a chemical injection pump, and a chemical reservoir. Since most vegetable production systems utilize drip irrigation under polyethylene mulch, they are an ideal choice for using chemigation. To achieve optimal results an initial wetting period is used to get any air out of the irrigation lines and to ensure initial water movement into the soil. The desired chemical is injected after this wetting period, and after injection the system is flushed with fresh water to expel any remaining chemicals from the drip irrigation lines. There are a few possible disadvantages to drip application of agricultural chemicals such as the need for additional equipment (injection pump) and increased application times. However, these disadvantages are generally offset by the many advantages of chemigation which can include increased applicator safety and chemical movement to desired zone, as well as decreased compaction and damage from chemical drift (Thomas et al., 2003; Wang et al., 2009). Along with these advantages, weed control through drip-applied herbicides can increase production efficiency of crops through lowering application, labor, and fuel costs (Johnson et al., 1986). While many studies exist reporting the potential of using drip-application systems in vegetable production for fumigant application (Ajwa et al., 2002; Candole et al., 2007; Chase et al., 2006; Locascio et al., 1997), fewer studies have been conducted on herbicide injection. Recent studies have shown drip-application of *S*-metolachlor and halosulfuron to be competitive with spray applications in controlling yellow nutsedge under polyethylene mulch when no crop was present (Adcock, 2007). These two herbicides were also found to be safe for tomatoes as well as effective in controlling yellow nutsedge in polyethylene-mulched tomato production systems (Santos et al., 2008, Dittmar et al., 2012a, Dittmar et al., 2012b).

A limiting factor in the acceptance of drip application of herbicides has been herbicide movement. It has been reported in recent studies (Dittmar et al., 2012b, Monday et al., 2015) that yellow nutsedge control is observed to be reduced as distance from the drip tape emitters increases, and that two drip tapes were required for uniform application of herbicides across the bed surface. These same trends have also been noted in studies examining drip-tape application of fumigants in polyethylene-mulched beds (Fennimore et al., 2003, Candole et al., 2007, and Chase et al. 2006). Keeping this in mind, it is necessary to improve lateral movement of drip-applied herbicides in polyethylene-mulched beds for the optimization of nutsedge control as well as to allow for multi-cropping of a single application of polyethylene mulch Monday et al. (2015) reported that for Marvyn sandy loam comprised of after 7 hours of irrigation using a single drip tape on a polyethylene mulched bed, emitter-to-emitter coverage was achieved and approximately 70% of the bed surface had been wetted. Additional irrigation did not result in an increase in lateral movement of the moisture field across the bed surface. It should be noted that different soil types can affect lateral movement of the moisture field in polyethylene-mulched beds and therefore herbicide movement.

Conclusion

Weed control is an important and difficult task for vegetable producers. With the EPA phase out of methyl bromide, a soil fumigant that had been used extensively in agriculture as a soil sterilant, some farmers have been left searching for effective alternatives for hard to control weeds such as nutsedge. The ability of nutsedge species to punctures polyethylene plastic has led to them being declared some of the world's worst weed species. Some recent work has shown promise in Methyl bromide replacements with certain herbicides, fumigants, and combinations of both. Previous work at Auburn has shown that drip applied herbicides can offer competitive

control to a sprayed application (Monday et al., 2015). While this work was promising, the large volume of water used at time of application leached herbicides lower into the soil profile out of their target zone and possibly into the crop root zone. A need exists in drip application of agricultural chemicals for increased lateral movement of the wetting zone and herbicides with minimal herbicide leaching. In this study, the use of either a single drip tape centered in the bed or two drip tapes spaced equidistance across the bed width was evaluated to determine if the second drip tape increased lateral movement of herbicides, if the use of a second drip tape decreased nutsedge punctures, and if the use of a second drip tape would cause injury to a tomato crop. The double drip tape system, if proven effective in controlling nutsedge punctures, could extend the life of polyethylene mulch to allow for a multi cropping system and therefore extend the increased cost of drip tape over multiple crops.

Materials and Methods

Field studies were conducted in the summer of 2015 and 2016 at the E.V. Smith Research Center (EVS) located in Shorter, AL. The soil type was a Marvyn sandy loam (fine-loamy, kaolinitic, thermic type **Kanhadpludults**) comprised of 75.6, 6.8, and 17.5% sand, silt, and clay, respectively, with pH 5.7. Fields used in the experiment had a history of heavy purple nutsedge infestation. In both years, soil was prepared and formed using a bedder (Reddick fumigants, Williamson, NC) into four raised beds 61 m long, 91 cm wide, 13 cm high, and covered with white polyethylene mulch (1.25 mil, white on black, embossed; Berry Plastics Corp., Evansville, IN). Each of the four rows (spaced 2 meters apart) contained 8 4.57-m plots with a 3-m buffer between plots. In both years, experimental units contained 10 tomato plants spaced 0.4-m apart. Transplants were started on March 18 and April 14 in 2015 and 2016, respectively. Transplants for both years were grown at Auburn University's Plant Sciences Research Center. Transplants

received fertilization of 200 ppm N once per week, beginning two weeks after germination. Tomatoes were transplanted on June 10 and June 1 in 2015 and 2016, respectively. Fertility and management of tomatoes followed commercial growing standards (Kemble, 2013). Prior to mulch application, drip tapes (Toro Ag., Bloomington, MN) were placed under the mulch. All drip tape was buried to a depth of approximately 5 cm. Drip tape emitters were spaced 30.5 cm apart delivering 1.02 L h^{-1} .

The experiment was conducted in a completely randomized design with four replications. Treatments were arranged in a factorial consisting of two drip tape arrangements and three PRE-applied herbicide treatments [halosulfuron (54 g ai ha^{-1}), *S*-metolachlor (1.4 kg ha^{-1}), and fomesafen (280 g ha^{-1})]. The two drip tape arrangement methods were either a single drip tape placed in the middle of the bed or two drip tapes placed equidistance from bed shoulders. All drip tapes were buried 5 cm deep. An additional treatment was included to represent a commercial standard of one drip tape placed in the middle of the bed, with no herbicides applied. Drip treatments were applied along with approximately $14,000 \text{ L ha}^{-1}$ of water with Dosatron® D14MZ2 injectors (Dosatron International Inc., Clearwater, FL) and a custom injection manifold. The large quantity of water used in application of treatments was necessary to saturate beds fully and promote herbicide movement throughout the bedded surface. Length of application time was based on Csinos et al. (2002) dye injection test for tracing water and pesticide movement in polyethylene mulched beds. From each port on the manifold, a section of 1.27-cm plastic tubing was connected to the front of each corresponding plot. Plots of the same treatments were then connected by splicing into the drip tape and capped where needed.

Quantity of herbicide applied to each treatment was based on the combined area of the four individual plots utilized per treatment. Single drip tape treatments required 3.5 hours to

inject while the double drip tape treatments required half that, at 1.75 hours. Treatments were applied on 3 June and 10 May in 2015 and 2016, respectively. Treatments were applied 7 d prior to transplanting tomatoes, per herbicide label recommendations. Nutsedge punctures were counted at 30 and 60 days after treatment (DAT) from a 1.0 m² section of the plot. Tomato height (base of plant to the top of the growing point) was measured 30 and 60 days after planting (DAP) to evaluate potential herbicide injury. Additionally, tomato fruit was harvested when fruit were 5 cm or larger in diameter, in breaker to red stage, and were graded as marketable or nonmarketable per U.S. Department of Agriculture standards (USDA, 1991) Fruit were harvested from the entire plot; additionally, fruit were harvested four times in 2015 and twice in 2016.

Data were analyzed with generalized linear models with the use of GLMMIX procedure of SAS (version 9.2; SAS Institute, Cary, NC) with the normal distribution and identity link function for plant height and yield and negative binomial distribution and log link function for puncture counts. Tomato height, nutsedge punctures, marketable yield, and unmarketable yield were included in the models as random factors. Herbicide by application method interactions were not significant for all variables; therefore, levels within main effects were examined. Least-squares means for tomato height were compared to those for the control and other plots with the use of lower-tailed *t* tests. In addition, least-squares means for nutsedge puncture and marketable and unmarketable yield were compared to those for the commercial standard by two-tailed *t* tests. All P values for tests of differences between least-squares means were adjusted with the use of the Shaffer-Simulated method ($\alpha=0.10$).

Results and Discussion

Purple Nutsedge Punctures. Purple nutsedge punctures were not influenced by the interaction of drip tape treatment and herbicide; therefore, main effects were examined (Table 2).

30 DAT. Nutsedge punctures counted 30 DAT were influenced by drip tape treatment only.

Double drip tape treatments had less punctures (57 m^{-2}) than the single drip tape treatments (102 m^{-2}). Comparisons of individual treatments revealed double drip tape fomesafen treatments had less punctures (48 m^{-2}) than the nontreated control (88 m^{-2}) and single tape treatments with any herbicide (108 , 106 , and 92 m^{-2} for fomesafen, halosulfuron, and *S*-metolachlor, respectively; Table 2).

60 DAT. Nutsedge punctures counted 60 DAT were influenced by both herbicide and drip tape treatment (Table 2). Punctures were lower in double tape treatments (86 m^{-2}) than in single drip tape treatments (161 m^{-2}). Furthermore, treatments containing fomesafen had lower punctures (91 m^{-2}) than those containing either halosulfuron or *S*-metolachlor (134 and 126 m^{-2} , respectively). Comparisons among individual treatments revealed that double drip tape fomesafen treatments had less punctures (70 m^{-2}) than single drip tape halosulfuron and *S*-metolachlor treatments (180 m^{-2} and 184 m^{-2} , respectively), as well as the nontreated control (154 m^{-2})(Table 2).

Tomato Response. Tomato height was not influenced by the interaction of drip tape treatment and herbicide; therefore, main effects were examined (Table 2).

30 DAP. Tomato height measured 30 DAP was influenced by the main effect of both drip tape treatment and herbicide. Plant height was reduced across single drip tape treatments compared to double drip tape treatments (60.9 and 63.3 cm , respectively). Moreover, comparisons among individual treatments revealed significant differences (Table 2). Plant height in single drip tape

fomesafen treatments were reduced (42.7 cm) compared to the nontreated control (48.4 cm), and single drip tape and double drip tape halosulfuron (46.5, and 48.0 cm, respectively) and single drip tape and double drip tape *S*-metolachlor (46.3, and 48.3 cm, respectively).

60 DAP. Tomato height measured 60 DAP was not influenced by the main effect of drip tape treatment (103.7 and 103.3 cm for single and double, respectively) or herbicide (103.2, 104.3, and 102.9 cm for fomesafen, halosulfuron, and *S*-metolachlor, respectively; Table 2).

Furthermore, comparisons of individual treatments showed similar plant height among all treatments (range: 78.2 to 80.2 cm; Table 2)

Yield. Tomato yield was not influenced by the interaction of drip tape treatment and herbicide; therefore, main effects were examined (Table 2). Tomato yield was influenced by drip tape treatment only. Marketable yield was reduced across single drip tape treatments compared to double drip tape treatments (22.2 kg and 25.2 kg, respectively). There was no significant difference in yields among herbicides. Moreover, comparisons of individual treatments showed no significant difference in tomato yield (Table 2).

Discussion

Across all collected data, purple nutsedge punctures were lowest in double drip tape plots regardless of herbicide treatment. Plots receiving fomesafen treatments showed a reduction in purple nutsedge punctures 60 DAT when compared to the other herbicide treatments. Previous research has shown drip-applied herbicides in polyethylene-mulched tomato provided similar control of nutsedge spp. compared to the commercial standard of *S*-metolachlor spray-applied to the bedded surface prior to polyethylene mulch application (Monday et al. 2015). Use of two drip tapes in the application of these herbicides provided better control of purple nutsedge punctures (quantified by puncture counts), produced greater yields, and failed to result in negative growth

responses (quantified by plant height and yield) when compared to the use of a single drip tape for herbicide application. It is important to note that these studies were conducted on a sandy loam soil and studies conducted on soils containing higher amounts of sand or clay could yield different results. Additional research on those soil types is needed to determine possible outcomes and recommendations.

The main goal of this research was to examine two drip tapes versus one to improve herbicide efficacy and herbicide lateral movement throughout the bed. Utilization of two drip tapes for herbicide application resulted in less injury 30 DAP, reduced purple nutsedge punctures, and an increase in marketable yield compared to the use of a single drip tape for herbicide application. Use of double drip tape for herbicide (and other chemicals) applications methods would reduce the length of application times and therefore time pumps would need to run to reach adequate irrigation levels.

In situations of heavy purple nutsedge populations the use of second drip tape in drip application of PRE herbicides could significantly increase purple nutsedge control (approximately 44% reduction in punctures), with the greatest possible level of control coming from double drip tape plots treated with fomesafen. Some stunting was seen early on with this treatment, but plants showed no sign of stunting by 60 DAT and had no difference in marketable yield. Single drip tape plots had reduced yield, likely due to herbicide movement into the crop root zone and increased purple nutsedge competition

Overall, the data shows that double drip tape treated plots had higher yields than single drip tape treated plots. A cost-benefit analysis would be required to make any cost saving claim, and that was not part of this research project. Without further research, it would be unwise to make definite claims, but in some settings a second drip tape at the time of PRE herbicide

treatment could indeed prove beneficial.

Table 5: Purple nutsedge puncture count following treatment of herbicides and single and double drip tapes; E.V. Smith Research Center, Shorter, AL. 2015 and 16 pooled data.								
Treatment ^a		Nutsedge Punctures		Tomato height		Tomato Yield		
Drip Tape ^a	Herbicide	30 DAT ^b	60 DAT	30 DAT	60 DAT	Marketable	Nonmarketable	
<i>Comparisons among main effects:</i>								
		no./m ²		cm		kg		
Single	-	102 a ^c	161 a	45.2 b	79.4 ns	22.2 b	4.4 ns	
Double	-	57 b	86 b	47.3 a	78.8	25.2 a	4.7	
	Fomesafen	72 ns	91 c	44.2 b	78.8 ns	22.3 ns	3.8 ns	
	Halosulfuron	83	134 b	47.3 a	80.1	24.5	5.1	
	S-metolachlor	73	126 b	47.3 a	78.7	24.2	4.6	
<i>Comparisons among individual treatments:</i>								
Single	Fomesafen	108 a	118 abc	42.7 b	79.2 ns	20.6 ns	3.5 ns	
	Halosulfuron	106 a	180 a	46.5 a	80.0	22.2	5.6	
	S-metolachlor	92 ab	184 a	46.3 a	79.1	23.8	3.9	
Double	Fomesafen	48 c	70 c	45.6 ab	78.5	23.9	4.2	
	Halosulfuron	65 bc	101 bc	48.0 a	80.2	27.1	4.7	
	S-metolachlor	58 bc	86 bc	48.3 a	78.2	24.5	5.2	
	Nontreated ^d	88 ab	154 ab	48.4 a	78.4	22.5	4.6	
^a Single: single drip tape laid in the center of each plastic mulched bed; Double: two drip tapes laid equidistantly down each plastic mulched bed. Herbicide rates: fomesafen = 280 g ai ha ⁻¹ , halosulfuron = 54 g ai ha ⁻¹ , S-metolachlor = 1,400 g ai ha ⁻¹ ^b Abbreviations: DAT, days after treatment; ns, no significant difference. ^c Means followed by the same letter do not differ according to the Shaffer-Simulated test ($\alpha = 0.10$). ^d Nontreated = no herbicide and with single drip tape.								

Chapter IV

Final Discussion

Methyl bromide had previously been the industry standard for nutsedge control, and its phase out left a void that has yet to be filled. Researched alternatives include herbicides, other fumigants, steam, and solarization. Injection of herbicides through drip tape systems under polyethylene mulched beds has been shown to be a possible alternative to methyl bromide for nutsedge control (Monday et al., 2015, Adcock, 2007, Dittmar et al., 2012). However, the vast amount of water needed to move the herbicide throughout the bed is believed to have resulted in excessive leaching of the herbicides. This study compared the use of two drip tapes versus one drip tape for applying three PRE-herbicides under polyethylene mulched beds for nutsedge control. The three herbicides used in this study were fomesafen, halosulfuron, and *S*-metolachlor. Nutsedge puncture incidence, tomato height, and tomato yield were recorded for comparisons of herbicide efficacy and crop injury.

In chapter II, field studies were conducted in an area infested with mainly yellow nutsedge (*Cyperus esculentus*). Utilization of a second drip tape did not reduce nutsedge punctures, but the use of *S*-metolachlor did. Tomato plant heights and yield were greater across all double drip tape treatments compared to single drip tape treatments. This research suggests that while two drip tapes may not improve yellow nutsedge control, it may reduce initial injury and subsequent yield loss when using drip-applied herbicides. This research also reaffirms the ability of *S*-metolachlor to control yellow nutsedge.

In chapter III, field studies were conducted in an area of heavy nutsedge infestation, which was almost entirely purple nutsedge (*Cyperus rotundus*). At this site, the use of a second drip tape significantly reduced purple nutsedge punctures 30 and 60 DAT (47 and 44% respectively compared to single drip tape treatments). Fomesafen offered the greatest control later in the season (60 DAT) when compared to other herbicide treatments. Marketable yields were also greater in double drip tape treatments compared to single drip tape treatments. This research suggests that, in heavy purple nutsedge infestations, the use of a second drip tape could be beneficial to producers, especially when used in combination with fomesafen.

While the use of a second drip tape in the application of drip applied herbicides shows promise, more research is needed to determine viable soil types for this system. Different soil compositions could lead to increased leaching and need for different irrigation schedules. Different soil types could also impact the efficacy and residual effect of herbicides. Research into the use of surfactants at injection to increase lateral movement and reduce the volume of water for application could also prove beneficial.

Figure 1. Injection system



Figure 2. Drip tapes connected via treatment



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