Effects of Application Method and Surfactants on Control of Yellow Nutsedge with Drip-Applied Herbicides in Polyethylene-Mulched Tomato

by

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Abstract

Use of polyethylene mulch in vegetable production provides many benefits including improved weed control; however, not all weed species are adequately controlled. Yellow nutsedge (*Cyperus esculentus* L.) can penetrate polyethylene mulch, degrading its durability, and is a serious concern for growers wanting to use the mulch for multicropping systems. To manage nutsedge species in these systems, halosulfuron (Sandea®) and *S*-metolachlor (Dual Magnum®) are often sprayed to beds prior to mulch application. However, application of herbicides through drip irrigation has become more prevalent and offers several benefits over sprayed applications. Research has shown the potential for use of drip-applied herbicides in commercial production; however, some issues need to be addressed. Recent research has indicated that yellow nutsedge control diminishes with increasing distance from drip emitters. Therefore, a need exists to improve the movement of drip-applied herbicides in polyethylene-mulched beds.

Field studies were conducted to evaluate three selected application methods for improving movement of drip-applied halosulfuron, *S*-metolachlor, and fomesafen in polyethylene-mulched tomato. Treatments were evaluated based on their effect on yellow nutsedge punctures and the corresponding responses (plant height and yield) of a tomato (*Solanum lycopersicum*) crop. Drip-applied treatments were compared to a commercial standard, *S*-metolachlor, which was sprayed to the bed surface prior to mulch application. A nontreated control (beds with polyethylene mulch without herbicides) was included for comparison. The experiment was a factorial treatment arrangement of three drip application methods and three PRE-applied herbicides (halosulfuron at 54 g ai ha^{-1}, *S*-metolachlor at 1.4 kg ha^{-1}, and fomesafen at 280 g ha^{-1}). Herbicides were applied either immediately following saturation of the planting beds (method A), along with an extended period used to saturate beds (method B), or just prior to bed saturation (method C). Results indicated that fomesafen applied with method B was the only treatment that provided a significant reduction in yellow nutsedge punctures (55% compared to commercial standard) while maintaining marketable yields comparable to the commercial standard. Furthermore, fomesafen and halosulfuron, each applied with method C, provided similar control of yellow nutsedge punctures and similar yields to the commercial standard. These results suggest, when applied with the appropriate method, drip-applied fomesafen and halosulfuron may provide suitable control of yellow nutsedge punctures in polyethylene-mulched tomato while maintaining desirable yields.

Additional field studies were conducted to evaluate two nonionic surfactants, Integrate® 20 and Tween® 20, for improving movement of drip-applied halosulfuron, *S*-metolachlor, and fomesafen in polyethylene-mulched tomato. Treatments were again evaluated based on their effect on yellow nutsedge punctures and the corresponding responses of a tomato crop (plant height and yields). Drip-applied treatments were compared to a commercial standard of *S*-metolachlor which was sprayed to the bed surface prior to mulch application. A nontreated control (beds with polyethylene mulch without herbicides) was included for comparison. The experiment was a factorial treatment arrangement of three surfactant levels [Integrate® 20 at 2.8 kg ha^{-1}, Tween® 20 at 2.8 kg ha^{-1} and no surfactant (i.e. none)] and three PRE-applied herbicides (halosulfuron at 54 g ai ha^{-1}, *S*-metolachlor

at 1.4 kg ha^{1}, and fomesafen at 280 g ha^{-1}). Application of surfactants with drip-applied herbicides failed to reduce yellow nutsedge punctures relative to herbicides applied without surfactants. Results are likely due to the failure of surfactants to improve lateral movement of the herbicides underneath the polyethylene-mulched beds.

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Table of Contents

Abstract....................ii

Acknowledgements....................v

List of Tables....................viii

List of Figures....................x

Chapter I: Introduction and Literature Review....................1

Introduction....................1

Literature Cited....................13

Chapter II: Yellow Nutsedge (*Cyperus esculentus*) Control and Crop Response to Application Methods of Drip-Applied Herbicides in Polyethylene-Mulched Tomato

Abstract....................21

Introduction....................23

Materials and Methods....................26

Results and Discussion....................30

Literature Cited....................36

Chapter III: Yellow Nutsedge (*Cyperus esculentus*) Control and Crop Response to Drip-Applied Herbicides Applied with Nonionic Surfactants in Polyethylene-Mulched Tomato

Abstract....................48

Introduction....................50

Materials and Methods....................54

Results and Discussion....................57

Literature Cited..62

Chapter IV: Final Discussion..72

List of Tables

Chapter II:

Table 1: Plant height and early season yield of tomato following treatment with herbicides using selected drip-application methods at the E.V. Smith Research Center in Shorter, AL in 2013 only....39

Table 2: Plant height and early season yield of tomato following treatment with herbicides using selected drip-applied methods at the Old Agronomy Farm in Auburn, AL in 2013 only....40

Table 3: Yellow nutsedge punctures and yield of tomato following treatment with herbicides using selected drip-application methods at the E.V. Smith Research Center in Shorter, AL. Data for 2012 and 2013 are pooled....41

Table 4: Yellow nutsedge punctures and yield of tomato following treatment with herbicides using selected drip-application methods at the Old Agronomy Farm in Auburn, AL. Data for 2012 and 2013 are pooled....42

Table 5: Yellow nutsedge control in tomato following treatment with herbicides using selected drip-application methods at the E.V. Smith Research Center in Shorter, AL. Data for 2012 and 2013 are pooled....43

Table 6: Yellow nutsedge control in tomato following treatment with herbicides using selected drip-application methods at the Old Agronomy Farm in Auburn, AL. Data for 2012 and 2013 are pooled....44

Chapter III:

Table 1: Yellow nutsedge punctures and yield of tomato following treatment with herbicides applied with and without surfactants at the E.V. Smith Research Center in Shorter, AL. Data for 2012 and 2013 are pooled....66

Table 2: Yellow nutsedge punctures and yield of tomato following treatment with herbicides applied with and without surfactants at the Old Agronomy Farm in Auburn, AL. Data for 2012 and 2013 are pooled..67

Table 3: Plant height and marketable yield of tomato following treatment with herbicides applied with and without surfactants at the E.V. Smith Research Center in Shorter, AL in 2013 only...68

Table 4: Plant height and marketable yield of tomato following treatment with herbicides applied with and without surfactants at the Old Agronomy Farm in Auburn, AL in 2013 only...69

List of Figures

Chapter II:

Figure 1: Equipment setup for application of drip-applied herbicides. The equipment includes a backflow prevention valve (A), Dosatron® injection pump (B), buckets to hold injected herbicides (C), and a custom-built injection manifold..45

Figure 2: Herbicide treatments were delivered to polyethylene-mulched beds by splicing main delivery lines (1.27 cm plastic tubing) into the drip tape using drip tape connectors..46

Chapter III:

Figure 1: Equipment setup for application of drip-applied herbicides. The equipment includes a backflow prevention valve (A), Dosatron® injection pump (B), buckets to hold injected herbicides (C), and a custom-built injection manifold..70

Figure 2: Herbicide treatments were delivered to polyethylene-mulched beds by splicing main delivery lines (1.27 cm plastic tubing) into the drip tape using drip tape connectors..71

Chapter I

Introduction and Literature Review

Weed control in vegetable cropping systems is one of the most difficult tasks faced by growers throughout the world. The existence of weeds in these systems can have a significant impact on yield and profit potential. Under most circumstances, vegetable crops do not possess the competitive abilities to overcome weeds for resources such as light, water, nutrients, and space (Gilreath and Santos 2004). The introduction of polyethylene mulch has completely changed the landscape of vegetable cropping systems in the last two decades. Polyethylene mulch can provide earlier crop maturity, better yields and quality, improved disease, insect and weed control, and more efficient use of fertilizer and water (McCraw and Motes 2000). While polyethylene mulches can be an effective component of weed management in vegetable production, not all weed species are adequately controlled. Yellow nutsedge (*Cyperus esculentus* L.) is persistent and proliferates in these systems. Yellow nutsedge is problematic due to its ability to penetrate and emerge through the polyethylene mulch allowing it to compete with the crop and degrade mulch durability (Devkota et al. 2013; Webster 2005). Therefore, infestation is a serious concern for growers who want to use polyethylene mulch for multiple growing seasons (i.e. multicropping) with a single mulch application (Morales-Payan et al. 1997).

In polyethylene-mulched tomato production, weed management is a primary practice and often accounts for a significant portion of the total operating costs (Devkota et al.

2013). In the past, tomato (*Solanum lycopersicum* L.) growers have relied heavily on methyl bromide for effective management of yellow nutsedge as well as other weeds common in tomato fields (Locascio et al. 1997). However, in 2005, the Montreal Protocol and U.S. Clean Air Act mandated a ban on production and conventional agricultural use of methyl bromide. Currently, weed control options for polyethylene-mulched tomato are limited, and no single alternative technology has been able to readily substitute for methyl bromide while maintaining cost effectiveness and availability (Culpepper et al. 2009). With polyethylene mulch on top of the bed and drip tape underneath, mechanical and hand weeding methods are not practical; therefore, herbicide-based weed management is a potential alternative to methyl bromide compared to manual, mechanical, or cultural weed control in polyethylene-mulched tomato production (Devkota et al. 2013). To manage nutsedge species in these systems, herbicides including halosulfuron (Sandea®; Gowan Co., Yuma, AZ) and *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, Greensboro, NC) are often sprayed onto pre-formed beds prior to mulch application. However, in recent years, the application of herbicides through drip tape (i.e. drip-applied) has gained considerable interest in many areas of fruit and vegetable production. Drip-application of herbicides has several benefits over sprayed applications (Thomas et al. 2003; Wang et al. 2009), and preliminary research (Adcock 2007; Dittmar et al. 2012a; Santos et al. 2008) has shown it has potential for use in commercial production. However, there are questions that have yet to be addressed. One of the main concerns with using drip-applied herbicides in polyethylene-mulched beds is the lack of herbicide movement throughout the bedded area which often leads to inconsistent weed control. A recent study by Dittmar et al.

(2012b) on the tolerance of tomato to drip-applied herbicides indicated that control of yellow nutsedge farther away from the drip emitters was lower than control closer to the drip emitters, and two drip tapes were required to ensure uniform application of herbicides across the beds. While possibly more effective, the use of multiple drip tapes increases production costs and requires specialized equipment for application. Similarly, albeit with soil fumigants which tend to stay in the soil for shorter periods, studies conducted by Fennimore et al. (2003), Candole et al. (2007), and Chase et al. (2006) reported seeing a decrease in weed control with increasing distance from drip irrigation emitters in polyethylene-mulched beds. Therefore, a need exists to explore techniques to improve movement of drip-applied herbicides in polyethylene-mulched beds to maximize control of yellow nutsedge punctures and allow for a single mulch application to be used in multicropping systems. Additionally, the herbicide fomesafen (Reflex®; Syngenta Crop Protection, Greensboro, NC) was recently labeled (underwritten by Syngenta Crop Protection) in several states in the southeastern U.S. for use in tomato production. Fomesafen has been used extensively in row crop agriculture for years, is considered safe as a PRE application in tomatoes, and has good activity on yellow nutsedge (Dittmar 2013). Fomesafen has performed well as a sprayed application in tomato production (Culpepper et al. 2009); however, very little information currently exits on drip-applied applications in tomato.

The objectives of this research were to evaluate three selected application methods, in addition to two nonionic surfactants, for improving movement of drip-applied halosulfuron, *S*-metolachlor, and fomesafen in polyethylene-mulched beds. Treatments were evaluated based on their effect on yellow nutsedge punctures and the corresponding responses of a tomato crop (plant height and yield). Drip-applied treatments were compared to a commercial standard of *S*-metolachlor which was sprayed to the bed surface prior to mulch application. A nontreated control (beds with polyethylene mulch without herbicides) was included for comparison.

Herbicides Utilized in Experiments. Halosulfuron is a systemic-active, sulfonylurea, herbicide which inhibits acetolactate synthase, a key enzyme in the biosynthesis of the branch-chained amino acids leucine, isoleucine, and valine. PRE applications cause the shoot growing point to become chlorotic and necrotic soon after seedling emergence (Russell et al. 2002). Halosulfuron has short to moderate persistence in the soil and a low-leaching potential. Halosulfuron (Sandea®) is currently registered for use in numerous vegetable crops including tomato (Anonymous 2012).

S-metolachlor is a systemic-active, chloroacetamide herbicide that is a biosynthesis inhibitor of several plant components including fatty acids, lipids, proteins, isoprenoids, and flavonoids. Use of safeners, added to herbicides to aid in protecting the desirable crop or commodity, has secured and extended the application of chloroacetamides making them important components in recently developed herbicide mixtures (Boger et al. 2000). Most susceptible weeds simply fail to emerge from the soil (Senseman 2007). Results with drip-applied *S*-metolachlor for weed control in tomato have been promising (Santos et al. 2008). *S*-metolachlor (Dual Magnum®) has short to moderate persistence in the soil and is moderately mobile. *S*-metolachlor is labeled for use in tomatoes for control of annual grasses, yellow nutsedge, and a number of broadleaf weed species (Anonymous 2011).

Fomesafen is a systemic-active, diphenyl ether herbicide that inhibits protoporphyrogen oxidase or PROTOX which results in lipid peroxidation, disruption of cell membranes, and ultimately plant death (Ensminger and Hess 1985). Leaves of susceptible plants become chlorotic and then desiccated and necrotic within 1-3 d after application (Senseman 2007). Fomesafen has fairly long persistence in the soil and is moderately mobile. Fomesafen (Reflex®) is currently labeled for soybeans, cotton, and potatoes for control of a number of broadleaf weeds as well as sedges (Anonymous 2013). However, fomesafen has recently been evaluated for use in a number of vegetables crops and has received labels for use in tomato and pepper production in Georgia, Florida and North Carolina (Culpepper 2012). A recent study (Dittmar 2013) showed fomesafen to have similar levels of control and a similar weed species control spectrum as *S*-metolachlor; however, fomesafen provides an important tool for rotation of herbicide mode of action.

Yellow Nutsedge Overview. Nutsedge belongs to the family *Cyperaceae* (sedge) and genus *Cyperus.* The *Cyperaceae* consists of 17 different genera in the southeastern U.S. While several of these genera are weedy, those commonly described as most troublesome are found in the genus *Cyperus* (Radford el al. 1968). Of the 45 *Cyperus* spp. found in the southeastern U.S., 29 are perennials. Two of these perennial species, purple nutsedge and yellow nutsedge, can be separated from the rest due to their economic impact on agriculture (Webster 2003). All nutsedge species have triangular stems distinguishing them from grasses. Purple and yellow nutsedge can be difficult to separate; however, there are distinguishing characteristics for each. Yellow nutsedge has a yellowish-brown colored seedhead, whereas the seedhead of purple nutsedge is more reddish-brown (Colvin et al. 1992). Yellow and purple nutsedge both produce achenes from aerial inflorescences; however, the main source of propagation for both sedges is tuber production (Kemble et al. 2004a). Purple nutsedge tubers are cylindrical with a brownish-black coat, are susceptible to desiccation, and have a pungent taste. Yellow nutsedge tubers are also cylindrical; however, they are yellow-beige in color, can be dried to a wrinkly consistency with minimal effect on viability, and have a pleasant nutty taste (Webster 2003). The two nutsedge species have different distributions in the U.S. Yellow nutsedge is found throughout the continental U.S., whereas purple nutsedge is primarily restricted to the coastal states of the southeastern U.S. and along the Pacific coast in California and Oregon (Stoller and Wax 1973).

Croplands worldwide are populated by yellow nutsedge, making it one of the worst weed problems on the planet (Earl et al. 2004). A 2010 weed survey, conducted by the Southern Weed Science Society, revealed yellow nutsedge to be the most troublesome and fourth most common weed found in vegetable production systems in Alabama (Webster 2010). These results were similar for data collected in Georgia, Florida and North Carolina. Yellow nutsedge has the ability to survive harsh conditions and thrive under optimal conditions (Wang et al. 2008). Tubers are able to remain dormant throughout the winter and produce shoots the subsequent growing season (Lollar 2010). Tests have shown shoots can emerge from tubers as deep as 30.5 cm (Ransom et al. 2009) and tubers can survive for up to six years in the field (Rotteveel and Naber 1993). In addition, a recent study (Webster et al. 2008) reported that in just 10 weeks, a single yellow nutsedge plant can produce up to 50 additional tubers. These findings are comparable to research performed in the early 1960s by Tumbleson and Kommedahl (1961) which stated that over the course of one year, a single plant was capable of producing up to 1,900 shoots and 6,900 additional tubers. Additional research has indicated that yellow nutsedge is able to thrive as a weed in vegetable crops due to its rapid and abundant reproduction, widespread distribution, and difficulty to control (Johnson and Mullinax 2008; Webster 2003).

The effect of weed interference on crop yield is usually time- and density-dependent, with yield declining as weeds emerge earlier and density increases (Cousens 1991). Yellow nutsedge interference has proven to greatly reduce the yield of many crops. In corn and soybean, yellow nutsedge reduced yields up to 79 and 87%, respectively when left uncontrolled during the growing season (Earl et al. 2004). Buker et al. (2003) reported a 40% yield loss in direct-seeded and transplanted watermelons with a population of only 12 yellow nutsedge plants per square meter. Ransom and Ishida (1998) concluded that when nutsedge was left uncontrolled for an entire growing season, marketable onion yields were reduced up to 77%. Studies conducted by Motis et al. (2003) reported yield of bell peppers grown on polyethylene mulch were reduced 10% with fewer than five nutsedge tubers per square meter while yield losses of up to 74% were observed at nutsedge densities of 30 tubers per square meter. They further concluded that, in the absence of methyl bromide, weed control strategies with high efficacy against yellow nutsedge will be needed for bell pepper production. The same trends hold true in tomato production. Gilreath and Santos (2004) reported season-long nutsedge interference at a density of 113 plants per square meter resulted in a 51% yield loss in tomato compared to a weed-free control. Similarly, Morales-Payan et al. (2003) reported total marketable yield loss in tomato to be 25, 55, and 65% when yellow nutsedge emerged at densities of 25, 50 and 100 plants per square meter, respectively.

They also stated that at densities of 25 to 50 plants per square meter, yellow nutsedge suppression for the first eight weeks after transplanting would be necessary to prevent >5% total marketable loss.

Chemigation and Drip-Applied Herbicides. Chemigation is the process of applying an agricultural chemical to the soil or plant surface with an irrigation system by injecting the chemical into the irrigation water (Buffington and McDonald 2006). This method was initially developed and utilized to deliver plant nutrients that generally required incorporation into the soil. However, improvements in chemigation technology expanded its use to allow for other materials such as herbicides, fungicides, insecticides, and growth regulators to be used (Wang et al. 2009). A basic chemigation system can vary greatly; however, it usually consists of an irrigation pumping system, a chemical injection pump, a reservoir for the chemical, and a backflow prevention system (Johnson et al. 1986). In vegetable production systems, herbicides and other chemicals are injected through irrigation drip tape that is often underneath polyethylene mulch. This drip-application technique typically involves a pre-application wetting or priming period to get the air out of the system and water flowing properly prior to injection of the chemical. Following injection, the system is flushed to allow any remaining chemical to be removed. While drip application may have a few disadvantages such as longer application times (with some chemicals) and the need for additional equipment, there are many more advantages. These can include better movement of the chemical into the target root zone, increased applicator safety, decreased costs, timeliness, reduced compaction and reduced crop damage due to drift (Thomas et al. 2003; Wang et al. 2009).

Control of weeds in crops by drip-applied herbicides increases crop production efficiency by reducing costs of application, labor, and fuel (Johnson et al. 1986). A number of recent studies have shown the potential use of drip-application in applying fumigants (Ajwa et al. 2002, Candole et al. 2007, Chase et al. 2006, Locascio et al. 1997) in fruit and vegetable production systems; however, fewer studies exist for herbicide application. While limited, research in this area has been promising. Adcock (2007) reported drip-applied treatments of *S*-metolachlor and halosulfuron performed as well or in some cases better than their sprayed counterparts in controlling yellow nutsedge underneath polyethylene mulch (no crop). Similarly, drip-applied *S*-metolachlor (Santos et al. 2008) and halosulfuron (Dittmar et al. 2012a; Dittmar et al. 2012b) have been shown to be safe and effective for controlling yellow nutsedge in polyethylene-mulched tomato in comparison to sprayed applications.

Use of Surfactants in Horticulture. Overcoming pesticide water solubility issues was a monumental task in the 1950s and 1960s. Most pesticides were not formulated to use water as their carrier; however, today, the majority of pesticides are formulated to use water. The waxy surfaces of many insects, fungi, and plants make it difficult for most water-based spray solutions to penetrate their target. To overcome this barrier, adjuvants have been developed (Czarnota and Thomas 2013). Adjuvant is a broad term describing any additive to a spray tank that enhances pesticide activity. Examples of adjuvants include surfactants, spreader stickers, crop oils, anti-foaming materials, buffering agents, and compatibility agents.

Surfactants are the most widely used adjuvant in agriculture (Miller and Westra 1998). They are formulated to facilitate or improve the emulsifying, dispersing, spreading, sticking, or penetrating of liquids (Wang 2008). Surfactants alter the energy relationships at interferences and lower surface tension and interfacial tension (Miller and Westra 1998). Surfactants were initially used to enhance the penetration and effectiveness of foliar-applied herbicides, defoliants, and insecticides; however, they now have a much broader and more intensive use in a variety of industries such as food, fragrance, immunocytochemistry, pharmacy, cosmetics, and agriculture (Myers 2006).

Tween® 20 (polyoxyethylene sorbitan monolaurate) is a nonionic polysorbate surfactant produced by Croda International Plc. (Yorkshire, England). Its stability and relative non-toxicity allow it to be used as a detergent and emulsifier in a number of domestic, scientific, and pharmacological applications (Sigma-Aldrich, Inc. 2013). Tween 20 is inexpensive, chemically inert, pH neutral, water soluble, and highly efficient at decreasing surface tension at low concentrations, making it an ideal candidate for use as an irrigation-applied adjuvant (Colwell and Rixon 1961). While research is limited, Tween 20 has shown promising results for increasing herbicide mobility and longevity (Helling 1971; Johnson and Dureja 2002) in soils. Additional research in these areas is warranted.

Integrate® 20 (15.25% tri block co-polymer and 4.75% glucoethers) is a non-ionic, soil surfactant produced by Engage Agro USA (Prescott, AZ). It was designed to allow for proper infiltration and residual lateral movement of water in coarse soils for improved crop uniformity and yield potential. Integrate 20 increases water efficiency, nutrient utilization and pesticide efficacy. It can be applied alone or mixed in with liquid fertilizers and applied as a sprayed, drip-applied, or drenched application (Engage Agro 2013). A recent study by Santos et al. (2013) investigated the performance of the fumigant metam potassium against yellow nutsedge when Integrate 20 was applied to the soil. Results revealed that with a single drip tape, lateral movement of the moisture field increased by 68% (in a 1 h period) while nutsedge control increased by 25-30% when Integrate 20 was combined with metam potassium. The improvement in nutsedge control was attributed to increased lateral movement of the metam potassium carried in water.

Tomato Production. Tomatoes are members of the *Solanaceae* family which include bell peppers, hot peppers, eggplants, and Irish potatoes (Kemble et al. 2004b). Initially, tomatoes were produced for use in herbal remedies in addition to production for ornamental value, while fruit were rarely eaten because they were thought to be poisonous (Peralta and Spooner 2007). The importance of the tomato as a nutritious vegetable was not fully realized until the 20th century. In Alabama, George Washington Carver played a pivotal role in promoting the tomato as an excellent source of vitamins and nutrients for the poor (Jones, 1998). In 2011, an estimated 1.8 billion kg of fresh market tomatoes were produced in the U.S., representing a market value of approximately $1 billion. Likewise, during the same time period, Alabama produced 18.8 million kg valued at 4.1 million dollars (USDA-NASS 2013). In the latest census, Alabama ranked 14th in the U.S. for fresh market tomato production (USDA 2007).

Tomatoes prefer a well-drained, sandy loam to clay loam soil with a pH of 6.0 to 6.8. Fertility requirements (per ha) are as follows: 168 to 202 kg of nitrogen (N) and 224 to 280 kg of phosphorus (P_2O_5)d and potash (K_2O) (Kemble at al. 2004b). Typically 50% of the recommended N and K_2O and 100% of P_2O_5 are applied prior to planting. The remaining fertilizer is injected through the irrigation system on a set schedule. In commercial production, tomatoes are planted on raised beds covered in polyethylene mulch. Beds are typically 15 cm in high and range from 74 to 91 cm wide. Spring planted tomatoes are established on black polyethylene mulch, while late-season tomatoes are planted on white polyethylene mulch or black polyethylene mulch painted with exterior, white latex paint and water (Konsler and Gardner 2010). Tomatoes are 85 to 95% water and therefore need between one and four cm of water per week for proper development (Kemble et al. 2004b). In commercial production, drip irrigation is generally laid along with or prior to the application of the polyethylene mulch. Use of this system has led to a drastic improvement in overall tomato quality and yield.

Tomato transplants are planted 46 to 61 cm apart within the row with rows spaced 1.2 to 1.8 m (Kemble et al. 2004b). Staking and tying is required for successful tomato production. Wooden stakes, 1.2 to 1.5 m in length, are placed between every other plant and driven into the ground until secure. Tomatoes are tied three to four times during the season depending on plant height and variety selection (Kemble et al. 2004b). Following the first tying, initial pruning of the tomato plant occurs. Pruning of suckers, or axillary shoots on the main stem, helps to maintain the desired balance between vegetative growth and fruit production (Konsler and Gardner 2010).

Tomatoes destined for fresh market are hand harvested, either with or without a harvesting 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).

Literature Cited

Adcock CW (2007) Combinations of selected sulfonylurea herbicides with *S*-metolachlor for nutsedge control in tomatoes. Electronic Thesis and Dissertation. Auburn, AL: Auburn University

Ajwa HA, Trout T, Mueller J, Wilhelm S, Nelson SD, Soppe R, Shatley D (2002) Application of alternative fumigants through drip irrigation systems. Phytopathology 92:1349-1355

Anonymous (2011) Dual Magnum herbicide label SCP 816A-L1U 1210. Greensboro, NC; Syngenta Crop Protection. 50 p

Anonymous (2012) Sandea herbicide label 02-R0913EPA. Yuma, AZ; Gowan Company. 9 p

Anonymous (2013) Reflex herbicide label SCP 993A-L1M 0413. Greensboro, NC; Syngenta Crop Protection. Pp. 28-35

Boger P, Matthes B, Schmalfuß J (2000) Towards the primary target of chloroacetamides – new findings pave the way. Pest Mgmt. Sci. 56:497-508

Buffington EJ, McDonald SK (2006) Chemigation fact sheet. Colorado State University Environmental Pesticide Education Program. Fort Collins, CO. Pesticide Fact Sheet 302

Buker III RS, Stall WM, Olson SM, Schilling DG (2003) Season-long interference of yellow nutsedge (*Cyperus esculentus*) with direct-seeded and transplanted watermelon (*Citrullus lanatus*). Weed Technol. 17:751-754

Candole BL, Csinos AS, Wang D (2007) Concentrations in soil and efficacy of drip-applied 1,3-D + chloropicrin and metam sodium in plastic-mulched sandy soil beds.

Crop Protection 26:1801-1809

Chase CA, Stall WM, Simmone EH, Hochmuth RC, Dukes MD, Weiss AW (2006) Nutsedge control with drip-applied 1, 3-dichloropropene plus chloropicrin in a sandy soil. HortTechnology 16:641-648

Colvin DL, Dickens R, Everest JW, Hall D, McCarty LB (1992) Weeds of southern turfgrasses. Alabama Cooperative Extension System. Alabama A&M and Auburn Universities.14-19 p

Colwell CE, Rixon RE (1961) Consideration in the use of nonionic surface-active agents. Am. Dyest. Rep. 50:679-682

Cousens R, (1991) Aspects of the design and interpretation of competition (interference) experiments. Weed Technol. 5:664-673

Culpepper AS, Grey TL, Webster TM (2009) Vegetable response to herbicides applied to low-density polyethylene mulch prior to transplant. Weed Technol. 23:444-449

Culpepper AS (2012) Vegetable Weed Control Update. University of Georgia Cooperative Extension System. http://www.gaweed.com/slides/GFVGA-newproducts2012/GFVGA-newproducts2012.pdf. Accessed: October 31, 2012

Czarnota M, Thomas P (2013) Using surfactants, wetting agents, and adjuvants in the greenhouse. The University of Georgia Cooperative Extension Service. Bulletin 1314

Devkota PJ, Norsworthy K, Rainey R (2013) Efficacy and economics of herbicide programs compared to methyl bromide for weed control in polyethylene-mulched tomatoes. Weed Technol. 27:580-589

Dittmar PJ (2013) Weed control strategies in tomato. University of Florida Tomato

Institute Proc. 24 p

Dittmar PJ, Monks DW, Jennings KM (2012a) Effect of drip-applied herbicides on yellow nutsedge (*Cyperus esculentus*) in plasticulture. Weed Technol. 26:243-247

Dittmar PJ, Monks DW, Jennings KM, Booker FL (2012b) Tolerance of tomato to herbicides applied through drip irrigation. Weed Technol. 26: 684-690

Earl HJ, Ferrell JA, Vencill WK, Van Iersel MW, Czarnota MA (2004) Effects of three herbicides on whole plant carbon fixation and water use by yellow nutsedge (*Cyperus esculentus*). Weed Sci. 52:213-216

Engage Agro (2013) Integrate soil surfactant technical bulletin. http://www.engageagrousa.com. Accessed: October 9, 2013

Ensminger MP, Hess FD (1985) Photosynthesis involvement in the mechanism of action of diphenyl ether herbicides. Plant Physiol. 78:46-50

Fennimore SA, Haar MJ, Ajwa HA (2003) Weed control in strawberry provided by shank- and drip-applied methyl bromide alternative fumigants. HortScience 38:55-61

Gilreath JP, Santos BM (2004) Efficacy of methyl bromide alternatives on purple nutsedge control (*Cyperus rotundus*) in tomatoes and peppers. Weed Technol. 18:141-145

Helling CS (1971) Pesticide mobility in soils II: applications of soil thin-layer chromatography. Soil Sci. Soc. Am. J. 35:737–743

Johnson AW, Young JR, Threadgill ED, Dowler CC, Sumner DR (1986) Chemigation for crop production management. Plant Disease 70:998-1004

Johnson S, Dureja P (2002) Effects of surfactants on persistence of azadirachtin-A (a neem-based pesticide). J. Environ. Sci. Health. 37: 75-80

Johnson III WC, Mullinax Jr. BG (2008) Cultural control of yellow nutsedge (*Cyperus esculentus*) in transplanted cantaloupe (*Cucumis melo*) by varying application timing and type of thin-filmed mulches. Crop Protection 27:735-739

Jones Jr. JB (1998) Tomato plant culture: in the field, greenhouse, and home garden. CRC Press LLC, Boca Raton, FL

Kemble JM, Patterson MG, Everest JW (2004a) Nutsedge control in commercial vegetables. Alabama Cooperative Extension System. Alabama A&M and Auburn Universities. ANR-1073

Kemble JM, Tyson TW, Curtis LM (2004b) Guide to commercial staked tomato production in Alabama. Alabama Cooperative Extension System Alabama A&M and Auburn Universities. ANR-1156

Konsler TR, Gardner RG (2010) Commercial production of staked tomatoes in North Carolina – Revised. North Carolina Cooperative Extension. North Carolina State University and North Carolina A&T University. AG-405

Locascio SJ, Gilreath RJ, Dickson DW, Kucharek TA, Jones JP, Noling JW (1997) Fumigant alternatives of methyl bromide for polyethylene mulched tomato. HortScience 32:1208-1211

Lollar MC (2010) Combinations of selected sulfonylurea herbicides and diazinon for yellow nutsedge control in tomatoes. Auburn University, Auburn, Alabama. Diss. Abstr. 2 p

McCraw D, Motes JE (2000) Use of plastic mulch and row covers in vegetable production. Oklahoma Cooperative Extension Service. Oklahoma State University. HLA-6034

Miller P, Westra P (1998) How surfactants work. Colo. State Univ. Coop. Ex., Prod. Crop Ser. No. 564

Morales-Payan JP, Santos BM, Stall WM, Bewick TA (1997) Effect of purple nutsedge (*Cyperus rotundus*) on tomato (*Lycopersicon esculentum*) and bell pepper *(Capsicum annum)* vegetative growth and fruit yield. Weed Technol. 11:672-676

Morales-Payan JP, Stall WM, Shilling DG, Charudattan RC, Dusky JA, Bewick TA (2003) Above- and below-ground interference of purple and yellow nutsedge (*Cyperus* spp.) with tomato. Weed Sci. 51:181-185

Motis TN, Locascio SJ, Gilreath JP, Stall W (2003) Season-long interference of yellow nutsedge (*Cyperus esculentus*) with polyethylene-mulched bell pepper (*Capsicum annuum*). Weed Technol. 17:543-549

Myers D (2006) Surfactant science and technology. 3rd ed. Willey, Hoboken, N.J. Pp. 97-108

Peralta IE, Spooner DM (2007) History, origin and early cultivation of tomato (Solanaceae). Pp. 1-27. *In* Genetic Improvement of Solanaceous Crops Vol. II. MK Razden and AK Mattoo. editors. Science Publishers, Enfield, CT

Radford AE, Ahles HE, Bell CR (1968) Manual of the vascular flora of the Carolinas. The University of North Carolina Press. Chapel Hill, NC. 1183 p

Ransom CV, Ishida J (1998) Control of yellow nutsedge and emerging weeds in onions. Oregon State University Malheur Experiment Station Special Report 1005:68-75

Ransom CV, Rice CA, Shock CC (2009) Yellow nutsedge (*Cyperus esculentus*) growth and reproduction in response to nitrogen and irrigation. Weed Sci. 57:21-25

Rotteveel AW, Naber H (1993) Decline of yellow nutsedge (*Cyperus esculentus*) when tuber formation is prevented. Brighton Crop Protect. Conf., Brighton, UK, 22-25 November 1993. 1:311-316

Russell MH, Saladin JL, Lichtner F (2002) Sulfonylurea herbicides. Pesticide Outlook. August 2002. Pp. 166-172

Santos BM, Gilreath JP, Lugo ML, Rivera LE (2008) Managing weeds with drip-applied herbicides in tomato. Crop Prot. 27:101-103

Santos BM, Jacoby TP, Boyd NS (2013) Improved nutsedge control on bed edges with metam potassium and soil surfactants. University of Florida Tomato Institute Proc. Pp. 22-23

Senseman SA, ed (2007) Herbicide handbook, 9th ed. Champaign, IL: Weed Science Society of America. Pp. 77, 207, 276

Sigma-Aldrich, Inc (2013) Tween® 20 product information sheet. http://www.sigmaaldrich.com/sigma-aldrich/product_information_sheet/p7949pis.pdf. Accessed: October 6, 2013

Stoller E, Wax L (1973) Yellow nutsedge shoot emergence and tuber longevity. Weed Sci. 53:839-845

Thomas JG, Pennington DA, Schmidt AM, Pringle L (2003) Chemigation. Mississippi State Extension Service. Publication 1551

Tumbleson ME, Kommedahl T (1961) Reproductive potential of *Cyperus esculentus* by tubers. Weeds 9:646-653

[USDA] United States Department of Agriculture (2007) Census of Agriculture-State Data: Alabama. Washington, D.C: USDA

[USDA-NASS] US Department of Agriculture; National Agricultural Statistics

Service (2013) Quick Stats-U.S. Tomato Production. Washington, D.C: USDA.

Wang G, McGiffen Jr. ME, Ogbuchiekwe JE (2008) Crop rotation effects on *Cyperus rotundus* and *C. esculentus* population dynamics in southern California vegetable production. Weed Res. 48:420-428

Wang X (2008) Effects of a nonionic surfactant on plant growth and physiology. Auburn University, Auburn, Alabama. Diss. Abstr. Pp. 6-10

Wang X, Zhu H, Reding ME, Locke JC, Leland JE, Derksen RC, Spongberg AL, Krause CR (2009) Delivery of chemical and microbial pesticides through drip irrigation systems. Appl. Engr. Agr. 25:883-893

Webster TM (2003) Nutsedge (*Cyperus* spp.) eradication: Impossible dream? Pages 21-25 *in* Riley LE, Dumroese RK, Landis TD (eds.) National proceedings: Forest and Conservatory Nursery Associations - 2002. Ogden, UT. Proceedings RMRS-P-28

Webster TM (2005) Patch expansion of purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) with and without polyethylene mulch. Weed Sci. 53:839-845

Webster TM (2010) Weed survey – Southern states: vegetable, fruit, and nut crops subsection. Proc. South. Weed Sci. Soc. 63:246-257

Webster TM, Culpepper AS (2005) Eggplant tolerance to halosulfuron applied through drip irrigation. HortScience 40: 1796-1800

Webster TM, Grey T, Davis JW, Culpepper AS (2008) Glyphosate hinders purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) tuber production. Weed Sci. 56:735-742

Chapter II

Yellow Nutsedge (*Cyperus esculentus*) Control and Crop Response to Application Methods of Drip-Applied Herbicides in Polyethylene-Mulched Tomato

(In the format appropriate for submission to Weed Technology)

Yellow Nutsedge (*Cyperus esculentus*) Control and Crop Response to Application Methods of Drip-Applied Herbicides in Polyethylene-Mulched Tomato

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Drip-applied herbicides provide farmers with a more timely and cost-effective approach for applying preemergence (PRE) herbicides compared with sprayed applications; however, herbicide movement can be limited. Field studies were conducted to evaluate selected application methods with the goal of improving movement of drip-applied herbicides in polyethylene-mulched tomato. Treatments were evaluated based on their effect on yellow nutsedge punctures (through the polyethylene mulch) and the corresponding responses of a tomato crop (plant height and yields). The experiment was a factorial treatment arrangement of three drip-application methods and three PRE-applied herbicides (halosulfuron at 54 g ai ha^{-1}, *S*-metolachlor at 1.4 kg ha^{-1}, and fomesafen at 280 g ha^{-1}). Herbicides were applied either immediately following saturation of the planting beds (method A), over an extended period used to saturate the

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beds (method B), or just prior to bed saturation (method C). Additional treatments included a commercial standard of *S*-metolachlor sprayed to the bed surface prior to mulch application and a nontreated control (beds with polyethylene mulch without herbicides). Fomesafen applied with method B was the only treatment that provided a significant reduction (55% fewer punctures compared with the commercial standard) in yellow nutsedge punctures while maintaining marketable yields comparable to the commercial standard. Fomesafen and halosulfuron, each applied with method C, provided control of yellow nutsedge punctures and marketable yields comparable to the commercial standard. These results suggest that, when applied by the appropriate method, drip-applied fomesafen and halosulfuron may provide suitable control of yellow nutsedge punctures in polyethylene-mulched tomato while maintaining desirable yields.

Nomenclature: Fomesafen; halosulfuron; *S*-metolachlor; tomato, *Solanum lycopersicum* L.; yellow nutsedge, *Cyperus esculentus* L.

Key words: diphenyl ether; chloroacetamides; sulfonylureas; alternative weed control; chemigation; methyl bromide alternatives.

Use of polyethylene mulch in vegetable production provides many benefits including improved weed control (McCraw and Motes 2000); however, not all weed species are adequately controlled. Yellow nutsedge (*Cyperus esculentus* L.) can penetrate polyethylene mulch, thereby competing with the crop, degrading mulch durability, and preventing use in multicropping systems (Webster 2005). A 2010 weed survey, conducted by the Southern Weed Science Society, reported yellow nutsedge to be the most troublesome and fourth most common weed found in vegetable production in Alabama (Webster 2010). Research (Johnson and Mullinax 2008; Webster 2003) has shown that yellow nutsedge is able to thrive in vegetable production systems due to its rapid and abundant reproduction, widespread distribution, and difficulty in control. Yellow nutsedge interference can significantly reduce yield of many vegetable crops including tomato (*Solanum lycopersicum* L.). Gilreath and Santos (2004) reported that season-long nutsedge interference at a density of 113 plants per square meter reduced tomato yield by 51% in comparison to a weed-free control. Similarly, Morales-Payan et al. (2003) reported total marketable yield loss in tomato to be 25, 55, and 65% when yellow nutsedge emerged at densities of 25, 50 and 100 plants per square meter, respectively. Furthermore, at densities of 25 to 50 plants per square meter, yellow nutsedge suppression for the first eight weeks after transplant would be necessary to prevent > 5% total marketable loss.

Prior to its ban, tomato production relied heavily on methyl bromide for effective management of nutsedge spp. (Locascio et al. 1997). Currently, weed control options for polyethylene-mulched tomato are limited, and no single alternative technology has been able to readily substitute for methyl bromide while maintaining cost effectiveness and availability (Culpepper et al. 2009). To manage nutsedge species in these systems, herbicides including halosulfuron (Sandea$^{®}$; Gowan Co., Yuma, AZ) and *S*-metolachlor (Dual Magnum$^{®}$; Syngenta Crop Protection, Greensboro, NC) are often sprayed onto pre-formed beds prior to polyethylene mulch application. However, in recent years, application of herbicides through drip irrigation has become more prevalent and offers several benefits over sprayed applications (Thomas et al. 2003; Wang et al. 2009). Preliminary research (Adcock 2007; Dittmar et al. 2012a; Santos et al. 2008) has shown the potential for use of drip-applied herbicides in commercial production; however, some issues need to be addressed. In working with drip-applied herbicides in the past, observations have indicated that yellow nutsedge control diminishes the further you move away from drip emitters. A recent study by Dittmar et al. (2012b) on the tolerance of tomatoes to drip-applied herbicides, stated similarly that weed control often decreases with increasing distance from drip emitters and two drip tapes were required to ensure uniform application of herbicides across the beds. While possibly more effective, use of multiple drip tapes increases production costs and requires specialized bedding equipment. Additionally, this trend has also been observed in studies evaluating weed control with fumigants in polyethylene-mulched beds (Candole et al. 2007; Chase et al. 2006 Fennimore et al. 2003). Therefore, a need exists to explore strategies to improve movement of drip-applied herbicides in polyethylene-mulched beds to maximize yellow nutsedge control and allow for a single mulch application to be used in multicropping systems

Halosulfuron is a systemic-active, sulfonylurea herbicide which inhibits acetolactate synthase, a key enzyme in the biosynthesis of the branch-chained amino acids.

Halosulfuron has short to moderate persistence in the soil and a low-leaching potential. Halosulfuron (Sandea) is currently registered for use in numerous vegetable crops including tomato (Anonymous 2012).

S-metolachlor is a systemic-active, chloroacetamide herbicide which inhibits the synthesis of several plant components including fatty acids, lipids, proteins, isoprenoids, and flavonoids. Most susceptible weeds simply fail to emerge from the soil (Senseman 2007). Results with drip-applied *S*-metolachlor for weed control in tomato have been promising (Santos et al. 2008). *S*-metolachlor has short to moderate persistence in the soil and is considered moderately mobile. *S*-metolachlor (Dual Magnum) is labeled for use in tomatoes for control of annual grasses, yellow nutsedge, and number of broadleaf weeds (Anonymous 2011).

Fomesafen is a systemic-active, diphenyl ether herbicide which inhibits protoporphyrogen oxidase or PROTOX resulting in lipid peroxidation and disruption of cell membranes. Fomesafen has fairly long persistence in the soil and is considered moderately mobile. Fomesafen (Reflex®; Syngenta Crop Protection, Greensboro, NC) is labeled for soybeans, cotton, and potatoes for control of a number of broadleaf weeds as well as sedges (Anonymous 2013). Fomesafen has recently been evaluated for use in a number of vegetables crops and has received labels (underwritten by Syngenta Crop Protection) for use in tomato and pepper production in Georgia, Florida and North Carolina (Culpepper 2012). Fomesafen provides similar levels of control and a similar weed species control spectrum as *S*-metolachlor; however, fomesafen offers an important tool for rotation of herbicide mode of action (Dittmar 2013).

The objective of this study was to evaluate three selected application methods for improving movement of drip-applied halosulfuron, *S*-metolachlor, and fomesafen in polyethylene-mulched tomato. Treatments were evaluated based on their effect on yellow nutsedge punctures (through the polyethylene mulch) and the corresponding responses of a tomato crop (plant height and yields). Drip-applied treatments were compared to a commercial standard of *S*-metolachlor, which was sprayed to the bed surface prior to mulch application. A nontreated control (beds with polyethylene mulch without herbicides) was included for comparison.

Materials and Methods

Field studies were conducted in the summer of 2012 and 2013 at the E.V. Smith Research Center (EVS), Shorter, AL (32°26'N, 85°53'W) and at the Old Agronomy Farm (OAF), Auburn, AL (32°35'N, 85°29'W). Soil type at both locations was a Marvyn sandy loam (fine-loamy, kaolinitic, thermic-type Kanhapludults) comprised of 75.6, 6.8, and 17.5 % sand, silt and clay respectively, with pH 5.7 (EVS) and 76.3, 5.0, and 18.8 % sand, silt and clay respectively, with pH 6.2 (OAF). Fields used in experiment had a history of heavy yellow nutsedge infestation. In both years, soil was disked and formed into four raised beds approximately 21 m long, 91 cm wide (46 cm wide at OAF), 13 cm high, and covered with 1.25 mil white polyethylene mulch (1.25 mil; Berry Plastics Corp., Evansville, IN). Each of the four rows contained 13, 5.5-m long plots with a 0.60-m buffer between plots. Rows were spaced 6.1 m apart. In 2012, a crop was not planted as to allow evaluation of herbicide treatments on yellow nutsedge punctures only. In 2013, each experimental plot contained 12 tomato plants (cv. Mountain Glory) spaced 0.45 m apart. Fertility and management of tomatoes followed commercial growing standards (Kemble 2013). Prior to mulch application, a single drip tape (Toro Ag., Bloomington, MN) delivering 516 L 100 m^{-1} h^{-1} was placed in the center of each mulched bed and buried approximately 5 cm. Drip tape emitters were spaced 30.5 cm apart delivering 1.02 L hr^{-1}.

The experiment was conducted in a randomized complete block design with four replications. Treatments were a factorial arrangement of three drip application methods and three PRE-applied herbicides (halosulfuron at 54 g ai ha^{-1}, *S*-metolachlor at 1.4 kg ha^{-1}, and fomesafen at 280 g ha^{-1}). The three application methods were: (A) 6-h (EVS) or 3-h (OAF) wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h (EVS) or 3-h (OAF) herbicide application followed by a 30-min flush; and (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h (EVS) or 3-h (OAF) flush. In essence, herbicides were applied either immediately following saturation of the planting beds (method A), along with an extended saturation period (method B), or just prior to saturating the bed (method C). Additional treatments included a commercial standard treatment in which *S*-metolachlor was sprayed onto the bed surface prior to mulch application and a nontreated control (bedded with polyethylene mulch without herbicides) for a total of 11 treatments. The commercial standard treatment was applied with a battery-powered backpack sprayer (SHURflo, Costa Mesa, CA) equipped with one 11004 flat-fan nozzle (Spraying Systems Co., Wheaton, IL) calibrated to deliver 224 L ha^{-1}. Drip-applied treatments were applied along with 14,000 L ha^{-1} of water using Dosatron® D14MZ2 injectors (Dosatron International Inc., Clearwater, FL) and a custom injection manifold (Figure 1). The large quantity of water used in application of drip-applied treatments was necessary to fully saturate planting 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 receiving the same treatments were connected together by splicing into the drip tape and capped where appropriate (Figure 2).

Herbicide quantity applied to each treatment was based on the combined area of the four individual plots utilized per treatment. Individual plots were 5.5 m long and 0.6 m wide at EVS and 5.5 m long and 0.3 m wide at OAF. Length of application methods (wetting plus herbicide application plus flush) were based on dye injection tests developed by Csinos et al. (2002) for tracing water and pesticide movement in polyethylene-mulched beds. At both locations, two 30.5-m polyethylene-mulched beds (same width and height as those used in experiment) were formed in the same general area used for the experiments prior to initiation of the study. Hi Light® dye (1000 ml; Becker Underwood, Ames, IA) was injected into the beds using a Dosatron injection pump set at the maximum ratio of 1:50 followed by timed irrigation. After each hour of irrigation, sections of polyethylene mulch were removed from the beds to examine the wetted area. The initial concept required running the irrigation system until the bed surface was completely covered by the moisture field. Length of application methods would then be based on the length of time required for this to be accomplished. However, at EVS, complete coverage was never achieved during the 10-h irrigation test. After 7 h, emitter-to-emitter coverage was attained, the moisture field covered approximately 70% of the bed surface, and water had started to run out at the base of the bed shoulders. Additional irrigation failed to result in an increase in lateral movement of the moisture field; therefore, application methods at EVS were 7 h long. At OAF, the moisture field completely covered the bed surface after approximately 4 h of irrigation. Therefore, application methods used at OAF were 4 h long.

Treatments were applied on 30 July (2012) and 14 May (2013) at EVS and on 21 Aug. (2012) and 21 May (2013) at OAF. In the 2013 studies, herbicide treatments were applied seven days prior to transplanting tomatoes per herbicide label recommendations. In both years, nutsedge punctures were counted at 28 and 56 days after treatment (DAT) from a 1.0 m^2 section of the plot. In the 2013 studies, tomato plant height (soil surface at base of plant to the top of growing point) was measured at 14 and 28 days after planting (DAP) to evaluate potential herbicide injury. In addition, tomato fruit was harvested weekly on 1, 8, 15 and 22 Aug. at EVS and on 12, 19, 26 Aug. and 3 Sept. at OAF when fruit were 5 cm or larger in diameter, in breaker to red stage, and graded as marketable or nonmarketable according to U.S. Department of Agriculture standards (USDA 1991). Marketable fruit consisted of medium, large, extra-large, and jumbo fruit grades. Early harvest data includes fruit harvested on 1 Aug. (EVS) and 12 Aug. (OAF) only and was utilized to determine if herbicide treatments delayed fruit ripening. Fruit weight was summed over harvests to determine total marketable and unmarketable yield.

Data were analyzed with generalized linear models using the 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. Plant height, puncture counts, early season yield, marketable yield, and nonmarketable yield were the response variables. Block and year were included in the models as random factors. Data were analyzed separately by study location due to significant interactions ($P < 0.10$) of treatments with locations. When herbicide-by-application method interactions were significant, simple effects were examined; and when nonsignificant, levels within main effects were examined. Least squares means for plant height and early season yield were compared to those for the commercial standard using lower-tailed *t*-tests. In addition, least-squares means for punctures and marketable and nonmarketable yield were compared to those for the commercial standard using two-tailed *t*-tests. All *p* values for tests of differences between least squares means were adjusted using the Shaffer-Simulated method ($\alpha = 0.10$).

Results and Discussion

Tomato Plant Height and Early Season Yield.

EVS. Herbicide-by-application method interactions were significant for tomato plant height measured at 14 and 28 DAP, and nonsignificant for early season yield. Analysis of simple effects for plant height revealed differences for both dates (not presented in table). At 14 DAP, plant height was reduced by fomesafen applied with method A (15.9 cm) compared to application with either method B or method C (17.2 and 17.6 cm, respectively; Table 1). Additionally, *S*-metolachlor applied with method A reduced plant height (14.3 cm) compared to application with method C (16.4 cm). The application method used for halosulfuron did not influence plant height. At 28 DAP, plant height was again reduced by fomesafen when applied with method A (57.9 cm) in comparison to application with either method B or method C (62.8 and 61.3 cm, respectively; Table 1). Furthermore, halosulfuron applied with method B reduced plant height (57.8 cm) compared to application with method C (61.9 cm). The application method used for *S*-metolachlor did not influence plant height. Early season yield did not differ between herbicide or application method (Table 1). Comparisons of individual treatments with the commercial standard revealed differences for plant height (at both dates) and early season yield (Table 1). With the exception of fomesafen applied with method C, plant height was reduced by all treatments 14 DAP in comparison to the commercial standard. At 28 DAP, plant height was reduced by fomesafen applied with method A and halosulfuron applied with method B; however, plant height in all remaining treatments was similar to the commercial standard. Additionally, early season yield was reduced by all treatments, with the exception of halosulfuron applied with method C, compared to the commercial standard.

OAF. Herbicide-by-application method interactions were significant for tomato plant height measured at 28 DAP and nonsignificant for plant height measured at 14 DAP and early season yield. At 14 DAP, plant height was influenced by the main effects of both herbicide and application method (Table 2). Plant height was reduced in treatments containing *S*-metolachlor (23.4 cm) compared to those containing halosulfuron (24.6 cm). Moreover, plant height was reduced in treatments applied with method B (23.6 cm) in comparison to those applied with method C (24.7 cm). Analysis of simple effects for plant height measured at 28 DAP revealed significant differences (not presented in table). Plant height was reduced by halosulfuron applied with either method A or method C (67.8 and 67.3 cm, respectively) compared to application with method B (71.5 cm). Furthermore, *S*-metolachlor applied with method B reduced plant height (65.7 cm) compared to application with method A (70.1 cm). The application method used for fomesafen did not influence plant height. Early season yield did not differ between herbicide or application method (Table 2). Comparisons of individual treatments with the commercial standard revealed no significant differences for plant height or early season yield (Table 2).

Reduction in plant height and early season yield were not expected as previous research by Adcock et al. (2008), Santos et al. (2008) and Dittmar et al. (2012b) had reported no crop injury in tomatoes receiving drip-applied halosulfuron or *S*-metolachlor. However, height reduction may be attributed to the excessive amount of water needed for application of herbicide treatments (14,000 L ha^{-1}) which may have caused herbicides to leach down into the plant root zone causing plant injury.

Yellow Nutsedge Punctures.

EVS. Herbicide-by-application method interactions were nonsignificant for counts of yellow nutsedge punctures (through the polyethylene mulch) at 28 and 56 DAT. At 28 DAT, puncture counts were influenced by herbicide only (Table 3). Punctures were reduced in treatments receiving fomesafen and halosulfuron (1.6 m^{-2} in both cases) compared to those receiving *S*-metolachlor (2.7 m^{-2}). At 56 DAT, puncture counts were influenced by both herbicide and application method (Table 3). Punctures were reduced in treatments receiving fomesafen (2.9 m^{-2}) compared with treatments receiving halosulfuron (5.6 m^{-2}) or *S*-metolachlor (7.3 m^{-2}). Furthermore, punctures counts were reduced when herbicides were applied with method B (4.1 m^{-2}) compared to when applied with method A (7.0 m^{-2}). Comparisons of individual treatments with the commercial standard revealed significant differences for nutsedge puncture counts measured at 56 DAT only (Table 3). At 56 DAT, punctures in treatments receiving fomesafen applied with method B (2.4 m^{-2}) were significantly less than those found in the commercial standard (5.8 m^{-2}). Otherwise, puncture count was similar to the commercial standard across all remaining treatments.

With one exception, puncture counts were highest in treatments receiving herbicides applied with method A, which called for beds to be saturated prior to herbicide application. It is possible that herbicides applied with this method immediately leached down into the soil profile (due to prior bed saturation) and out of target zone resulting in lack of nutsedge control.

OAF. Herbicide-by-application method interactions were nonsignificant for yellow nutsedge puncture counts at 28 and 56 DAT. Differences among main effects were also found to be nonsignificant (Table 4). Additionally, comparisons of individual treatments to the commercial standard revealed no significant differences for puncture counts measured at either date (Table 4).

Tomato Yield.

EVS. Herbicide-by-application method interactions were nonsignificant for marketable and nonmarketable yield. Marketable yield was influenced by herbicide only (Table 3) and was significantly higher in treatments receiving fomesafen (60.6 t ha^{-1}) compared to treatments receiving halosulfuron (51.5 t ha^{-1}) or *S*-metolachlor (38.6 t ha^{-1}). Nonmarketable yield was also influenced by herbicide only (Table 3) and was lowest in treatments receiving *S*-metolachlor (12.6 t ha^{-1}); however, marketable yield was also lowest in this treatment and was likely the reason for this occurrence. Comparisons of individual treatments to the commercial standard revealed significant differences only for marketable yield (Table 3). Marketable yields were similar to the commercial standard in treatments receiving fomesafen applied using method B and method C as well as halosulfuron applied using method C. Marketable yield was significantly reduced by all other treatments.

OAF. Herbicide-by-application method interactions were nonsignificant for marketable and nonmarketable yield. Differences among main effects were also nonsignificant (Table 4). Furthermore, comparisons of individual treatments to the commercial standard revealed no significant differences (Table 4).

Implications for Control. The majority of treatments failed to adequately (< 90% compared to the nontreated) control yellow nutsedge at both 28 and 56 DAT (Table 5; Table 6). As alluded to earlier, drip-applied treatments were applied with an application volume of approximately 14,000 L ha^{-1}. This is an enormous amount of water compared with the 240 L ha^{-1} needed for typical sprayed applications. With this in mind, it is possible that herbicide treatments leached down into the soil resulting in crop damage (i.e. reduction in plant height), poor nutsedge control, and ultimately reduction in yield. Fomesafen applied with method B was the only treatment that provided a significant reduction (55% compared to commercial standard at EVS) in yellow nutsedge punctures while maintaining marketable yields that were comparable to the commercial standard. Furthermore, fomesafen and halosulfuron, each applied with method C, provided control of yellow nutsedge punctures and marketable yields comparable to the commercial standard. Previous studies evaluating drip-applied fomesafen in tomato are lacking; however, a recent trial by Dittmar (2013) seems to support these findings as he reported fomesafen resulted in a 12% increase in nutsedge control over *S*-metolachlor at 25 DAT when both were sprayed to raised beds prior to mulch application. These results suggest that, when applied by the appropriate method, drip-applied fomesafen and halosulfuron may provide suitable control of yellow nutsedge punctures in polyethylene-mulched tomato while maintaining desirable yields. Future studies are planned to examine drip-applied fomesafen in tomato production as well as application methods for applying drip-applied herbicides using lower application volumes in order to limit herbicide leaching.

Literature Cited

Adcock CW (2007) Combinations of selected sulfonylurea herbicides with *S*-metolachlor for nutsedge control in tomatoes. Electronic Thesis and Dissertation. Auburn, AL: Auburn University

Adcock CW, Foshee III WG, Wehtje GR, Gilliam CH (2008) Herbicide combinations in tomato to prevent nutsedge (*Cyperus esculentus*) punctures in plastic mulch for multi-cropping systems. Weed Technol. 22:136-141

Anonymous (2011) Dual Magnum herbicide label SCP 816A-L1U 1210. Greensboro, NC; Syngenta Crop Protection. 50 p

Anonymous (2012) Sandea herbicide label 02-R0913EPA. Yuma, AZ; Gowan Company. 9 p

Anonymous (2013) Reflex herbicide label SCP 993A-L1M 0413. Greensboro, NC; Syngenta Crop Protection. Pp. 28-35

Candole BL, Csinos AS, Wang D (2007) Concentrations in soil and efficacy of drip-applied 1,3-D + chloropicrin and metam sodium in plastic-mulched sandy soil beds. Crop Protection 26:1801-1809

Chase CA, Stall WM, Simmone EH, Hochmuth RC, Dukes MD, Weiss AW (2006) Nutsedge control with drip-applied 1, 3-dichloropropene plus chloropicrin in a sandy soil. HortTechnology 16:641-648

Csinos AS, Laska JE, Childers S (2002) Dye injection for predicting pesticide movement in micro-irrigated polyethylene film mulch beds. Pest Mgmt. Sci. 58:381-384

Culpepper AS, Grey TL, Webster TM (2009) Vegetable response to herbicides applied to low-density polyethylene mulch prior to transplant. Weed Technol. 23:444-449

Culpepper AS (2012) Vegetable Weed Control Update. University of Georgia Cooperative Extension System. http://www.gaweed.com/slides/GFVGA-newproducts2012/GFVGA-newproducts2012.pdf. Accessed: October 31, 2012

Dittmar PJ (2013) Weed control strategies in tomato. University of Florida Tomato Institute Proc. 24 p

Dittmar PJ, Monks DW, Jennings KM (2012a) Effect of drip-applied herbicides on yellow nutsedge (*Cyperus esculentus*) in plasticulture. Weed Technol. 26:243-247

Dittmar PJ, Monks DW, Jennings KM, Booker FL (2012b) Tolerance of tomato to herbicides applied through drip irrigation. Weed Technol. 26: 684-690

Fennimore SA, Haar MJ, Ajwa HA (2003) Weed control in strawberry provided by shank- and drip-applied methyl bromide alternative fumigants. HortScience 38:55-61

Gilreath JP, Santos BM (2004) Efficacy of methyl bromide alternatives on nutsedge control (*Cyperus rotundus*) in tomatoes and peppers. Weed Technol. 18:141-145

Johnson III WC, Mullinax Jr. BG (2008) Cultural control of yellow nutsedge (*Cyperus esculentus*) in transplanted cantaloupe (*Cucumis melo*) by varying application timing and type of thin-filmed mulches. Crop Protection 27:735-739

Kemble JM, ed (2013) Vegetable Crop Handbook for Southeastern US – 2013. Lincolnshire, IL: Vance Publishing. Pp 99-102

Locascio SJ, Gilreath RJ, Dickson DW, Kucharek TA, Jones JP, Noling JW (1997) Fumigant alternatives of methyl bromide for polyethylene mulched tomato. HortScience 32:1208-1211

McCraw D, Motes JE (2000) Plastic mulch and row covers in vegetable production. Oklahoma Cooperative Extension Service. Oklahoma State University. HLA-6034

Morales-Payan JP, Stall WM, Shilling DG, Charudattan RC, Dusky JA, Bewick TA (2003) Above- and belowground interference of purple and yellow nutsedge (*Cyperus* spp.) with tomato. Weed Sci. 51:181-185

Santos BM, Gilreath JP, Lugo ML, Rivera LE (2008) Managing weeds with drip-applied herbicides in tomato. Crop Protection 27:101-103

Senseman SA, ed (2007) Herbicide handbook, 9th ed. Champaign, IL: Weed Science Society of America. Pp. 77, 207, 276

Thomas JG, Pennington DA, Schmidt AM, Pringle L (2003) Chemigation. Mississippi State Extension Service. Publication 1551

[USDA] US Department of Agriculture (1991) United States Standards for Grades of Fresh Tomatoes. http://www.ams.usda.gov/AMSv1.0/getfile?dDo-Name=STELPRDC5050331. Accessed: October 15, 2013

Wang X, Zhu H, Reding ME, Locke JC, Leland JE, Derksen RC, Spongberg AL, Krause CR (2009) Delivery of chemical and microbial pesticides through drip irrigation systems. Appl. Engr. Agr. 25:883-893

Webster TM (2003) Nutsedge (*Cyperus* spp.) eradication: Impossible dream? Pages 21-25 *in* L.E. Riley, R. K. Dumroese and T. D. Landis (eds.) National proceedings: Forest and Conservatory Nursery Associations - 2002. Ogden, UT. Proceedings RMRS-P-28

Webster TM (2005) Patch expansion of purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) with and without polyethylene mulch. Weed Sci. 53:839-845

Webster TM (2010) Weed survey – Southern states: vegetable, fruit, and nut crops subsection. Proc. South. Weed Sci. Soc. 63:246-257

Table 1. Plant height and early season yield of tomato following treatment with herbicides using selected drip-application methods at the E.V. Smith Research Center in Shorter, AL in 2013 only.

Treatment			Height		
Application method[a]	Herbicide	Rate	14 DAP[b]	28 DAP	Early season yield[c]
Comparisons among main effects:					
		g ai ha^{-1}	cm		t ha^{-1}
A		-	15.7[d]	58.8[d]	3.6 A[e]
B		-	16.3	59.8	3.2 A
C		-	16.6	60.9	6.9 A
	Fomesafen	280	16.9	60.6	4.5 A
	Halosulfuron	54	16.3	59.6	6.8 A
	S-metolachlor	1,400	15.3	59.3	2.3 A
Comparisons among individual treatments with the commercial standard:					
A	Fomesafen	280	15.9	57.9	3.5
	Halosulfuron	54	16.8	59.3 *[f]	6.3
	S-metolachlor	1,400	14.3	59.3 *	1.0
B	Fomesafen	280	17.2	62.8 *	2.4
	Halosulfuron	54	16.4	57.8	1.8
	S-metolachlor	1,400	15.3	58.9 *	5.5
C	Fomesafen	280	17.6 *	61.3 *	7.8
	Halosulfuron	54	15.7	61.9 *	12.3 *
	S-metolachlor	1,400	16.4	59.6 *	0.5
	Standard[g]	1,400	18.5	62.6	18.5
	Nontreated	-	18.6	58.7	16.3

[a] Application methods: (A) 6-h wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h herbicide application followed by a 30-min flush; (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h flush.

[b] Abbreviations: DAP, days after planting.

[c] Marketable yield from first harvest (1 Aug.) only.

[d] Main effect means are presented for clarity purposes even though application method x herbicide interactions were significant. Analyses of simple effects are presented in the text only.

[e] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test (α = 0.10).

[f] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test (α = 0.10).

[g] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 2. Plant height and early season yield of tomato following treatment with herbicides using selected drip-application methods at the Old Agronomy Farm in Auburn, AL in 2013 only.

Treatment			Height		
Application method[a]	Herbicide	Rate	14 DAP[b]	28 DAP	Early season yield[c]
Comparisons among main effects:					
		g ai ha^{-1}	cm		t ha^{-1}
A		-	23.9 AB[e]	67.8[d]	13.6 A
B		-	23.6 B	68.5	12.7 A
C		-	24.7 A	68.0	11.8 A
	Fomesafen	280	24.2 AB	67.3	12.1 A
	Halosulfuron	54	24.6 A	68.8	13.3 A
	S-metolachlor	1,400	23.4 B	68.1	12.6 A
Comparisons among individual treatments with the commercial standard:					
A	Fomesafen	280	24.2 *[f]	65.5 *	16.9 *
	Halosulfuron	54	23.9 *	67.8 *	12.2 *
	S-metolachlor	1,400	23.5 *	70.1 *	11.7 *
B	Fomesafen	280	23.3 *	68.2 *	9.2 *
	Halosulfuron	54	24.7 *	71.5 *	13.6 *
	S-metolachlor	1,400	22.9 *	65.7 *	15.3 *
C	Fomesafen	280	25.2 *	68.3 *	10.3 *
	Halosulfuron	54	25.2 *	67.3 *	14.3 *
	S-metolachlor	1,400	23.8 *	68.4 *	10.8 *
	Standard[g]	1,400	26.8	68.9	14.5
	Nontreated	-	24.2	68.4	16.8

[a] Application methods: (A) 6-h wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h herbicide application followed by a 30-min flush; (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h flush.

[b] Abbreviations: DAP, days after planting.

[c] Marketable yield from first harvest (12 Aug.) only.

[d] Main effect means are presented for clarity purposes even though application method x herbicide interactions were significant. Analyses of simple effects are presented in the text only.

[e] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test ($\alpha = 0.10$).

[f] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test ($\alpha = 0.10$).

[g] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 3. Yellow nutsedge punctures and yield of tomato following treatment with herbicides using selected drip-application methods at the E.V. Smith Research Center in Shorter, AL. Data for 2012 and 2013 are pooled.

Treatment		Punctures		Yield	
Application method[a]	Herbicide[b]	28 DAT[c]	56 DAT	Marketable	Nonmarketable
Comparisons among main effects:					
		no. m^{-2}		t ha^{-1}	
A		2.2 A[d]	7.0 B	49.6 A	14.9 A
B		1.9 A	4.1 A	47.2 A	14.7 A
C		2.4 A	5.2 AB	53.9 A	15.5 A
	Fomesafen	1.6 A	2.9 A	60.6 A	16.1 A
	Halosulfuron	1.6 A	5.6 B	51.5 B	16.4 A
	S-metolachlor	2.7 B	7.3 B	38.6 C	12.6 B
Comparisons among individual treatments with the commercial standard:					
A	Fomesafen	1.6 *[e]	2.8 *	55.0	17.1 *
	Halosulfuron	2.0 *	8.8 *	47.7	13.6 *
	S-metolachlor	3.0 *	9.3 *	46.1	14.1 *
B	Fomesafen	1.8 *	2.4	62.1 *	14.3 *
	Halosulfuron	1.5 *	4.3 *	46.7	17.2 *
	S-metolachlor	2.4 *	5.6 *	32.8	12.5 *
C	Fomesafen	1.9 *	3.5 *	64.7 *	16.9 *
	Halosulfuron	1.8 *	4.5 *	60.1 *	18.4 *
	S-metolachlor	3.5 *	7.6 *	37.1	11.1 *
	Standard[f]	2.8	5.8	73.1	16.7
	Nontreated	9.0	28.6	48.0	16.9

[a] Application methods: (A) 6-h wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h herbicide application followed by a 30-min flush; (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h flush.

[b] Rates: fomesafen at 280 g ai ha^{-1}, halosulfuron at 54 g ha^{-1} and *S*-metolachlor at 1,40 0 g ha^{-1}.

[c] Abbreviations: DAT, days after treatment.

[d] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test ($\alpha = 0.10$).

[e] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test ($\alpha = 0.10$).

[f] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 4. Yellow nutsedge punctures and yield of tomato following treatment with herbicides using selected drip-application methods at the Old Agronomy Farm in Auburn, AL. Data for 2012 and 2013 are pooled.

Treatment		Punctures		Yield	
Application method[a]	Herbicide[b]	28 DAT[c]	56 DAT	Marketable	Nonmarketable
Comparisons among main effects:					
		no. m^{-2}		t ha^{-1}	
A		7.1 A[d]	9.2 A	61.8 A	16.9 A
B		6.9 A	9.5 A	64.1 A	17.3 A
C		7.6 A	9.6 A	58.3 A	16.4 A
	Fomesafen	7.0 A	9.8 A	57.8 A	16.0 A
	Halosulfuron	7.4 A	8.7 A	67.7 A	18.7 A
	S-metolachlor	7.6 A	9.8 A	58.7 A	16.0 A
Comparisons among individual treatments with the commercial standard:					
A	Fomesafen	7.7 *[e]	10.0 *	60.8 *	13.9 *
	Halosulfuron	4.8 *	6.7 *	63.5 *	17.7 *
	S-metolachlor	8.7 *	11.0 *	61.1 *	19.3 *
B	Fomesafen	7.2 *	11.0 *	57.8 *	15.2 *
	Halosulfuron	7.7 *	9.7 *	68.1 *	20.3 *
	S-metolachlor	5.7 *	7.7 *	66.4 *	16.5 *
C	Fomesafen	6.2 *	8.5 *	54.7 *	18.8 *
	Halosulfuron	8.0 *	9.7 *	71.5 *	18.2 *
	S-metolachlor	8.5 *	10.7 *	48.6 *	12.1 *
	Standard[f]	9.5	10.5	59.7	19.5
	Nontreated	25.4	36.7	59.1	15.9

[a] Application methods: (A) 6-h wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h herbicide application followed by a 30-min flush; (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h flush.

[b] Rates: fomesafen at 280 g ai ha^{-1}, halosulfuron at 54 g ha^{-1} and *S*-metolachlor at 1,400 g ha^{-1}.

[c] Abbreviations: DAT, days after treatment.

[d] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test (α = 0.10).

[e] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test (α = 0.10).

[f] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 5. Yellow nutsedge control in tomato following treatment with herbicides using selected drip-application methods at the E.V. Smith Research Center in Shorter, AL. Data for 2012 and 2013 are pooled.

Application method[a]	Herbicide	Rate	Control[b] 28 DAT[c]	Control[b] 56 DAT
Comparisons of individual treatments with the commercial standard:				
		g ai ha^{-1}	%	%
A	Fomesafen	280	82 *[d]	90 *
	Halosulfuron	54	78 *	69 *
	S-metolachlor	1,400	67 *	67 *
B	Fomesafen	280	79 *	88 *
	Halosulfuron	54	83 *	85 *
	S-metolachlor	1,400	73 *	80 *
C	Fomesafen	280	80 *	92
	Halosulfuron	54	80 *	84 *
	S-metolachlor	1,400	61 *	73 *
	Standard[e]	1,400	69	80
	Nontreated	-	0	0

[a] Application method: (A) 6 h wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h herbicide application followed by a 30-min flush; (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h flush.

[b] Percent (%) control is based off of the number of punctures in the nontreated.

[c] Abbreviations: DAT, days after treatment.

[d] Individual treatment means followed by an asterisk (*) do not differ from the mean of the commercial standard according to the Shaffer-Simulated test ($\alpha = 0.10$).

[e] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 6. Yellow nutsedge control in tomato following treatment with herbicides using selected drip-application methods at the Old Agronomy Farm in Auburn, AL. Data for 2012 and 2013 are pooled.

			Control[b]	
Application method[a]	Herbicide	Rate	28 DAT[c]	56 DAT
Comparisons of individual treatments with the commercial standard:				
		g ai ha^{-1}	%	
A	Fomesafen	280	70 *[d]	73 *
	Halosulfuron	54	81 *	82 *
	S-metolachlor	1,400	66 *	70 *
B	Fomesafen	280	76 *	77 *
	Halosulfuron	54	70 *	74 *
	S-metolachlor	1,400	78 *	79 *
C	Fomesafen	280	72 *	70 *
	Halosulfuron	54	69 *	74 *
	S-metolachlor	1,400	67 *	71 *
	Standard[e]	1,400	63	71
	Nontreated		0	0

[a] Application method: (A) 6-h wetting period followed by a 30-min herbicide application followed by a 30-min flush; (B) 30-min wetting period followed by a 6-h herbicide application followed by a 30-min flush; (C) 30-min wetting period followed by a 30-min herbicide application followed by a 6-h flush.

[b] Percent (%) control is based off of the number of punctures in the nontreated.

[c] Abbreviations: DAT, days after treatment.

[d] Individual treatment means followed by an asterisk (*) do not differ from the mean of the commercial standard according to the Shaffer-Simulated test ($\alpha = 0.10$).

[e] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

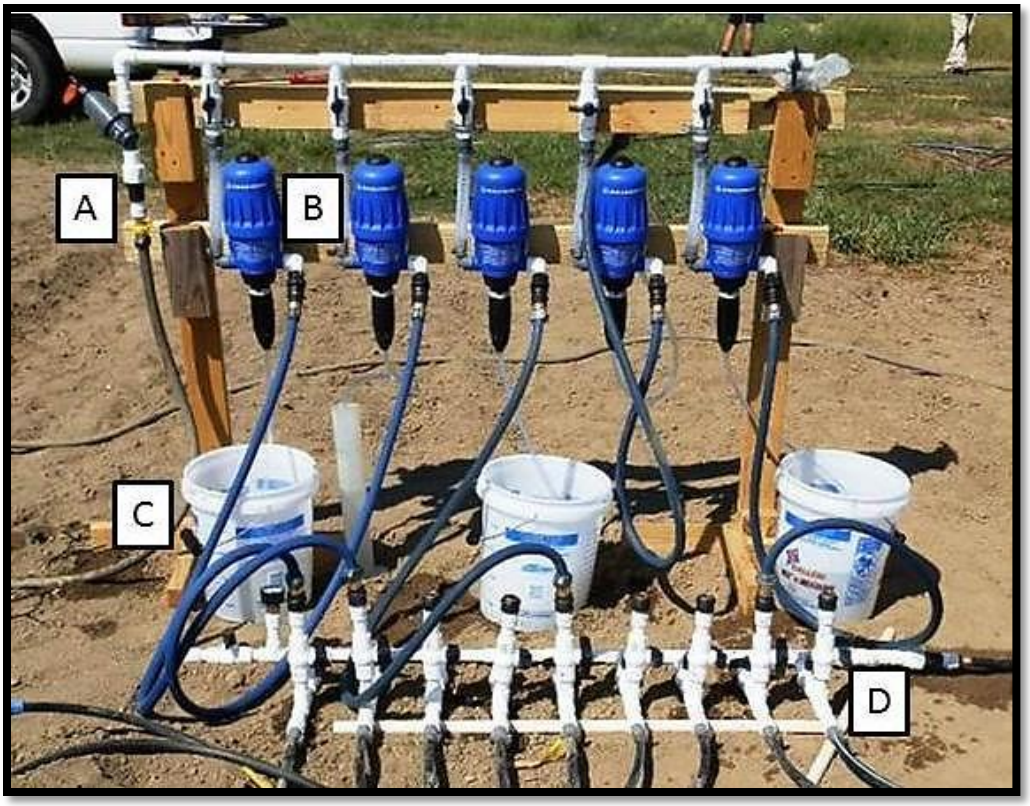

Figure 1. Equipment setup for application of drip-applied herbicides. The equipment includes a backflow prevention valve (A), Dosatron® injection pump (B), buckets to hold injected herbicides (C), and a custom-built injection manifold (D).

Figure 2. Herbicide treatments were delivered to polyethylene-mulched beds by splicing main delivery lines (1.27 cm plastic tubing) into the drip tape using drip tape connectors.

Chapter III

Yellow Nutsedge (*Cyperus esculentus*) Control and Crop Response to Drip-Applied Herbicides Applied with Nonionic Surfactants in Polyethylene-Mulched Tomato

(In the format appropriate for submission to Weed Technology)

Drip-applied herbicides with surfactants

Yellow Nutsedge (*Cyperus esculentus*) Control and Crop Response to Drip-Applied Herbicides Applied with Nonionic Surfactants in Polyethylene-Mulched Tomato

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Drip-applied herbicides provide a timelier and more cost-effective approach for applying PRE herbicides compared with sprayed applications; however, herbicide movement can be limited. Field studies were conducted to evaluate selected nonionic surfactants with the goal of improving movement of drip-applied herbicides in polyethylene-mulched tomato. Treatments were evaluated based on their effect on yellow nutsedge punctures (through the polyethylene mulch) and the corresponding responses of a tomato crop (plant height and yield). The experiment was a factorial treatment arrangement of three surfactants levels [Integrate® 20 at 2.8 kg ha^{-1}, Tween® 20 at 2.8 kg ha^{-1}, and no surfactant (i.e. none)] and three PRE-applied herbicides (halosulfuron at 54 g ai ha^{-1}, *S*-metolachlor at 1.4 kg ha^{-1}, and fomesafen at 280 g ha^{-1}). Additional treatments included a

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commercial standard of *S*-metolachlor (no surfactant; sprayed to bed surface prior to polyethylene mulch application) and a nontreated control (no herbicide or surfactant). Application of surfactants along with drip-applied fomesafen, halosulfuron and *S*-metolachlor failed to reduce yellow nutsedge punctures relative to herbicides applied without a surfactant. These results are likely due to the failure of surfactant-containing treatments to improve lateral movement of the herbicides underneath the polyethylene-mulched beds. Studies examining application of surfactants along with PRE-applied herbicides are lacking. However, these results suggest application of nonionic surfactants may not improve lateral movement of herbicides under polyethylene mulch and subsequent reduction in yellow nutsedge punctures when applied along with fomesafen, halosulfuron, and *S*-metolachlor through drip-irrigation on a sandy loam soil.

Nomenclature: Fomesafen; halosulfuron; *S*-metolachlor; Tween 20; Integrate 20; tomato, *Solanum lycopersicum* L.; yellow nutsedge, *Cyperus esculentus* L.

Key words: Chloroacetamide; diphenyl ether; sulfonylurea; alternative weed control; chemigation; methyl bromide alternatives

Polyethylene mulch provides many benefits to vegetable producers including better weed control (McCraw and Motes 2000); however, not all weed species are effectively controlled. Yellow nutsedge (*Cyperus esculentus* L.) penetrates the polyethylene mulch leading to early degradation and the inability for use in multicropping systems (Webster 2005). A weed survey, conducted by the Southern Weed Science Society, reported yellow nutsedge to be the most troublesome and fourth most common weed found in vegetable production in Alabama (Webster 2010). Results were similar for other southeastern states. Yellow nutsedge is able to thrive in vegetable production systems due to its rapid and abundant reproduction, widespread distribution, and difficulty in control (Johnson and Mullinax 2008; Webster 2003). Moreover, yellow nutsedge interference can significantly reduce the yield of many vegetable crops including tomato (*Solanum lycopersicum* L.). Gilreath and Santos (2004) reported season-long nutsedge interference at a density of 113 plants per square meter reduced tomato yield 51% in comparison to a weed-free control. Morales-Payan et al. (2003) reported marketable yield loss in tomato to be 25, 55, and 65% when yellow nutsedge emerged at densities of 25, 50 and 100 plants per square meter, respectively. Furthermore, at densities of 25 to 50 plants per square meter, yellow nutsedge suppression for the first eight weeks after transplanting would be necessary to prevent greater than 5% total marketable loss.

Soil fumigation with methyl bromide is the most effective method of controlling nutsedges, but because of ozone depletion, the phase-out of methyl bromide has complicated nutsedge control in polyethylene-mulched tomato and other vegetable crops (Bangarwa et al. 2012). Currently, weed control options for polyethylene-mulched tomato are limited, and no single alternative technology has been able to readily substitute for methyl bromide while maintaining cost effectiveness and availability (Culpepper et al. 2009). To manage nutsedge species in these systems, herbicides including halosulfuron (Sandea®; Gowan Co., Yuma, AZ) and *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, Greensboro, NC) are sometimes sprayed to beds prior to polyethylene mulch application. However, in recent years, drip-application of herbicides has become more prevalent and offers several benefits over sprayed applications (Thomas et al. 2003; Wang et al. 2009). Preliminary research (Adcock 2007; Dittmar et al. 2012a; Santos et al. 2008) has shown favorable results for the possible use of drip-applied herbicides in commercial production systems; however, there are issues that need to be addressed. In previous work with drip-applied herbicides, observations have indicated that yellow nutsedge control appears to decrease with increasing distance away from drip emitters. A recent study by Dittmar et al. (2012b) on the tolerance of tomato to drip-applied herbicides, similarly reported diminished weed control with increasing distance from drip emitters. In this study, two drip tapes were utilized to ensure uniform application of herbicides across the beds. While possibly more effective, use of multiple drip tapes increases production costs and requires specialized bedding equipment. Additionally, this trend has also been observed in studies evaluating weed control with fumigants in polyethylene-mulched beds (Fennimore et al. 2003; Candole et al. 2007; Chase et al. 2006). Therefore, a need exists to improve movement of drip-applied herbicides in polyethylene-mulched beds to maximize yellow nutsedge control and extend the durability and use of a single application of mulch.

Overcoming pesticide water solubility issues was a monumental task in the 1950s and 1960s as most pesticides were not formulated for using water as their carrier. However, the majority of pesticides are now formulated to use water. The waxy surfaces of many plants make it difficult for water-based spray solutions to penetrate their target. To overcome this barrier, adjuvants have been developed (Czarnota and Thomas 2013). Adjuvant is a broad term describing any additive to a spray tank that enhances pesticide activity. Examples of adjuvants include surfactants, spreader stickers, crop oils, anti-foaming materials, buffering agents, and compatibility agents. Of these, surfactants are the most widely used adjuvant in agriculture (Miller and Westra 1998). Surfactants are formulated to facilitate or improve the emulsifying, dispersing, spreading, sticking, or penetrating of liquids (Wang 2008). Surfactants alter the energy relationships at points of interference and lower surface and interfacial tension (Miller and Westra 1998). Research examining the effect of surfactants on drip-applied herbicides in mulched beds is limited; however, a recent study by Santos et al. (2013) investigated the performance of the fumigant metam potassium on nutsedge density when applied with the nonionic soil surfactant Integrate® 20 (15.25% tri block co-polymer and 4.75% glucoethers; Engage Agro USA, Prescott, AZ). Results revealed that with a single drip tape, lateral movement of the moisture field increased by 68% (in a 1 h period) which led to a 25-30% improvement in nutsedge control when Integrate 20 was combined with metam potassium. The improvement in nutsedge control was attributed to increased lateral movement of the metam potassium carried in water.

Integrate® 20 is a nonionic, soil surfactant designed to allow for proper infiltration and residual lateral movement of water in coarse soils for improved crop uniformity and yield potential. Integrate 20 increases water efficiency, nutrient utilization and pesticide efficacy. It can be applied alone or mixed with liquid fertilizers and applied as a sprayed, drip-applied, or drenched application (Engage Agro 2013).

Tween® 20 (polyoxyethylene sorbitan monolaurate; Croda International, Yorkshire, England) is a nonionic polysorbate surfactant that is used as a detergent and emulsifier in a number of domestic, scientific, and pharmacological applications (Sigma-Aldrich, Inc. 2013). Tween 20 is inexpensive, chemically inert, pH neutral, water soluble, and highly efficient at decreasing surface tension at low concentrations, making it an ideal candidate for use as an irrigation-applied adjuvant (Colwell and Rixon 1961). In limited research, Tween 20 has shown promising results for increasing herbicide mobility (Helling 1971) and longevity (Johnson and Dureja 2002) in soils.

Halosulfuron is a systemic-active, sulfonylurea herbicide that inhibits acetohydroxyacid synthase, a key enzyme in the production of the branch-chained amino acids. Halosulfuron (Sandea®) is registered for use in numerous vegetable crops including tomato for control of broadleaf weeds and sedges (Anonymous 2012).

S-metolachlor is a systemic-active, chloroacetamide herbicide which inhibits the synthesis of fatty acids along with several other plant components. Results with drip-applied *S*-metolachlor for weed control in tomato have been promising (Santos et al. 2008). *S*-metolachlor (Dual Magnum®) is labeled for use in tomatoes for control of annual grasses, yellow nutsedge, and number of small-seeded broadleaf weeds (Anonymous 2011).

Fomesafen is a systemic-active, diphenyl ether herbicide which inhibits protoporphyrogen oxidase resulting in the disruption of the synthesis of chlorophyll. Fomesafen (Reflex®; Syngenta Crop Protection, Greensboro, NC) is labeled for soybeans, cotton, and potatoes for control of a number of broadleaf weeds as well as sedges (Anonymous 2013). Fomesafen has recently been evaluated for use in a number of vegetables crops and has received labels for use in tomato and pepper production in Georgia, Florida and North Carolina (Culpepper 2012). Fomesafen provides similar levels of control and a similar weed species control spectrum as *S*-metolachlor; however, it offers an important tool for rotation of herbicide mode of action (Dittmar 2013).

This study was conducted to evaluate selected nonionic surfactants with the goal of improving movement of drip-applied herbicides in polyethylene-mulched tomato. Treatments were evaluated based on their effect on yellow nutsedge punctures (through the polyethylene mulch) and the corresponding responses of a tomato crop (plant height and yield). Drip-applied treatments were compared to a commercial standard of *S*-metolachlor sprayed (without surfactants) onto raised beds prior to mulch application. A nontreated control (no herbicide or surfactant) was included for comparison.

Materials and Methods

Field studies were conducted in the summer of 2012 and 2013 at the E.V. Smith Research Center (EVS), Shorter, AL (32°26’N, 85°53’W) and the Old Agronomy Farm (OAF), Auburn, AL (32°35’N, 85°29’W). Soil type at both locations was a Marvyn sandy loam (fine-loamy, kaolinitic, thermic-type Kanhapludults) comprised of 75.6, 6.8, and 17.5% sand, silt and clay respectively, with pH 5.7 (EVS) and 76.3, 5.0, and 18.8% sand, silt and clay respectively, with pH 6.2 (OAF). Fields used in experiments had a history of heavy nutsedge infestation. In both years, soil was disked and formed into four raised beds approximately 21 m long, 91 cm wide (46 cm wide at OAF), 13 cm high, and covered with white polyethylene mulch (1.25 mil; Berry Plastics Corp., Evansville, IN). Each of the four rows (spaced 6.1 m apart) contained 13, 5.5-m long plots with a 0.60-m buffer between plots. In 2012, a crop was not planted to allow evaluation of herbicide treatments on nutsedge punctures only. In 2013, each experimental plot contained 12 tomato plants (cv. Mountain Glory) spaced 0.45 m apart. Fertility and management of tomatoes followed commercial growing standards (Kemble 2013). Prior to mulch application, a single drip tape (Toro Ag., Bloomington, MN) delivering 516 L 100 m^{-1} h^{-1} was placed in the center of each bed and buried approximately 5 cm. Drip tape emitters were spaced 30.5 cm apart delivering 1.02 L hr^{-1}.

The experiment was conducted in a randomized complete block design with four replications. Treatments were a factorial arrangement of three surfactants levels [Integrate 20 at 2.8 kg ai ha^{-1}), Tween 20 at 2.8 kg ha^{-1} and no surfactant (i.e. none)]; and three PRE-applied herbicides (halosulfuron at 54 g ha^{-1}, *S*-metolachlor at 1.4 kg ha^{-1}, and fomesafen at 280 g ha^{-1}). Additional treatments included a commercial standard treatment in which *S*-metolachlor was sprayed (without a surfactant) onto the bed surface prior to mulch application and a nontreated control (bedded with polyethylene mulch without herbicides or surfactants) for a total of 11 treatments. The commercial standard treatment was applied with a battery-powered backpack sprayer (SHURflo, Costa Mesa, CA) equipped with one 11004 flat-fan nozzle (Spraying Systems Co., Wheaton, IL) calibrated to deliver 224 L ha^{-1}. Soil surfactants were mixed with the PRE-applied herbicides prior to application using Dosatron® (Dosatron International Inc., Clearwater, FL) D14MZ2 injectors and a custom injection manifold (Figure 1). Surfactants were applied at a rate of 2.8 kg ai ha^{-1} (or 0.2% v/v) along with 2240 L ha^{-1} of water per

Integrate 20 label recommendations. From each port on the manifold, a section of 1.27-cm plastic tubing was connected to the front of each corresponding plot. Plots receiving the same treatments were then connected together by splicing into the drip tape and capped where appropriate (Figure 2). Herbicide quantity applied to each treatment was based on the combined area of the four individual plots utilized per treatment. Plots were 5.5 m long and 0.6 m wide at EVS and 5.5 m long and 0.3 m wide at OAF.

Treatments were applied on 30 July (2012) and 14 May (2013) at EVS and on 21 Aug. (2012) and 21 May (2013) at OAF. In the 2013 studies, herbicide-containing treatments were applied 7 d prior to transplanting tomatoes per herbicide label recommendations. In both years, nutsedge punctures were counted at 28 and 56 d after treatment (DAT) from a 1.0 m^2 section of the plot. In the 2013 studies, tomato plant height (soil surface at base of plant to the top of growing point) was measured at 14 and 28 d after planting (DAP) to evaluate potential herbicide injury. In addition, tomato fruit was harvested weekly on 1, 8, 15 and 22 Aug. at EVS, and on 12, 19, 26 Aug. and 3 Sept. at OAF when fruit were 5 cm or larger in diameter, in breaker to red stage, and graded as either marketable or nonmarketable according to U.S. Department of Agriculture standards (USDA 1991). Marketable fruit consisted of medium, large, extra-large, and jumbo fruit grades. Fruit weight was summed over harvests to determine total marketable yield.

Data were analyzed with generalized linear models using the GLIMMIX 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. Plant height, puncture counts, and marketable yield were the response variables. Block and year were included in the models as random factors.

Data were analyzed separately by study location due to significant interactions (*P* <0.10) of treatment combinations with locations. When herbicide-by-surfactant interactions were significant, simple effects were examined; and when nonsignificant, levels within main effects were examined. Least squares means for plant height were compared to those for the commercial standard using lower-tailed *t*-tests. In addition, least-squares means for punctures and marketable yield were compared to those for the commercial standard using two-tailed *t*-tests. All *p* values for tests of differences between least squares means were adjusted using the Shaffer-Simulated method (α = 0.10).

Results and Discussion

All Data

Herbicide-by-surfactant interactions were nonsignificant (*P* ≤0.10) for counts of yellow nutsedge punctures, plant height, and yield in preliminary analyses; therefore, main-effects-only models were used for final analyses.

Yellow Nutsedge Punctures

EVS. Puncture counts measured at 28 DAT were influenced by main effects of both surfactant and herbicide (Table 1). Punctures in treatments without a surfactant (3.0 m^{-2}) were reduced compared to those with Tween 20 (3.9 m^{-2}). Additionally, punctures were reduced in treatments with fomesafen (2.3 m^{-2}) compared to those with either halosulfuron (3.6 m^{-2}) or *S*-metolachlor (4.4 m^{-2}), regardless of surfactant. Puncture counts at56 DAT were influenced by the main effect of herbicide only (Table 1). Punctures were again lowest in treatments with fomesafen (4.6 m^{-2}) compared to those with either halosulfuron (10.6 m^{-2}) or *S*-metolachlor (10.5 m^{-2}), regardless of surfactant.

Comparisons of individual treatments with the commercial standard revealed significant differences for nutsedge puncture counts at 56 DAT only (Table 1). Nutsedge punctures were similar to the commercial standard (5.8 m^{-2}) in treatments with fomesafen, applied with all surfactant combinations (5.0 m^{-2} with Integrate 20, 5.3 m^{-2} with Tween 20, and 3.6 m^{-2} without a surfactant) , halosulfuron applied with Integrate 20 (8.5 m^{-2}) , and *S*-metolachlor applied without a surfactant (8.8 m^{-2}). Puncture counts in all remaining treatments were significantly higher than the commercial standard.

OAF. Puncture counts at 28 DAT were influenced by main effects of both surfactant and herbicide (Table 2). Puncture counts in treatments without a surfactant (4.0 m^{-2}) were lower compared to treatments with a surfactant (5.6 m^{-2} with Integrate 20 and 5.5 m^{-2} with Tween 20). Additionally, puncture counts were lower in treatments with fomesafen (3.5 m^{-2}) compared to treatments with either halosulfuron (6.0 m^{-2}) or *S*-metolachlor (5.4 m^{-2}), regardless of surfactant. Puncture counts at 56 DAT were also influenced by main effects of both surfactant and herbicide (Table 2). Puncture counts were again lowest in treatments without a surfactant (7.1 m^{-2}) compared to those with a surfactant (9.5 m^{-2} with Integrate 20; 9.6 m^{-2} with Tween 20). Moreover, treatments with fomesafen had lower puncture counts (7.1 m^{-2}) compared to those with either halosulfuron (10.2 m^{-2}) or *S*-metolachlor (8.9 m^{-2}), regardless of surfactant. Comparisons of individual treatments with the commercial standard revealed significant differences for nutsedge puncture counts measured at 56 DAT only (Table 2). Puncture counts were similar to the commercial standard (5.3 m^{-2}) in treatments with fomesafen applied with either Tween 20 or without a surfactant (6.3 m^{-2} and 6.6 m^{-2}, respectively) as well as *S*-metolachlor applied without a surfactant (5.9 m^{-2}). Puncture counts in all remaining treatments were significantly higher than the commercial standard.

Plant Height

EVS. At 14 DAP, plant height was influenced by the main effect of herbicide only (Table 3). Plant height was reduced in treatments with *S*-metolachlor (18.7 cm) compared to those with either fomesafen (20 cm) or halosulfuron (20.6 cm), regardless of surfactant. At 28 DAP, plant height was not influenced by main effects of either surfactant or herbicide (Table 3). Comparisons of individual treatments with the commercial standard revealed no significant differences at either date (Table 3).

OAF. Plant height (at both dates) was not influenced by main effects of surfactant or herbicide (Table 4). Comparisons of individual treatments with the commercial standard revealed significant differences for plant height measured at 14 DAP only (Table 4). *S*-metolachlor applied with Integrate 20 reduced plant height compared to the commercial standard, otherwise plant height was similar to the commercial standard.

Tomato Yield

EVS. Marketable yield was influenced by main effects of both surfactant and herbicide (Table 3). Yield was reduced in treatments with Integrate 20 (46.8 t ha^{-1}) compared to those with either Tween 20 (56.1 t ha^{-1}) or no surfactant (57.4 t ha^{-1}). Additionally, yield was reduced in treatments with *S*-metolachlor (42.4 t ha^{-1}) compared to those with either fomesafen (60.4 t ha^{-1}) or halosulfuron (57.5 t ha^{-1}), regardless of surfactant. Comparisons of individual treatments with the commercial standard revealed significant differences for yield (Table 3). Marketable yield was similar to the commercial standard in treatments with fomesafen, applied with all surfactant levels (55.5 t ha^{-1} with Integrate

20 and 62.9 t ha^{-1} with both Tween 20 and no surfactant) and halosulfuron applied with Tween 20 (64 t ha^{-1}) and without a surfactant (58.3 t ha^{-1}). Marketable yield in all remaining treatments was reduced in comparison to the commercial standard.

OAF. Marketable yield was not influenced by main effects of surfactant or herbicide (Table 4). Furthermore, comparisons of individual treatments with the commercial standard revealed yield was similar to the commercial standard across all treatments (Table 4).

Application of Tween 20 and Integrate 20 surfactants along with drip-applied fomesafen, halosulfuron and *S*-metolachlor failed to reduce yellow nutsedge punctures relative to herbicides applied without a surfactant. Results are likely due to the failure of surfactant-containing treatments to improve lateral movement of herbicides underneath the polyethylene-mulched beds. Previous research (Ditmar et al. 2012a) examined the effect of surfactants applied along with drip-applied fumigants and reported a significant improvement in nutsedge control; however, lateral movement of fumigants within the soil is typically much greater than herbicides. Studies examining application of surfactants along with PRE-applied herbicides have shown mixed results. Koren (1972) reported that nonionic surfactants increased both depth of water movement and herbicide movement in soil when applied along with trifluralin and oryzalin in a sandy soil. Helling (1971) reported increased leaching of 2,4-D with the addition of non-ionic surfactants. In a study of herbicide mobility as affected by surfactants, Foy (1992) found that surfactants caused variable effects on water movement and herbicide movement, depending on the herbicide, surfactant and its concentration, soil type, and preleaching conditions. Studies examining the effect of nonionic surfactants on drip-applied herbicides in polyethylene mulched beds are lacking. However, these results suggest that nonionic surfactants may not improve lateral movement of herbicides and subsequent reduction in yellow nutsedge punctures when applied along with fomesafen, halosulfuron, and *S*-metolachlor through drip-irrigation in polyethylene-mulched beds.

It is important to note that these studies were conducted on a sandy loam soil with low (< 1%) organic matter content. Studies performed on a soil with higher clay or organic matter content may produce different results. Alternative practices to increase lateral movement of herbicides must be devised to improve yellow nutsedge control at bed edges; therefore research efforts will continue to be of utmost importance.

Literature Cited

Adcock CW (2007) Combinations of selected sulfonylurea herbicides with *S*-metolachlor for nutsedge control in tomatoes. Electronic Thesis and Dissertation. Auburn, AL: Auburn University

Anonymous (2011) Dual Magnum herbicide label SCP 816A-L1U 1210. Greensboro, NC; Syngenta Crop Protection. 50 p

Anonymous (2012) Sandea herbicide label 02-R0913EPA. Yuma, AZ; Gowan Company. 9 p

Anonymous (2013) Reflex herbicide label SCP 993A-L1M 0413. Greensboro, NC; Syngenta Crop Protection. Pp. 28-35

Candole BL, Csinos AS, Wang D (2007) Concentrations in soil and efficacy of drip-applied 1,3-D + chloropicrin and metam sodium in plastic-mulched sandy soil beds. Crop Protection 26:1801-1809

Chase CA, Stall WM, Simmone EH, Hochmuth RC, Dukes MD, Weiss AW (2006) Nutsedge control with drip-applied 1, 3-dichloropropene plus chloropicrin in a sandy soil. HortTechnology 16:641-648

Colwell CE, Rixon RE (1961) Consideration in the use of nonionic surface-active agents. Am. Dyest. Rep. 50:679-682

Culpepper AS, Grey TL, Webster TM (2009) Vegetable response to herbicides applied to low-density polyethylene mulch prior to transplant. Weed Technol. 23:444-449

Culpepper AS (2012) Vegetable Weed Control Update. University of Georgia Cooperative Extension System. http://www.gaweed.com/slides/GFVGA-newproducts2012/GFVGA-newproducts2012.pdf. Accessed: October 31, 2012

Czarnota M, Thomas P (2013) Using surfactants, wetting agents, and adjuvants in the greenhouse. The University of Georgia Cooperative Extension Service. Bulletin 1314

Dittmar PJ (2013) Weed control strategies in tomato. University of Florida Tomato Institute Proc. 24 p

Dittmar PJ, Monks DW, Jennings KM (2012a) Effect of drip-applied herbicides on yellow nutsedge (*Cyperus esculentus*) in plasticulture. Weed Technol. 26:243-247

Dittmar PJ, Monks DW, Jennings KM, Booker FL (2012b) Tolerance of tomato to herbicides applied through drip irrigation. Weed Technol. 26:684-690

Engage Agro (2013) Integrate soil surfactant technical bulletin. http://www.engageagrousa.com . Accessed: October 9, 2013

Fennimore SA, Haar MJ, Ajwa HA (2003) Weed control in strawberry provided by shank- and drip-applied methyl bromide alternative fumigants. HortScience 38:55-61

Foy CL (1992) Influence of certain surfactants on the mobility of selected herbicides in soil, *in* Adjuvants and Agrichemicals. Foy CL ed., CRC Press, Boca Raton, FL. 349 p.

Gilreath JP, Santos BM (2004) Efficacy of methyl bromide alternatives on purple nutsedge (*Cyperus rotundus*) control in tomatoes and peppers. Weed Technol. 18:141-145

Helling CS (1971) Pesticide mobility in soils II: Applications of soil thin-layer chromatography. Soil Sci. Soc. Am. J. 35:737–743

Johnson S, Dureja P (2002) Effects of surfactants on persistence of azadirachtin-A (a neem-based pesticide). J. Environ. Sci. Health. 37: 75-80

Johnson III WC, Mullinax Jr. BG (2008) Cultural control of yellow nutsedge (*Cyperus* *esculentus*) in transplanted cantaloupe (*Cucumis melo*) by varying application timing and type of thin-filmed mulches. Crop Protect. 27:735-739

Kemble JM, ed (2013) Vegetable Crop Handbook for Southeastern US – 2013. Lincolnshire, IL: Vance Publishing. Pp. 99-102

Koren E (1971) Leaching of trifluralin and Oryzalin in soil with three surfactants. Weed Sci. 20:230-232

McCraw D, Motes JE (2000) Use of plastic mulch and row covers in vegetable production. Oklahoma Cooperative Extension Service. Oklahoma State University. HLA-6034

Miller P, Westra P (1998) How surfactants work. Colo. State Univ. Coop. Ex., Prod. Crop Ser. No. 564

Morales-Payan JP, Stall WM, Shilling DG, Charudattan RC, Dusky JA, Bewick TA (2003) Above- and belowground interference of purple and yellow nutsedge (*Cyperus* spp.) with tomato. Weed Sci. 51:181-185

Sanjeev K. Bangarwa, Jason K. Norsworthy, Edward E. Gbur (2012) Effect of turnip soil amendment and yellow nutsedge (*Cyperus esculentus*) tuber densities on interference in polyethylene-mulched tomato. Weed Technology 26:364-370

Santos BM, Gilreath JP, Lugo ML, Rivera LE (2008) Managing weeds with drip-applied herbicides in tomato. Crop Prot. 27:101-103

Santos BM, Jacoby TP, Boyd NS (2013) Improved nutsedge control on bed edges with metam potassium and soil surfactants. University of Florida Tomato Institute Proc. Pp. 22-23

Sigma-Aldrich, Inc (2013) Tween® 20 product information sheet.

http://www.sigmaaldrich.com/sigma-aldrich/product_information_sheet/p7949pis.pdf. Accessed: October 6, 2013

Thomas JG, Pennington DA, Schmidt AM, Pringle L (2003) Chemigation. Mississippi State Extension Service. Publication 1551

[USDA] US Department of Agriculture (1991) United States Standards for Grades of Fresh Tomatoes. http://www.ams.usda.gov/AMSv1.0/getfile?dDoName=STELPRDC5050331. Accessed: October 15, 2013

Wang X (2008) Effects of a nonionic surfactant on plant growth and physiology. Auburn University, Auburn, Alabama. Diss. Abstr. Pp. 6-10

Wang X, Zhu H, Reding ME, Locke JC, Leland JE, Derksen RC, Spongberg AL, Krause CR (2009) Delivery of chemical and microbial pesticides through drip irrigation systems. Appl. Engr. Agr. 25:883-893

Webster TM (2003) Nutsedge (*Cyperus* spp.) eradication: Impossible dream? Pages 21-25 *in* L.E. Riley, R. K. Dumroese and T. D. Landis (eds.) National proceedings: Forest and Conservatory Nursery Associations - 2002. Ogden, UT. Proceedings RMRS-P-28

Webster TM (2005) Patch expansion of purple nutsedge (*Cyperus rotundus*) and yellow nutsedge (*Cyperus esculentus*) with and without polyethylene mulch. Weed Sci. 53:839-845

Webster TM (2010) Weed survey – Southern states: Vegetable, fruit, and nut crops subsection. Proc. South. Weed Sci. Soc. 63:246-257

Table 1. Yellow nutsedge punctures in polyethylene-mulched tomato following treatment with herbicides applied with and without surfactants at the E.V. Smith Research Center in Shorter, AL. Data for 2012 and 2013 are pooled.

Treatment			Punctures		
Surfactant[a]	Herbicide	Herbicide rate	28 DAT[b]	56 DAT	Reduction[c]
Comparisons among main effects:					
		g ai ha^{-1}	no. m^{-2}		%
Integrate 20		-	3.4 AB[d]	8.6 A	81 A
Tween 20		-	3.9 B	9.2 A	79 A
None		-	3.0 A	7.9 A	83 A
	Fomesafen	280	2.3 A	4.6 A	90 A
	Halosulfuron	54	3.6 B	10.6 B	76 B
	S-metolachlor	1,400	4.4 B	10.5 B	77 B
Comparisons of individual treatments with the commercial standard:					
Integrate 20	Fomesafen	280	2.4 *[e]	5.0 *	89 *
	Halosulfuron	54	3.9 *	8.5 *	81 *
	S-metolachlor	1,400	3.9 *	12.4	73
Tween 20	Fomesafen	280	2.9 *	5.3 *	88 *
	Halosulfuron	54	4.4 *	12.1	73
	S-metolachlor	1,400	4.6 *	10.4	77
None	Fomesafen	280	1.5 *	3.6 *	92 *
	Halosulfuron	54	2.6 *	11.3	75
	S-metolachlor	1,400	4.8 *	8.8 *	81 *
	Standard[f]	1,400	2.8	5.8	87
	Nontreated	-	17.9	45.5	0

[a] Both surfactants were applied at a rate of 2.8 kg ha^{-1} (or 0.2% v/v).

[b] Abbreviations: DAT, days after treatment.

[c] Reduction in punctures relative to the nontreated at 56 DAT.

[d] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test (α = 0.10).

[e] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test (α = 0.10).

[f] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 2. Yellow nutsedge punctures in polyethylene-mulched tomato following treatment with herbicides applied with and without surfactants at the Old Agronomy Farm in Auburn, AL. Data for 2012 and 2013 are pooled.

Treatment			Punctures		
Surfactant[a]	Herbicide	Herbicide rate	28 DAT[b]	56 DAT	Reduction[c]
		Comparisons among main effects:			
		g ai ha^{-1}	——— no. m^{-2} ———		%
Integrate 20		-	5.6 B[d]	9.5 B	73 B
Tween 20		-	5.5 B	9.6 B	74 B
None		-	4.0 A	7.1 A	81 A
	Fomesafen	280	3.5 A	7.1 A	81 A
	Halosulfuron	54	6.0 B	10.2 B	72 B
	S-metolachlor	1,400	5.4 B	8.9 B	76 B
		Comparisons of individual treatments with the commercial standard:			
Integrate 20	Fomesafen	280	4.8 *[e]	8.3	78
	Halosulfuron	54	6.4 *	10.4	72
	S-metolachlor	1,400	5.6 *	9.8	73
Tween 20	Fomesafen	280	3.6 *	6.3 *	83 *
	Halosulfuron	54	6.5 *	11.3	69
	S-metolachlor	1,400	6.3 *	11.1	70
None	Fomesafen	280	2.6 *	6.6 *	82 *
	Halosulfuron	54	5.1 *	8.8	76
	S-metolachlor	1,400	4.3 *	5.9 *	84 *
	Standard[f]	1,400	4.8	5.3	86
	Nontreated	-	13.3	36.9	0

[a] Both surfactants were applied at a rate of 2.8 kg ha^{-1} (or 0.2% v/v).

[b] Abbreviations: DAT, days after treatment.

[c] Reduction in punctures relative to the nontreated at 56 DAT.

[d] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test ($\alpha = 0.10$).

[e] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test ($\alpha = 0.10$).

[f] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 3. Plant height and marketable yield of tomato following treatment with herbicides applied with and without surfactants at the E.V. Smith Research Center in Shorter, AL in 2013 only.

Treatment			Height		
Surfactant[a]	Herbicide	Herbicide rate	14 DAP[b]	28 DAP	Yield
		Comparisons of main effects:			
		g ai ha^{-1}	cm		t ha^{-1}
Integrate 20		-	19.6 A[c]	59.9 A	46.8 B
Tween 20		-	19.7 A	59.5 A	56.1 A
None		-	20.0 A	60.3 A	57.4 A
	Fomesafen	280	20.0 A	60.1 A	60.4 A
	Halosulfuron	54	20.6 A	59.9 A	57.5 A
	S-metolachlor	1400	18.7 B	59.7 B	42.4 B
	Comparisons of individual treatments with the commercial standard:				
Integrate 20	Fomesafen	280	19.3 *[d]	60.7 *	55.5 *
	Halosulfuron	54	21.6 *	58.2 *	50.1
	S-metolachlor	1,400	18.0 *	60.8 *	34.8
Tween 20	Fomesafen	280	20.8 *	58.6 *	62.9 *
	Halosulfuron	54	19.8 *	61.6 *	64.0 *
	S-metolachlor	1,400	18.4 *	58.3 *	41.3
None	Fomesafen	280	19.9 *	61.1 *	62.9 *
	Halosulfuron	54	20.6 *	60.0 *	58.3 *
	S-metolachlor	1,400	19.6 *	59.9 *	51.1
	Standard[e]	1,400	19.4	62.6	73.1
	Nontreated	-	21.9	61.3	62.6

[a] Both surfactants were applied at a rate of 2.8 kg ha^{-1} (or 0.2 % v/v).

[b] Abbreviations: DAP, days after planting.

[c] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test ($\alpha = 0.10$).

[d] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test ($\alpha = 0.10$).

[e] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

Table 4. Plant height and marketable yield of tomato following treatment with herbicides applied with and without surfactants at the Old Agronomy Farm in Auburn, AL in 2013 only.

Treatment			Height		
Surfactant[a]	Herbicide	Herbicide rate	14 DAP[b]	28 DAP	Yield
Comparisons of main effects:					
		g ai ha^{-1}	cm	cm	t ha^{-1}
Integrate 20		-	25.6 A[c]	69.9 A	54.1 A
Tween 20		-	27.0 A	71.1 A	61.5 A
None		-	26.0 A	70.6 A	53.8 A
	Fomesafen	280	26.5 A	71.3 A	56.3 A
	Halosulfuron	54	26.2 A	70.7 A	59.4 A
	S-metolachlor	1400	26.0 A	70.5 A	53.8 A
Comparisons of individual treatments with the commercial standard:					
Integrate 20	Fomesafen	280	25.8 *[d]	69.3 *	60.2 *
	Halosulfuron	54	26.3 *	73.6 *	56.0 *
	S-metolachlor	1,400	24.7	69.6 *	46.2 *
Tween 20	Fomesafen	280	27.4 *	71.6 *	53.9 *
	Halosulfuron	54	26.9 *	69.7 *	64.8 *
	S-metolachlor	1,400	26.8 *	69.3 *	65.9 *
None	Fomesafen	280	26.3 *	72.9 *	54.8 *
	Halosulfuron	54	25.3 *	68.9 *	57.4 *
	S-metolachlor	1,400	26.4 *	72.7 *	49.3 *
	Standard[e]	1,400	26.8	68.9	59.7
	Nontreated	-	26.3	68.4	53.4

[a] Both surfactants were applied at a rate of 2.8 kg ha^{-1} (or 0.2% v/v).

[b] Abbreviations: DAP, days after planting.

[c] Main effect means followed by the same uppercase letter do not differ according to the Shaffer-Simulated test (α = 0.10).

[d] Individual treatment means followed by an asterisk (*) do not differ from the commercial standard according to the Shaffer-Simulated test (α = 0.10).

[e] *S*-metolachlor (Dual Magnum®) sprayed to raised beds prior to polyethylene mulch application.

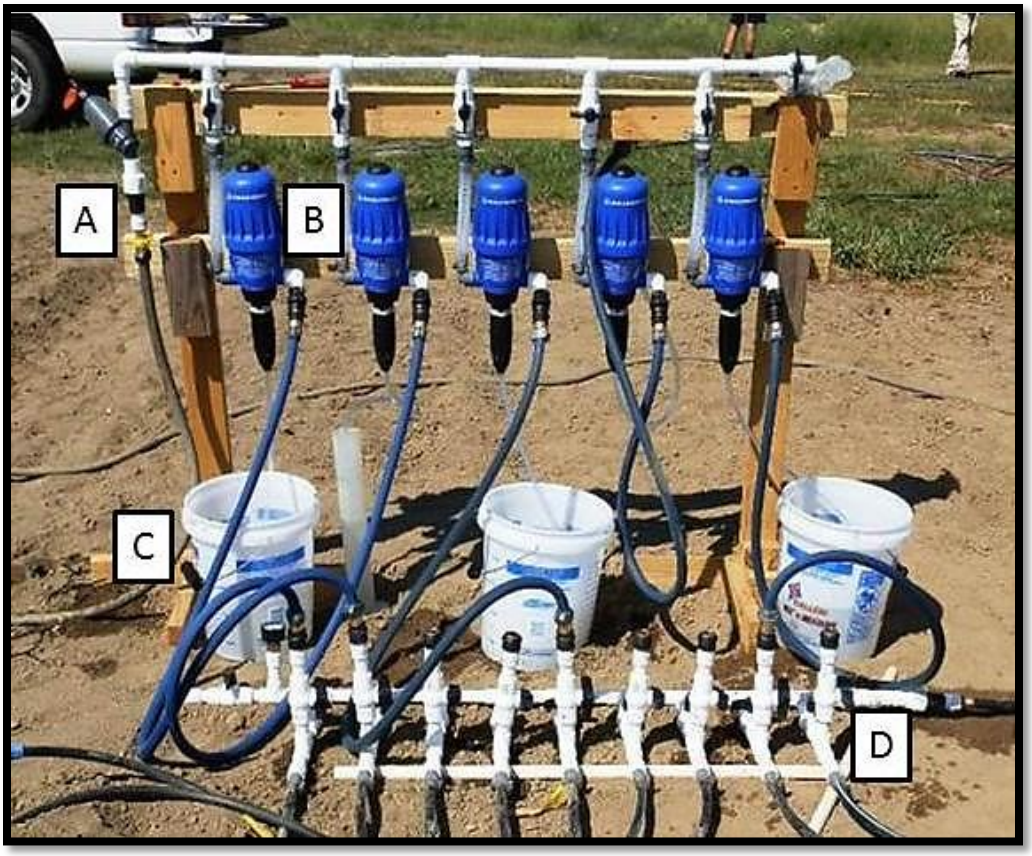

Figure 1. Equipment setup for application of drip-applied herbicides. The equipment includes a backflow prevention valve (A), Dosatron® injection pump (B), buckets to hold injected herbicides (C), and a custom-built injection manifold (D).

Figure 2. Herbicide treatments were delivered to polyethylene-mulched beds by splicing main delivery lines (1.27 cm plastic tubing) into the drip tape using drip tape connectors.

Chapter IV

Final Discussion

Use of polyethylene mulch in vegetable production provides many benefits including improved weed control. However, not all weed species are adequately controlled. Yellow nutsedge (*Cyperus esculentus* L.) can penetrate the mulch, degrading its durability, and is a serious concern for growers wanting to use the mulch for multicropping systems. To manage nutsedge species in these systems, halosulfuron (Sandea®) and *S*-metolachlor (Dual Magnum®) are often sprayed onto pre-formed beds prior to polyethylene mulch application. However, application of herbicides through drip irrigation has become more prevalent and offers several benefits over sprayed applications. Preliminary research has indicated the potential for use of drip-applied herbicides in commercial production; however, some issues need to be addressed. Recent research and personal observations have indicated that yellow nutsedge control diminishes with increasing distance from drip emitters. Therefore, a need exists to explore strategies to improve movement of drip-applied herbicides in polyethylene-mulched beds to maximize yellow nutsedge control and allow for a single application of mulch to be used in multicropping systems.

In chapter II, field studies were conducted to evaluate drip-application methods for applying PRE herbicides under polyethylene mulch on yellow nutsedge punctures and the corresponding responses (plant height and yield) of a tomato crop. The experiment was a factorial treatment arrangement of three drip application methods and three PRE-applied herbicides [halosulfuron (54 g ai ha^{-1}), *S*-metolachlor (1.4 kg ha^{-1}), and fomesafen (280 g ha^{-1})]. Herbicides were applied either immediately following saturation of the planting beds (method A), over an extended period used to saturate the beds (method B), or prior to bed saturation (method C). Additional treatments included a commercial standard of *S*-metolachlor (sprayed to bed surface prior to polyethylene mulch application) and a nontreated control. In this study, the majority of treatments failed to adequately (< 90% compared to the nontreated) control yellow nutsedge at both 28 and 56 DAT. Drip-applied treatments were applied with an application volume of approximately 14,000 L ha^{-1}. This is an enormous amount of water compared with the 240 L ha^{-1} needed for typical sprayed applications. With this in mind, it is possible that herbicide treatments leached down into the soil resulting in crop damage (i.e. reduction in plant height), poor nutsedge control, and ultimately reduction in yield. Fomesafen applied with method B was the only treatment that provided a significant reduction (55% compared to commercial standard) in yellow nutsedge punctures while maintaining marketable yields that were comparable to the commercial standard. Furthermore, fomesafen and halosulfuron, applied with method C, provided similar yellow nutsedge control and similar yields compared to the commercial standard.

In chapter III, field studies were conducted to evaluate nonionic surfactants applied in combination with drip-applied halosulfuron, *S*-metolachlor, and fomesafen on the effect on yellow nutsedge punctures and the corresponding responses of a tomato crop. The experiment was a factorial treatment arrangement of three surfactant levels [Integrate® 20 (2.8 kg ha^{-1}), Tween® 20 (2.8 kg ha^{-1}) and none] and three PRE-applied herbicides [halosulfuron (54 g ai ha^{-1}), *S*-metolachlor (1.4 kg ha^{-1}), and fomesafen (280 g ha^{-1})] along with a nontreated control. Application of surfactants along with drip-applied herbicides failed to reduce yellow nutsedge punctures relative to herbicides applied without a surfactant. Results are likely due to the failure of surfactant-containing treatments to improve lateral movement of the herbicides underneath the polyethylene-mulched beds. It is important to note that these studies were conducted on a sandy loam soil with low (< 1%) organic matter. Studies performed on a soil with higher clay or organic matter content may produce different results. Alternative practices to increase lateral movement of herbicides must be devised to improve yellow nutsedge control at bed edges; therefore research efforts will continue to be of utmost importance.

Results from these studies suggest that drip-applied fomesafen and halosulfuron, when applied by the appropriate method, can provide suitable control of yellow nutsedge punctures in polyethylene-mulched tomato while maintaining expected yields. However, use of nonionic surfactants may not improve yellow nutsedge control when applied along with fomesafen, halosulfuron, and *S*-metolachlor through drip-irrigation. Future studies are planned to examine drip-applied fomesafen in tomato production as well as application methods for applying drip-applied herbicides using lower application volumes in order to limit herbicide leaching.