ABSTRACT

COLEMAN, LAUREN BRIANNE. Stale Seedbed Manipulation, Increased Rates of Flumioxazin, and Wick-Applied Herbicides for Palmer Amaranth Control in ‘Covington’ Sweetpotato. (Under the direction of Dr. Katie M. Jennings and Dr. David W. Monks).

The most common and troublesome weed in North Carolina sweetpotato is Palmer amaranth, an upright, branching, annual weed with competitive growth and reproductive characteristics. North Carolina sweetpotato growers have become increasingly interested in alternative Palmer amaranth management strategies that will provide season-long Palmer amaranth control and maximize sweetpotato storage root yield. Thus, field studies were conducted in 2012 and 2013 to 1) develop a Palmer amaranth management program with flumioxazin for stale seedbed sweetpotato, 2) determine the effect of increased rates of flumioxazin on foliar crop injury and storage root yield and quality, and 3) determine the effect of wick-applied paraquat and d-limonene on Palmer amaranth control and sweetpotato storage root yield and quality.

Stale seedbed herbicide treatments consisted of flumioxazin at 72, 90, and 109 g ai ha\(^{-1}\) 45 d before transplanting (DBP) alone or followed by (fb) flumioxazin at 72, 90, and 109 g ha\(^{-1}\) 0 DBP, flumioxazin at 72, 90, and 109 g ha\(^{-1}\) 0 DBP alone or fb S-metolachlor at 800 g ai ha\(^{-1}\) 0, 5 to 7, or 10 d after planting (DAP), flumioxazin at 72, 90, and 109 g ha\(^{-1}\) plus clomazone at 630 g ai ha\(^{-1}\) 45 DBP fb S-metolachlor at 800 g ha\(^{-1}\) 10 DAP, or fomesafen at 280 g ai ha\(^{-1}\) 45 DBP. Treatments consisting of flumioxazin 45 DBP fb flumioxazin 0 DBP or flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP provided the greatest Palmer amaranth control of 91 and 80% 109 DAP, respectively. Delayed flumioxazin
application timings at 0 DBP allowed for Palmer amaranth emergence and resulted in reduced control. Sweetpotato storage root yield was low in treatments that did not provide sufficient Palmer amaranth control. A control program consisting of flumioxazin at 109 g ha\(^{-1}\) plus clomazone at 630 g ha\(^{-1}\) 45 DBP fb S-metolachlor at 800 g ha\(^{-1}\) 0 to 10 DAP provides an effective herbicide program for Palmer amaranth control in stale seedbed production systems in North Carolina sweetpotato.

Increased rates of flumioxazin were applied immediately prior to sweetpotato transplanting at 0 (weed-free check), 72, 109, 145, 217, 289, and 362 g ai ha\(^{-1}\), which corresponds to 0, 0.7, 1.0, 1.3, 2.0, 2.7, and 3.3 times the registered rate for Palmer amaranth control in sweetpotato. Foliar crop injury was minimal (< 10%) for all flumioxazin treatments. Flumioxazin at 109 g ha\(^{-1}\) resulted in the greatest yield of No. 1 storage roots, which is consistent with product label recommendations. To maximize yield and decrease the risk of herbicide resistance, North Carolina sweetpotato growers should continue to apply the registered rate of flumioxazin at 109 g ha\(^{-1}\) in sweetpotato production.

Paraquat and \(d\)-limonene applied through an LMC Cross-Wick Bar were evaluated for Palmer amaranth control in Covington sweetpotato. Wick-applied treatments consisted of wick-applied paraquat at 5, 6, or 7 wk after transplanting (WAP), and wick-applied \(d\)-limonene 5 WAP alone or fb 7 WAP, 6 WAP alone or fb 10 WAP, or 7 WAP alone or fb 11 WAP. Treatments consisting of wick-applied paraquat at 6 or 7 WAP provided the greatest (88% or greater) Palmer amaranth control 84 DAP. Palmer amaranth control 84 DAP ranged from 30 to 53% for wick-applied \(d\)-limonene treatments. No internal or external
injury of sweetpotato storage roots was observed. Yield of jumbo, No. 1, and marketable grades of sweetpotato storage roots was greatest in the weed-free control.
Stale Seedbed Manipulation, Increased Rates of Flumioxazin, and Wick-Applied Herbicides for Palmer Amaranth Control in ‘Covington’ Sweetpotato

by
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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science

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DEDICATION

To the pursuit of knowledge.

May there always be questions left to answer.
BIOGRAPHY

Lauren Brianne Coleman was born April 19, 1988 in Titusville, FL to Marty and Denise Coleman. Surrounded by the unique ecosystems of Atlantic Coastal Florida, she gained an early appreciation for nature and the surrounding world. She graduated from Astronaut High School in 2006. In May 2010, Lauren graduated from the University of Florida with a Bachelor of Science Degree in Botany. While at the University of Florida, she had the privilege to work in various Horticultural Science labs with people whose enthusiasm for plant science was truly inspirational. Lauren moved to Raleigh, NC in August 2011 to pursue a Master of Science Degree in Horticultural Science at North Carolina State University. Lauren is looking forward to the future.
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Thank you to the staff and crew at the Horticultural Crops Research Station in Clinton, NC, to fellow graduate students, and to everyone else who worked with us in the field during those hot summer days.

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EVALUATION OF HERBICIDE TIMINGS FOR PALMER AMARANTH CONTROL IN A STALE SEEDBED SWEETPOTATO PRODUCTION SYSTEM

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Studies were conducted in 2012 and 2013 at Clinton, NC to determine the effect of herbicide timing in a stale seedbed production system on Palmer amaranth control and 'Covington' sweetpotato yield and quality. Treatments consisted of flumioxazin at 72, 90, and 109 g ai ha\(^{-1}\) 45 d before transplanting (DBP) alone or followed by (fb) flumioxazin at 72, 90, and 109 g ha\(^{-1}\) pretransplant 0 DBP, flumioxazin at 72, 90, and 109 g ha\(^{-1}\) pretransplant 0 DBP alone or fb S-metolachlor at 800 g ai ha\(^{-1}\) 0, 5 to 7, or 10 d after planting (DAP), flumioxazin at 72, 90, and 109 g ha\(^{-1}\) plus clomazone at 630 g ai ha\(^{-1}\) 45 DBP fb S-metolachlor at 800 g ha\(^{-1}\) 10 DAP, or fomesafen at 280 g ai ha\(^{-1}\) 45 DBP. Herbicide application timing had a significant effect on Palmer amaranth control, while herbicide rate did not. Treatments consisting of flumioxazin 45 DBP fb flumioxazin pretransplant or flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP provided the greatest Palmer amaranth control of 91 and 80% 109 DAP, respectively. Delayed flumioxazin application timings pretransplant allowed for Palmer amaranth emergence and resulted in only 65, 62, 48, and 17% 14, 32, 68, and 109 DAP, respectively. Sweetpotato storage root yield was low in treatments that did not provide sufficient Palmer amaranth control. A control program consisting of flumioxazin at 109 g ha\(^{-1}\) plus clomazone at 630 g ha\(^{-1}\) 45 DBP fb S-metolachlor at 800 g ha\(^{-1}\) 0 to 10 DAP provides an effective herbicide program for Palmer amaranth control in stale seedbed production systems in North Carolina sweetpotato.
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**Nomenclature:** flumioxazin; *S*-metolachlor; clomazone; fomesafen; Palmer amaranth, *Amaranthus palmeri* S. Wats. AMAPA; sweetpotato, *Ipomoea batatas* L. Lam. ‘Covington’.

**Key words:** weed control, yield loss.

**Abbreviations:** DBP, days before transplanting; fb, followed by; DAP, days after transplanting
Approximately 52,488 ha of marketable sweetpotato [Ipomoea batatas (L.) Lam.] storage roots with a value of over $505 million were harvested in 2011 (USDA-NASS 2012). The Southern United States, including North Carolina, Mississippi, Arkansas, and Louisiana, produce over 75% of the nation’s total sweetpotatoes (USDA-NASS 2012). Sweetpotato production in North Carolina accounted for more than 26,000 ha harvested, and yielded a record high 25,088 kg ha\(^{-1}\) (NCDA & CS 2012). Due to sweetpotatoes’ low canopy, storage root yield and quality can be limited by pests, especially competitive weed species (Glaze and Hall 1990; La Bonte et al. 1999; Meyers et al. 2010b; Seem et al. 2003). Sweetpotato production in the Southeastern United States consists of crop rotation with soybean (Glycine max L. Merr.), tobacco (Nicotiana tabacum L.), cotton (Gossypium hirsutum L.), or corn (Zea mays L.) (Haley and Curtis 2006). Palmer amaranth (Amaranthus palmeri S. Watson), including glyphosate- and ALS-resistant biotypes, are among the most troublesome weed species in North Carolina tobacco (L. Fisher, Department of Crop Science, NC State University, personal communication); Arkansas, Florida, and Georgia soybean; North Carolina and Georgia cotton; and Alabama, Florida, Georgia, and Mississippi corn (Webster 2013). Palmer amaranth is the most common and troublesome weed species in North Carolina sweetpotato (Webster 2010).

Palmer amaranth is a tall, upright, and dioecious summer annual that is native to the arid Sonoran desert region of the Southwestern United States and Northwestern Mexico (Sauer 1957). As a result, Palmer amaranth demonstrates adaptability to harsh environmental conditions and has developed a wide range of competitive physiological and reproductive characteristics. Palmer amaranth, like other Amaranthus species, utilizes C\(_4\) photosynthesis.
which provides increased biochemical efficiency of the carbon fixation pathway when compared to C_3 plants (Ehleringer et al. 1997). Vegetative growth parameters, including leaf area, growth rate, and biomass accumulation, are greater in Palmer amaranth than other Amaranthus species (Horak and Loughin 2000). Under ideal growing conditions, Palmer amaranth has the potential to reach maximum heights exceeding 2 m, with the greatest proportion (80%) of photosynthetically active leaf area well above the sweetpotato canopy of 0.5 m (Massinga et al. 2003; Meyers et al. 2010b). Palmer amaranth plants maximize light interception and photosynthetic potential through the use of diaheliotropism, or solar tracking, an evolved adaption that results in the perpendicular orientation of leaves to sunlight and contributes to rapid growth of young seedlings (Ehleringer and Forseth 1980). Palmer amaranth produces prolific root systems that effectively penetrate soil layers with high bulk densities and are more efficient at water and nitrogen uptake than other crop and weed species (Place et al. 2008). Female Palmer amaranth plants can produce between 200,000 and 600,000 seeds per plant (Keeley et al. 1987), and viable seeds typically germinate within one day under favorable germination conditions (Steckel et al. 2004). In addition, development of resistance to five different herbicide families, including ALS-inhibitors, dinitroanilines, triazines, glyphosate, and HPPD inhibitors, as well as several cases of cross resistance, has been confirmed in Palmer amaranth in seventeen states across the United States (Heap 2013).

Season-long Palmer amaranth densities of 8 plants m^{-1} of row reduced yields of corn and soybean 91 and 79%, respectively (Bensch et al. 2003; Massinga et al. 2001), and one Palmer amaranth m^{-1} of crop row reduced peanut and cotton yield 28 and 13%, respectively (Burke
et al. 2007; Morgan et al. 2001). Even at low densities, competition of Palmer amaranth contributes to relatively high light interception, shading, and subsequent yield losses, especially in low-growing crops with a short canopy. Sweetpotato, a member of the morningglory family, has a vining growth habit that expands horizontally along the soil surface to produce a crop canopy that rarely exceeds 0.5 m (Huaman 1992). Meyers et al. (2010b) reported Palmer amaranth densities of 0.5 to 6.5 plants m$^{-1}$ reduced marketable sweetpotato yield 36 to 81% in ‘Beauregard’ and ‘Covington’ sweetpotato, and regardless of Palmer amaranth density, light interception was at least 42%. The multitude of advantageous growth and reproductive characteristics, as well as the capacity to evolve a diversity of resistance mechanisms to commonly used herbicides, contribute to the overall difficulty in Palmer amaranth management in crop production in the Southeast.

In North Carolina sweetpotato, Palmer amaranth management methods include the use of PREPLANT, PRE, or POST herbicides, cultivation, mowing, wicking, and hand removal (Haley and Curtis 2006). North Carolina sweetpotato growers have become interested in the implementation of reduced tillage production practices, including stale seedbed preparation, because they provide an effective, cost-efficient means of reducing soil erosion, increasing soil organic matter, and improving water conservation and nutrient-holding capacities of soils (Hobbs et al. 2008; Kassam et al. 2009). From a weed management perspective, reduced tillage production practices help mitigate the evolution of herbicide resistance by reducing selection through diversification of weed control techniques, minimizing the spread of resistance genes and genotypes via pollen or propagule dispersal, and eliminating additions of weed seeds to the soil seedbank (Norsworthy et al. 2012). A stale seedbed involves soil
preparation of a plant bed at least 30 days before planting (DBP) that is left undisturbed until planting. The goal of stale seedbed preparation is that the desired crop emerges in a weed-free environment and ultimately gains an early-season competitive advantage to weed pressure. Mechanical weed control techniques, such as rotary tillage or harrowing, can be used to control emerged weed seedlings, but do not provide residual control of troublesome weed species and can often promote the movement of weed seeds deep in the soil profile into the germination zone. In agronomic crops, an intensive herbicide program consisting of PRE residual herbicides are often applied to stale seedbeds to inhibit early germination of weeds, and POST herbicides can be applied after planting to control emerged weed seedlings that escape early-season control (Carroll and Mullinix 1995). In addition, sweetpotato growers often face a stale seedbed situation as fields are often prepared by bedding several days ahead of transplanting (Monks et al. 2012).

Stale seedbeds have been investigated for use in agronomic, horticultural, and organic crop production, and results often indicate that weed control systems that utilize both chemical and mechanical techniques provide the greatest control. Previous research indicates that stale seedbed preparation followed by shallow tillage reduced emerged weed populations when compared to treatments without stale seedbeds in peanut (Carroll and Mullinix 1995), corn (Cloutier and LeBlanc 2002), cucumber (Lonsbary et al. 2003), and organic spinach production (Boyd et al. 2006). Heatherly et al. (1993) reported use of PRE herbicides in conjunction with preplant foliar-applied glyphosate and POST cultivation provided increased soybean yield and resulted in a higher net return with the least input in stale seedbed soybean production. However, herbicide treatments that do not disturb weed seeds below the
germination zone in the soil profile can provide excellent reduction of weed density and biomass of weeds in vegetable production (Caldwell and Mohler 2001). Walters and Young (2012) reported PRE and POST herbicide applications produced larger pumpkin fruit and provided increased overall pumpkin yields when compared with single herbicide applications.

Although the benefits of weed management programs consisting of both PRE and POST herbicide applications has been well documented in agronomic crop production (Askew et al. 2002; Grichar et al. 2013; Whitaker et al. 2011), research evaluating these techniques in stale seedbed systems for sweetpotato does not exist. Thus, this study was conducted to investigate PRE and POST herbicide applications and timings on Palmer amaranth control, and sweetpotato storage root yield and quality in stale seedbed culture.

**Materials and Methods**

Studies were conducted in 2012 and 2013 at the Horticultural Crops Research Station (35°1’12”N, 78°16’48”W) near Clinton, NC. Covington sweetpotato transplants were harvested from field propagation beds by hand (Kemble 2012). Non-rooted Covington slips approximately 18 to 28 cm long were transplanted mechanically 7 to 10 cm deep on 18 to 28 cm tall ridges with 23 to 30 cm in-row spacing using a tractor-mounted sweetpotato planter on June 27, 2012 and June 14, 2013. Soil was an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0.56% humic matter and pH 6.3. Plot size was two rows each 1.1 m wide by 6.1 m long. The first row of each plot was nontreated, and
served as a buffer row. The second row of each plot was treated. The experimental design was a randomized complete block with four replications.

Treatments consisted of flumioxazin (Valor® SX, Valent U.S.A. Corp., P.O. Box 8025, Walnut Creek, CA 94596) at 72, 90, and 109 g ha\(^{-1}\) 45 DBP alone or fb flumioxazin at 72, 90, and 109 g ha\(^{-1}\) pretransplant 0 DBP, flumioxazin at 72, 90, and 109 g ha\(^{-1}\) pretransplant 0 DBP alone or fb S-metolachlor (Dual Magnum®, Syngenta Crop Protection, Inc., Greensboro, NC) at 800 g ha\(^{-1}\) 0, 5 to 7, or 10 d after planting (DAP), flumioxazin at 72, 90, and 109 g ha\(^{-1}\) plus clomazone (Command 3ME®, FMC Corp., Philadelphia, PA) at 630 g ha\(^{-1}\) 45 DBP fb S-metolachlor at 800 g ha\(^{-1}\) 10 DAP, or fomesafen (Reflex®, Syngenta Crop Protection, Inc., Greensboro, NC) at 280 g ha\(^{-1}\) 45 DBP (Table 1.1). Herbicide applications at 45 DBP were applied to prepared stale seedbeds 50 and 38 DBP on May 8, 2012 and May 7, 2013, respectively. Sethoxydim (Poast®, BASF Corp., Research Triangle Park, NC) at 180 g ai ha\(^{-1}\) plus 1% v/v crop oil (Agri-Dex®, Helena Holding Co., Collierville, TN) was applied POST as needed to control goosegrass (*Eleusine indica* L. Gaertn.) and large crabgrass (*Digitaria sanguinalis* L. Scop.). Herbicide treatments were applied with a CO\(_2\)-pressurized backpack sprayer calibrated to deliver 187 L ha\(^{-1}\) with two XR11002 nozzle tips (TeeJet XR 11002, TeeJet Technologies) at 260 kPa.

Beds were prepared with a rotary harrow at 52 and 40 DBP on May 6, 2012 and May 5, 2013, respectively. On June 27, 2012 and June 14, 2013, beds that were non-treated at planting contained emerged weed vegetation and were mowed with a chain mower prior to transplanting to minimize equipment malfunctions due to weed infestations and provide a suitable environment for sweetpotato slip transplanting. In an effort to avoid disturbing the
surface of the stale seedbeds, plants were initially cut to approximately 7 to 10 cm tall and were then cultivated using a tractor-mounted cultivator. Plots with dense Palmer amaranth populations were cut a second time with a weed whacker to a height of approximately 1.5 cm. Palmer amaranth roots were left intact at transplanting.

Palmer amaranth control was recorded for stale seedbed treatments at 14 to 17 DBP, and approximately 14, 32, 68 and 109 DAP. Visual Palmer amaranth control ratings were based on a scale of 0 (no Palmer amaranth control) to 100 % (Palmer amaranth control). On October 10, 2012 (105 DAP) and October 2, 2013 (110 DAP) plots were mowed twice with a flail chop mower. Sweetpotato storage roots were dug 106 and 110 DAP on October 11, 2012 and October 2, 2013, respectively, using a tractor-mounted single row sweetpotato chain digger, and then hand graded into jumbo (> than 8.9 cm in diameter), No. 1 (> than 4.4 cm but < 8.9 cm), and canner (> 2.5 cm but < 4.4 cm) grades (USDA 2005). Marketable yield was calculated as the sum of jumbo, No. 1, and canner grades.

Data were subjected to ANOVA and analyzed by SAS PROC GLM (SAS, 2010. SAS/STAT® 9.2 User’s Guide. SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513). Means were separated using t-tests with LSD and P = 0.05. Weedy and weed-free checks were not included in the Palmer amaranth control analysis, but were included in sweetpotato storage root yield analysis. Yield of jumbo grade sweetpotato storage roots was subjected to square root transformation.
Results and Discussion

Palmer Amaranth Control.

Palmer amaranth control ratings 32 and 68 DAP were reported as means of treatments averaged across 2012 and 2013 years because there was no year by location interaction. Palmer amaranth control ratings 14 and 109 DAP were limited to 2013 only. Control ranged from 39 to 100%, 55 to 100%, 34 to 100%, and 9 to 97% 14, 32, 68, and 109 DBP (Table 1.2). Treatments consisting of flumioxazin at 90 or 109 g ha\(^{-1}\) pretransplant 0 DBP fb S-metolachlor 5 to 7 or 10 DAP provided the least (39 and 40%, respectively) control 14 DAP, while treatments consisting of flumioxazin at 90 or 109 g ha\(^{-1}\) pretransplant 0 DBP alone provided the least (16 and 9%, respectively) control 109 DAP. The greatest and most consistent control of Palmer amaranth in a sweetpotato stale seedbed production system was achieved by flumioxazin at 109 g ha\(^{-1}\) 45 DBP fb flumioxazin at 109 g ha\(^{-1}\) pretransplant 0 DBP.

Palmer amaranth control was 100% at transplanting for all herbicide treatments applied to prepared beds at 50 and 38 DAT in 2012 and 2013, respectively, including flumioxazin at 72, 90, or 109 g ha\(^{-1}\), flumioxazin at 72, 90, or 109 g ha\(^{-1}\) plus clomazone at 630 g ha\(^{-1}\), or fomesafen 280 g ha\(^{-1}\) (data not shown). Weeds emerged in undisturbed stale seedbed plots that were formed but not treated with herbicide 45 DBP. As a result, delayed herbicide applications at transplant or POST transplant were generally less efficacious in Palmer amaranth control when applied to beds with weeds present. Therefore, herbicide application timing had a significant effect on Palmer amaranth control. Differences were not observed
across herbicide rates, thus Palmer amaranth control data was averaged across treatments with similar flumioxazin application timing, regardless of rate (Table 1.3).

Treatments containing sequential applications of flumioxazin 45 DBP fb flumioxazin pretransplant 0 DBP provided 91% Palmer amaranth control 109 DAP (Table 1.3). Treatments consisting of flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP provided statistically similar Palmer amaranth control (80%) 109 DAP when compared to sequential flumioxazin applications. Flumioxazin 45 DBP only provided statistically similar control 14 DAP to treatments consisting of sequential flumioxazin applications, but did not provide comparable control 109 DAP. Treatments of flumioxazin 45 DBP were applied 38 DBP in 2013, thus Palmer amaranth control ratings at 109 DAP corresponded to 147 d after treatment (DAT). Based on these results, a single application of flumioxazin made to freshly prepared beds at least 30 DBP is not sufficient to provide control of Palmer amaranth for the extended duration of stale seedbed management. Jha and Norsworthy (2009) reported Palmer amaranth seedlings can emerge from March to October, which encompasses the entire sweetpotato growing season in North Carolina. In sweetpotato stale seedbed production, additional weed control methods must be utilized at transplanting to manage vigorous Palmer amaranth emergence and optimize season-long weed control. Lonsbary et al. (2003) reported similar recommendations for stale seedbed preparation in cucumber production, and found that when stale seedbed preparation was expanded to 40 DBP, an application of glyphosate at 20 DBP was required to optimize cucumber yield.

Flumioxazin applied pretransplant 0 DBP, including treatments containing S-metolachlor at 0, 5 to 7, or 10 DAP, provided the least Palmer amaranth control when compared to other
flumioxazin treatments, only 65, 62, 48, and 17% 14, 32, 68, and 109 DAP, respectively (Table 1.3). As mentioned above, Palmer amaranth was already present in stale seedbeds that were formed and not treated with flumioxazin until transplanting. Delayed flumioxazin application allowed Palmer amaranth plants to germinate, grow, and establish while the stale seedbed was fallow. As a result, these plants were much harder to control at transplanting after approximately 30 days of growth, especially when compared with plots treated at 45 DBP that were weed-free. POST S-metolachlor applications did not improve Palmer amaranth control because the majority of Palmer amaranth emergence appeared to occur prior to S-metolachlor application (Table 1.2).

Flumioxazin pretransplant 0 DBP fb S-metolachlor immediately after transplanting provided 50% greater Palmer amaranth control 14 DAP when compared to flumioxazin pretransplant 0 DBP fb S-metolachlor at 5 to 7 or 10 DAP (Table 1.3). However, no differences in Palmer amaranth control were observed 109 DAP for any S-metolachlor application timing, and control ranged from 19 to 38%. Meyers et al. (2013) reported similar reductions in Palmer amaranth control with POST S-metolachlor applications because S-metolachlor does not provide POST weed control (Anonymous 2013).

Fomesafen at 280 g ha\(^{-1}\) provided 94% Palmer amaranth control 32 DAP, which corresponds to 77 d after treatment (DAT), and control was statistically similar to treatments consisting of flumioxin or flumioxazin plus clomazone 45 DBP. However, Palmer amaranth control quickly declined and was 78 and 50% 69 and 109 DAP, respectively (Table 1.2). These results are consistent with previous research that reported pretransplant applications of fomesafen provided at least 97% Palmer amaranth control 74 DAP in North
Carolina grown sweetpotato (Meyers et al. 2013). Palmer amaranth control by fomesafen applied 45 DBP to stale seedbeds could be improved by including an additional herbicide application at transplanting. Future research could focus on supplemental weed management strategies to increase season-long Palmer amaranth control with fomesafen in sweetpotato stale seedbed culture.

**Sweetpotato Yield.**

Sweetpotato yield data were reported as means averaged across 2012 and 2013 studies because no interaction was observed between year, location, or treatment. Nontreated, hand-weeded control plots yielded 8,225; 20,685; 2,816; and 31,726 kg ha\(^{-1}\) of jumbo, No. 1, canner, and marketable roots, respectively (Table 1.4). Weedy control plots yielded 1,635; 9,087; 3,477; and 14,199 kg ha\(^{-1}\) of jumbo, No.1, canner, and marketable roots, respectively. Sweetpotato storage root yield was greater for treatments that provided the greatest Palmer amaranth control.

Flumioxazin application time had a significant effect on yield of jumbo, No. 1, and marketable roots, while flumioxazin rate did not influence yield of any sweetpotato grade. Relative to the weed-free control, treatments consisting of herbicide applications 45 DBP, including flumioxazin 45 DBP only, flumioxazin 45 DBP fb flumioxazin pretransplant 0 DBP, flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP, and fomesafen 45 DBP only, resulted in statistically similar jumbo, No.1, and marketable storage root yield (Table 1.4). Treatments consisting of flumioxazin applied to the stale seedbed at transplanting, including flumioxazin pretransplant 0 DBP only or flumioxazin pretransplant 0 DBP fb S-
metolachlor 0, 5 to 7, or 10 DAP resulted in fewer No. 1 and marketable sweetpotato storage roots when compared to treatments with flumioxazin 45 DBP, including flumioxazin 45 DBP only, flumioxazin 45 DBP fb flumioxazin pretransplant 0 DBP, and flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP (Table 1.3). S-metolachlor applications at 0, 5 to 7, or 10 DAP did not improve yield of any grade of sweetpotato storage roots for treatments with flumioxazin pretransplant 0 DBP, as yield of all storage root grades was statistically similar in the weedy control and the POST transplant S-metolachlor treatments (Table 1.4). Palmer amaranth was present at the time of pretransplant flumioxazin application in stale seedbeds that were formed but not treated until pretransplant. Therefore, in a stale seedbed weed management system that contains flumioxazin, an initial application of flumioxazin should be applied at least 30 DBP to weed-free stale seedbeds immediately after bed formation. Any delay in flumioxazin application after stale seedbeds are formed will result in decreased Palmer amaranth control and subsequent yield reduction. Future research should be conducted to determine the optimal length of time between stale seedbed preparation and sweetpotato transplanting, including ideal application time of flumioxazin while the stale seedbed is undisturbed, that maximizes weed control, as well as yield and quality of sweetpotato storage roots.

The greatest marketable yield was achieved with treatments consisting of flumioxazin 45 DBP fb additional herbicides at 0 to 10 DAP, including flumioxazin 45 DBP fb flumioxazin pretransplant 0 DBP or flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP (Table 1.3). Weed control must be optimized throughout the entirety of the 2 to 6 WAP (14 to 42 DAP) critical weed-free period of sweetpotato in a conventional sweetpotato
production system (Seem et al. 2003). Likewise, based on our studies it is also true in a stale seedbed production system for sweetpotato. Weed control throughout the critical weed-free period in this system can be achieved with an initial application of a residual herbicide at least 30 DBP fb a second herbicide application at pretransplant 0 DBP, or immediately after transplanting between 0 to 10 DAP, or through hand weeding during this time. However, it is important to consider herbicide resistance with Palmer amaranth in North Carolina sweetpotato when selecting a herbicide for the first and second applications in a stale seedbed system for sweetpotato. Within the herbicide system, herbicides should be rotated based on modes of action (MOAs). Growers should use herbicides with different MOAs, that is a herbicide that does not utilize protoporphyrinogen oxidase (PPO) inhibition, or the MOA of the herbicide that was applied at stale seedbed formation. Also, if hand weeding, growers should insure to hand weed before pollen or seeds are produced, and Palmer amaranth and its vegetation trash completely removed from the field. These preemptive actions ensure the efficacy of currently registered MOAs, reduce viable seeds left in the soil seedbank, prevent the outcrossing of resistant genetics, and ultimately mitigate future weed pressure.

Flumioxazin plus clomazone 45 DBP fb S-metolachlor at 10 DAP yielded fewer jumbo storage roots but statistically similar No. 1, canner, and marketable sweetpotato storage roots when compared to flumioxazin 45 DBP fb flumioxazin pretransplant 0 DBP (Table 1.3). However, despite the results of this study, which highlight the efficacy of multiple applications of flumioxazin on Palmer amaranth control and increased storage root yield in stale seedbed sweetpotato, implementation of this program as a viable weed control option is not recommended. As discussed above, back-to-back applications of the same herbicide
promotes MOA resistance in troublesome weeds, especially Palmer amaranth. In addition, resistance to herbicides that inhibit protoporphyrinogen oxidase (PPO), including flumioxazin, has recently been confirmed in two *Amaranthus* species in the United States (Riggins and Tranel 2012). Therefore, POST transplant applications of *S*-metolachlor prior to Palmer amaranth emergence may be considered as a viable option for late-season residual control of Palmer amaranth in stale seedbed sweetpotato production. Meyers et al. (2010a) reported flumioxazin fb *S*-metolachlor immediately after transplanting provided greater than 90% season-long Palmer amaranth control in conventional North Carolina sweetpotato production.

To maintain season-long control of Palmer amaranth and maximize yield and quality of sweetpotato storage roots in stale seedbed production, a residual herbicide should be applied at least 30 DBP to weed-free stale seedbeds immediately after bed formation, followed by an additional herbicide application applied within 10 DAP, before weed emergence. Results indicate a control program consisting of flumioxazin at 109 g ha\(^{-1}\) plus clomazone at 630 g ha\(^{-1}\) 45 DBP fb *S*-metolachlor at 800 g ha\(^{-1}\) 0 to 10 DAP provides an effective herbicide program for Palmer amaranth control in stale seedbed production systems in North Carolina sweetpotato.
Literature Cited


Table 1.1. Herbicide treatments applied to ‘Covington’ sweetpotato in stale seedbed production systems at Clinton, NC, in 2012 and 2013.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>45 DBP</th>
<th>Pretransplant 0 DBP</th>
<th>POST transplant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Herbicide</td>
<td>Rate(^b)</td>
<td>Herbicide</td>
</tr>
<tr>
<td>1</td>
<td>Weed-free</td>
<td></td>
<td>Weed-free</td>
</tr>
<tr>
<td>2</td>
<td>Weed-free</td>
<td></td>
<td>Weed-free</td>
</tr>
<tr>
<td>3</td>
<td>Flumioxazin</td>
<td>72</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>4</td>
<td>Flumioxazin</td>
<td>90</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>5</td>
<td>Flumioxazin</td>
<td>109</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>6</td>
<td>Flumioxazin</td>
<td>90</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>7</td>
<td>Flumioxazin</td>
<td>109</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>8</td>
<td>Flumioxazin</td>
<td>72</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>9</td>
<td>Flumioxazin</td>
<td>90</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>10</td>
<td>Flumioxazin</td>
<td>109</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>11</td>
<td>Flumioxazin</td>
<td>72</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>12</td>
<td>Flumioxazin</td>
<td>90</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>13</td>
<td>Flumioxazin</td>
<td>109</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>14</td>
<td>Flumioxazin</td>
<td>109</td>
<td>Flumioxazin</td>
</tr>
<tr>
<td>15</td>
<td>Clomazone</td>
<td>72</td>
<td>Clomazone</td>
</tr>
<tr>
<td>16</td>
<td>Clomazone</td>
<td>90</td>
<td>Clomazone</td>
</tr>
<tr>
<td>17</td>
<td>Clomazone</td>
<td>109</td>
<td>Clomazone</td>
</tr>
<tr>
<td>18</td>
<td>Fomesafen</td>
<td>280</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Abbreviations: DBP, days before transplanting; DAP, days after transplanting.

\(^b\) Herbicide application rates (g ai ha\(^{-1}\)).

\(^c\) S-metolachlor applied at rates of 800 g ai ha\(^{-1}\).
Table 1.2. Effect of herbicide treatments on Palmer amaranth control in stale seedbed production systems at Clinton, NC, in 2012 and 2013a.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Ratec</th>
<th>14c</th>
<th>32d</th>
<th>68d</th>
<th>109c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weed-free</td>
<td>---</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Weedy</td>
<td>---</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>72</td>
<td>95 a</td>
<td>91 abcd</td>
<td>79 abc</td>
<td>76 abc</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>90</td>
<td>98 a</td>
<td>85 abcd</td>
<td>74 abcd</td>
<td>70 abcd</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>109</td>
<td>98 a</td>
<td>91 abcd</td>
<td>86 ab</td>
<td>60 bcd</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP</td>
<td>72</td>
<td>75 ab</td>
<td>66 abcd</td>
<td>49 bcde</td>
<td>26 ef</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP</td>
<td>90</td>
<td>61 bc</td>
<td>63 bcd</td>
<td>47 cde</td>
<td>16 f</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP</td>
<td>109</td>
<td>60 bc</td>
<td>55 d</td>
<td>41 de</td>
<td>9 f</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>72</td>
<td>100 a</td>
<td>99 ab</td>
<td>97 a</td>
<td>91 ab</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>90</td>
<td>98 a</td>
<td>98 ab</td>
<td>99 a</td>
<td>86 ab</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>109</td>
<td>100 a</td>
<td>100 a</td>
<td>100 a</td>
<td>97 a</td>
</tr>
</tbody>
</table>
Table 1.2 continued.

<table>
<thead>
<tr>
<th>Treatment Description</th>
<th>Rating</th>
<th>Control</th>
<th>Control</th>
<th>Control</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flumioxazin 0 DBP fb S-metolachlor 0 DAP</td>
<td>109%</td>
<td>81 ab</td>
<td>56 d</td>
<td>41 de</td>
<td>19 ef</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP fb S-metolachlor 5 to 7 DAP</td>
<td>109%</td>
<td>39 c</td>
<td>56 d</td>
<td>34 e</td>
<td>28 ef</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP fb S-metolachlor 10 DAP</td>
<td>109%</td>
<td>40 c</td>
<td>59 cd</td>
<td>51 bcde</td>
<td>38 def</td>
</tr>
<tr>
<td>Flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP</td>
<td>72%</td>
<td>98 a</td>
<td>97 ab</td>
<td>85 abc</td>
<td>78 abc</td>
</tr>
<tr>
<td>Flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP</td>
<td>90%</td>
<td>97 a</td>
<td>99 ab</td>
<td>96 a</td>
<td>84 ab</td>
</tr>
<tr>
<td>Flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP</td>
<td>109%</td>
<td>97 a</td>
<td>92 abcd</td>
<td>89 a</td>
<td>76 abc</td>
</tr>
<tr>
<td>Fomesafen 45 DBP</td>
<td>280%</td>
<td>84 ab</td>
<td>94 abc</td>
<td>78 abcd</td>
<td>50 cde</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td></td>
<td>26</td>
<td>37</td>
<td>38</td>
<td>31</td>
</tr>
</tbody>
</table>

* Abbreviations: AMAPA, Palmer amaranth; DAP, days after transplanting; DBP, days before transplanting; fb, followed by.
* Rating: 0% = no control; 100% = complete control.
* Control reported as means averaged in 2013 only.
* Control reported as means averaged across 2012 and 2013.
* Herbicide application rates (g ai ha⁻¹).
* LSD conducted at the P = 0.05 level of significance. Means with the same letters within columns are not statistically different.
Table 1.3. Effect of flumioxazin application timing on Palmer amaranth control and yield of ‘Covington’ sweetpotato storage roots in stale seedbed sweetpotato production at Clinton, NC, in 2012 and 2013\(^a\).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>AMAPA Control (DAP)(^b)</th>
<th>Sweetpotato yield</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14(^c)</td>
<td>32(^d)</td>
<td>68(^d)</td>
<td>109(^c)</td>
<td>Jumbo</td>
</tr>
<tr>
<td>Flumioxazin 45 DBP(^f) fb flumioxazin 0 DBP(^h)</td>
<td>97 a</td>
<td>90 a</td>
<td>81 a</td>
<td>69 b</td>
<td>5,662 b</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP(^g) fb flumioxazin 45 DBP(^i)</td>
<td>99 a</td>
<td>99 a</td>
<td>98 a</td>
<td>91 a</td>
<td>9,824 a</td>
</tr>
<tr>
<td>Flumioxazin plus clomazone 45 DBP fb S-metolachlor 10 DAP(^j)</td>
<td>97 a</td>
<td>96 a</td>
<td>91 a</td>
<td>80 ab</td>
<td>7,300 b</td>
</tr>
<tr>
<td>LSD (0.05)(^j)</td>
<td>14</td>
<td>20</td>
<td>17</td>
<td>17</td>
<td>3,226</td>
</tr>
</tbody>
</table>

\(^a\) Abbreviations: AMAPA, Palmer amaranth; DAP, days after transplanting; DBP, days before transplanting; fb, followed by.

\(^b\) Rating: 0%, no control; 100% complete control.

\(^c\) Control reported as means averaged in 2013 only.

\(^d\) Control reported as means averaged across 2012 and 2013.

\(^e\) Marketable is the aggregate of jumbo, No. 1, and canner grades of sweetpotato storage roots.

\(^f\) Averaged across treatments 3, 4, and 5 (see Table 1.1).

\(^g\) Averaged across treatments 6, 7, 8, 12, 13, and 14.

\(^h\) Averaged across treatments 9, 10, and 11.

\(^i\) Averaged across treatments 15, 16, and 17.

\(^j\) LSD conducted at the P = 0.05 level of significance. Means with the same letters within columns are not statistically different.
Table 1.4. Effect of herbicide treatments on yield of ‘Covington’ sweetpotato storage roots in stale seedbed sweetpotato production at Clinton, NC, in 2012 and 2013\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Rate\textsuperscript{c}</th>
<th>Sweetpotato yield \textsuperscript{kg ha\textsuperscript{-1}}</th>
<th>Sweetpotato yield \textsuperscript{Jumbo}</th>
<th>Sweetpotato yield \textsuperscript{No. 1}</th>
<th>Sweetpotato yield \textsuperscript{Canner}</th>
<th>Sweetpotato yield \textsuperscript{Marketable\textsuperscript{b}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weed-free</td>
<td>---</td>
<td>8,225 ab</td>
<td>20,685 abcd</td>
<td>2,816 bcd</td>
<td>31,726 abcd</td>
<td></td>
</tr>
<tr>
<td>Weedy</td>
<td>---</td>
<td>1,635 d</td>
<td>9,087 e</td>
<td>3,477 abcd</td>
<td>14,199 e</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>72</td>
<td>5,028 abcd</td>
<td>14,986 bcde</td>
<td>4,042 abcd</td>
<td>24,056 cde</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>90</td>
<td>6,627 abc</td>
<td>20,222 abcd</td>
<td>5,014 a</td>
<td>31,864 abcd</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 45 DBP</td>
<td>109</td>
<td>5,331 abc</td>
<td>21,940 abc</td>
<td>4,502 abc</td>
<td>31,773 abcd</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 0 DBP</td>
<td>72</td>
<td>4,925 bcd</td>
<td>12,359 cde</td>
<td>3,406 abcd</td>
<td>20,691 de</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 0 DBP</td>
<td>90</td>
<td>3,554 cd</td>
<td>10,378 de</td>
<td>2,312 d</td>
<td>16,244 e</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 0 DBP</td>
<td>109</td>
<td>5,878 abc</td>
<td>9,703 e</td>
<td>2,688 cd</td>
<td>18,269 e</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 45 DBP fb</td>
<td>72</td>
<td>10,480 a</td>
<td>26,399 a</td>
<td>3,691 abcd</td>
<td>40,571 a</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 45 DBP fb</td>
<td>72</td>
<td>9,998 a</td>
<td>22,051 abc</td>
<td>4,258 abcd</td>
<td>36,307 abc</td>
<td></td>
</tr>
<tr>
<td>Flumioxazin 45 DBP fb</td>
<td>109</td>
<td>8,993 a</td>
<td>23,377 ab</td>
<td>3,855 abcd</td>
<td>36,224 abc</td>
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Table 1.4 continued.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>DBP</th>
<th>DAP</th>
<th>Yield (kg/ha)</th>
<th>LSD (0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flumioxazin 0 DBP fb S-metolachlor 0 DAP</td>
<td>109</td>
<td>800</td>
<td>3,776 cd</td>
<td>935e</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP fb S-metolachlor 5 to 7 DAP</td>
<td>109</td>
<td>800</td>
<td>3,483 cd</td>
<td>10,310</td>
</tr>
<tr>
<td>Flumioxazin 0 DBP fb S-metolachlor 10 DAP</td>
<td>109</td>
<td>800</td>
<td>3,603 bcd</td>
<td>2,039</td>
</tr>
<tr>
<td>Flumioxazin plus clomazone 45 DBP</td>
<td>72,</td>
<td>630</td>
<td>6,594 abc</td>
<td>26,014 bcde</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flumioxazin plus clomazone 45 DBP</td>
<td>90,</td>
<td>630</td>
<td>10,289 a</td>
<td>4,799 ab</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td></td>
<td></td>
<td>32,670 abcd</td>
</tr>
<tr>
<td>Flumixoazin plux clomazone 45 DBP</td>
<td>109,</td>
<td>630</td>
<td>5,016 abcd</td>
<td>32,779 abcd</td>
</tr>
<tr>
<td></td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fomesafen 45 DBP</td>
<td>280</td>
<td></td>
<td>8,056 abc</td>
<td>15,134 bcde</td>
</tr>
<tr>
<td><strong>LSD (0.05)</strong></td>
<td></td>
<td></td>
<td>935e</td>
<td>10,310</td>
</tr>
</tbody>
</table>

a Abbreviations: DBP, days before transplanting; fb, followed by; DAP, days after transplanting.
b Marketable is the aggregate of jumbo, No. 1, and canner grades of sweetpotato storage roots.
c Herbicide application rates (g ai ha⁻¹).
d LSD conducted at the P = 0.05 level of significance. Means with the same letters within columns are not statistically different.
e LSD significance is based on ANOVA of square root transformed yields of jumbo grade roots.
TOLERANCE OF ‘COVINGTON’ SWEETPOTATO TO INCREASED RATES OF FLUMIOXAZIN

Lauren B. Coleman, Katherine M. Jennings, David W. Monks, Jonathan R. Schultheis, and Stephen L. Meyers*

Studies were conducted in 2012 and 2013 at Clinton, NC to determine the effect of increased rates of flumioxazin on ‘Covington’ crop injury, and sweetpotato storage root yield and quality. Flumioxazin was applied PREPLANT immediately prior to sweetpotato transplanting at 0 (weed-free check), 72, 109, 145, 217, 289, and 362 g ai ha$^{-1}$. These rates correspond to 0, 0.7, 1.0, 1.3, 2.0, 2.7, and 3.3 times the registered rate for Palmer amaranth control in sweetpotato. Foliar crop injury was minimal (< 10%) for all flumioxazin treatments. Flumioxazin at 109 g ha$^{-1}$ resulted in the greatest yield of No. 1 storage roots, which is consistent with product label recommendations. Jumbo, canner, and marketable yields were similar among treatments. To maximize yield and decrease the risk of herbicide resistance, North Carolina sweetpotato growers should continue to apply the registered rate of flumioxazin at 109 g ha$^{-1}$ for residual control of Palmer amaranth in sweetpotato production.

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Key words: herbicide injury, yield loss.
Sweetpotato [*Ipomoea batatas* (L.) Lam.] is one of the most important crops grown in the southeastern United States. North Carolina has ranked first among all states in sweetpotato production since 1971, and accounted for more than 45% of the nation’s total hectarage in 2011 (USDA-NASS 2012). In 2011, 25,900 ha of marketable sweetpotato storage roots were harvested in North Carolina with an average yield of 25,088 kg ha\(^{-1}\) and a gross farm value of $226.5 million (NCDA & CS 2012). Sweetpotato is a member of the Convolvulaceae family, which includes 1,600 to 1,700 species of mostly herbaceous vines, with a predominantly prostrate growth habit and vine system that expands horizontally along the soil surface (Huaman 1992; Stefanovic et al 2002). Vegetative characteristics, including vine growth rate, canopy closure, and competitive ability, vary by cultivar, and sweetpotato canopy height rarely exceeds 0.5 m tall (LaBonte et al. 1999; Seem et al. 2003). Yield and quality of sweetpotato storage roots can be significantly limited by pests, especially weeds (Glaze and Hall 1990; La Bonte et al. 1999; Meyers et al 2010b; Seem et al. 2003).

Palmer amaranth (*Amaranthus palmeri* S. Watson) is the most common and troublesome weed species in North Carolina sweetpotato (Webster 2010), and glyphosate-resistant (GR) Palmer amaranth biotypes have become the most economically damaging weeds in the Southeast since 2004 (Beckie 2011; Culpepper et al. 2010; Webster 2012). Palmer amaranth utilizes C\(_4\) photosynthesis which results in a lower CO\(_2\) compensation point and greater photosynthetic rate, growth rate, and water use efficiency (Ehleringer et al. 1997; Horak and Loughin 2000; Massinga et al. 2003). Palmer amaranth can reach maximum heights above 2 m, well above the sweetpotato canopy of 0.5 m (Meyers et al. 2010b; Norsworthy et al. 2008). Female Palmer amaranth plants are highly fecund (Keeley et al.
1987), and each seed, measuring no greater than 1 mm, can be easily spread via water, animals, and common agricultural activities, including plowing and harvesting.

Development of resistance to five different herbicide families, including ALS-inhibitors, dinitroanilines, triazines, glyphosate, and HPPD inhibitors, as well as several cases of cross resistance, has been confirmed in Palmer amaranth in seventeen states across the United States (Heap 2013). Resistance traits of Palmer amaranth can be transmitted by wind dispersal of GR male pollen grains (Sosnoskie et al. 2012), and interspecific hybridization between monoecious and dioecious Amaranthus species also contributes to the outcrossing of resistance genes (Franssen et al. 2001; Tranel et al. 2002; Trucco et al. 2005). Palmer amaranth in ‘Beauregard’ and ‘Covington’ sweetpotato in North Carolina reduced marketable sweetpotato yield 36 to 81% for Palmer amaranth densities of 0.5 to 6.5 plants m\(^{-1}\), and regardless of Palmer amaranth density, light interception was at least 42% (Meyers et al. 2010b).

North Carolina sweetpotato growers control Palmer amaranth through the use of PRE or POST herbicides, cultivation, mowing, wicking of row middles, and hand weeding. In North Carolina, 96% of sweetpotato growers cultivate their sweetpotato fields approximately three times per season (Haley and Curtis 2006). However, cultivation does not provide residual weed control and applications are limited to a short window of time prior to crop canopy closure. Thirty-three percent of North Carolina sweetpotato growers manage weeds that extend above the sweetpotato canopy with mowing, and 19% utilize wick-applied herbicides (Haley and Curtis 2006). Mowing and wicking of row middles requires that weeds be above the canopy level of sweetpotato, which results in light interception and
subsequent yield reduction, especially with Palmer amaranth (Meyers 2009). Hand-hoeing or pulling weeds are used one to four times per growing season by 65% of North Carolina sweetpotato growers (Haley and Curtis 2006). Although effective, hand weeding is expensive and does not completely remove viable seeds from the soil seedbank (Menges 1987). Seventy percent of North Carolina’s total sweetpotato hectarage is treated with herbicides 2.4 times per growing season (Haley and Curtis 2006). Herbicides, especially when applied PRE, are affordable, reduce early season weed interference, and often improve season-long control of troublesome weeds, including Palmer amaranth (Culpepper and York 1998; Keeling et al 2006; Whitaker et al. 2011).

Flumioxazin is an N-phenyl phthalimide herbicide that inhibits protoporphyrinogen oxidase (PPO), an enzyme involved in chlorophyll biosynthesis (Hess 2000). Inhibition of PPO induces accumulation of protoporphyrinogen IX which is converted to protoporphyrin IX, a photodynamic precursor of chlorophyll (von Wettstein et al. 1995). In the presence of light, protoporphyrin IX generates highly reactive singlet oxygen species, leading to oxidative breakdown of cell membranes, and subsequent plant death (Dayan and Dayan 2011). Flumioxazin is registered for residual control of annual broadleaf weeds, including *Amaranthus* species, in a number of crops, including cotton, dry bean, corn, soybean, peanut, sugarcane, and sweetpotato (Anonymous 2013). The recommended rate of flumioxazin to control Palmer amaranth in North Carolina sweetpotato is 109 g ai ha⁻¹ (Anonymous 2013).

Flumioxazin has been widely investigated in the Southeast as it provides excellent control of pigweed species, including Palmer amaranth, and other troublesome weed species in agronomic and horticultural crops. In a regional evaluation, flumioxazin PRE controlled
up to 30 broadleaf weed species, including Palmer amaranth, common purslane (*Portulaca oleracea* L.) and common lambsquarters (*Chenopodium album* L.), and controlled an additional 12 broadleaf weed species POST (Cranmer et al. 2000). Flumioxazin applied PRE provided over 95% Palmer amaranth control from 20 through 60 DAT in cotton at Oglethorpe, GA in 2006 (Whitaker et al. 2011). Similarly, Askew et al. (2002) reported that flumioxazin applied PRE at 72 and 109 g ha$^{-1}$ provided over 90% control of Palmer amaranth, smooth pigweed (*Amaranthus hybridus* L.), and slender amaranth (*Amaranthus viridis* L.) in North Carolina cotton. Comparable weed control has been reported in peanut studies conducted in North Carolina and Texas (Grichar and Colburn 1996; Jordan et al. 2009). In sweetpotato, 86% control of spiny amaranth (*Amaranthus spinosus* L.) and 99% control of Palmer amaranth has been observed at 50 and 74 DAP, respectively (Kelley et al. 2006; Meyers et al. 2013). Dobrow et al. (2011) reported that flumioxazin applied PRE maintained populations of <1 Palmer amaranth m$^{-1}$ for a duration of 67 DAP in Florida peanut with an infestation of ALS-resistant Palmer amaranth ranging between 75 and 100 plants per m$^2$.

Investigation of crop tolerance to increased rates of flumioxazin has been conducted on sugarcane and soybean. Susceptibility to flumioxazin damage varies by crop species and cultivar, and is most likely due to differential tolerance to peroxidative stress caused by the herbicide (Dayan et al. 1997). Richard and Dalley (2006) reported flumioxazin applied PRE at 280 g ha$^{-1}$ and 420 g ha$^{-1}$, corresponding to 2 and 4X the labeled rate, resulted in 4 and 11% yield reduction, respectively, in one of three sugarcane varieties tested, while causing 0% yield reduction in other varieties. No foliar crop injury was observed and stalk heights
were comparable to nontreated checks for all treatments (Richard and Dalley 2006). Conversely, Taylor-Lovell et al. (2001) reported soybean stand count reductions, ranging from 16 to 83%, and visible injury, ranging from 55 to 70%, with increasing flumioxazin rates up to 4X the recommended rate. Soybean yields were not reduced at 1X rates, but were reduced at 2 and 4X use rates of flumioxazin, 10 to 20% and 5 to 30%, respectively (Taylor-Lovell et al. 2001).

Despite the varying potential for crop injury and yield losses reported at 2 and 4X recommended rates, increased rates at lower magnitudes have been shown to increase control of troublesome weeds. A recent study conducted in North Carolina and Georgia evaluating residual effectiveness of flumioxazin and other registered herbicides applied PRE in cotton found that herbicides at 1.5X rates were an average of 9% more effective 20 DAT compared with 1X rates, and that flumioxazin was among the most effective herbicides in each environment (Whitaker et al. 2011). Similarly, Meyers et al. (2010a) found that flumioxazin at 109 g ha\(^{-1}\) (1X rate) provided 9% greater Palmer amaranth control than flumioxazin at 91 g ha\(^{-1}\) (0.8X rate) 126 DAP.

Although flumioxazin tolerance studies have been conducted in agronomic crops, sweetpotato tolerance studies evaluating increased rates of flumioxazin are limited. Research has been conducted evaluating sweetpotato tolerance to POST herbicides, including halosulfuron (MacRae et al. 2007b), thifensulfuron (MacRae et al. 2007a), metribuzin (Motsenbocker and Monaco 1993), and S-metolachlor (Meyers et al. 2010a, 2013), but these herbicides, with the exception of S-metolachlor, are no longer registered for use in sweetpotato. Tolerance of twelve cultivars and experimental clones to clomazone applied
PRE has been evaluated in a greenhouse study (Harrison and Jackson 2011). However, clomazone alone does not provide effective control of Palmer amaranth and must be used in combination with other herbicides to achieve the broad spectrum of control needed for weed management in sweetpotato production. Investigation of sweetpotato tolerance to flumioxazin is limited to ≤ 1X recommended rate. Flumioxazin was evaluated PRE and POST at 36, 72, and 109 g ha\(^{-1}\), corresponding to 0.3, 0.6, and 1X rates, in field-grown ‘Beauregard’ sweetpotato in Louisiana. Kelley et al. (2006) reported flumioxazin PRE at 109 g ha\(^{-1}\) (1X rate) caused < 8% injury 9 DAT, while POST at 109 g ha\(^{-1}\) caused < 20% injury 9 DAT, and no injury was observed by 34 DAT. Greatest total marketable yield of sweetpotato storage roots was achieved with flumioxazin PRE at 109 g ha\(^{-1}\), and POST treatments resulted in lower yields compared with all PRE treatments (Kelley et al. 2006). Flumioxazin at 109 g ha\(^{-1}\) controlled 96% of Palmer amaranth 101 DAP in Beauregard and Covington sweetpotato in North Carolina with minimal crop injury (Meyers et al. 2010a). A recent study conducted in North Carolina found that flumioxazin pretransplant at 107 g ha\(^{-1}\) provided excellent Palmer amaranth control of over 99% through 74 DAP in Covington sweetpotato with little crop injury (Meyers et al. 2013).

The objective of this study was to determine the effect of increased rates of flumioxazin on crop injury, and sweetpotato storage root yield and quality.

**Materials and Methods**

Two studies were conducted during 2012 and 2013 at the Horticultural Crops Research Station (35°1’12”N, 78°16’48”W) near Clinton, NC to determine the effect of
increased flumioxazin rates on crop injury, and yield and quality of sweetpotato storage roots. Covington sweetpotato transplants (slips) were cut by hand approximately 2.5 cm above the soil line and were 18 to 28 cm in length. Non-rooted Covington slips were transplanted mechanically on June 13, 2012 and June 18, 2013 on Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0.56% humic matter and pH 6.3. Plot size was two rows each 1.1 m wide by 6.0 m long. The first row of each plot was nontreated, and served as a border row. The experimental design was a randomized complete block with four replications.

Flumioxazin (Valor® SX, Valent U.S.A. Corporation, P.O. Box 8025, Walnut Creek, CA 94596) was applied PREPLANT immediately prior to sweetpotato transplanting on June 13, 2012 and on June 18, 2013. Flumioxazin was applied at 0 (weed-free check), 72, 109, 145, 217, 289, and 361 g ha⁻¹. These rates correspond to 0, 0.7, 1.0, 1.3, 2.0, 2.7, and 3.3X the registered rate for sweetpotato. Treatments were applied with a CO₂-pressurized backpack sprayer equipped with 2 8002VS flat-fan nozzles (Teejet DG 8002, Teejet® Technologies, P.O. Box 7900, Wheaton, IL 60187) calibrated to deliver 187 L ha⁻¹ at 260 kPa. All treatments received irrigation or rainfall following treatment application and transplanting. Studies were maintained weed-free using hand weeding as needed throughout the growing season. Cultural sweetpotato management practices were followed for conventionally produced sweetpotato (Kemble 2012). Sethoxydim (Poast®, BASF Corp., Research Triangle Park, NC) at 180 g ai ha⁻¹ plus 1% v/v crop oil (Agri-Dex®, Helena Holding Co., Collierville, TN) was applied POST as needed to control goosegrass (Eleusine indica L. Gaertn.) and large crabgrass (Digitaria sanguinalis L. Scop.).
Data recorded included visual crop injury 14, 28, 56, and 98 d after transplanting (DAP) based on a scale of 0 (no crop injury) to 100 percent (crop death). Sweetpotato storage root yield by weight and grade was recorded. On October 10, 2012 and October 2, 2013 plots were mowed twice with a flail chop mower prior to harvest. Sweetpotatoes were dug 119 and 106 DAP in 2012 and 2013, respectively, using a tractor-mounted single row chain digger and were hand graded into jumbo (> than 8.9 cm in diameter), No. 1 (> than 4.4 cm but < 8.9 cm), and canner (> 2.5 cm but < 4.4 cm) grades (USDA 2005). Marketable yield was calculated as the sum of jumbo, No. 1, and canner grades.

Data were subjected to ANOVA and analyzed by SAS PROC GLM (SAS, 2010. SAS/STAT® 9.2 User’s Guide. SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513). The means of the main effects were analyzed using contrast statements to test for linear rate effects. Means were separated using t-tests with LSD and P = 0.05. Weed-free checks were included in yield analysis. Injury ratings from these treatments were not included in analysis as injury was 0% for all nontreated, weed-free plots.

Results and Discussion

Sweetpotato Injury.

In 2012 and 2013, sweetpotato foliar crop injury was minimal (< 10%) for all flumioxazin treatments 14 DAP, and injury was 0% by 38 DAP (data not shown). Previous research investigating ‘Covington’ sweetpotato tolerance to flumioxazin applied above 1X recommended rate is limited. However, results of this study are consistent with previous research that found flumioxazin at 91 and 109 g ha⁻¹ (0.8 and 1X rate) applied pretransplant 2
DBP caused less than 3% stunting injury 28 and 64 DAP in ‘Covington’ and ‘Beauregard’ sweetpotato (Meyers et al. 2010a). Kelley et al. (2006) reported ‘Beauregard’ sweetpotato to be similarly tolerant to flumioxazin applied PRE at rates up to 109 g ha\(^{-1}\) (1X). In addition, Meyers et al. (2012) reported 3 and 4X rates of S-metolachlor applied immediately after transplanting caused greater stunting injury (11%) 84 DAP when compared to 1X rates (1%) in ‘Covington’ sweetpotato. Although susceptibility to flumioxazin damage varies by crop species and cultivar (Dayan et al. 1997), ‘Covington’ and ‘Beauregard’ cultivars of sweetpotato demonstrate considerable herbicide tolerance to flumioxazin.

**Sweetpotato Yield.**

Sweetpotato yield data was reported as means averaged across years because there was no year by location interaction. As a result of high precipitation and cool, cloudy weather in 2013, greater overall yields were observed in 2012 compared to 2013 (data not shown). Total precipitation at 14 DAP was 18 cm in 2013 compared with 1.0 cm in 2012 (Appendix A). However, this did not result in a significant treatment by year interaction. The nontreated check yielded 15,296; 25,447; 4,153; and 44,896 kg ha\(^{-1}\) of jumbo, No. 1, canner, and marketable roots, respectively (Table 2.1). Flumioxazin rate did not have a significant influence on yields of jumbo, canner, or marketable roots, as yield was similar among treatments. However, flumioxazin rate did influence yield of No. 1 roots. The greatest numerical amount of No. 1 storage roots was obtained with flumioxazin at 109 g ha\(^{-1}\) (1X rate), while the lowest yield of No. 1 roots was obtained from flumioxazin at 362 g ha\(^{-1}\) (3.3X rate). These findings are consistent with the flumioxazin label that recommends 109 g
ha\(^{-1}\) for use in sweetpotato with little to no crop injury (Anonymous 2013). Although increased rates of flumioxazin did not improve sweetpotato storage root yield, future research could be conducted to determine if increased rates of flumioxazin will provide greater Palmer amaranth control than the currently registered rate of 109 g ha\(^{-1}\).

Results of this study indicate that ‘Covington’ sweetpotato is tolerant to increased rates of flumioxazin up to 362 g ha\(^{-1}\), equivalent to 3.3X labeled rate, as these rates caused minimal (<10%) foliar crop injury. Flumioxazin at 109 g ha\(^{-1}\) (1X rate) provided the greatest No. 1 storage root yield, while flumioxazin at 362 g ha\(^{-1}\) (3.3X rate) provided the least No. 1 storage root yield. Use of an increased rate is not recommended for North Carolina sweetpotato production because there are no economic or environmental advantages inherent in the use of higher herbicide rates in a weed management strategy. Norsworthy et al. (2012) reported that application of labeled herbicide rates at appropriate stages of weed development is an essential management practice that mitigates the evolution of herbicide resistance by reducing selection pressure in troublesome weed populations. In addition, resistance to herbicides that utilize PPO inhibition, including flumioxazin, has been confirmed in four weed species, two of which are *Amaranthus* species, and the evolution of PPO resistance in Palmer amaranth is highly probable, especially if increased rates of flumioxazin are applied (Riggins and Tranel 2012). Therefore, to maximize yield and decrease the risk of herbicide resistance, North Carolina sweetpotato growers should continue to use the currently registered rate of flumioxazin at 109 g ha\(^{-1}\).
Literature Cited


Table 2.1. Effect of increased flumioxazin rates on ‘Covington’ sweetpotato yield at Clinton, NC in 2012 and 2013.

<table>
<thead>
<tr>
<th>Treatment Flumioxazin -- g ai ha⁻¹ --</th>
<th>Rate¹</th>
<th>Jumbo kg ha⁻¹</th>
<th>No. 1</th>
<th>Canner</th>
<th>Marketableᵇ</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0X</td>
<td>15,296 ab</td>
<td>25,447 bc</td>
<td>4,153 a</td>
<td>44,896 a</td>
</tr>
<tr>
<td>72</td>
<td>0.7X</td>
<td>11,839 a</td>
<td>24,718 bc</td>
<td>3,237 a</td>
<td>39,794 a</td>
</tr>
<tr>
<td>109</td>
<td>1.0X</td>
<td>12,225 a</td>
<td>29,971 a</td>
<td>3,464 a</td>
<td>45,660 a</td>
</tr>
<tr>
<td>145</td>
<td>1.3X</td>
<td>14,015 a</td>
<td>26,128 b</td>
<td>3,099 a</td>
<td>43,242 a</td>
</tr>
<tr>
<td>217</td>
<td>2.0X</td>
<td>13,726 a</td>
<td>26,299 ab</td>
<td>3,388 a</td>
<td>43,413 a</td>
</tr>
<tr>
<td>289</td>
<td>2.7X</td>
<td>16,212 a</td>
<td>27,269 ab</td>
<td>3,188 a</td>
<td>46,669 a</td>
</tr>
<tr>
<td>362</td>
<td>3.3X</td>
<td>14,077 a</td>
<td>21,777 c</td>
<td>3,347 a</td>
<td>39,201 a</td>
</tr>
<tr>
<td>LSD (0.05)ᶜ</td>
<td>NSᵈ</td>
<td>3,829 NS</td>
<td>NS</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

¹ Magnitude of rate is based on registered rate of flumioxazin for Palmer amaranth control in sweetpotato.

ᵇ Marketable is the aggregate of jumbo, no. 1, and canner grades of sweetpotato storage roots.

ᶜ LSD conducted at the P = 0.05 level of significance. Means with the same letters within columns are not statistically different.

d Not significant within column at the P=0.05 level of significance.
WICK-APPLIED PARAQUAT AND d-LIMONENE FOR PALMER AMARANTH

(Amaranthus palmeri) CONTROL IN ‘COVINGTON’ SWEETPOTATO

Lauren B. Coleman, Katherine M. Jennings, David W. Monks, Jonathan R. Schultheis, and
Stephen L. Meyers*

A study was conducted in 2013 at Clinton, NC to determine the effect of wick-applied paraquat and d-limonene on Palmer amaranth control and ‘Covington’ sweetpotato storage root yield and quality. Treatments consisted of wick-applied paraquat at 5, 6, or 7 wk after transplanting (WAP), and wick-applied d-limonene at 5 WAP alone or followed by (fb) 7 WAP, 6 WAP alone or fb 10 WAP, or 7 WAP alone or fb 11 WAP. Treatments consisting of wick-applied paraquat at 6 or 7 WAP provided the greatest (88% or greater) Palmer amaranth control 84 d after transplanting (DAP). Palmer amaranth control ranged from 30 to 53% for wick-applied d-limonene treatments 84 DAP. Reduced control was most likely due to interference from Palmer amaranth plants below the sweetpotato canopy that escaped treatments prior to, between, and after wick-applied d-limonene treatments. No internal or external injury of sweetpotato storage roots was observed. Yield of jumbo, No. 1, and marketable grades of sweetpotato storage roots was greatest in the weed-free control. Most wick-applied d-limonene treatments resulted in No. 1 storage root yield that was similar to the weed-free control. Wick-applied paraquat at 42 DAP provided 80% Palmer amaranth control through 105 DAP, but yield of all sweetpotato storage root grades was comparable to the weedy control. Competition from eclipta (Eclipta prostrata L.) that emerged in these plots approximately 35 DAP due to favorable wet conditions contributed to yield losses in treatments consisting of wick-applied paraquat at 42 DAP.
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Nomenclature: paraquat; \textit{d}-limonene; Palmer amaranth, \textit{Amaranthus palmeri} S. Wats. AMAPA; sweetpotato, \textit{Ipomoea batatas} L. Lam. ‘Covington’.

Key words: weed control, yield loss.

Abbreviations: WAP, weeks after transplanting; DAP, days after transplanting.
Over 45% of sweetpotato \textit{Ipomoea batatas} (L.) Lam.] grown in the United States is produced in North Carolina (USDA-NASS 2012). North Carolina ranked first among all states, including California, Mississippi, Arkansas and Louisiana, in sweetpotato production in 2011 (NCDA & CS 2012). North Carolina sweetpotato production consists of mechanically transplanting nonrooted vegetative stem tip cuttings (slips) 20 to 25 cm long from propagation beds into production fields, consisting of bedded rows 20 to 25 cm tall and 92 to 106 cm wide (Kemble 2012). Sweetpotato cuttings are generally planted from early May to late June, and storage roots are harvested 90 to 120 days later (Kemble 2012). As a member of the morningglory family, sweetpotato has a predominantly prostrate growth habit, with an herbaceous vine system that expands horizontally along the soil surface (Huaman 1992). Vegetative characteristics, competitive ability, and canopy closure of sweetpotato vary by cultivar and planting date (LaBonte et al. 1999; Seem et al. 2003). Due to the low stature of the canopy, which rarely exceeds 0.5 m in height, yield and quality of sweetpotato storage roots can be limited by pests, especially weeds (Glaze and Hall 1990; La Bonte et al. 1999; Meyers et al. 2010b; Seem et al. 2003; Treadwell et al. 2007).

Palmer amaranth (\textit{Amaranthus palmeri} S. Watson) is the most common and troublesome weed species in North Carolina sweetpotato (Webster 2010), and continues to be the most common and troublesome weed species throughout agronomic and horticultural crops in the southern United States (Webster and Nichols 2012). Palmer amaranth is a tall, upright, and dioecious summer annual that is native to the arid Sonoran desert region of the Southwestern United States and Northwestern Mexico (Sauer 1957). Due to its invasive physiological characteristics, Palmer amaranth spread to the eastern United States in the early
20\textsuperscript{th} century, and was first reported in South Carolina in 1957 (Culpepper et al. 2010). Palmer amaranth utilizes C\textsubscript{4} photosynthesis (Ehleringer 1997), has a growth rate faster than other Amaranthus weed species (Horak and Loughin 2000), and can reach maximum heights above 2 m, well above the sweetpotato canopy of 0.5 m (Meyers et al. 2010b; Norsworthy et al. 2008b). Individual female Palmer amaranth produce between 200,000 and 600,000 seeds (Keeley et al. 1987), and recent evidence strongly suggests that Palmer amaranth can produce seed both sexually and without fertilization when isolated from a pollen source (Ribeiro et al. 2012). At 30°C, a daytime temperature frequently observed in North Carolina sweetpotato production areas, Palmer amaranth seed germination occurs within one day, while other Amaranthus species require up to eight days to achieve germination (Steckel et al. 2004). These factors contribute to the overall competitive ability of Palmer amaranth with row crops. Interference of Palmer amaranth decreased the growth and yield of Georgia and Texas cotton (MacRae et al. 2013; Morgan et al. 2001), Kansas corn (Massinga et al. 2001), Kansas and Arkansas soybean (Bensch et al. 2003; Klingaman and Oliver 1994), North Carolina peanut (Burke et al. 2007), and South Carolina and North Carolina plasticulture-grown bell pepper (Norsworthy et al. 2008b). Palmer amaranth at densities of 0.5 to 6.5 plants m\textsuperscript{-1} in North Carolina grown ‘Beauregard’ and ‘Covington’ sweetpotato reduced marketable storage root yield 36 to 81\%, and regardless of Palmer amaranth density, light interception by this weed was at least 42\% (Meyers et al. 2010b).

Palmer amaranth populations have also become increasingly difficult to manage because of the development of resistant biotypes to herbicides. Resistance to five herbicide families, including ALS-inhibitors, dinitroanilines, triazines, glyphosate, and HPPD
inhibitors, as well as several cases of cross resistance, has been confirmed in Palmer amaranth in seventeen states across the United States (Heap 2013). Of these resistance mechanisms, glyphosate-resistant (GR) Palmer amaranth biotypes have become the most troublesome and economically damaging weeds in the Southeast since 2004 (Beckie 2011; Culpepper et al. 2006; Webster 2013).

Glyphosate-resistant Palmer amaranth populations have independently evolved a diversity of resistance mechanisms, including target-site mutations, altered translocation due to sequestration, and gene amplification, which contribute to the challenges involved in weed management (Shaner et al. 2012; Whitaker et al. 2013). A novel mechanism of resistance, originally found in GR Palmer amaranth in Georgia, has been characterized as over-amplification of the EPSPS (5-enolpyruvylshikimate-3-phosphate synthase) gene, which results in increased metabolic activity of the target enzyme (Gaines et al. 2010). The GR trait can be transmitted from GR male Palmer amaranth plants to glyphosate-susceptible females via wind dispersed male pollen grains up to 300 m under natural field conditions (Sosnoskie et al. 2012). Interspecific hybridization between monoecious and dioecious Amaranthus species, including Palmer amaranth, can result in the outcrossing of GR genes to other common pigweed species (Franssen et al. 2001; Tranel et al. 2002; Trucco et al. 2005). Rapid evolution of resistance mechanisms to commonly used herbicides, as well as the competitive growth and reproductive characteristics of Palmer amaranth define the difficulty inherent in Palmer amaranth management in crop production in the southeastern United States.
In North Carolina sweetpotato production, Palmer amaranth management methods include herbicides, cultivation, mowing, wicking, and hand removal (Haley and Curtis 2006). The current recommended herbicide program for Palmer amaranth control in sweetpotato is flumioxazin pretransplant at 109 g ai ha\(^{-1}\) followed by (fb) S-metolachlor at 800 g ai ha\(^{-1}\) 7 to 10 d after planting (DAP). Meyers et al. (2010a, 2013) reported over 90% residual Palmer amaranth control with flumioxazin fb S-metolachlor in ‘Beauregard’ and ‘Covington’ sweetpotato in North Carolina. However, even at low densities, competition from Palmer amaranth that escape herbicide treatments will contribute to relatively high light interception and subsequent yield losses, especially in sweetpotato (Meyers et al. 2010b).

Due to prolific seed production (Keeley et al. 1987), fast germination rates (Steckel et al. 2004), and a long emergence period from March to October (Jha and Norsworthy 2009), Palmer amaranth escapes are common in most crops, including sweetpotato (Meyers 2009). To avoid yield losses and persistence of viable seeds in the soil seedbank, control of Palmer amaranth escapes throughout the growing season is essential to weed management in sweetpotato production. Cultivation is utilized for control of early-season Palmer amaranth escapes by 96% of North Carolina sweetpotato growers approximately three times per season (Haley and Curtis 2006), but late-season use is limited because sweetpotato vines trail along the ground and grow into between-row spaces at the onset of canopy closure. Five POST herbicides are registered for use in sweetpotato, including carfentrazone-ethyl, clethodim, fluazifop, sethoxydim, and glyphosate (Kemble 2012). However, clethodim, fluazifop, and sethoxydim only control grasses, while carfentrazone-ethyl is most effective on broadleaf weeds less than 10 cm tall. Glyphosate is registered for use in row middles only, but is no
longer an available weed management resource given the evolution of GR Palmer amaranth biotypes across the United States (Culpepper et al. 2006; Heap 2013). Mowing is used by 33% of North Carolina sweetpotato growers for control of Palmer amaranth escapes, but contributes to lateral shoot growth above the sweetpotato canopy (Meyers 2009), and has been reported to only be an effective control strategy for Palmer amaranth plants less than 15 cm tall (Prostko 2011).

Due to the limited amount of POST Palmer amaranth management strategies, North Carolina sweetpotato growers have become increasingly interested in applying POST herbicides via a wicking apparatus as a supplemental weed control option for late-season weed control. Non-selective rope wick applicators and wipers are available in many forms and provide considerable weed control based on a weed-crop height differential, with little to no injury to crops (Dale 1978). Application of herbicides with tractor-mounted rope wick applicators involves movement of a chemical solution from a reservoir to the exposed portion of rope, which is then wiped against the desired portion of weed vegetation that extends above the crop canopy. Although treatments will not necessarily contribute to increased yields, implementation of late-season weed control can improve harvest efficiency and reduce the soil seedbank of troublesome weed species. Norsworthy (2008) reported that the Palmer amaranth seedbank in the top 5 cm of soil declined 99% during the first cropping season as a result of herbicide-based management, and seedbank densities were exhausted after four years of treatment.

Previous research has demonstrated the efficacy of wick-applied glyphosate as an alternative weed management strategy to control troublesome weeds that extend above the
crop canopy, but late-season management of weeds below the canopy that escape control remains challenging. In cotton, treatments consisting of a single application of wick-applied glyphosate provided greater control of johnsongrass 2 and 3 WAT and increased seed cotton yield 81% when compared to cultivation (Keeley 1984a, 1984b). Similarly, Meyers (2009) reported wick-applied glyphosate treatments at 7 WAP provided 90% control of Palmer amaranth populations with average heights of 1.1 m 9 WAP in ‘Covington’ sweetpotato. However, competition from johnsongrass and Palmer amaranth prior to the initial application of treatments, as well as competition from escapes between treatments resulted in excessive yield losses of cotton and sweetpotato storage roots (Keeley 1984a, 1984b; Meyers 2009). Glyphosate-resistant biotypes of johnsongrass and Palmer amaranth have both been confirmed in the United States (Heap 2013). Therefore, results of these studies could be influenced by ineffective herbicide activity resulting from GR biotypes in treated populations.

Based on the potential of wick-applied herbicides as a supplemental late-season weed management option and the limited research evaluating the use of alternative wick-applied herbicides in sweetpotato, a study to investigate efficacy of wick-applied paraquat and d-limonene on Palmer amaranth control was conducted in sweetpotato. Paraquat is a POST applied bipyridylium herbicide that interferes with photosynthesis by diverting high energy electrons from photosystem I, producing free oxygen radicals which cause rapid cell damage and subsequent plant death (Funderburk and Lawrence 1964; Hart and DiTomaso 1994). Paraquat is a contact herbicide registered for use in most agronomic and horticultural crops for control of many broadleaf and grass weed species (Anonymous 2013b). Paraquat POST
at 1,050 g ai ha$^{-1}$ provided over 99% control of GR Palmer amaranth accessions 28 DAT (Norsworthy et al. 2008a), and may be an excellent option for management of escaped Palmer amaranth in sweetpotato. Wick-applied paraquat at 50 and 100% solutions have demonstrated good Palmer amaranth control in Georgia peanut production (Prostko 2011).

$d$-limonene, an essential oil extracted from the rinds of citrus fruit, is a natural product that is OMRI (Organic Materials Review Institute) approved and registered for use in certified organic crops for non-selective POST control of grasses and broadleaf weeds less than 15 cm tall (Anonymous 2013a). The phytotoxic mechanism of $d$-limonene involves the degradation of the waxy plant cuticle which results in leaf dessication and subsequent plant death (Anonymous 2013a). The use of natural products for weed control has become increasingly popular, particularly for organic and sustainable agriculture production systems (Duke et al. 2002). In a recent study, all North Carolina organic sweetpotato growers surveyed indicated that weed control was their greatest management challenge (J. Kimber, North Carolina SweetPotato Commission Foundation Project Director, personal communication). Weed control provided by natural product herbicides generally varies widely and is dependent on weed species and height at the time of application (Abouziena et al. 2009; Evans and Bellinder 2009; Tworkoski 2002).

Active promotion of alternative weed management strategies, including integration of herbicides with diverse modes of action, is especially pertinent to agricultural crop production in the United States. Therefore, the objective of this study was to evaluate the efficacy of wick-applied paraquat and $d$-limonene on Palmer amaranth control in sweetpotato
and determine the effects of these herbicides on yield and quality of ‘Covington’ sweetpotato storage roots.

**Materials and Methods**

A study was conducted in 2013 at the Horticultural Crops Research Station

(35°1′12″N, 78°16′48″W) near Clinton, NC. Paraquat (Gramoxone Inteon®, Syngenta Crop Protection, Inc., 410 South Swing Road, Greensboro, NC 27409 USA) and d-limonene (Avenger AG ® Cutting Edge Formulations, Inc., 3326 W. Mineral King Ave., Visalia, CA 93291 USA) were wick-applied to control Palmer amaranth. ‘Covington’ sweetpotato transplants were harvested from field propagation beds by hand cutting plants approximately 2.5 cm above the soil line. Non-rooted ‘Covington’ slips 18 to 28 cm long were transplanted mechanically using a tractor-mounted sweetpotato planter on June 18, 2013 into a field with historically high Palmer amaranth densities. In-row spacing was 25 to 30 cm and planting depth was 10 to 12.5 cm. Soil type was an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) with 0.6% humic matter and pH 6. Plots were three rows each 1.1 m wide by 12.2 m long. The first row of each plot was a nontreated buffer row. The second and third rows of each plot were treated.

Treatments consisted of wick-applied paraquat solution (50% Gramoxone Inteon v/v with water) at 5, 6, or 7 wk after transplanting (WAP) and wick-applied d-limonene solution (50% Avenger AG v/v with water) at 5 WAP alone or followed by (fb) 7 WAP, 6 WAP alone or fb 10 WAP, or 7 WAP alone or fb 11 WAP. Sequential applications of paraquat were not applied because initial wick-applied paraquat treatments resulted in complete
Palmer amaranth death from foliage to roots, and Palmer amaranth plants did not emerge to a height above the sweetpotato canopy suitable for a second wicking treatment. Paraquat and \textit{d}-limonene treatments were applied using a 2-row LMC Cross-Wick Bar applicator (LMC Cross-Wick Bar, Cross Equipment LMC, 1715 S. Slappey Blvd., Albany, Georgia 31701 USA) 2.5 m wide. A polyvinyl chloride pipe (PVC) 7.6 cm wide and 2 m long was mounted on a sealed metal frame which functioned as a reservoir for herbicide solution (Figure 3.1). Eight pieces of rope 40 cm long were positioned on the front of the system in a V-shape and were connected to the PVC reservoir via a pressurized plastic tube. The sealed frame that held the wick was filled with compressed air which provided pressure to maintain wick saturation. Flow rate was adjusted by the use of a pressure knob connected to one end of the PVC reservoir. The entire unit was tractor-mounted 30.5 cm above the sweetpotato canopy. Treatments were applied in two passes across both directions (front to back, back to front) for each plot at 3.5 km h$^{-1}$, with the tractor in 3$^{rd}$ gear, 1$^{st}$ range, and with an output of 323 L ha$^{-1}$. Flow rate for paraquat and \textit{d}-limonene treatments was maintained at approximately 15 and 22, respectively, according to manufacturer recommendations. A higher flow rate was required for \textit{d}-limonene treatments because \textit{d}-limonene is an essential oil with a viscous consistency, higher than that of water. Target wick height for each application was to achieve coverage of at least 50% of Palmer amaranth foliage above the sweetpotato canopy. Treatment heights varied due to rapid Palmer amaranth growth. Treatments of both paraquat and \textit{d}-limonene at 5 and 6 WAP were applied at Palmer amaranth heights between 19 and 52 cm, while treatments at 7 WAP were applied at Palmer amaranth heights between 38 cm and 1.2 m. Sequential treatments of \textit{d}-limonene at 10 and 11 WAP were applied at Palmer
amaranth heights between 23 cm and 1.8 m. Additional height adjustments were made manually as needed to increase application accuracy and accommodate for various sizes of Palmer amaranth.

Palmer amaranth control was recorded 41, 49, 64, 73, 84, and 105 DAP based on a scale of 0 (no Palmer amaranth control) to 100% (complete Palmer amaranth control). Palmer amaranth heights were also measured 1 d prior to treatment (DBT) within each plot before treatment. Treated Palmer amaranth plants that were located near sweetpotato plant roots were tagged. Storage roots of these plants were manually dug prior to harvest and visually inspected for external and internal injury, as demonstrated by Meyers (2009). On October 22, 2013 (126 DAP) sweetpotato storage roots were dug using a tractor-mounted single row chain digger and then picked up by hand and graded into jumbo (> than 8.9 cm in diameter), No. 1 (> than 4.4 cm but < 8.9 cm), and canner (> 2.5 cm but < 4.4 cm) grades (USDA 2005). Marketable yield was calculated as the sum of jumbo, No. 1, and canner grades.

Data were subjected to ANOVA and analyzed by SAS PROC GLM (SAS, 2010. SAS/STAT® 9.2 User’s Guide. SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513). The means of the main effects were separated using t-tests with LSD and P = 0.05. Weed-free and weedy checks were included in yield analysis, but were not included in Palmer amaranth control analysis because ratings for these treatments were 100 and 0%, respectively.
Results and Discussion

**Palmer Amaranth Control.**

Paraquat treatments applied at 6 or 7 WAP provided the greatest (over 88%) Palmer amaranth control 84 DAP (Table 3.1). Wick-applied paraquat 5 WAP provided 37 and 50% less control of Palmer amaranth 84 and 105 DAP, respectively, when compared to later wick-applied paraquat treatments at 6 or 7 WAP. Palmer amaranth control was less in all wick-applied d-limonene treatments when compared with paraquat treatments wicked at 6 or 7 WAP. Control of Palmer amaranth ranged from 30 to 53% and 12 to 32% at 84 and 107 DAP, respectively, in treatments consisting of wick-applied d-limonene.

Palmer amaranth control provided by single applications of wick-applied d-limonene at 5 WAP declined from 60 to 32% between 41 and 105 DAP, and a similar trend was observed for treatments consisting of single applications of wick-applied d-limonene at 6 or 7 WAP (Table 3.1). For treatments consisting of sequential applications of wick-applied d-limonene 5 WAP fb 7 WAP, 6 WAP fb 10 WAP, or 7 WAP fb 11 WAP, Palmer amaranth control was improved immediately after the second d-limonene application, from 3 to 47%, 25 to 57%, and 40 to 53%, respectively. However, control quickly declined after the second application due to competition from Palmer amaranth escapes prior to, between, and after these treatments. No differences in Palmer amaranth control were observed for any wick-applied d-limonene treatments 105 DAP, as control ranged from 12 to 32% 105 DAP.

Palmer amaranth management programs utilizing wick-applied d-limonene may require the implementation of multiple d-limonene applications per growing season to optimize season-long Palmer amaranth control in sweetpotato.
Due to the necessity for physical contact with the herbicide, high densities of Palmer amaranth populations likely contributed to reduced Palmer amaranth control provided by wick-applied d-limonene. Authors observed that when Palmer amaranth greater than 91 cm tall were wiped with the ropewick, plants were forced to bend below the wicking apparatus, as well as over and across other plants located towards the center of treatment plots. Keeley et al. (1984a, 1984b) observed reduced control of johnsongrass with wick-applied glyphosate because johnsongrass shoots were in high density and could not be reached by the wicking apparatus. In addition, wick-applied d-limonene did not result in complete Palmer amaranth death. Although d-limonene treatments were injurious to a significant portion of Palmer amaranth foliage that was contacted by the ropewick, vegetative regrowth was observed within 14 d after treatment (DAT) from Palmer amaranth foliage that appeared to be dead (data not shown).

Efficacy of wick-applied paraquat and d-limonene was based on physical contact of the ropewick apparatus with the Palmer amaranth foliage above the sweetpotato canopy. Therefore, the decreased late-season control of Palmer amaranth observed for wick-applied paraquat 5 WAP and all wick-applied d-limonene treatments was likely due to competition from Palmer amaranth below the sweetpotato canopy that escaped the initial treatment or emerged after the treatment and continued to grow and compete with the sweetpotato crop throughout the growing season.
Sweetpotato Storage Root Injury.

Sweetpotato storage root cracking has been observed from plant exposure to glyphosate via chemical drips from the ropewick apparatus (Meyers 2009). However, wick-applied paraquat or d-limonene treatments did not cause internal or external damage to sweetpotato storage roots in this experiment. Paraquat irreversibly binds to soil particles (Anonymous 2013a), thus any paraquat that may have leached from Palmer amaranth roots or dripped from the ropewick apparatus that did not contact the plant would immediately adsorb to soil particle surface area and be unavailable to cause injury to sweetpotato storage roots. Similarly, d-limonene is a contact herbicide that has no residual activity in the soil (Anonymous 2013a). Also, due to the high viscosity of d-limonene, little to no dripping of d-limonene herbicide solution from the ropewick apparatus was observed.

Sweetpotato Yield.

Yield of jumbo, No. 1, and marketable grades of sweetpotato storage roots was greatest in the weed-free control (Table 3.2). Treatment did not affect canner grade yield. Most treatments consisting of single or sequential d-limonene applications resulted in yield of No. 1 grade sweetpotato roots that were similar to the weed-free control. Treatments consisting of single applications of paraquat resulted in yield of jumbo and marketable storage roots that were similar to the weedy control.

Yield of jumbo, No. 1, and marketable storage roots were similar to the weed-free control for treatments consisting of single applications of d-limonene wicked at 5 or 6 WAP, as well as sequential applications of d-limonene wicked at 6 WAP fb 10 WAP (Table 3.2).
Seem et al. (2003) reported the critical weed-free period of sweetpotato to be 2 to 6 WAP. These treatments provided control of Palmer amaranth during the critical weed-free period of sweetpotato and resulted in a subsequent yield increase. However, $d$-limonene wicked at 7 WAP resulted in yield of jumbo, No. 1, and marketable storage roots that were similar to the weedy control. These results clearly demonstrate the importance of weed management during the critical weed-free period of sweetpotato. Also, Palmer amaranth plant height for treatments applied at 7 WAP ranged from 38 cm to 1.2 m. Light interception and subsequent competition from Palmer amaranth vegetation well above the sweetpotato canopy of 0.5 m likely contributed to yield loss from this treatment. These findings are similar to those reported in Palmer amaranth competition studies in corn and sweetpotato production (Massinga et al. 2001; Meyers 2010).

Sequential applications of $d$-limonene wicked at 5 WAP fb 7 WAP, 6 WAP fb 10 WAP, or 7 WAP fb 11 WAP, did not improve yield of any storage root grades when compared to single $d$-limonene applications wicked at 5, 6, or 7 WAP, as yield of all storage root grades was similar for all wick-applied $d$-limonene treatments, with the exception of jumbo yield for treatments with $d$-limonene wicked at 7 WAP (Table 3.2). Palmer amaranth plants escaped control by the wicking apparatus because some plants were below the sweetpotato canopy and were not contacted by the herbicide at the time of application, and late-season seedling emergence occurred after herbicide treatment. Palmer amaranth escapes continued to grow in the weeks between sequential $d$-limonene treatments and compete with the sweetpotato crop for light, water, and, nutrients, compromising storage root yield. Similarly, Meyers et al. (2009) reported sequential applications of wick-applied glyphosate at
4 WAP fb 7 WAP provided the greatest and most consistent control of Palmer amaranth when compared to treatments consisting of mowing or single applications of wick-applied glyphosate, but interference from Palmer amaranth escapes prior to and between glyphosate treatment applications contributed to large sweetpotato yield losses. As mentioned above, the critical weed-free period of sweetpotato is 2 to 6 WAP (Seem et al. 2003). Sweetpotato storage root yield could be improved if wick-applied \(d\)-limonene treatments were applied earlier, within the 2 to 6 WAP critical weed-free period, and more frequently, one application per week for the entire duration of the critical weed-free period. Sequential applications of wick-applied herbicides are an essential component of a wick-based weed management strategy. Future research should be conducted to develop an application schedule for wick-applied \(d\)-limonene to control season-long Palmer amaranth escapes and maximize sweetpotato storage root yield.

All treatments of wick-applied paraquat resulted in yield of jumbo, canner, and marketable sweetpotato storage roots that were similar to the weedy control (Table 3.2). Yield of No. 1 storage roots in paraquat treatments wicked at 7 WAP was similar to the weed-free control, while paraquat treatments wicked at 5 and 6 WAP were similar to the weedy control. Although the treatment of wick-applied paraquat at 7 WAP is beyond the critical weed-free period of sweetpotato of 2 to 6 WAP (Seem et. al 2003), reduced injury on sweetpotato foliage as a result from chemical drips of paraquat from the ropewick may have provided a yield increase (data not shown). At the later application time of 7 WAP, increased density of Palmer amaranth foliage may have absorbed a significant amount of wick-applied paraquat and contributed to physically guarding the sweetpotato plants below
from chemical drips, resulting in subsequent yield increase. Further evaluation of the optimal application time of wick-applied paraquat within the 2 to 6 WAP critical weed-free period of sweetpotato would contribute to the development of a wick-based weed management strategy.

Wick-applied paraquat provided greater Palmer amaranth control but resulted in decreased sweetpotato storage root yield when compared to wick-applied d-limonene treatments. Excellent Palmer amaranth control is often correlated with improved yield. However, in this study, Palmer amaranth control ultimately provided a less competitive environment for both the sweetpotato crop and other weeds. These ecological changes, including increased light penetration and increased availability of water and nutrients, created an environment that encouraged the emergence of high densities of eclipta (Eclipta prostrate L.) populations in plots treated with wick-applied paraquat. Eclipta is a highly branched, prostrate summer annual that thrives in damp, muddy soils of cultivated areas (Bryson and DeFelice 2009). Eclipta stems have a thick, waxy cuticle that facilitates vigorous rooting at stem nodes, especially under wet conditions. As a result of increased precipitation throughout the growing season of 2013 (Appendix A) and Palmer amaranth control provided by wick-applied paraquat causing areas for eclipta to establish, eclipta quickly became a dominant weed that competed with sweetpotato and resulted in significant yield losses. In this study, eclipta plants reached heights of approximately 1.0 m and, although extended above the sweetpotato canopy, were not tall enough to be controlled using the wicking apparatus. Attempts to control eclipta with wick-applied herbicides would be injurious to sweetpotato foliage because eclipta branches did not extend far enough above the
sweetpotato canopy. Future research evaluating the efficacy of wick-applied paraquat in sweetpotato should consider a weed management strategy that includes the application of PRE herbicides, such as flumioxazin or S-metolachlor, for control of troublesome weeds that do not extend above the sweetpotato canopy.

Wick-applied paraquat and wick-applied d-limonene demonstrate potential for use as a weed management tool in sweetpotato production. However, more research should be conducted to develop a weed management program that encompasses solutions to the unique challenges inherent in utilizing wick-applied herbicides for Palmer amaranth control in sweetpotato production.
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Council of America.

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Table 3.1. Effect of wick-applied paraquat and \textit{d}-limonene on Palmer amaranth control at Clinton, NC in 2013\textsuperscript{a}.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>AMAPA control (DAP)\textsuperscript{b} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>41</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>Paraquat 5 WAP</td>
<td>92</td>
</tr>
<tr>
<td>Paraquat 6 WAP</td>
<td>--</td>
</tr>
<tr>
<td>Paraquat 7 WAP</td>
<td>--</td>
</tr>
<tr>
<td>\textit{d}-limonene 5 WAP</td>
<td>60</td>
</tr>
<tr>
<td>\textit{d}-limonene 6 WAP</td>
<td>--</td>
</tr>
<tr>
<td>\textit{d}-limonene 7 WAP</td>
<td>--</td>
</tr>
<tr>
<td>\textit{d}-limonene 5 WAP fb 7 WAP</td>
<td>30</td>
</tr>
<tr>
<td>\textit{d}-limonene 6 WAP fb 10 WAP</td>
<td>--</td>
</tr>
<tr>
<td>\textit{d}-limonene 7 WAP fb 11 WAP</td>
<td>--</td>
</tr>
<tr>
<td>LSD (0.05)\textsuperscript{c}</td>
<td>16</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Abbreviations: AMAPA, Palmer amaranth; DAP, days after transplanting; WAP, weeks after transplanting; fb, followed by.
\textsuperscript{b} Rating: 0\%, no control; 100\% complete control.
\textsuperscript{c} LSD conducted at the \textit{P} = 0.05 level of significance. Means with the same letters within columns are not statistically different.
Table 3.2. Effect of wick-applied paraquat and d-limonene on ‘Covington’ sweetpotato storage root yield at Clinton, NC in 2013a.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Jumbo</th>
<th>No. 1</th>
<th>Canner</th>
<th>Marketableb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weed-free</td>
<td>16,750 a</td>
<td>26,929 a</td>
<td>3,934 ab</td>
<td>47,613 a</td>
</tr>
<tr>
<td>Weedy</td>
<td>1,050 c</td>
<td>6,971 c</td>
<td>2,587 b</td>
<td>10,608 bcd</td>
</tr>
<tr>
<td>Paraquat 5 WAP</td>
<td>7,255 bc</td>
<td>16,371 b</td>
<td>4,432 ab</td>
<td>28,058 bc</td>
</tr>
<tr>
<td>Paraquat 6 WAP</td>
<td>5,158 bc</td>
<td>15,220 bc</td>
<td>4401 ab</td>
<td>24,779 bcd</td>
</tr>
<tr>
<td>Paraquat 7 WAP</td>
<td>7,357 bc</td>
<td>19,148 ab</td>
<td>4,386 ab</td>
<td>30,891 bc</td>
</tr>
<tr>
<td>d-limonene 5 WAP</td>
<td>11,924 ab</td>
<td>21,977 ab</td>
<td>4,227 ab</td>
<td>38,128 ab</td>
</tr>
<tr>
<td>d-limonene 6 WAP</td>
<td>9,810 ab</td>
<td>21,418 ab</td>
<td>5,331 a</td>
<td>36,559 ab</td>
</tr>
<tr>
<td>d-limonene 7 WAP</td>
<td>1,565 c</td>
<td>15,731 bc</td>
<td>4,691 a</td>
<td>21,987 bcd</td>
</tr>
<tr>
<td>d-limonene 5 WAP fb 7 WAP</td>
<td>8,769 bc</td>
<td>19,652 ab</td>
<td>3,984 ab</td>
<td>32,405 bc</td>
</tr>
<tr>
<td>d-limonene 6 WAP fb 10 WAP</td>
<td>11,167 ab</td>
<td>20,715 ab</td>
<td>4,110 ab</td>
<td>35,992 ab</td>
</tr>
<tr>
<td>d-limonene 7 WAP fb 11 WAP</td>
<td>5,426 bc</td>
<td>23,406 ab</td>
<td>4,299 ab</td>
<td>33,131 ab</td>
</tr>
<tr>
<td>LSD (0.05)c</td>
<td>7,954</td>
<td>9,053</td>
<td>2,041</td>
<td>14,997</td>
</tr>
</tbody>
</table>

Abbreviations: WAP, weeks after transplanting; fb, followed by.
Marketable is the aggregate of jumbo, no. 1, and canner grades of sweetpotato storage roots.
LSD conducted at the P = 0.05 level of significance. Means with the same letters within columns are not statistically different.
Figure 3.1. (A) Tractor-mounted LMC Cross-Wick Bar. (B) Close up of pressurized PVC chemical reservoir where herbicide is added to wicking system. (C) Close up of individual ropewick being saturated with green paraquat solution. (D) LMC Cross-Wick Bar application of wick-applied paraquat to Palmer amaranth plants above the sweetpotato canopy.
Appendix A. Weather data collected at Clinton, NC in 2012 and 2013.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Average of 2m Daily Max Air Temperature</th>
<th>Average of 2m Daily Min Air Temperature</th>
<th>Sum of 1m Daily Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>May</td>
<td>28</td>
<td>16.94</td>
<td>11.37</td>
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<tr>
<td></td>
<td>June</td>
<td>30</td>
<td>17.2</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>33.55</td>
<td>22.72</td>
<td>15.69</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>30.2</td>
<td>21.05</td>
<td>9.93</td>
</tr>
<tr>
<td></td>
<td>September</td>
<td>27.61</td>
<td>16.38</td>
<td>3.45</td>
</tr>
<tr>
<td></td>
<td>October</td>
<td>24.94</td>
<td>10.83</td>
<td>4.77</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>------</td>
<td>------</td>
<td>48.89</td>
</tr>
<tr>
<td>2013</td>
<td>May</td>
<td>26</td>
<td>14.33</td>
<td>4.75</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>29.67</td>
<td>20.11</td>
<td>27.94</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>30.88</td>
<td>22.27</td>
<td>15.49</td>
</tr>
<tr>
<td></td>
<td>August</td>
<td>30</td>
<td>20.44</td>
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