ABSTRACT

MOORE, LEVI DAVID. Palmer Amaranth (*Amaranthus palmeri*) Competition, Early Seedbank Management, and Chemical Control. (Under the direction of Dr. Katherine M. Jennings).

Palmer amaranth (*Amaranthus palmeri*) is the most troublesome weed in vegetable crops in the U.S. This is due in part to its large and rapid growth and high fecundity. High fecundity and obligate outcrossing create relatively large genetic diversity in offspring, which, when coupled with intensive herbicidal selection pressure, has caused herbicide resistance to become commonplace. Sweetpotato is a major vegetable crop in the United States. In North Carolina, sweetpotato is the 3rd most economically important crop, with a value of $375 million in 2020. However, production can be limited due to the prostrate and slow-growing habit of sweetpotato providing low competitive ability against Palmer amaranth. Thus, the objectives of this dissertation were to evaluate herbicides for Palmer amaranth control and evaluate the effects of Palmer amaranth light interception in sweetpotato. Further experiments were conducted to evaluate the influence of herbicides on gynoecious Palmer amaranth plants retaining seeds and to screen Palmer amaranth accessions collected in North Carolina for susceptibility to herbicides with known resistant biotypes in the U.S.

Field studies were conducted to determine sweetpotato tolerance to and weed control from management systems that included linuron. Treatments included flumioxazin (107 g ai ha^{-1}) preplant followed by (fb) *S*-metolachlor (800 g ai ha^{-1}), oryzalin (840 g ai ha^{-1}), or linuron (280, 420, 560, 700, and 840 g ai ha^{-1}) alone or in combination applied 7 d after planting (DAP). Weeds did not emerge before treatment applications. Flumioxazin fb linuron plus *S*-metolachlor did not improve Palmer amaranth management and decreased marketable yield by up to 28% compared with flumioxazin fb *S*-metolachlor.

To further evaluate the utility of linuron in sweetpotato, field studies were conducted to evaluate linuron for POST control of Palmer amaranth. Treatments consisted of linuron (420 and 700 g ai ha^{-1}) applied alone or mixed with a nonionic surfactant (NIS), *S*-metolachlor, or NIS plus *S*-metolachlor applied 8 DAP. Including NIS with linuron did not increase Palmer amaranth control compared to linuron alone, but increased sweetpotato injury and subsequently decreased total sweetpotato yield by 25%. Including *S*-metolachlor with linuron resulted in the greatest Palmer amaranth control, but increased crop foliar injury to 36%.

Additional field studies were conducted to compare the response of sweetpotato to shade cloth light interception and Palmer amaranth competition. Treatments consisted of shade cloth with an average measured light interception of 41, 59, 76 and 94% or *A. palmeri* thinned to 0.6 or 3.1 plants m^{-2}. Increasing shade cloth light interception by 1% linearly increased yield loss by 1%. Analysis provided no evidence that the presence of yield loss from *A. palmeri* light interception caused yield loss different than that explained by the shade cloth.

Lab and greenhouse studies were conducted to evaluate the effects of chemical treatments applied to Palmer amaranth seeds or gynoecious plants retaining seeds on seed germination and quality. When applied to physiologically mature Palmer amaranth seed, dicamba, ethephon, halosulfuron, oryzalin, trifluralin, and 2,4-D decreased the average seedling length by at least 50%. When applied to gynoecious Palmer amaranth inflorescence, seed viability was greater than 95%. No treatments applied to Palmer amaranth inflorescence affected average seedling length.

To determine Palmer amaranth susceptibility to atrazine, dicamba, *S*-metolachlor, and 2,4-D in the North Carolina Coastal Plain, seeds collected from 120 accessions across 22 counties in 2016 were treated in greenhouse studies. Plants with green leaves and apical meristems 3 wk after herbicide application were considered survivors. Accessions with a 95% confidence interval not containing 0% were considered to have reduced sensitivity. Survival from *S*-metolachlor (22%) and 2,4-D (47%) differed from 0% survival. Of these accessions, 18 survived both *S*-metolachlor and 2,4-D.

Palmer Amaranth (*Amaranthus palmeri*) Competition, Early Seedbank Management, and Chemical Control

by
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BIOGRAPHY

Levi Moore was born in Tifton, Georgia on June 26, 1997. Levi was raised in Chula, Georgia on the family agricultural research farm. Some of Levi's earliest childhood memories are jumping around in cotton wagons for compaction, eating fresh peaches and watermelon, and riding around the farm on the hood of a truck to check irrigation pivots. In his adolescence, he assisted with the research and farming. After high school graduation, Levi attended Abraham Baldwin Agricultural College, then the University of Georgia's Tifton Campus, while continuing to assist with the research farm. In addition, Levi interned with Bayer CropScience's Early Development Research Technology Station in Sycamore, Georgia as a research assistant, where he gained an interest in the regulatory process for agricultural technology. These experiences led Levi to desire more information about applied agricultural science. It was through this internship that he was introduced to Dr. Katie Jennings. Working in South Georgia, the majority of his education was focused on the primary row crops of cotton and peanut, so the opportunity to work with small fruits and vegetables while studying the most problematic weed in the United States, Palmer amaranth, was the perfect fit to his educational intrigue. Levi recently completed his PhD under the direction of Dr. Katie Jennings. Upon graduation, Levi will begin working with his Father and Brother at Southeast Ag Research in Chula, Georgia.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Herbicide Systems Including Linuron for Palmer Amaranth (*Amaranthus palmeri*) Control in Sweetpotato

(In the format appropriate for submission to Weed Technology)

Herbicide Systems Including Linuron for Palmer Amaranth (*Amaranthus palmeri*) Control in Sweetpotato

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Abstract

Field studies were conducted to determine sweetpotato tolerance to and weed control from management systems that included linuron. Treatments included flumioxazin preplant (107 g ai ha^{-1}) followed by (fb) *S*-metolachlor (800 g ai ha^{-1}), oryzalin (840 g ai ha^{-1}), or linuron (280, 420, 560, 700, and 840 g ai ha^{-1}) alone or mixed with *S*-metolachlor or oryzalin applied 7 d after transplanting. Weeds did not emerge before the treatment applications. Two of the four field studies were maintained weed free throughout the season to evaluate sweetpotato tolerance without weed interference. The herbicide program with the greatest sweetpotato yield was flumioxazin fb *S*-metolachlor. Mixing linuron with *S*-metolachlor did not improve Palmer amaranth management and decreased marketable yield by up to 28% compared with flumioxazin fb *S*-metolachlor. Thus, linuron should not be applied POST in sweetpotato if Palmer amaranth has not emerged at the time of application.

Nomenclature: Flumioxazin; linuron; oryzalin; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Watson AMAPA

Key words: Weed control; herbicide tillage; herbicide cultivation.

Sweetpotato is a major vegetable crop in the United States, with a production value of $654 million (USDA-NASS 2019). North Carolina leads national sweetpotato production, accounting for more than 50% of the national hectares harvested in 2018, with a value of $236 million (USDA-NASS 2019). However, the prostrate and slow-growing habit of sweetpotato provides low competitive ability against weeds (Basinger et al. 2019; Meyers et al. 2010a; Seem et al. 2003; Smith et al. 2020), which are becoming an increasing problem for North Carolina growers.

Palmer amaranth is the most common and troublesome weed in sweetpotato (Webster 2010; Smith and Moore, unpublished data) due to many factors, including large and vigorous growth and high fecundity. Palmer amaranth can grow 0.18 to 0.21 cm growing degree d^{-1} and reach 2 m tall, with greater than 80% leaf area above the sweetpotato canopy (Horak and Loughin 2000; Meyers et al. 2010a; Sellers et al. 2003). In addition, one female plant produces 200,000 to 600,000 1-mm diam seeds (Keeley et al. 1987; Sellers et al. 2003; Sosnoskie et al. 2014). High Palmer amaranth densities can reduce sweetpotato yield to up to 93%, but even 1 plant m^{-1} can cause 50% yield loss (Barkley et al. 2016; Basinger et al. 2019; Meyers et al. 2010a, 2010b, 2016, 2017). Palmer amaranth resistant to eight herbicide mechanisms of action has been reported in the United States, further increasing management difficulty (Heap 2020). Glyphosate and acetolactate synthase–inhibiting herbicide-resistant Palmer amaranth is common in North Carolina (Poirier et al. 2014; DJ Mahoney, personal communication); however, foreseeably most troubling to North Carolina sweetpotato production is the protoporphyrinogen oxidase (PPO)-inhibiting herbicide-resistant Palmer amaranth recently reported in North Carolina (DJ Mahoney, personal communication).

Flumioxazin, a PPO-inhibiting herbicide, applied preplant followed by (fb) *S*-metolachlor 10 to 14 d after transplanting (DAP) is the common herbicide program used in North Carolina sweetpotato production (Beam et al. 2018; Smith and Moore, unpublished data). North Carolina growers participating in a survey indicated that 100% of conventionally grown sweetpotato acres received flumioxazin in 2018 (Smith and Moore, unpublished data). Meyers et al. (2010b) reported flumioxazin preplant fb *S*-metolachlor 0 DAP can provide greater than 90% season-long Palmer amaranth control, but when *S*-metolachlor applications are delayed to 14 DAP, control can be variable (38 to >90%) because *S*-metolachlor does not control Palmer amaranth that has emerged prior to application (Anonymous 2015). However, applying *S*-metolachlor 0 DAP rather than 14 DAP can cause greater stunting, yield losses, and rounded sweetpotato storage roots (Meyers et al. 2012, 2013b). Applying *S*-metolachlor in combination with an herbicide with POST activity on Palmer amaranth could provide season-long control while maintaining sweetpotato yield and quality.

Linuron is a photosystem II–inhibiting herbicide in the substituted urea family (WSSA Group 7) that provides PRE and POST control of broadleaf and grass weeds (Anonymous 2013). Linuron has been submitted for registration in sweetpotato through the Interregional-4 project (Batts 2019). Brandenberger et al. (2009) reported 90% or greater Palmer amaranth control 5 wk after treatment (WAT) from linuron PRE (335 g ai ha^{-1}) and 76% or greater control 6 WAT from linuron PRE or POST (335 g ai ha^{-1}) in cilantro (*Coriandrum sativum* L.). Miller et al (2013) reported 99% or better goosegrass control 4 WAT from linuron PRE (840 g ai ha^{-1}). Whitaker et al. (2011) reported linuron PRE (1,120 g ai ha^{-1}) controlled Palmer amaranth 73% to 92% 3 WAT, but only 0% to 47% 8 WAT in cotton (*Gossypium hirsutum* L.).

Injury to sweetpotato from linuron applied POST can be variable; Beam et al. (2018) reported at least 48% chlorosis/necrosis and at least 23% stunting from linuron (420 to 1,120 g ai ha^{-1}), Rouse et al. (2015) reported not more than 38% injury from linuron (560 to 1120 g ai ha^{-1}), and Miller et al. (2013) reported not more than 11% injury from linuron (840 g ai ha^{-1}). Beam et al. (2018) observed increased chlorosis/necrosis when linuron was applied 14 DAP compared with 7 DAP. Furthermore, mixing linuron with *S*-metolachlor increased sweetpotato injury but caused similar yields as linuron alone under weed-free conditions (Beam et al. 2018).

Oryzalin has been evaluated for Palmer amaranth control in sweetpotato to increase available control options. Oryzalin is a microtubule-inhibiting dinitroaniline herbicide (WSSA Group 3) that provides PRE control of broadleaves and annual grasses (Anonymous 2014). Meyers et al. (2017) reported 85% Palmer amaranth control 10 WAT from oryzalin (560 to 1,120 g ai ha^{-1}) applied 0 DAP and less than 8% sweetpotato injury. Chaudhari et al. (2018) reported less than 10% sweetpotato injury from oryzalin (560 to 1,120 g ai ha^{-1}) applied 0 or 14 DAP and similar yields to nontreated plots. A weed-control program with multiple herbicide mechanisms of action, in addition to cultural control methods, can provide an integrated approach to sweetpotato weed management. The addition of photosystem II–inhibiting herbicides to integrated weed management systems could help delay or reduce herbicide-resistant weed populations in sweetpotato. Thus, field studies were conducted to determine sweetpotato tolerance and weed control from management systems that include linuron.

Materials and Methods

Field studies were conducted in 2018 and 2019 at a research station and commercial farms in North Carolina having soils commonly planted to sweetpotato (Table 1.1). The experiment was arranged in a randomized complete block design with a factorial of three herbicide combinations each including five rates of linuron. Treatments included flumioxazin preplant fb linuron alone or mixed with *S*-metolachlor or oryzalin applied 7 DAP (Table 1.2). In addition, flumioxazin preplant fb *S*-metolachlor, oryzalin, or hand roguing were included for comparison. Preplant applications were applied after bed formation using a tractor-mounted sprayer equipped with AITTJ60-11003VP nozzles (TeeJet Technologies, Wheaton, IL) calibrated to apply 234 L ha^{-1} at 414 kPa. POST treatments were applied using a CO_2-pressurized backpack sprayer calibrated to apply 187 L ha^{-1} at 150 kPa through a two-nozzle boom equipped with flat-fan XR 8003VS nozzles spaced 50 cm apart.

Plots consisted of two rows each 1.07-m wide by 6.1-m long and were mechanically transplanted with nonrooted cuttings (slips) to a 30-cm in-row spacing. The first row was a nontreated buffer that was maintained weed-free season-long by hand roguing, and the second received a treatment and was used for data collection. Weeds between rows were removed using cultivation. The location for weedy fields in Clinton, NC (35.022°N, 78.280°W), in 2018 and 2019 (Clin18WD and Clin19WD, respectively) had a high Palmer amaranth population (50 to 100 plants m^{-2}) and the weed-free fields in Faison, NC (35.149°N, 78.204°W), in 2018 (Fais18WF) and in Bowdens, NC (35.073°N, 78.113°W) (Bow18WF), were kept weed-free during the season by hand roguing and cultivation. Clin18WD and Clin19WD were irrigated as needed and Fais18WF and Bow18WF were not. Clin18WD and Clin19WD received 1.3 cm of irrigation within 1.5 ± 0.5 d after post-transplant treatment. Study fertility, disease, and insect control were maintained according to commercial sweetpotato growing recommendations.

Foliar injury and stunting were visually estimated using a scale of 0% (no treatment effect) to 100% (crop death) 1, 2, 4, 6, and 8 wk after post-transplant treatment (WAPT) (Frans et al. 1986). Palmer amaranth and goosegrass control was rated in Clin18WD and Clin19WD on the basis of populations in the field using a scale of 0% (weedy) to 100% (weed free) (Frans et al.1986). Palmer amaranth control was rated 1, 2, 4, 6, and 8 WAPT, and goosegrass control was rated 3 WAPT. After the 3 WAPT goosegrass control rating, clethodim plus 1% vol/vol crop oil

(Table 1.2) was applied over the entire area of each study to minimize confounding weed competition and prevent harvesting inefficiencies from grasses. Sweetpotato storage roots were harvested using a chain-digger (Clin18WD and Clin19WD) or disc turn plow (Fais18WF and Bow18WF) 122 ± 11 DAP; hand sorted into canner (>2.5 to 4.4 cm diam), no. 1 (>4.4 to 8.9 cm), and jumbo (>8.9 cm) grades (USDA 2005); and then weighed. Marketable yield was calculated as the sum of jumbo and no. 1 grades.

Data were checked for homogeneity of variance by plotting residuals. Arcsine transformations were used for injury and goosegrass control data and square-root transformations were used for jumbo-grade yield data to normalize the distribution of residuals. Back-transformed data were presented in figures and tables for interpretability. ANOVA was conducted using PROC MIXED in SAS, version 9.4 (SAS Institute, Cary, NC). Fixed effects included herbicide combination, linuron rate, and their interaction, whereas study, replication nested within study, and interactions including study were considered random effects for sweetpotato injury analyses. However, not all studies contained similar weed levels; therefore, herbicide combination, linuron rate, study, and their interactions were considered fixed effects, and replication nested within study was considered a random effect for weed control and yield analyses.

Flumioxazin fb hand roguing, *S*-metolachlor, or oryzalin were not included in injury analyses because all observations equaled 0%. Likewise, flumioxazin fb hand roguing was not included in the weed control analyses because all observations equaled 100%. Treatments including *S*-metolachlor were also not included in the goosegrass control analysis, because all observations equaled 100%. When no significant interaction ($P > 0.05$) was present between herbicide combination and linuron rate, the main effect least square means were presented. Means were separated according to Fisher protected LSD using a significance level of $\alpha = 0.05$.

Linear and nonlinear regression of least square means were conducted using PROC REG and PROC NLIN, respectively, in SAS when linuron rate effects were significant ($P \leq 0.05$). Effect of linuron rate on foliar injury was described using the following three-parameter logistic equation (Equation 1):

$$Y = a / [1 + k \times \exp(-b \times x)] \qquad [1]$$

where Y is foliar injury, a is the foliar injury upper asymptote, x is the linuron rate, and b and k are constants. The effect of linuron rate on stunting and weed control and were described using the following linear model (Equation 2):

$$Y = a \times x + b \qquad [2]$$

where Y is the dependent variable, x is the linuron rate, a is the slope and b is the intercept.

Results and Discussion

Sweetpotato Tolerance. Injury from herbicide treatments with linuron appeared as interveinal chlorosis and necrosis (foliar injury) on older leaves fb stunting, similar to that observed by Beam et al. (2018). Previous research found oryzalin (1.1 to 4.5 kg ai ha^{-1}) applied 14 DAP caused up to 13% sweetpotato injury (Chaudhari et al. 2018), and flumioxazin preplant (91 to 109 g ai ha^{-1}) fb *S*-metolachlor 14 DAP (0.8 to 1.3 kg ai ha^{-1}) caused less than 3% sweetpotato injury (Meyers et al. 2010b). However, no sweetpotato injury was observed from similar herbicide treatments in our studies. This difference could be due to differing environmental factors. Significant herbicide combination effects on foliar injury were present 1 ($P = 0.0002$) and 2 ($P = 0.011$) WAPT (Table 1.3), and foliar injury was influenced by linuron rate 1 WAPT ($P < 0.0001$). The interaction between herbicide combination and linuron rate was not significant

($P > 0.3$). Treatments of flumioxazin fb linuron alone resulted in 13% foliar injury 1 WAPT and was similar when combined with oryzalin. Flumioxazin fb linuron plus *S*-metolachlor caused 19% foliar injury 1 WAPT, which was greater than with other herbicide treatments. Foliar injury 1 WAPT from increasing linuron rate was described by a three-parameter logistic equation (Equation 1) with a maximum asymptote of 22.6% foliar injury ($P = 0.005$) (Figure 1.1). In this experiment, we did not evaluate linuron application rates greater than 840 g ai ha^{-1}; however, Beam et al. (2018) observed foliar injury to be similar between linuron at 840 and 1,120 g ai ha^{-1} 1 WAPT when applied to 'Covington' or 'Murasaki' sweetpotato cultivars. Foliar injury was transient and was less than 4% regardless of herbicide combination 2, 4, 6, and 8 WAPT (Table 1.3).

New growth showed no signs of chlorosis or necrosis, but growth was stunted from herbicide treatments that included linuron. Significant herbicide combination effect on stunting was observed 2 ($P = 0.0054$) and 4 ($P = 0.0003$) WAPT (Table 1.3), and stunting was influenced by linuron rate 2 WAPT ($P = 0.0032$). Herbicide combination by linuron rate interaction was not significant ($P > 0.5$). Treatments of flumioxazin fb linuron alone or combined with oryzalin resulted in 4% or less stunting. The addition of *S*-metolachlor caused up to 8% stunting. Stunting 2 WAPT from increasing linuron rate and was described with a linear model (Equation 2) with a slope of 0.015 ($P = 0.002$) (Figure 1.1). Increasing linuron rate from 280 to 840 g ai ha^{-1} increased estimated stunting by 8%. Stunting 4, 6, and 8 WAPT was 6% or less regardless of herbicide combination (Table 1.3).

Applying linuron mixed with *S*-metolachlor increased sweetpotato injury compared with applying linuron alone, whereas combining linuron with oryzalin did not. Beam et al. (2018) also reported that mixing linuron with *S*-metolachlor increased foliar injury and stunting. Research has shown that sweetpotato injury from linuron POST, using rates similar to those applied in the present experiment, varies from no more than 11% to 48% or greater (Beam et al. 2018; Miller et al. 2013; Rouse et al. 2015). The varying response of sweetpotato to linuron could be due to environmental conditions differing, or differences in the quality of the sweetpotato slips at transplant.

Weed Control. Palmer amaranth and goosegrass did not emerge before post-transplant applications; therefore, all treatments had only PRE activity on weeds. Significant ($P \leq 0.05$) herbicide combination and linuron rate by study interactions were present for Palmer amaranth and goosegrass control analyses; therefore, data were analyzed by study. In Clin18WD, herbicide combination caused a significant ($P < 0.0001$) effect on Palmer amaranth control, and linuron rate had a significant effect on Palmer amaranth control 2 WAPT ($P = 0.0411$). Herbicide combination by linuron rate interactions were not significant ($P > 0.5$). Flumioxazin fb linuron provided poor control (≤26%) of Palmer amaranth in Clin18WD (Table 1.4), which is inconsistent with previous research reporting 66 to greater than 90% control with linuron (335 to 2,240 g ai ha^{-1}) PRE until at least 3 WAT (Brandenberger et al. 2009; Grichar et al. 2015; Volmer et al. 2014; Whitaker et al. 2011). Flumioxazin fb oryzalin with or without linuron resulted in less than 50% Palmer amaranth control. Meyers et al. (2017) reported greater than 85% Palmer amaranth control from oryzalin (560 g ai ha^{-1}), and Gossett et al. (1992) reported 63% or greater control from oryzalin (800 g ai ha^{-1}). Greater than 80% Palmer amaranth control was achieved from treatments including *S*-metolachlor, which were not improved when combined with linuron. Similarly, Meyers et al. (2010b, 2013a) reported 80% or better season-long Palmer amaranth control from *S*-metolachlor (800 g ai ha^{-1}).

Increase in linuron rate caused Palmer amaranth control to increase in a linear trend (Equation 2) with a slope of 0.03 (P = 0.001) (Figure 1.2). Increasing linuron rate from 280 to 840 g ai ha^{-1} resulted in an estimated 17% increase in Palmer amaranth control when rates were pooled across herbicide combinations. Palmer amaranth control was 95% or better in Clin19WD for all treatments as a result of flumioxazin applications. Flumioxazin (91 to 107 g ai ha^{-1}) has been reported to provide greater than 90% Palmer amaranth control for more than 7 WAT (Barkley et al. 2016; Meyers et al. 2010b, 2013a), though flumioxazin persistence varies among environmental conditions and soil types (Anonymous 2016; Whitaker et al. 2011).

Goosegrass emerged later than Palmer amaranth and was only rated 3 WAPT (Table 1.4). In Clin18WD, herbicide combination and linuron rate had a significant ($P \leq 0.002$) effect on goosegrass control, and the herbicide combination by linuron rate interaction was not significant (P = 0.233). Flumioxazin fb linuron or oryzalin resulted in poor control (<30%) of goosegrass. Previous research is inconsistent for goosegrass control from linuron. Miller et al. (2013) reported 99% or greater goosegrass control from linuron (840 g ai ha^{-1}), whereas Lugo Torres et al. (2016) reported less than 50% control from linuron (2,240 g ai ha^{-1}). Johnson (1997) reported variable goosegrass control of 19% to 86% from oryzalin (800 to 3,400 g ai ha^{-1}). When linuron was combined with oryzalin, goosegrass control increased to 62%. Treatments including *S*-metolachlor resulted in 100% goosegrass control. Observed control was greater than in previous research, which reported 68% goosegrass control from *S*-metolachlor (1,400 g ai ha^{-1}) (Clewis et al. 2007). Linuron rate effect on goosegrass control was best described by a linear model (Equation 2) with a slope of 0.082 (P = 0.0454) (Figure 1.2). An increase in linuron rate from 280 to 840 g ai ha^{-1} resulted in an estimated 46% increase in goosegrass control. Goosegrass control in Clin19WD was at least 99% for all treatments.

In Clin18WD, a close between-row cultivation 1 d prior to POST treatment applications disturbed the soil near the sweetpotato plants, leaving a noncultivated area of less than 15 cm fb each cultivation thereafter, leaving an approximately 20-cm noncultivated area around the sweetpotato plants. In Clin19WD, all cultivations left an approximately 20-cm noncultivated area. Because of the close cultivation in Clin18WD, more Palmer amaranth emerged, compared with the same field the following year (Clin19WD). Most Palmer amaranth that emerged in Clin18WD were present in the area where the first cultivation disturbed the soil, but the following cultivations did not disturb the soil (Figure 1.3). More research is needed to study the effects of between-row cultivation on herbicide system efficacy and longevity in sweetpotato. Because of the differences observed between Clin18WD, Clin19WD, and previous studies, more research is needed to evaluate the efficacy of herbicide systems including linuron in sweetpotato.

Yield. Significant ($P \leq 0.05$) herbicide combination by study interactions were present for yield analyses; therefore, data were analyzed by study. Herbicide combination main effects were significant ($P \leq 0.05$) depending on storage root grade and study (Table 1.5), but linuron rate main effects were not. Bow18WF, on average, yielded less than Clin18WD, Fais18WF, and Clin19WD. Bow18WF was grown using Beauregard sweetpotato, which yields similarly to Covington sweetpotato (Yencho et al. 2008). The lower yield observed in Bow18WF is thought to be more of a factor of heat stress at the time of planting, because Bow18WF was planted later than other studies, rather than differences between the cultivars. Poor Palmer amaranth control from flumioxazin fb linuron, oryzalin, and linuron plus oryzalin in Clin18WD resulted in at least 34%, 77%, and 51% reduction in no. 1, jumbo, and marketable yield, respectively, compared with flumioxazin fb hand roguing. Sweetpotato in the flumioxazin fb oryzalin and linuron plus oryzalin treatments yielded similarly under weedy conditions in Clin18WD, and both treatments similarly decreased no. 1 and marketable yield by at least 22% and at least 26%, respectively, compared with flumioxazin fb hand roguing when weed competition was not a factor (in Fais18WF). Sweetpotato yield loss from oryzalin observed in this experiment differed from previous research, which reported similar marketable yield to nontreated plots (Chaudhari et al. 2018; Meyers et al. 2017). The reason for the difference between our experiment and previous research is unknown, though the absence of irrigation in Fais18WF could have played a role. More research is needed to evaluate sweetpotato response to oryzalin in adverse conditions.

Because of the differing results between Clin18WD and Clin19WD, more research is needed to evaluate weed control from linuron and the herbicide systems. PRE weed control from linuron can be improved by increasing the application rate. Registered application rates are up to 2,240 g ai ha^{-1} depending on use, but a reduced rate is required to minimize sweetpotato injury. Because of the reduced use rates and absence of weeds at the time of application, mixing linuron with *S*-metolachlor did not improve weed management and caused decreased marketable yield by 24% and 28% in Clin18WD and Fais18WF, respectively, compared with flumioxazin fb *S*-metolachlor. Beam et al. (2018) observed similar yield between linuron alone and linuron plus *S*-metolachlor, though increased injury was observed from the mixture. The greater injury observed by Beam et al. (2018) was likely due to differing environmental conditions, though environmental data were not provided.

Although *S*-metolachlor without linuron provided good Palmer amaranth control in Clin18WD and, subsequently, optimal yield, *S*-metolachlor does not have POST activity (Anonymous 2015). Linuron has POST activity and can control problematic weeds that may emerge prior to an *S*-metolachlor application (Anonymous 2013; Batts 2019). As proposed by Beam et al. 2018, less than 560 g ai ha^{-1} linuron applied 7 DAP fb *S*-metolachlor 14 DAP could control Palmer amaranth that emerges before *S*-metolachlor application. However, in this experiment, when flumioxazin was used preplant, weeds did not emerge before 14 DAP and thus were not present at *S*-metolachlor application. Similarly, Meyers et al. (2010b) reported flumioxazin PRE (109 g ai ha^{-1}) controlled Palmer amaranth 100% 2 WAT. Thus, when flumioxazin is applied to susceptible populations, linuron would likely not be beneficial unless Palmer amaranth have emerged before *S*-metolachlor applications.

PPO-resistant Palmer amaranth populations have been reported in parts of North America, including North Carolina (Giacomini et al. 2017; Heap 2020; Mahoney et al. 2020; Salas-Perez et al. 2017; Varanasi et al. 2018). Controlling weeds that escape flumioxazin applications is critical for delaying resistance severity. Sweetpotato in the flumioxazin fb linuron treatments yielded similarly to hand-rogued plots in Fais18WF, Bow18WF, and Clin19WD, and sweetpotato injury can be minimized as linuron rate is reduced; therefore, additional research is needed to investigate linuron efficacy applied POST to control Palmer amaranth that may escape flumioxazin application. When registered, linuron should only be applied POST if Palmer amaranth is emerged at application.

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Table 1.1 Properties of studies and study locations.

Location	Soil series[a]	pH	Humic matter	Planting date	Cultivar	Palmer amaranth[b]	Goosegrass[b]
			%				
Horticultural Crops Research Station near Clinton, NC (35.022°N, 78.280°W)	Orangeburg[c]	5.9	0.5	June 14, 2018	Covington	Yes	Yes
Grower field, near Faison, NC (35.149°N, 78.204°W)	Goldsboro[d]	5.5	1.3	June 14, 2018	Covington	No	No
Grower field, Bowdens, NC (35.073°N, 78.113°W)	Norfolk[c]	5.9	0.9	July 3, 2018	Beauregard	No	No
Horticultural Crops Research Station near Clinton, NC (35.022°N, 78.280°W)	Orangeburg[c]	5.5	0.7	June 18, 2019	Covington	Yes	Yes

[a] All soil textures were loamy sand.
[b] Weeds in Fais18WF and Bow18WF were hand-rogued season long.
[c] Fine-loamy, kaolinitic, thermic Typic Kandiudults.
[d] Fine-loamy, siliceous, subactive, thermic Aquic Paleudults.

Table 1.2 Herbicides, rates, and sources used for the studies.

Active ingredient	Trade name	Rate	Manufacturer	City, State	Website
		g ai ha^{-1}			
Clethodim[a]	Select Max®	135	Valent U.S.A. Corporation	Walnut Creek, CA	www.valent.com
Flumioxazin	Valor® SX	107	Valent U.S.A. Corporation	Walnut Creek, CA	www.valent.com
Linuron	Linex® 4L	280, 420, 560, 700, 840	Tessenderlo Kerley, Inc.	Phoenix, AZ	www.novasource.com
Oryzalin	Surflan®	840	United Phosphorus, Inc.	Prussia, PA	www.upi-usa.com
S-metolachlor	Dual Magnum®	800	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta-us.com

[a] Crop oil concentrate included at 1% vol/vol

Table 1.3 Effect of herbicide treatment on sweetpotato foliar injury and stunting.[a,b]

Herbicide[d]	Foliar injury[c]		Stunting	
	1 WAPT	2 WAPT	2 WAPT	4 WAPT
	%[e]			
Flumioxazin fb[f] linuron	13b	2.3b	4b	2b
Flumioxazin fb linuron plus *S*-metolachlor	19a	3.4a	8a	6a
Flumioxazin fb linuron plus oryzalin	15b	2.6b	4b	3b

[a] Data pooled across studies and linuron rates (280, 420, 560, 700, and 840 g ai ha^{-1}).
[b] Means within a column followed by the same letter are not significantly different according to Fishers protected LSD ($P \leq 0.05$).
[c] Foliar injury was observed as chlorosis and necrosis.
[d] Abbreviations: fb, followed by; WAPT, wk after POST treatment application.
[e] Rating scale: 0%, no treatment effect; 100%, crop death
[f] Flumioxazin (107 g ai ha^{-1}) applied preplant followed by linuron (280, 420, 560, 700, and 840 g ai ha^{-1}), *S*-metolachlor (800 g ai ha^{-1}), and oryzalin (840 g ai ha^{-1}) applied 7 d after planting.

Table 1.4 Palmer amaranth and goosegrass control as affected by herbicide treatment.[a]

Herbicide[b]	Palmer amaranth control[c]						Goosegrass control[c]	
	2 WAPT[d]		4 WAPT		8 WAPT		3 WAPT	
	Clin18WD[e]	Clin19WD	Clin18WD	Clin19WD	Clin18WD	Clin19WD	Clin18WD[f]	Clin19WD
	%[g]							
Flumioxazin fb *S*-metolachlor	74a	100	92a	98	85a	96	100	100
Flumioxazin fb oryzalin	41b	100	43bc	100	35bc	99	28b	100
Flumioxazin fb linuron	17c	100	26c	95	19c	99	27b	100
Flumioxazin fb linuron plus *S*-metolachlor	81a	100	88a	97	82a	98	100	100
Flumioxazin fb linuron plus oryzalin	47b	100	49b	99	34b	99	62a	100

[a] Data pooled across linuron rates (280, 420, 560, 700, and 840 g ai ha^{-1}) when applicable.

[b] Flumioxazin (107 g ai ha^{-1}) applied preplant followed by linuron (280, 420, 560, 700, and 840 g ai ha^{-1}), *S*-metolachlor (800 g ai ha^{-1}), and oryzalin (840 g ai ha^{-1}) applied 7 d after planting.

[c] Means within a column followed by the same letter are not significantly different according to Fishers protected LSD ($P \leq 0.05$). Means within a column not followed by a letter are not significantly different according to a nonsignificant *F* statistic ($P > 0.05$).

[d] Abbreviations: fb, followed by; WAPT, wk after POST treatment application.

[e] A narrow between-row cultivation before POST treatment applications caused greater weed emergence in Clin18WD than in Clin19WD.

[f] Treatments including *S*-metolachlor were not included in goosegrass control analysis because all observations equaled 100%.

[g] Rating scale: 0%, weedy; 100%, weed-free.

Table 1.5 Sweetpotato storage root yield as affected by herbicide treatment.[a,b]

Herbicide[c,d]	Canner[e]				No. 1				Jumbo				Marketable[f]			
	Clin18 WD[g]	Fais18 WF	Bow18 WF	Clin19 WD	Clin18 WD	Fais18 WF	Bow18 WF	Clin19 WD	Clin18 WD	Fais18 WF	Bow18 WF	Clin19 WD	Clin18 WD	Fais18 WF	Bow18 WF	Clin19 WD
	1,000 kg ha^{-1}															
Flumioxazin fb hand roguing	3.7	6.7	2.7a	3.9	22.5a	32a	7.3	21.2	14.6a	4.2	2.4ab	15.8	37.1ab	36.2a	10.0	37.0
Flumioxazin fb *S*-metolachlor	5.1	7.4	2.3ab	3.3	24.5a	34.2a	7.5	21.9	13.7a	1.1	2.7ab	14.2	38.2a	35.3a	10.3	36.1
Flumioxazin fb oryzalin	7.6	8.4	1.9ab	2.9	12.2bc	24.2bc	7.2	17.7	1.7b	1.9	2.4ab	12.7	13.9c	26.2bc	9.6	30.4
Flumioxazin fb linuron	4.8	6.6	2.3a	3.2	11.1c	28.8ab	8.3	20.5	2.5b	1.6	4.1a	14.5	13.7c	30.4ab	12.4	35.0
Flumioxazin fb linuron plus *S*-metolachlor	4.5	4.3	1.6ab	3.3	21.1a	23.8c	7.7	20.0	7.9a	1.6	3.3ab	15.6	29.0b	25.4c	11.0	35.6
Flumioxazin fb linuron plus oryzalin	4.6	2.5	1.3b	3.4	14.9b	25.0c	7.6	20.6	3.3b	1.9	1.7b	15.0	18.3c	26.9bc	9.3	35.6

[a] Data pooled across linuron rates (280, 420, 560, 700, and 840 g ai ha^{-1}) when applicable.

[b] Means within a column followed by the same letter are not significantly different according to Fishers protected LSD ($P \leq 0.05$). Means within a column not followed by a letter are not significantly different according to a nonsignificant F statistic ($P > 0.05$).

[c] Flumioxazin (107 g ai ha^{-1}) applied preplant followed by linuron (280, 420, 560, 700, and 840 g ai ha^{-1}), *S*-metolachlor (800 g ai ha^{-1}), and oryzalin (840 g ai ha^{-1}) applied 7 d after planting.

[d] Abbreviations: Bow18WF, weed-free field in Bowdens, NC, 2018; Clin18WD, weedy field in Clinton, NC, 2018; Clin19WD, weedy field in Clinton, NC, 2019; Fais18WF, weed-free field in Faison, NC, 2018; fb, followed by.

[e] Sweetpotato storage roots were hand graded into canner (2.5 to 4.4 cm diam), no. 1 (4.4 to 8.9 cm), and jumbo (>8.9 cm).

[f] Marketable yield is the sum of no. 1 and jumbo storage-root grades.

[g] Clin18WD, Fais18WF, and Clin 19WD were transplanted with ‘Covington’ sweetpotato, and Bow18WF was transplanted with ‘Beauregard’ sweetpotato. Fais18WF and Bow18WF were maintained weed-free season-long. A narrow between-row cultivation prior to POST treatment applications caused greater weed emergence in Clin18WD than in Clin19WD.

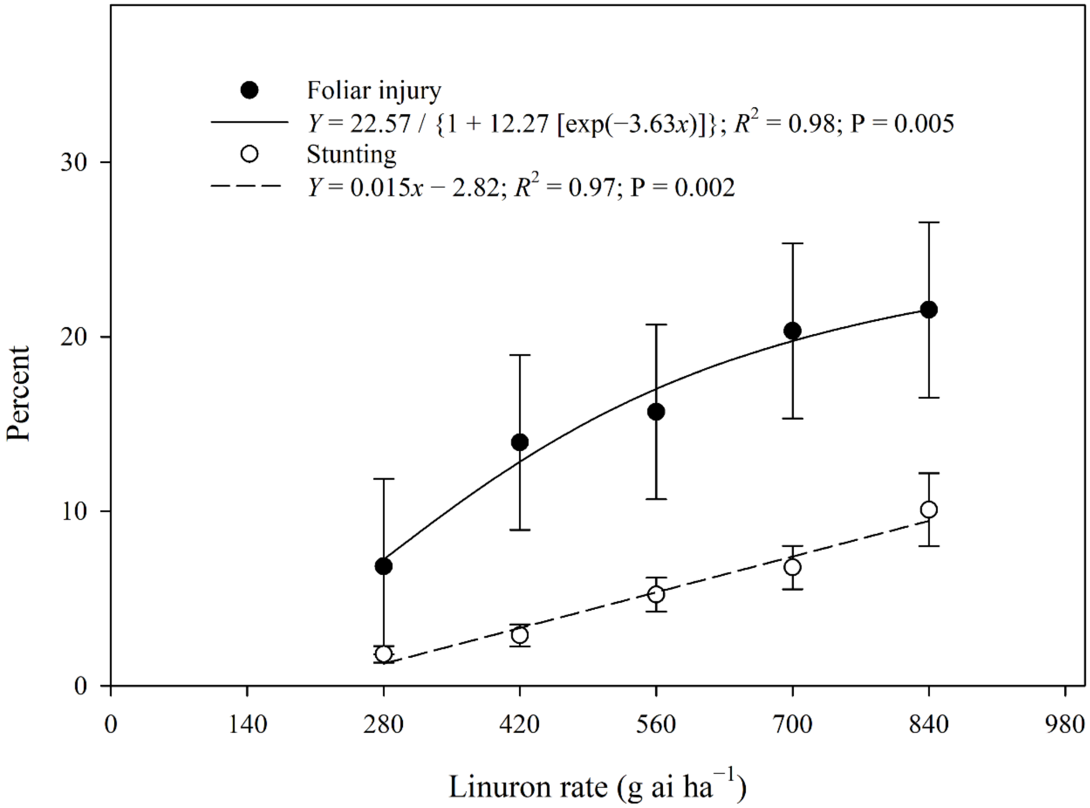

Figure 1.1 The influence of linuron rate on sweetpotato foliar injury and stunting pooled across studies and herbicide combinations. Visual foliar injury and stunting were rated on a scale of 0% (no treatment effect) to 100% (crop death). Points represent means and vertical bars represent means ± SE.

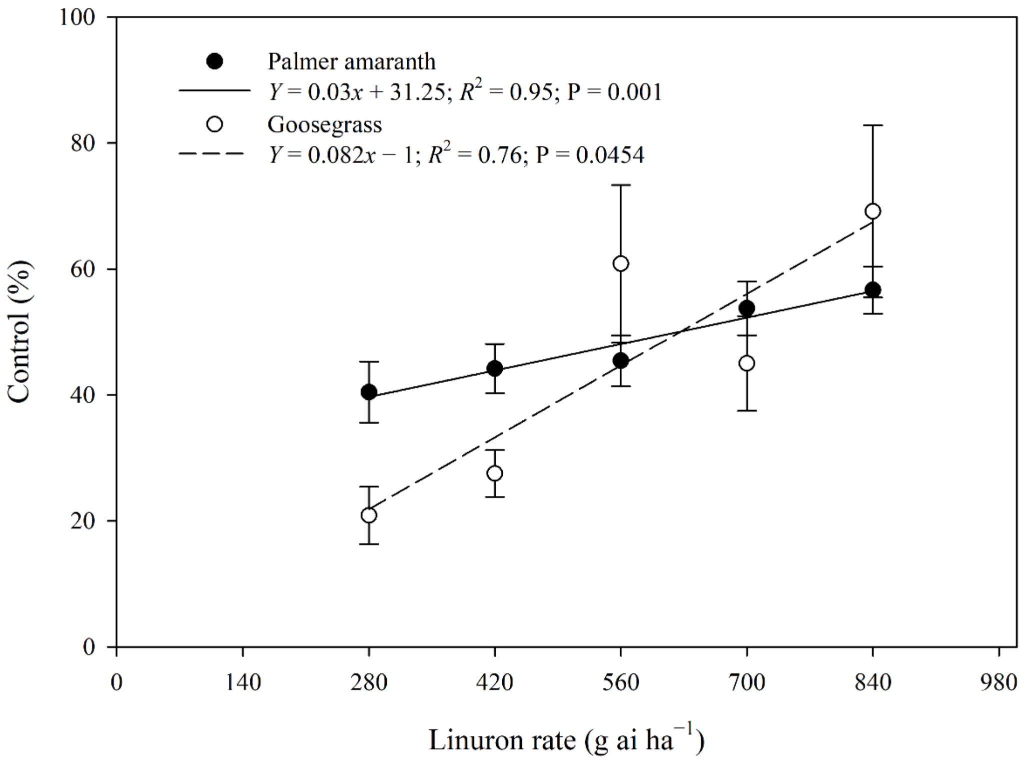

Figure 1.2 Palmer amaranth control 2 wk after post-transplant treatment (WAPT) and goosegrass control 3 WAPT in the weedy Clinton, NC, site in 2018 as affected by linuron rate. Palmer amaranth control data are pooled across herbicide combination, and goosegrass control are pooled across linuron alone and linuron plus oryzalin. Control was visually rated on a scale of 0% (weedy) to 100% (weed-free).

Figure 1.3 Palmer amaranth 2 wk after post-transplant treatment in the weedy Clinton, NC, site in 2018 primarily growing in the area beside the sweetpotato that was disturbed by an initial narrow cultivation but escaped succeeding cultivations.

CHAPTER 2

Safety and Efficacy of Linuron with or without an Adjuvant or *S*-metolachlor for POST Control of Palmer Amaranth (*Amaranthus palmeri*) in Sweetpotato

(In the format appropriate for submission to Weed Technology)

Safety and Efficacy of Linuron with or without an Adjuvant or *S*-metolachlor for POST Control of Palmer Amaranth (*Amaranthus palmeri*) in Sweetpotato

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Abstract

Field studies were conducted to evaluate linuron for POST control of Palmer amaranth in sweetpotato to minimize reliance on protoporphyrinogen oxidase (PPO)-inhibiting herbicides. Treatments were arranged in a two by four factorial where the first factor consisted of two rates of linuron (420 and 700 g ai ha^{-1}), and the second factor consisted of linuron applied alone or in combinations of linuron plus a nonionic surfactant (NIS) (0.5% v/v), linuron plus *S*-metolachlor (800 g ai ha^{-1}), or linuron plus NIS plus *S*-metolachlor. In addition, *S*-metolachlor alone and nontreated weedy and weed-free checks were included for comparison. Treatments were applied to ‘Covington’ sweetpotato 8 d after transplanting (DAP). *S*-metolachlor alone provided poor

Palmer amaranth control because emergence had occurred at applications. All treatments that included linuron resulted in at least 98 and 91% Palmer amaranth control 1 and 2 wk after treatment (WAT), respectively. Including NIS with linuron did not increase Palmer amaranth control compared to linuron alone, but increased sweetpotato injury and subsequently decreased total sweetpotato yield by 25%. Including *S*-metolachlor with linuron resulted in the greatest Palmer amaranth control 4 WAT, but increased crop foliar injury to 36% 1 WAT compared to 17% foliar injury from linuron alone. Marketable and total sweetpotato yield was similar between linuron alone and linuron plus *S*-metolachlor or *S*-metolachlor plus NIS treatments, though all treatments resulted in at least 39% less total yield than the weed-free check resulting from herbicide injury and/or Palmer amaranth competition. Because of the excellent POST Palmer amaranth control from linuron 1 WAT, a system including linuron applied 7 DAP followed by *S*-metolachlor applied 14 DAP could help to extend residual Palmer amaranth control further into the critical period of weed control while minimizing sweetpotato injury.

Nomenclature: Linuron; *S*-metolachlor; Palmer amaranth, *Amaranthus palmeri* S. Wats AMAPA; *Ipomoea batatas* (L.) Lam. ‘Covington’

Key words: Weed control; surfactant; nonionic surfactant; tank mix.

Palmer amaranth (*Amaranthus palmeri*) is the most problematic weed in sweetpotato (Smith and Moore unpublished data; Webster 2010). Palmer amaranth can reduce marketable sweetpotato yield 80 to 95% if left uncontrolled (Barkley et al. 2016; Basinger et al. 2019; Meyers et al. 2010a; Smith et al. 2020). These yield reductions are factors of Palmer amaranth's large and vigorous growth (Horak and Loughin 2000; Meyers et al. 2010a; Sellers et al. 2003), high fecundity (Keeley et al. 1987; Sellers et al. 2003; Sosnoskie et al. 2014), and resistance to many previously efficacious herbicidal modes of action (Heap 2020). The current herbicide program for Palmer amaranth control in sweetpotato is heavily reliant on PRE herbicides including flumioxazin or fomesafen preplant, and *S*-metolachlor posttransplant (Jennings, personal communication; Smith and Moore, unpublished data). The evolution of protoporphyrinogen oxidase (PPO)-inhibiting herbicide-resistant Palmer amaranth biotypes have been reported in the United States (Heap 2020), including North Carolina (Mahoney et al. 2020), the nation's most economically important sweetpotato production state (USDA-NASS 2020). Therefore, urgent need exists for alternatives to flumioxazin and fomesafen for Palmer amaranth control in sweetpotato.

Previous research demonstrates sweetpotato tolerance to linuron, a photosystem II-inhibiting herbicide (Batts 2019; Beam et al. 2018; Moore et al. 2020). However, increasing the rate of linuron, delaying application later than 7 d after planting (DAP), and combining it with *S*-metolachlor, a very long-chain fatty acid-inhibiting herbicide, can increase sweetpotato injury (Beam et al. 2018; Moore et al. 2020). *S*-metolachlor preemergence can provide 84% or greater Palmer amaranth control 10 wk after planting (WAP) in sweetpotato (Meyers et al. 2010b, 2013a) and is a key mode of action for resistance management weed control in sweetpotato. However, when applications were delayed to 2 WAP, control was variable because emerged weeds are not controlled (Meyers et al. 2010b, 2013a). Therefore, with the high populations of Palmer amaranth in many sweetpotato fields, the use of linuron with *S*-metolachlor would likely be beneficial for weed control.

Linuron PRE (335 to 2,240 g ai ha^{-1}) provided 58% to 100% Palmer amaranth control until at least 3 wk after treatment (WAT) (Grichar et al. 2015; Whitaker et al. 2011). However, Moore et al. (2020) reported 26% or less PRE Palmer amaranth control in North Carolina sweetpotato with linuron (280 to 840 g ai ha^{-1}). Because of increased foliar injury and subsequent yield reduction from tank mixing linuron with *S*-metolachlor, linuron was not recommended in a weed control program including flumioxazin followed by (fb) *S*-metolachlor (Moore et al. 2020). However, linuron is novel for sweetpotato weed control because it has POST efficacy on broadleaf weeds (Anonymous 2013). Moore et al. (2020) did not observe a POST weed control benefit from adding linuron to a herbicide program that included flumioxazin fb *S*-metolachlor because PPO-susceptible Palmer amaranth populations were present in these studies; therefore, weeds did not emerge prior to *S*-metolachlor application. In addition, the experiment did not account for planting or *S*-metolachlor application delays from weather or time constraints, which could allow weeds to emerge prior to *S*-metolachlor application.

POST Palmer amaranth control from linuron application rates low enough for Covington tolerance, the primary sweetpotato cultivar planted in North Carolina (NCDACS 2015), has yet to be demonstrated. Furthermore, the effects on sweetpotato injury and POST Palmer amaranth control from the addition of a surfactant, which is recommended by the product label to increase POST control (Anonymous 2013), or *S*-metolachlor is unknown. Thus, field studies were conducted without a preplant PPO-inhibiting herbicide to determine the efficacy of linuron applied POST with or without an adjuvant and/or *S*-metolachlor for Palmer amaranth control in sweetpotato.

Materials and Methods

Field studies were initiated in June 2019 (35.023°N, 78.280°W) and 2020 (35.024°N, 78.279°W) at the Horticultural Crops Research Station near Clinton, NC in fields with historically high Palmer amaranth populations (50 to 100 plants m^{-2}). Soil at the study sites were an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), pH 5.4 and 0.9% organic matter content in 2019, and a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), pH 6.3 and 0.7% organic matter content in 2020. Nonrooted Covington sweetpotato cuttings (slips) were mechanically transplanted at a 30 cm in-row spacing on 1.07 m wide beds. Commercial sweetpotato growing recommendations were followed (Kemble et al. 2019), and overhead irrigation was applied as needed.

The experimental design for each study was a randomized complete block with treatments replicated four times. Plots consisted of two 6.1 m long rows; the first a border row and the second row received a treatment and was used for data collection. Treatments were arranged in a two by four factorial where the first factor consisted of two rates of linuron (420 and 700 g ai ha^{-1}) (Linex 4L, Tessenderlo Kerley, Inc., Phoenix, AZ), and the second factor consisted of linuron applied alone or in combinations of linuron plus a nonionic surfactant (NIS) (0.5% v/v) (Scanner, Loveland Products, Inc., Loveland, CO), linuron plus *S*-metolachlor (800 g ai ha^{-1}) (Dual Magnum, Syngenta Crop Protection, LLC, Greensboro, NC), or linuron plus NIS plus *S*-metolachlor. In addition, *S*-metolachlor alone and nontreated weedy and weed-free checks were included for comparison. Weeds in the weed-free checks were hand-removed weekly. Treatments were applied 8 DAP using a CO_2-pressurized backpack sprayer calibrated to apply

187 L ha^{-1} at 150 kPa through a boom equipped with two flat-fan XR 8003VS nozzles (TeeJet Technologies, Wheaton, IL) spaced 50 cm apart. Interrow weeds were controlled using cultivation, and clethodim 135 g ai ha^{-1} (Select Max, Valent U.S.A. Corporation, Walnut Creek, CA) was applied to the whole study area for annual grass control.

Effects of treatments on visible sweetpotato foliar injury, stunting, and Palmer amaranth control were evaluated 1, 2, 3, 4 and 8 WAT using a scale of 0% (no treatment effect) to 100% (plant death) (Frans et al. 1986). Sweetpotato storage roots were harvested using a chain-digger 112 and 104 DAP in 2019 and 2020, respectively; hand sorted into canner (>2.5 to 4.4 cm diam), number (no.) 1 (>4.4 to 8.9 cm), and jumbo (>8.9 cm) grades (USDA 2005); and weighed. Marketable yield was calculated as the sum of jumbo and no. 1 grades and total yield was calculated as the sum of all grades.

Data were assessed for homogeneity of variance by examining residual plots. Arcsine square root transformations were required for injury and Palmer amaranth control data, and square root transformations were required for yield data to normalize the distribution of residuals. Back-transformed data were presented. ANOVA was conducted using PROC MIXED in SAS, version 9.4 (SAS Institute, Cary, NC). Fixed effects included year, herbicide combination, linuron rate, and their interactions, whereas replication nested within year was considered a random effect. The weedy and weed-free checks were not included in crop injury or Palmer amaranth control analyses because all observations equaled 0%, and similarly the *S*-metolachlor alone treatment was not included in the injury analyses. If all interactions between the years, herbicide combinations, and linuron rates were non-significant ($P > 0.05$), then the main effect least square means were presented. Least square means were separated according to Fisher’s protected LSD at a significance level of $\alpha = 0.05$.

Results and Discussion

Sweetpotato Tolerance. Injury from linuron appeared as interveinal chlorosis and necrosis (foliar injury) on older leaves fb stunting, similar to observations in Covington sweetpotato grown in North Carolina reported by Beam et al. (2018) and Moore et al. (2020). Treatments of *S*-metolachlor applied alone showed no visible injury symptoms. Significant year by herbicide combination ($P = 0.043$) and year by linuron rate ($P = 0.005$) interactions were present 2 WAT. However, graphs of the interaction means were assessed and adjudged biologically unimportant and uninformative (Vargas et al. 2015); therefore, data were pooled across years. All other foliar injury interactions were not significant ($P > 0.05$). Significant foliar injury effects for herbicide combinations and linuron rates were observed at 1 and 2 WAT ($P \leq 0.0001$). Significant stunting effects were present for herbicide combinations 2 WAT ($P = 0.036$) and linuron rates 2 ($P = 0.0034$) and 3 ($P = 0.0033$) WAT.

Linuron alone resulted in 17% foliar injury 1 WAT (Table 2.1). Injury from linuron alone was similar to observations by Moore et al. (2020), though previous reported foliar injury from linuron applied at similar rates is variable, ranging from 13% to 54% 1 WAT (Beam et al. 2018; Moore et al. 2020). At 2 WAT, foliar injury and stunting from linuron alone was 3 and 9%, respectively, in our experiment. The addition of NIS increased linuron foliar injury 1 WAT by 10% and the addition of *S*-metolachlor to linuron increased foliar injury by 19% 1 WAT, relative to linuron alone. Total foliar injury from linuron plus *S*-metolachlor was higher than reported by Moore et al. (2020) (19%) but lower than reported by Beam et al. (2018) (62%). Adding NIS to linuron plus *S*-metolachlor did not exacerbate injury. Increasing the linuron rate from 420 to 700 g ai ha^{-1} resulted in a 13% increase in foliar injury 1 WAT, and 9% increase in stunting 2 WAT. Sweetpotato injury was transient, thus not observed 4 WAT.

Palmer amaranth Control. Palmer amaranth emerged soon after planting both years, resulting in weeds at the cotyledon to 3-leaf growth stage at the time of applications. In 2020, Palmer amaranth were present in the field before preparing beds and no burn-down herbicide was applied. Preplant cultivation and bed preparation did not control many of these weeds, which resulted in plants up to 15 cm tall at treatment application. However, this difference in weed size did not result in significant year by herbicide combination ($P > 0.37$) or linuron rate ($P > 0.08$) interactions.

Herbicide combination had a significant ($P > 0.0001$) effect on Palmer amaranth control for each wk assessed. *S*-metolachlor applied alone provided unacceptable Palmer amaranth control because weeds emerged prior to application (Table 2.2). All treatments including linuron resulted in greater than 90% Palmer amaranth control 1 and 2 WAT. All treatments including linuron provided 84% to 92% Palmer amaranth control at 4 WAT, and the addition of *S*-metolachlor increased control. Adding NIS to linuron or linuron plus *S*-metolachlor did not increase efficacy. Increasing linuron rate increased control 5 and 9% at 4 and 8 WAT, respectively. At 8 WAT, Palmer amaranth control was 69% or less for all treatments.

Yield. Herbicide combination had an effect on no. 1 ($P = 0.001$), marketable ($P = 0.0005$), and total (0.003) yield grades. Linuron rate by year interactions were present for no. 1 ($P = 0.001$), jumbo ($P = 0.0084$), marketable ($P = 0.0004$), and total ($P = 0.002$) yield grades. Graphs of interaction means were assessed and deemed biologically important; thus, the effect of linuron rate was analyzed separately by year. Linuron rate had an effect on no. 1 ($P = 0.009$), jumbo ($P = 0.024$), marketable ($P = 0.005$), and total ($P = 0.012$) yield grades in 2019, but not in 2020 ($P > 0.05$).

Sweetpotato yield from herbicide combinations that included linuron were similar regardless of the addition of *S*-metolachlor or *S*-metolachlor plus NIS (Table 2.3). Adding NIS to linuron reduced no. 1, marketable and total yield 31%, 32%, and 25%, respectively. This yield reduction was likely the result of increased foliar injury with no benefit for weed control. *S*-metolachlor applied alone yielded similar to the weedy check because weeds had emerged before application, resulting in poor weed control. Because of Palmer amaranth escaping all treatments, it is not clear how much yield loss was due to crop injury or interference from Palmer amaranth alone. Palmer amaranth densities as low as 0.5 plants m^{-1} can reduce marketable sweetpotato yield by 36% (Meyers et al. 2010a). All treatments yielded at least 30%, 48%, and 39% less than the weed-free check for no. 1, marketable, and total yield grades, respectively. Increasing the rate of linuron increased no. 1, jumbo, marketable, and total yield in 2019 but not 2020 (Table 2.4).

Combining linuron with *S*-metolachlor is too phytotoxic for use in Covington sweetpotato (Beam et al. 2018; Moore et al. 2020), which was confirmed in our present experiment. Linuron applied at either rate provided excellent (≥ 98%) control of Palmer amaranth 1 WAT, and the 420 g ai ha^{-1} rate caused minimal sweetpotato injury; however, the residual Palmer amaranth control was poor 8 WAT. The typical recommendation for *S*-metolachlor application is a window between 7 and 14 DAP to increase sweetpotato tolerance while minimizing the risk that weeds emerge prior to application (Beam et al. 2019; Jennings, personal communication; Moore et al. 2020). *S*-metolachlor is safe when applied 2 WAP in sweetpotato (Meyers et al. 2010b; 2012; 2013b). Therefore, a system including 420 g ai ha^{-1} linuron applied 1 WAP fb *S*-metolachlor applied 2 WAP could supplement PRE activity such that weeds are better controlled during the critical period of weed control while minimizing the risk that weeds will be present at *S*-metolachlor application. Though linuron has POST efficacy, this herbicide will likely not replace a form of late season weed control in sweetpotato required to reduce the amount of weed seeds added into the soil seedbank, as is commonly practiced by sweetpotato growers in North Carolina using hand roguing (Smith and Moore, unpublished data).

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Table 2.1 Effect of herbicide treatment on Covington sweetpotato foliar injury and stunting at the Horticultural Crops Research Station near Clinton, NC in 2019 and 2020.[a,b]

Dependent variables[c]	Foliar injury[d]		Stunting	
	1 WAT[e]	2 WAT	2 WAT	3 WAT
Herbicide	%[f]			
Linuron	17c	3b	9b	5
Linuron plus NIS[g]	27b	5a	15ab	8
Linuron plus *S*-metolachlor	36a	7a	16a	8
Linuron plus *S*-metolachlor plus NIS	38a	7a	18a	9
Linuron rate (g ai ha^{-1})				
420	23b	4b	10b	5b
700	36a	7a	19a	10a

[a] Treatments applied 8 d after transplanting.

[b] Data pooled across years.

[c] Means within a column for dependent variables followed by the same letter are not significantly different according to Fisher's protected LSD, $\alpha = 0.05$. Means within a column not followed by a letter are not significantly different according to a nonsignificant F statistic ($P > 0.05$).

[d] Foliar injury was observed as chlorosis and necrosis.

[e] Abbreviations: WAT, wk after treatment application; NIS, nonionic surfactant.

[f] Rating scale: 0%, no treatment effect; 100%, plant death.

[g] NIS (0.5% v/v); *S*-metolachlor (800 g ai ha^{-1}).

Table 2.2 Palmer amaranth control as affected by herbicide treatment at the Horticultural Crops Research Station near Clinton, NC in 2019 and 2020.[a,b]

Dependent variables[c]	Palmer amaranth control			
	1 WAT[d]	2 WAT	4 WAT	8 WAT
Herbicide	%[e]			
S-metolachlor[f]	42b	60b	28c	11c
Linuron	98a	91a	86b	59b
Linuron plus NIS	98a	97a	84b	51b
Linuron plus *S*-metolachlor	99a	98a	90a	60ab
Linuron plus *S*-metolachlor plus NIS	99a	99a	92a	69a
Linuron rate (g ai ha^{-1})				
420	98	94	86b	55b
700	99	99	91a	64a

[a] Treatments applied 8 d after transplanting.

[b] Data pooled across years.

[c] Means within a column for dependent variables followed by the same letter are not significantly different according to Fisher's protected LSD, $\alpha = 0.05$. Means within a column not followed by a letter are not significantly different according to a nonsignificant F statistic ($P > 0.05$).

[d] Abbreviations: WAT, wk after treatment application; NIS, nonionic surfactant.

[e] Rating scale: 0%, no treatment effect; 100%, plant death.

[f] NIS (0.5% v/v); *S*-metolachlor (800 g ai ha^{-1}).

Table 2.3 Covington sweetpotato storage root yield as affected by herbicide treatments at the Horticultural Crops Research Station near Clinton, NC in 2019 and 2020.[a,b]

Herbicide[c]	Canner[d]	No.1	Jumbo	Marketable	Total
	$1{,}000\ \mathrm{kg\ ha^{-1}}$				
Nontreated weed-free	3.6	22.2a	10.8	33.0a	36.5a
Nontreated weedy	2.9	0.8d	0	0.8d	3.7d
S-metolachlor[e]	3.0	1.6d	0.1	1.7d	4.7d
Linuron	4.8	13.4b	1.4	14.9b	19.7b
Linuron plus NIS	4.4	9.3c	1.0	10.2c	14.7c
Linuron plus *S*-metolachlor	4.0	13.1b	2.1	15.2b	19.2b
Linuron plus *S*-metolachlor plus NIS	4.7	15.6b	1.7	17.3b	22.1b

[a] Treatments applied 8 d after transplanting.

[b] Data pooled across years and linuron rates (420 and 700 g ai $\mathrm{ha^{-1}}$).

[c] Means within a column followed by the same letter are not significantly different according to Fisher's protected LSD, $\alpha = 0.05$. Means within a column not followed by a letter are not significantly different according to a nonsignificant F statistic ($P > 0.05$).

[d] Sweetpotato storage roots were hand graded into canner (>2.5 to 4.4 cm diam), number (no.) 1 (>4.4 to 8.9 cm), and jumbo (>8.9 cm). Marketable yield is the sum of no. 1 and jumbo storage-root grades; total yield is the sum of all grades.

[e] Nonionic surfactant (NIS) (0.5% v/v); *S*-metolachlor (800 g ai $\mathrm{ha^{-1}}$).

Table 2.4 Covington sweetpotato storage root yield as affected by linuron rate at the Horticultural Crops Research Station near Clinton, NC.[a,b]

Linuron rate (g ai ha^{-1})[c]	Canner[d]		No.1		Jumbo		Marketable		Total	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
	1,000 kg ha^{-1}									
420	5.4	3.9	14.8b	9.8	1.6b	1.1	16.5b	10.9	21.9b	14.8
700	5.2	3.6	19.4a	7.5	2.7a	0.9	22.1a	8.3	27.3a	11.9

[a] Treatments applied 8 d after transplanting.

[b] Data pooled across years and herbicide combinations including linuron, linuron plus NIS (nonionic surfactant) (0.5% v/v), linuron plus *S*-metolachlor (800 g ai ha^{-1}), and linuron plus NIS plus *S*-metolachlor.

[c] Means within a column for main effects followed by the same letter are not significantly different according to Fisher's protected LSD, $\alpha = 0.05$. Means within a column not followed by a letter are not significantly different according to a nonsignificant F statistic ($P > 0.05$).

[d] Sweetpotato storage roots were hand graded into canner (>2.5 to 4.4 cm diam), number (no.) 1 (>4.4 to 8.9 cm), and jumbo (>8.9 cm). Marketable yield is the sum of no. 1 and jumbo storage-root grades; total yield is the sum of all grades.

CHAPTER 3

Evaluating Shade Cloth to Simulate Palmer Amaranth (*Amaranthus palmeri*) Competition in Sweetpotato

(In the format appropriate for submission to Weed Science)

Evaluating Shade Cloth to Simulate Palmer Amaranth (*Amaranthus palmeri*) Competition in Sweetpotato

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Abstract

Field studies were conducted in 2019 and 2020 to compare the effects of shade cloth light interception and Palmer amaranth *(Amaranthus palmeri* S. Watson) competition on ‘Covington’ sweetpotato [*Ipomoea batatas* (L.) Lam.]. Treatments consisted of a seven by two factorial arrangement, where the first factor included shade cloth with an average measured light interception of 41%, 59%, 76% and 94%; *A. palmeri* thinned to 0.6 or 3.1 plants m^{-2}; or a nontreated weed-free check and the second factor included shade cloth or *A. palmeri* removal timing at 6 or 10 wk after planting (WAP). *A. palmeri* light interception peaked around 710 to 840 growing degree days (base 10 C) (6 to 7 WAP) with a maximum light interception of 67%

and 84% for the 0.6 and 3.1 plants m^{-2} densities, respectively. Increasing shade cloth light interception by 1% linearly increased yield loss by 1% for no. 1, jumbo, and total yield. Yield loss increased by 36%, 23%, and 35% as shade cloth removal was delayed from 6 to 10 WAP for no. 1, jumbo, and total yield, respectively. *F*-tests comparing reduced vs full models of yield loss provided no evidence that the presence of yield loss from *A. palmeri* light interception caused yield loss different than that explained by the shade cloth at similar light-interception levels. Results indicate that shade cloth structures could be used to simulate Covington sweetpotato yield loss from *A. palmeri* competition, and light interception could be used as a predictor for expected yield loss from *A. palmeri* competition.

Key words: Light competition, light interception

Sweetpotato [*Ipomoea batatas* (L.) Lam.] in the United States has been worth an average of 641 million US dollars annually from 2015 to 2019 (USDA-NASS 2020). The primary sweetpotato production states include North Carolina, California, Mississippi, and Louisiana, respectively (USDA-NASS 2020). In North Carolina, sweetpotato is the 4th most economically important crop following tobacco, soybean, and corn (USDA-NASS 2020). Though sweetpotato is an important crop, there are relatively few sustainable weed management options to ensure consistent yields.

Marketable sweetpotato yield can be reduced up to 95% by weed competition (Barkley et al. 2016; Basinger et al. 2019; Smith et al. 2020). At low densities, Palmer amaranth (*Amaranthus palmeri* S. Watson) reduced total sweetpotato yield 36 to 50% from 0.5 to 1 plants m^{-2}, respectively (Meyers et al. 2010), compared to 18% yield loss from 5 yellow nutsedge (*Cyperus esculentus* L.) shoots m^{-2} (Meyers and Shankle 2015) or 35% yield loss from 1 large crabgrass [*Digitaria sanguinalis* (L.) Scop.] plants m^{-2} (Basinger et al. 2019). Compared to other *Amaranthus* species, *A. palmeri* accumulated more biomass and grew taller (Horak and Loughlin 2000; Sellers et al. 2003). Guo and Al-Khatib (2003) reported that *A. palmeri* produced lower biomass than other *Amaranthus* species at 15/10 C d/night; but comparatively produced greater biomass at 35/30 C. *Amaranthus palmeri* has C_4 photosynthesis and a relatively high maximum net photosynthesis rate, even compared to other plants with C_4 photosynthesis (Ehleringer 1983; Ward et al. 2013). This allows *A. palmeri* to quickly overcome sweetpotato in height and outcompete the crop (Meyers et al. 2010). In addition, *A. palmeri* is dioecious and has high fecundity (Keeley et al. 1987; Sellers et al. 2003; Ward et al. 2013). Large populations with high genetic diversity, combined with intensive selection pressure in rotational crops, has resulted in control failures from many important herbicides (Heap 2020). As a result, *A. palmeri* competition with sweetpotato is commonplace.

‘Covington’, an orange-flesh table-stock sweetpotato, is the primary sweetpotato cultivar planted in North Carolina because it yields similar to ‘Beauregard’ but with more consistent root sizing, resulting in more no. 1 grade roots, and has desirable insect and disease resistance traits (NCDACS 2015; Yencho et al. 2008). Meyers et al. (2010) reported that higher *A. palmeri* densities intercepted more light from sweetpotato and that there was a strong relationship between *A. palmeri* light interception and sweetpotato yield loss. Likewise, other researchers have reported that light interception in the absence of weed competition results in linearly decreased sweetpotato yields (Oswald et al. 1995).

Meyers et al. (2010) hypothesized that light interception is the primary cause of yield loss in Covington sweetpotato. However, a comparison of light interception to other sources of competition has not been conducted in sweetpotato. Using black polyethylene cloth as simulated weed competition has been conducted in soybean (Stoller and Wooley 1985). The authors reported that, based on the simulated weed light interception, most of the soybean yield loss from velvetleaf (*Abutilon theophrasti* Medik.) and jimsonweed (*Datura stramonium* L.) were due to competition for light, whereas around half of the soybean yield loss from common cocklebur (*Xanthium strumarium* L.) was due to competition for light (Stoller and Wooley 1985). The response of sweetpotato to shading has been evaluated in cultivars other than Covington (Nedunchezhiyan et al. 2008; Oswald ed at. 1995). However, because differential yield loss responses to light interception or weed competition have been observed among sweetpotato cultivars (Harrison and Jackson 2011; La Bonte et al. 1999; Oswald et al. 1995; SC Smith, personal communication), studies were conducted to compare the effects of light interception with shade cloth and by *A. palmeri* canopies on Covington sweetpotato.

Materials and Methods

Field studies were initiated on June 18, 2019 (35.023°N, 78.280°W) and June 10, 2020 (35.024°N, 78.279°W) at the Horticultural Crops Research Station near Clinton, NC. The soil was an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), pH of 5.3 and 0.8% organic matter in 2019, and a Norfolk loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult), pH 6.6 and 0.5% organic matter content in 2020, respectively. Nonrooted Covington sweetpotato cuttings (slips) were mechanically transplanted to a 30 cm in-row spacing. Overhead irrigation was applied before and after planting, nutrients were applied to achieve the target sufficiency range for the crop, and insects and diseases were managed according to commercial sweetpotato growing recommendations (Kemble et al. 2019).

Plots consisted of two rows each 1.07 m wide by 3.05 m long; the first row a border and the second row received a treatment. The experiment design was a randomized complete block with treatments replicated four times. Treatments consisted of a seven by two factorial arrangement, where the first factor included shade cloth with an average measured light interception (Equation 1) of 41%, 59%, 76% and 94% (30%, 50%, 70%, and 90% black knitted polyethylene film; Greenhouse Megastore, Danville, IL); *A. palmeri* thinned to 0.6 or 3.1 plants m^{-2}; or a nontreated weed-free check and the second factor included shade cloth or *A. palmeri* removal timing at 6 or 10 wk after planting (WAP). Before 3 WAP, plots assigned a density of *A. palmeri* were thinned so that the plants were evenly distributed across the plot. All other weeds in the study were hand-removed weekly. Shade cloth was fitted to custom-made metal

(1.3 to 1.9 cm diam) structures with the shape of a 305 by 105 by 60 cm rectangular prism topped with a 25 cm high triangular prism (Figure 3.1). Shade cloth structures were placed in the field 3 WAP to coincide with *A. palmeri* overcoming sweetpotato in height. Shade structures were removed and replaced within 4 h 4 WAP so that interrow weeds could be removed using cultivation.

***Amaranthus palmeri* height, width, and light interception.** *Amaranthus palmeri* height measured from the soil surface to the tallest part of the plant and width measured perpendicular to the sweetpotato row on the widest part of the plant were recorded on two plants per plot 3, 4, 5, and 6 WAP for both removal timings, as well as 7, 8, 9, and 10 WAP for the second removal timing. *Amaranthus palmeri* light interception was measured twice per row in non-overlapping areas between 10 am and 2 pm 3, 4, 5, and 6 WAP for both removal timings, as well as 7, 8, 9, and 10 WAP for the second removal timing using a 1 m LI-191R Line Quantum Light Sensor (LI-COR Bioscience, Lincoln, NE). The sensor was held parallel to the row at the top of the sweetpotato canopy without displacing *A. palmeri* leaves. Light interception was calculated using the following equation:

$$Y = 1 - \{[(i_1/a_1) + (i_2/a_2)]/2\} \qquad [1]$$

where i_1 and i_2 are the photosynthetically active radiation at the sweetpotato canopy and a_1 and a_2 are the ambient photosynthetically active radiation measured before each subsample.

Soil volumetric water content, and sweetpotato internode length and yield. Soil volumetric water content was estimated using a Field Scout TDR 300 (Spectrum Technologies, Aurora, IL) immediately after interference source removal, 6 or 10 WAP. The 12.2 cm long rods were inserted into the soil perpendicular to the row between sweetpotato plants, to avoid puncturing storage roots, in 4 evenly spaced subsamples across the plot. Sweetpotato internode length was quantified by recording the length of 5 internodes on the distal end of a vine beginning with the first fully opened leaf on 3 randomly selected plants per plot immediately after interference source removal, 6 or 10 WAP. Sweetpotato storage roots were harvested 16 WAP using a chain digger; graded into canner (> 2.5 to 4.4 cm in diam), number (no.) 1 (> 4.4 to 8.8 cm), jumbo (> 8.9 cm); and weighed (USDA 2005). Total yield was calculated as the sum of canner, no. 1, and jumbo grades. Yield for each grade was normalized over the number of plants per plot, and yield loss was calculated as a percent of the nontreated plots. Using an optical grader (Exter Engineering, Exeter, CA), the length to width ratio (LWR) of no. 1 storage roots was calculated using estimated length and largest estimated diam of each root, and root counts were recorded for each grade.

Data analysis. Data were checked for heteroscedasticity by plotting residuals. Log transformations were required for *A. palmeri* height and width data, and square root transformations were required for soil moisture, LWR of no. 1 sweetpotato storage roots, and jumbo grade sweetpotato yield data. Back-transformed least square means were presented for interpretability. ANOVA was conducted using PROC MIXED (SAS 9.4; SAS Institute, Cary, NC). For *A. palmeri* height, width, and light-interception data, fixed effects included year, *A. palmeri* density, growing degree days (GDD), and all interactions, and random effects included replication nested within year. A REPEATED statement was included where Group = GDD to allow error variance to differ between weekly measurements for *A. palmeri* height, width, and light-interception data. For soil moisture and sweetpotato internode length and yield data, fixed effects included year, interference source, removal timing, and all interactions, and random effects included rep nested within year. When no significant interactions ($P > 0.05$) were present between interference source, removal timing, and year, the main effect least square means were presented. When ANOVA indicated a significant ($P \leq 0.05$) effect, linear and nonlinear regression of least square means were conducted using SAS PROC REG and PROC NLIN, respectively. The following three–parameter sigmoidal equation best described the influence of GDD (base 10 C) on *A. palmeri* height and width:

$$Y = a / \{1 + \exp[-(\mathrm{GDD} - c) / b]\} \qquad [2]$$

where *a* is the maximum growth, *b* is the growth rate, and *c* is the inflection point. The influence of GDD on *Amaranthus palmeri* light interception was best described by the following cubic equation:

$$Y = a + (b \times \mathrm{GDD}) + (c \times \mathrm{GDD}^2) + (d \times \mathrm{GDD}^3) \qquad [3]$$

where *a*, *b*, *c*, and *d* are coefficients. The influence of shade cloth light interception on no. 1, jumbo, and total sweetpotato yield were best described by the following linear model:

$$Y = (a \times \text{light interception}) + b \qquad [4]$$

where *a* is the slope and *b* is the y-intercept. When significant ($P \leq 0.05$) interference source and removal timing effects were present, and no significant ($P > 0.05$) interaction was present between interference source and removal timing, data were presented as independent intercepts for each removal timing with a common slope (Ritz et al. 2015). Correlation of storage root counts to weights were conducted using SAS PROC CORR.

To compare the influence of *A. palmeri* competition to the influence of shade cloth light interception on sweetpotato yield, treatment means were regressed on light interception from shade cloth or *A. palmeri* for each removal timing. Differences between the two sources of competition (i.e., shade cloth versus *A. palmeri*) in their effects on yield were tested via comparison of the slopes and intercepts for the two types of competition, at each removal timing. The method used was an *F*-test for comparing a reduced model with the same slope and intercept for both types of competition against the full model with different slopes and intercepts for the two types of competition (Rawlings et al. 1998). Lack of fit to the full model provided the Error term, or denominator mean square, for the *F*-ratio.

Results and Discussion

***Amaranthus palmeri* height and width.** Significant *A. palmeri* density-by-year interactions were present for *A. palmeri* height and width results. Graphs of interaction means were assessed, and the interactions were deemed biologically uninformative; thus, the dependent variable means were obtained by pooling data across years. Because of a significant *A. palmeri* density-by-GDD interactions for *A. palmeri* height ($P < 0.004$) and width ($P < 0.0023$), data were analyzed by density. GDD had a significant ($P < 0.0001$) effect on *A. palmeri* height and width (Figure 3.2). The predicted maximum height of the high (3.1 plants m^{-2}) *A. palmeri* density (191 cm) was 21 cm greater than the maximum height of the low (0.6 plants m^{-2}) density (170 cm); however, the predicted maximum width of the low *A. palmeri* density (149 cm) was 38 cm greater than the high density (111 cm). Previous research similarly reported the predicted height of *A. palmeri* in sweetpotato increased from 177 to 197 cm at densities of 0.5 to 3.9 plants m^{-2} and predicted *A. palmeri* width decreased linearly from 145 to 69 cm at densities of 0.5 to 6.1 plants m^{-2} (Meyers et al. 2010).

***Amaranthus palmeri* light interception.** Significant *A. palmeri* density-by-year interactions were present for *A. palmeri* light-interception data. Graphs of interaction means were assessed, and the interactions were deemed biologically uninformative; thus, the depended variable means were obtained by pooling data across years. A significant *A. palmeri* density-by-GDD interaction ($P = 0.0023$) was present for *A. palmeri* light-interception data; therefore, data were analyzed by *A. palmeri* density. GDD had a significant ($P < 0.0001$) influence on *A. palmeri* light interception for each density ($P < 0.0001$). *Amaranthus palmeri* light interception peaked around 710 to 840 GDD (6 to 7 WAP) (Figure 3.3). This corresponds with the point in which *A. palmeri* is approaching the maximum height and width (Figure 3.2). After 840 GDD, the light interception begins to decrease for each *A. palmeri* density because of natural leaf senescence and defoliation from insects, primarily Lepidoptera. Meyers et al. (2010) reported greatest light interception 10 WAP, which decreased 13 to 14 WAP because of plant senescence and defoliation.

Soil Moisture. Because of a significant ($P < 0.0001$) removal timing-by-interference source interaction, data were analyzed separately by removal timing. Soil volumetric water content was significantly ($P < 0.026$) affected by interference source for both removal timings. Soil moisture could not be appropriately described using regression analysis; therefore, means were compared using Fisher's protected LSD, at a significance level $\alpha = 0.05$ (Table 3.1). Except for the 41% shade cloth treatment, shade cloth structures increased soil moisture relative to the nontreated check at both removal timings. At 6 WAP, *A. palmeri* decreased soil moisture compared to the nontreated check, but there were no differences between treatments containing *A. palmeri* and the nontreated check at 10 WAP. This indicates that *A. palmeri* were competing for soil moisture 6 WAP, but competition was not detectable at 10 WAP.

Sweetpotato internode length. Because of a significant ($P = 0.0023$) removal timing-by-interference source interaction for sweetpotato internode length, data were analyzed separately by removal timing. Sweetpotato internode length was significantly ($P < 0.0001$) affected by interference source for both removal timings. Sweetpotato internode length could not be appropriately described using regression analysis; therefore, means were compared using Fisher's protected LSD at a significance level of $\alpha = 0.05$ (Table 3.1). Sweetpotato internode length in treatments including *A. palmeri* were similar to the nontreated check 6 WAP but were longer than the nontreated check 10 WAP. At each removal timing, shade cloth increased the sweetpotato internode length relative to the nontreated check. Etiolation is a common plant response to competition for light, as was observed from increased internode length for plants under high shade in this experiment. Oswald et al. (1995) observed that shading increased the sink size of the shoots over the roots, where some cultivars evaluated had little total shoot dry weight effects from up to 60% shading. Similarly, Page et al. (2010) observed that corn partitioned less biomass to the kernels in response to shade.

Sweetpotato yield. Interactions between interference source and removal timing were not significant. Interference source and removal timing had a significant ($P < 0.0001$) effect on no. 1, jumbo, and total yield. The influence of shade cloth light interception on sweetpotato yield were fitted to linear models with a common slope for each removal timing (Figure 3.4). Increasing shade cloth light interception by 1% increased yield loss by 1% for no. 1, jumbo, and total yield. Yield loss was increased by 36%, 23%, and 35% as shade cloth removal was delayed from 6 to 10 WAP for no. 1, jumbo, and total yield, respectively. Yield from 41% shade removed 6 WAP was relatively similar to the nontreated check; therefore, sweetpotato may tolerate less competitive weeds at moderate densities, as suggested by Harrison and Jackson (2011). Canner yield data were more variable than other grades, the use of transformations did not normalize the residuals, the data were uninformative, and the grade is typically less valuable than other grades; therefore, data were not presented.

F-tests comparing reduced vs full models of yield loss were not significant for no. 1 ($P = 0.3$), jumbo ($P = 0.3$), or total ($P = 0.5$) yield. This provided no evidence that the presence of yield loss from *A. palmeri* light interception caused yield loss different than that explained by the shade cloth at similar light interception. However, more research is needed to confirm this at additional densities and removal timings of *A. palmeri*. Visual comparisons of plotted sweetpotato yield loss from *A. palmeri* light interception to predicted yield loss from shade cloth light interception appear relatively similar (Figure 3.4). It would be logical to expect, when comparing yield loss from the biotic vs simulated light interception, for weed competition to have caused yield reductions greater than or equal to the predicted yield loss from shade cloth at the same amount of light interception because of other factors of competition, such as the competition for water and nutrients. However, yield loss from some *A. palmeri* densities were slightly below the shade cloth predicted yield loss, depending on sweetpoato grade. This observation is likely because of two factors: the design of the shade structures did not allow the sweetpotato vines to grow away from the competition for light, whereas the sweetpotato in plots containing *A. palmeri* were able to grow laterally into the row middles and vertically by ascending the *A. palmeri* to receive more solar radiation; and secondly, the shade cloth provided constant light interception, whereas the *A. palmeri* light interception was dynamic during the same GDD in competition with sweetpotato (Figure 3.2), though yield losses from *A. palmeri* were only compared to the predicted yield loss from shade cloth light interception using the light interception at each timing of removal. For these reasons, this study cannot be used to declare what portion of yield loss is due to light interception, but rather to provide insight into the use of shade cloth as a model for simulating *A. palmeri* competition.

Percent reductions in the number of sweetpotato storage roots were strongly correlated ($P < 0.0001$) with yield loss from shade cloth treatments at the 6 ($r = 0.74$ and 0.71) and 10 WAP ($r = 0.63$ and 0.81) removal timings for no. 1 and total yield, respectively. Percent reductions in the number of sweetpotato storage roots were strongly correlated ($P \leq 0.0002$) with yield loss from *A. palmeri* treatments at the 6 ($r = 0.79$) and 10 WAP ($r = 0.9$) removal timings for no. 1 yield, but only correlated (P = 0.01) with total yield 10 WAP (r = 0.62). Semidey et al. (1987) reported that sweetpotato yield and number of roots were similarly decreased from weed competition. However, Nedunchezhiyan et al. (2008) reported that light interception decreased total sweetpotato yield but did not influence the total number of storage roots.

No. 1 sweetpotato are typically sold to the fresh market; therefore, the aesthetics of this grade are important for marketability. LWR gives an indication of the root shape. A lower value indicates a more round-shaped root, which may be considered less marketable in some fresh markets (KM Jennings, personal communication). Because of a significant interference source-by-removal timing interaction (P = 0.0006) for the LWR of no. 1 sweetpotato, data were analyzed separately by removal timing. Interference source had a significant effect on the LWR of no. 1 sweetpotato at the 6 (P = 0.004) and 10 (P = 0.001) WAP removal timing. The responses could not be appropriately described using regression analysis; thus, means were compared using Fisher's protected LSD at a significance level of $\alpha = 0.05$ (Table 3.1). The only treatment that influenced the LWR of no. 1 sweetpotato at the 6 WAP removal timing was the 76% shade cloth treatment (Table 3.1). At the 10 WAP removal timing, treatments including *A. palmeri* and the 76% and 94% light-interception shade cloth were similar to the nontreated check, but the 41% and 59% light-interception shade cloth treatments decreased the LWR compared to the nontreated check. All recorded values were relatively similar to the typical 2.0 LWR of Covington, and all values were greater than the typical 0.4 LWR of Beauregard sweetpotato (Yencho et al. 2008). Though statistical differences were reported, the responses between treatments were biologically similar.

Yield results indicate that light interception is an important contributor to yield loss from *A. palmeri* competition, but other aspects of *A. palmeri* competition cannot be disregarded. Soil samples taken from the whole study area after harvest indicated phosphorus and potassium were above recommended concentrations for NC sweetpotato (data not shown). If the experiment were to be replicated in conditions with limited nutrients, the influence of *A. palmeri* competition on yield loss could vary from the present experiment. Water was limited at times during the season and *A. palmeri* were in competition for water with sweetpotato. At the 6 WAP removal in both years, sweetpotato growing in competition with *A. palmeri* had visible leaf wilting compared to the nontreated check. Limited soil moisture can negatively affect sweetpotato root development (Pardales and Yamauchi 2003).

Sweetpotato responses varied between the shade cloth and *A. palmeri* treatments for some measurements, but yield responses were similar between the predicted yield loss from shade cloth and *A. palmeri*. Based on the present experiment in the evaluated environmental conditions, shade cloth structures could be used to simulate Covington sweetpotato yield loss from *A. palmeri* competition, and light interception could be used as a predictor for expected yield loss from *A. palmeri* competition. *Amaranthus palmeri* is the most common and troublesome weed in NC sweetpotato (SC Smith and LD Moore, unpublished data; Webster 2010); however, many fields may contain an array of weed species. Therefore, the efficacy of light interception as a predictor of yield loss should be evaluated with various weed species. With additional research evaluating the relationship between light interception and weed competition in sweetpotato, shade cloth structures could be used in place of weed competition when uniform weed populations are not available, weeds cannot be seeded, or the labor required to maintain desired weed densities are not available. Using shade cloth as simulated weed competition has the potential for use in sweetpotato weed research and should be further investigated for uses such as comparing sweetpotato cultivar tolerance to weed competition.

Furthermore, with additional research, measured weed light interception and duration of competition could be used to predict yield loss for informing the management decision making process.

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Table 3.1 The influence of shade cloth and *Amaranthus palmeri* on soil moisture, sweetpotato internode length, and the shape of no. 1 sweetpotato roots in 2019 and 2020, Clinton, NC.[a,b]

	Soil volumetric water content[c]		Sweetpotato internode length[d]		LWR of no. 1 sweetpotato[e]	
	6 WAP removal	10 WAP removal	6 WAP removal	10 WAP removal	6 WAP removal	10 WAP removal
	%		cm			
Nontreated weed-free check	2.8d	9.5b	5.3c	6.2d	1.97b	2.09ab
41% shade cloth light interception[f]	3.6cd	11.1ab	6.7b	8.0c	1.99b	1.90cd
59% shade cloth light interception[f]	4.3bc	11.3a	8.1a	9.0b	2.03b	1.85d
76% shade cloth light interception[f]	5.7a	11.3a	7.9a	10.4a	2.27a	2.00bcd
94% shade cloth light interception[f]	5.4ab	11.5a	8.6a	9.9ab	2.04b	2.27a
Low *A. palmeri* density[g]	1.4e	9.6b	5.1c	7.9c	1.99b	2.02bc
High *A. palmeri* density[g]	1.4e	9.6b	4.9c	7.8c	1.97b	2.05bc

[a] Abbreviations: LWR, length to width ratio; no., number; WAP, wk after planting.

[b] Responses were not appropriately described using regression analysis; thus, means were compared using Fisher's protected LSD, α = 0.05. Accordingly, means within a column followed by the same letter are not significantly different.

[c] Soil volumetric water content was estimated using a Field Scout TDR 300 immediately after interference source removal 6 or 10 WAP. The 12.2 cm long rods were inserted into the soil perpendicular to the row between sweetpotato plants, to avoid puncturing storage roots, in 4 evenly spaced subsamples across the plot.

[d] Sweetpotato internode length was quantified by recording the length of 5 internodes on the distal end of a vine beginning with the first fully opened leaf on 3 randomly selected plants per plot immediately after interference source removal, 6 or 10 WAP.

[e] Length and greatest diam of no. 1 sweetpotato (> 4.4 to 8.8 cm in diam) were estimated using an optical sorter.

[f] Shade cloth were fitted to custom-made metal (1.3 to 1.9 cm in diam) structures shaped as a 305 by 105 by 60 cm rectangular prism topped with a 25 cm high triangular prism and placed at 3 WAP to correspond with *A. palmeri* overcoming sweetpotato in height.

[g] *Amaranthus palmeri* were thinned to 0.6 and 3.1 plants m^{-2} spaced evenly across the plot area for the low and high density, respectively, before 3 WAP. All other weeds in the study were hand-removed weekly.

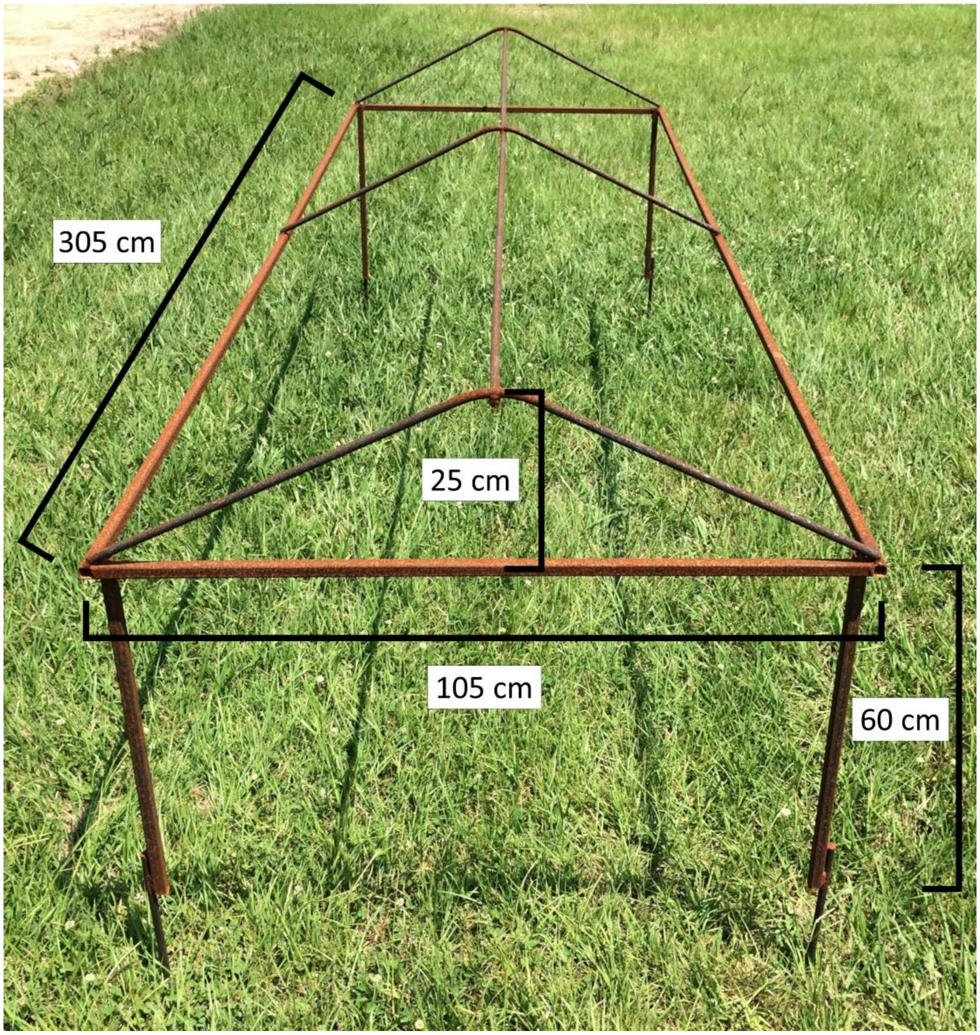

Figure 3.1 Metal (1.3 to 1.9 cm diam) custom-made structure to which shade cloth was fitted. The structures were shaped as a 305 by 105 by 60 cm rectangular prism topped with a 25 cm high triangular prism**.**

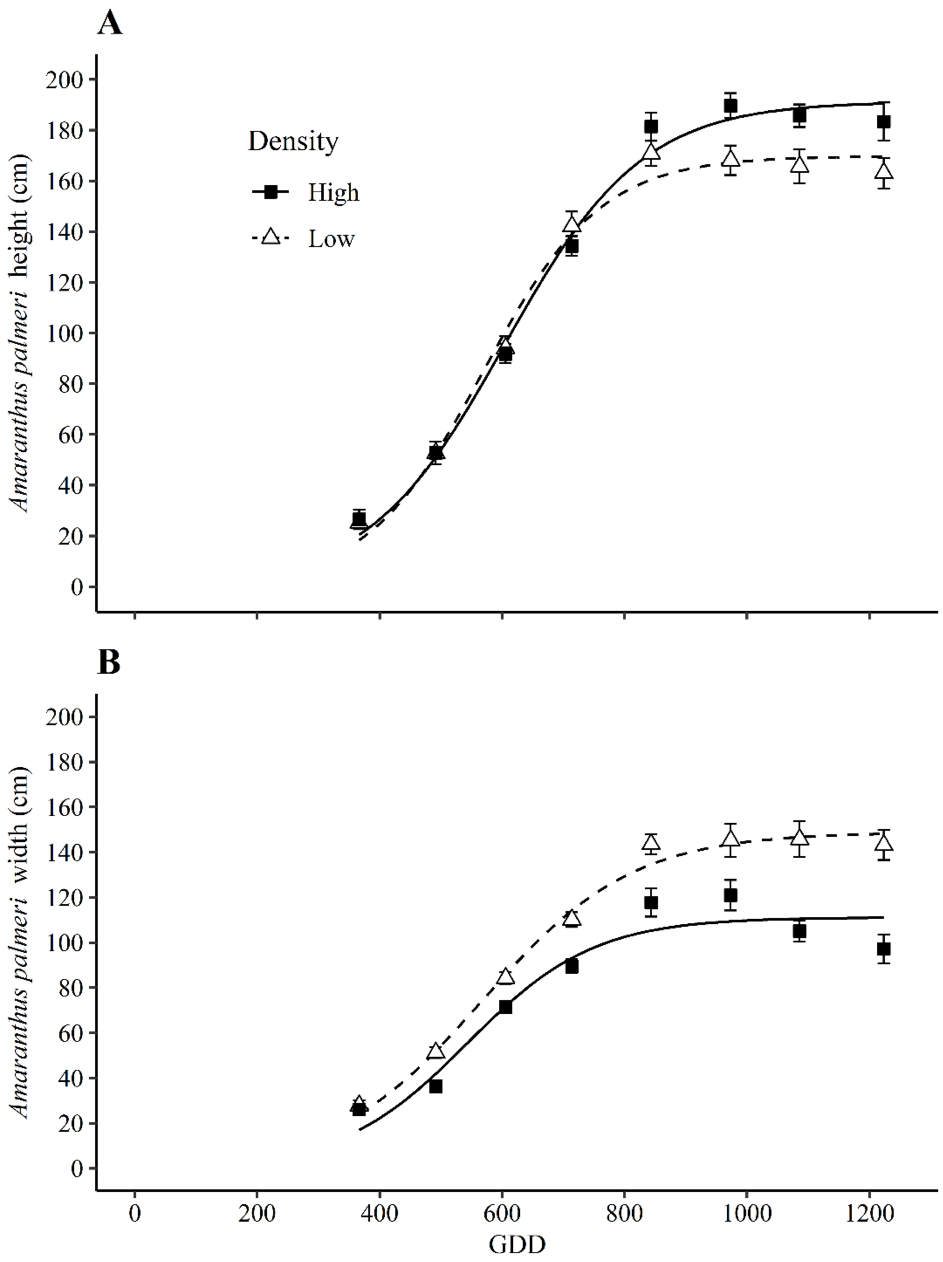

Figure 3.2 The influence of growing degree days (GDD) on the (A) height and (B) width of low (0.6 plants m^{-2}) and high (3.1 plants m^{-2}) *Amaranthus palmeri* densities growing in sweetpotato in 2019 and 2020, Clinton, NC. Data were recorded weekly from 3 to 10 wk after sweetpotato planting (WAP). Points represent means ± SE. Lines represent predicted values. Low density of *Amaranthus palmeri* height = 169.7 / {1 + exp[− (GDD − 568.9) / 95.9]}; $R^2 = 0.99$; $P < 0.0001$. High density of *Amaranthus palmeri* height = 191.3 / {1 + exp[− (GDD – 604.6) / 112.2]}; $R^2 = 0.99$; $P < 0.0001$. Low density of *Amaranthus palmeri* width = 148.8 / {1 + exp[− (GDD – 567.8) / 122.5]}; $R^2 = 0.99$; $P < 0.0001$. High density of *Amaranthus palmeri* width = 111.1 / {1 + exp[− (GDD – 543.4) / 103.5]}; $R^2 = 0.98$; $P < 0.0001$.

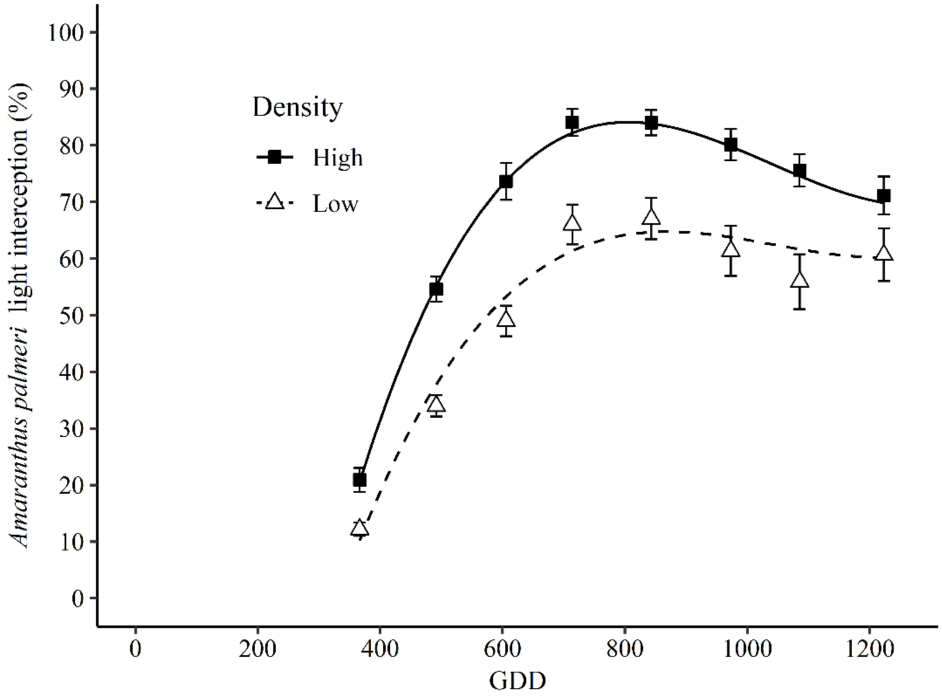

Figure 3.3 The influence of growing degree days (GDD) on the light interception of low (0.6 plants m^{-2}) and high (3.1 plants m^{-2}) *Amaranthus palmeri* densities growing in sweetpotato in 2019 and 2020, Clinton, NC. Data were recorded weekly from 3 to 10 wk after sweetpotato planting (WAP). Points represent means ± SE. Lines represent predicted values. Low density of *Amaranthus palmeri* light interception = −156.8 + (0.669 × GDD) + (−0.0007 × GDD^2) + (0.0000002 × GDD^3); $R^2 = 0.99$; $P = 0.003$. High density of *Amaranthus palmeri* light interception = −198.3 + (0.888 × GDD) + (−0.0009 × GDD^2) + (0.0000003 × GDD^3); $R^2 = 0.99$; $P < 0.0001$.

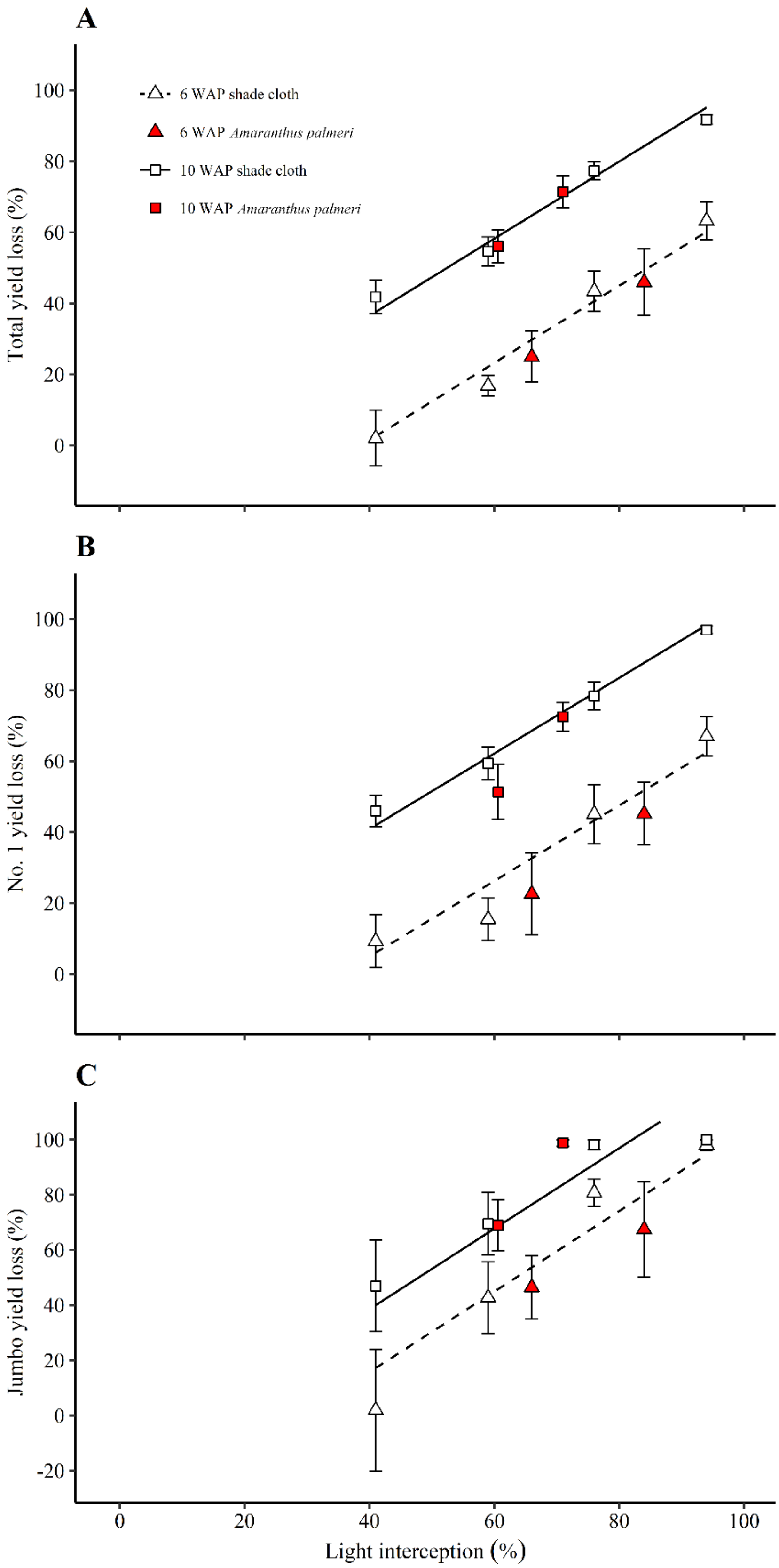

Figure 3.4 The influence of light interception on (A) total, (B) no. 1, and (C) jumbo grade

sweetpotato (*Ipomoea batatas*) yield loss in 2019 and 2020, Clinton, NC. Sweetpotato storage roots were harvested 16 wk after planting; graded into canner (> 2.5 to 4.4 cm in diam), number (no.) 1 (> 4.4 to 8.8 cm), jumbo (> 8.9 cm), and total (canner + no. 1 + jumbo) grades; and weighed. Yield loss was calculated as a percent of the nontreated weed-free check. Treatments of 30%, 50%, 70%, and 90% black knitted polyethylene film (shade cloth) and *Amaranthus palmeri* thinned to 0.6 or 3.1 plants m^{-2} were plotted based on their light interception at the timing of removal, 6 or 10 WAP. High densities of *Amaranthus palmeri* always intercepted more light than low densities. Points represent means ± SE. Lines represent predicted values of yield influenced by shade cloth light interception. Total yield loss from the 6 and 10 WAP removal shared a common slope of 1.09 with intercepts of -42 and -7, respectively; $R^2 = 0.99$; $P = 0.007$. No. 1 yield loss from the 6 and 10 WAP removal shared a common slope of 1.06 with intercepts of -38 and -2, respectively; $R^2 = 0.97$; $P = 0.01$. Jumbo yield loss from the 6 and 10 WAP removal shared a common slope of 1.46 with intercepts of -43 and -20 , respectively; $R^2 = 0.95$; $P = 0.02$.

CHAPTER 4

Influence of Herbicides on Germination and Quality of Palmer Amaranth (*Amaranthus palmeri*) Seed

(In the format appropriate for submission to Weed Technology)

Influence of Herbicides on Germination and Quality of Palmer Amaranth (*Amaranthus palmeri*) Seed

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Abstract

Laboratory and greenhouse studies were conducted to evaluate the effects of chemical treatments applied to Palmer amaranth seeds or gynoecious plants that retain seeds to determine seed germination and quality. Treatments applied to physiologically mature Palmer amaranth seed included acifluorfen, dicamba, ethephon, flumioxazin, fomesafen, halosulfuron, linuron, metribuzin, oryzalin, pendimethalin, pyroxasulfone, *S*-metolachlor, saflufenacil, trifluralin, and 2,4-D plus crop oil concentrate applied at 1× and 2× the suggested use rates from the manufacturer. Germination was reduced by 20% when 2,4-D was used, 15% when dicamba was used, and 13% when halosulfuron and pyroxasulfone were used. Use of dicamba, ethephon, halosulfuron, oryzalin, trifluralin, and 2,4-D resulted in decreased seedling length by an average of at least 50%. Due to the observed effect of dicamba, ethephon, halosulfuron, oryzalin, trifluralin, and 2,4-D, these treatments were applied to gynoecious Palmer amaranth inflorescence at the 2× registered application rates to evaluate their effects on progeny seed. Dicamba use resulted in a 24% decrease in seed germination, whereas all other treatment results were similar to those of the control. Crush tests showed that seed viability was greater than 95%, thus dicamba did not have a strong effect on seed viability. No treatments applied to Palmer amaranth inflorescence affected average seedling length; therefore, chemical treatments did not affect the quality of seeds that germinated.

Nomenclature: acifluorfen; dicamba; ethephon; flumioxazin; fomesafen; halosulfuron; linuron; metribuzin; oryzalin; pendimethalin; pyroxasulfone; *S*-metolachlor; saflufenacil; trifluralin; 2,4-D; Palmer amaranth, *Amaranthus palmeri* S. Watson; AMAPA

Key words: Seed viability

Palmer amaranth is the most troublesome weed in broadleaf, grass, fruit, and vegetable crops in the United States (Van Wychen 2019, 2020). The troublesome nature of this weed is due in part to its large and rapid growth (Horak and Loughin 2000; Keeley et al. 1987; Norsworthy et al. 2008; Sellers et al. 2003), high fecundity (Keeley et al. 1987; Sellers et al. 2003; Sosnoskie et al. 2014), and dioecious reproduction causing obligate outcrossing (Ward et al. 2013). The high fecundity and obligate outcrossing create large genetic diversity. High genetic diversity coupled with intensive herbicidal selection pressure has caused herbicide resistance in Palmer amaranth to become commonplace (Heap 2021), thereby increasing the difficulty of managing it.

Effective long-term Palmer amaranth management requires strategies that limit or eliminate contributions of this weed to the soil seedbank. Continuous control of weeds prior to reproductive maturity can provide minimal seedbank additions, however, weeds often escape management strategies and produce seeds. Flowering Palmer amaranth severed at the soil surface may resprout and produce 22,000 seeds plant^{-1} (Sosnoskie et al. 2012). Harvest weed seed control techniques have proven effective for Palmer amaranth management (Norsworthy et al. 2016; Schwartz-Lazaro et al. 2017a). Palmer amaranth seed retention at soybean [*Glycine max* (L.) Merr.] harvest was 95% to 100% (Schwartz et al. 2016). One month after soybean harvest, corresponding to 19 wk after planting (WAP), Palmer amaranth retained 95% of total seed produced (Schwartz-Lazaro et al. 2017b). Palmer amaranth seeds entering an integrated Harrington Seed Destructor mill were 100% destroyed (Schwartz-Lazaro et al. 2017a). Harvest weed seed control can reduce the amount of viable seeds added into the soil seedbank for crops harvested with a combine, but this technology has few applications in vegetable crops. Thus, additional methods for reducing weed seedbank additions from escaped weeds are needed.

Control of Palmer amaranth with herbicides is well documented (Barkley et al. 2016; Meyers et al. 2013; Moore et al. 2021; Ward et al. 2013; Whitaker et al. 2011). However, because herbicides are most effective in preventing weed interference when applied at early growth stages, little research has evaluated their effect on the viability of seeds present at application. Jha and Norsworthy (2012) reported that Palmer amaranth seed viability was reduced by 36% to 51% when 2,4-D, dicamba, glufosinate, and glyphosate were used and when plants were treated at first signs of female inflorescence. In addition, seed production was reduced by 62% to 95%. Other research evaluating 2,4-D, dicamba, glufosinate, and glyphosate applied at first female Palmer amaranth inflorescence resulted in decreased seed production but not germination or viability (Scruggs et al. 2020). Similarly, registered rates of acifluorfen, dicamba, fluthiacet, fomesafen, glyphosate, and lactofen applied to Palmer amaranth up to 90 cm tall did not affect seed viability but seed production was reduced (de Sanctis et al. 2021). Each of these studies evaluated herbicides that were applied before seed maturity. When Palmer amaranth plants were treated when inflorescences had mature seeds (i.e., brown to black seed coat), 2,4-D, dicamba, glufosinate, MSMA, paraquat, and pyraflufen-ethyl use resulted in a 35% reduction in viable seed production (Sarangi et al. 2020).

Only a few herbicides have been registered for use to control Palmer amaranth among vegetable crops, thus the use of hand removal is often required to prevent additions into the seedbank (SC Smith and LD Moore, unpublished data). Acifluorfen, flumioxazin, fomesafen, and saflufenacil (protoporphyrinogen oxidase inhibitors, Group 14); halosulfuron (an acetolactate synthase [ALS] inhibitor, Group 2); linuron and metribuzin (photosynthesis at PS II inhibitors, Group 5); oryzalin, pendimethalin, and trifluralin (microtubule assembly inhibitors, Group 3); and pyroxasulfone and *S*-metolachlor (very-long-chain fatty acid synthesis inhibitors, Group 15) are herbicides that have activity on susceptible biotypes of Palmer amaranth and are registered for use in certain vegetable crop production. Previous research reported that trifluralin (1.7 g ai kg seeds^{-1}) reduced cheat (*Bromus secalinus* L.) emergence by more than 90% when applied in a sprayer-equipped auger (Stone et al. 2001). Dicamba and 2,4-D are auxin-mimic herbicides (Group 4) that may be used as preplant burndown treatments in some vegetable crops. Ethephon is a plant growth regulator used for turf, apple (*Malus domestica* Borkh.), cotton (*Gossypium hirsutum* L.), and many vegetable crops (Anonymous 2019, 2020). Ethephon promotes fruit ripening, abscission, and flower induction (EPA 1995). In addition, ethephon can break the seed dormancy of several weed species (Goudey et al. 1987). Herbicides can reduce reproductive Palmer amaranth seed production by decreasing photosynthesis; however, the effects of chemicals on the viability of seeds already present at application are unknown. Thus, these studies were conducted to determine the seed germination and quality of Palmer amaranth seeds and gynoecious plants that retain seeds after chemical treatments used in vegetable crops.

Materials and Methods

Chemical Seed Treatment. Seeds were collected from mature Palmer amaranth at the Horticultural Crops Research Station near Clinton, NC (35.022°N, 78.280°W) in 2016 and stored at 4 C and 25% relative humidity (RH) for at least 2 yr before their use in evaluations. Resistance to glyphosate and ALS is common in this population, and susceptibility to other herbicides at labeled rates is still present. Laboratory studies were initiated on November 3 and November 13, 2018, in Raleigh, NC. The experimental design was completely randomized with four replications in each study. Treatments (Table 4.1) included herbicides, or a growth regulator (ethephon) applied at 1× and 2× registered application rates plus crop oil concentrate (1% vol vol^{-1}). Additionally, a control, treated with 1% vol vol^{-1} crop oil concentrate, was included for comparison. For each treatment, 20 mature (black) Palmer amaranth seeds per experimental unit were placed into a 14 by 14 by 2.5 cm-deep plastic weigh boat and misted with water for imbibition. After approximately 1 h, once imbibition was visually confirmed and excess water had evaporated from the weigh boats, treatments were applied to one experimental unit at a time in a spray chamber equipped with an 8002EVS nozzle (TeeJet Technologies, Springfield, IL) pressurized with 210 kPa CO_2 and calibrated to administer a 375 L ha^{-1} spray solution. The application pressure was confirmed to be low enough to prevent seeds from moving off of the weigh boats.

Approximately 2 h after treatment, once weigh boats containing seeds were dry, treated seeds from each experimental unit were transferred to a 10-cm-diam petri dish containing filter paper moistened with 10 ml of water. Dishes were placed on a laboratory bench with fluorescent lighting provided at an 8-h photoperiod. Temperature was set at 21 C, and additional water was added equally to all dishes daily. Germination was counted, then seedlings (radicle and hypocotyl) were imaged 3 d after treatment (DAT) using a flatbed scanner (Expression 10000 XL; Epson America, Long Beach, CA). Seedlings were arranged to avoid overlapping during scanning. Root measurement image analysis software (WinRHIZO 2019a; Regent Instruments, Quebec, QC, Canada) was used to measure total seedling length. Average seedling length was calculated by dividing the total length of seedlings by the number of germinated seeds in the experimental unit.

Residual plots were assessed for normality and homogeneity of variance. Arcsine square root transformations were applied for germination data. Data were subjected to ANOVA using the GLM procedure in SAS software (version 9.4; SAS Institute, Cary, NC). Dunnett’s test was used to compare treatments to the control ($\alpha = 0.05$). Back-transformed germination means were presented.

Chemical Inflorescence Treatment. Treatments from the *Chemical Seed Treatment* studies that limited the average seedling length to <1 cm were included in a further examination to determine their effects on Palmer amaranth progeny from treatments applied to reproductively mature plants. Studies were initiated at the North Carolina State University Method Road Greenhouses (35.788°N, 78.694°W) on October 30 and December 17, 2018. The experimental design was a randomized complete block with eight replications in each study. Palmer amaranth seeds, from the same lot as the *Chemical Seed Treatment* studies, were surface seeded into 10 by 10 by 9 cm-deep pots (Square Injection Molded Pots; Greenhouse Megastore, Danville, IL) containing moistened peat-perlite substrate (SunGro Fafard 4P Mix; Agawam, MA) and thinned to one plant per pot. Pots were overhead irrigated, temperature in the greenhouse was 30/25 ± 5 C d/night, and supplemental lighting was provided at 150 μmol m^{-2} s^{-1} for a 16-h photoperiod. Initially, contiguous arrangement of pots encouraged vertical growth with a single primary inflorescence. Once reproductive structures were visible, pots were spaced 10 cm apart and arranged so that each sex was aside the opposite. Additionally, androecious plants were shaken daily over gynoecious plants to ensure adequate pollination. On January 26, 2019, and March 16, 2019, gynoecious plants were grouped into blocks by plant height and treatments were applied at a 2× rate using a CO_2-pressurized backpack sprayer equipped with 8003VS nozzles pressurized with 170 kPa. Treatments were applied vertically to both sides of the plant directed at the inflorescence with a total output of 470 L ha^{-1}.

After treatment, plants were placed back into the greenhouse, without androecious plants, for 2 wk. Then, inflorescences were harvested and threshed, and seeds were separated from floral material using a vertical air column seed cleaner and stored at 4 C and 25% RH. Six months after being placed in cold storage, 30 mature (black) seeds per experimental unit were placed into 10-cm-diam petri dishes with filter paper moistened with 10 ml water, sealed with parafilm, and placed back into cold storage for 4 wk to overcome dormancy. Then, parafilm was removed, additional water was added equally to all dishes, and they were placed into a germination chamber at a 16-h photoperiod set to 35/25 C d/night and 100% RH for 3 d. Germination was determined, and seedling length was measured as previously described. Seed viability was assessed on 30 seeds per plot using a crush test (Sawma and Mohler 2002).

Residual plots were assessed for normality and homogeneity of variance. Data were subjected to ANOVA using the MIXED procedure in SAS software. Fixed effects included experimental run, treatment, and their interaction, and the random effect included replication nested within experimental run. Dunnett's test was used to compare treatments to the control ($\alpha = 0.05$).

Results and Discussion

Chemical Seed Treatment. Interactions with experimental run were not significant for germination ($P > 0.07$) or average ($P > 0.06$) and total ($P > 0.06$) seedling length data; therefore, data were pooled over experimental runs. For germination and total and average seedling length data, the treatment effect was significant ($P < 0.0001$), and the rate effect and treatment by rate interaction were not significant ($P > 0.5$); therefore, only treatment main effects are presented. Germination was reduced by 20% from 2,4-D, 15% from dicamba, and 13% from halosulfuron and pyroxasulfone (Table 4.2). Dicamba, ethephon, halosulfuron, oryzalin, trifluralin, and 2,4-D use resulted in a seedling length that was reduced by at least 50%; thus, these treatments were evaluated further in the *Chemical Inflorescence Treatment* studies.

Chemical Inflorescence Treatment. Interactions with experimental run were not significant for germination ($P = 0.09$) or average ($P = 0.2$) and total ($P = 0.5$) seedling length data; therefore, data were pooled over experimental runs. Treatment had a significant effect on seed germination ($P < 0.0001$). Germination was reduced by 24% when dicamba was used compared to crop oil alone (Table 4.3). Germination among all other treatments were similar to those of the control. Crush tests results showed that seeds from plants treated with dicamba had 95% viability compared with 98% viability in the crop oil control ($P = 0.01$; data not shown). Thus, treatments did not have a strong effect on seed viability. Total seedling length was reduced ($P = 0.01$) when dicamba and 2,4-D were used, but no treatments affected average seedling length ($P = 0.17$). Total seedling length is the compound effects of the number of germinated seeds and the seedling lengths, whereas average seedling length is the length of the seedlings regardless of the total number of germinated seeds. Therefore, because the average seedling lengths were not affected, treatments did not have a strong effect on the quality of seeds that germinated. The differences between results from the seed treatment and the inflorescence treatment studies were likely due to the inflorescences protecting seeds from direct contact with the full application rate of the chemicals.

Late-season herbicide applications can reduce seed production (de Sanctis et al. 2021; Jha and Norsworthy 2012; Sarangi et al. 2020; Scruggs et al. 2020). However, no treatments applied to Palmer amaranth after seed development caused a great decrease in seed viability in the present study, although previous research reported that trifluralin applied to cheat seed can reduce emergence by more than 90% (Stone et al. 2001). Based on the results of this study, late-season chemical application will likely not replace weed removal or seed destruction as a form of seedbank management.

Acknowledgments

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Table 4.1 Herbicides and growth regulator trade names, use rates, and manufacturers.[a]

Active ingredient	Trade name	Rates	Manufacturer	City, State	Website
		g ai/ae ha^{-1}			
Acifluorfen	Ultra Blazer	420, 840	United Phosphorus, Inc.	Prussia, PA	www.upi-usa.com
Dicamba	Xtendimax	1120, 2230	Bayer CropScience	St. Louis, MO	www.cropscience.bayer.us
Ethephon	Super Boll	1090, 2180	Nufarm Americas Inc.	Alsip, IL	www.nufarm.com
Flumioxazin	Valor SX	110, 210	Valent U.S.A. Corporation	Walnut Creek, CA	www.valent.com
Fomesafen	Reflex	420, 840	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta-us.com
Halosulfuron	Sandea	40, 80	Gowan Company	Yuma, AZ	www.gowanco.com
Linuron	Linex 4L	840, 1680	Tessenderlo Kerley, Inc.	Phoenix, AZ	www.novasource.com
Metribuzin	Tricor 4F	560, 1120	United Phosphorus, Inc.	Prussia, PA	www.upi-usa.com
Oryzalin	Surflan	1120, 2240	United Phosphorus, Inc.	Prussia, PA	www.upi-usa.com
Pendimethalin	Pendulum AquaCap	1070, 2130	BASF Corporation	Research Triangle Park, NC	www.basf.com
Pyroxasulfone	Zidua WG	120, 240	BASF Corporation	Research Triangle Park, NC	www.basf.com
S-metolachlor	Dual Magnum	800, 1600	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta-us.com
Saflufenacil	Detail	50, 100	BASF Corporation	Research Triangle Park, NC	www.basf.com
Trifluralin	Treflan 4L	1120, 2240	Loveland Products, Inc.	Greeley, Colorado	www.lovelandproducts.com
2,4-D	Enlist One	1070, 2130	Corteva Agriscience	Wilmington, DE	www.Corteva.com

[a] Crop oil concentrate (1% vol vol^{-1}) was included in all treatments.

Table 4.2 Influence of chemicals applied to Palmer amaranth seeds on germination and seedling length.[a, b, c]

	Germination	Average seedling length	Total seedling length
	%	cm	cm
Crop oil control	95 –	1.8 –	34 –
Acifluorfen	85	1.7	29
Dicamba	80 ***	0.9 ***	15 ***
Ethephon	96	0.9 ***	16 ***
Flumioxazin	88	1.5	26
Fomesafen	88	1.7	31
Halosulfuron	82 ***	0.9 ***	14 ***
Linuron	87	1.9	32
Metribuzin	92	1.7	32
Oryzalin	91	0.6 ***	12 ***
Pendimethalin	88	1.1 ***	20 ***
Pyroxasulfone	82 ***	1.4	23 ***
S-metolachlor	88	1.4	24
Saflufenacil	89	1.5	26
Trifluralin	91	0.8 ***	15 ***
2,4-D	75 ***	0.8 ***	11 ***

[a] Crop oil concentrate (1% vol vol^{-1}) was included in all treatments.

[b] Data were pooled across 1× and 2× registered use rates.

[c] Means followed by *** are statistically different from the control according to Dunnett's test ($\alpha = 0.05$).

Table 4.3 Influence of chemicals applied to Palmer amaranth inflorescence on progeny seed germination and seedling length.[a, b, c]

	Germination	Average seedling length	Total seedling length
	%	cm	cm
Crop oil control	82 –	4.1 –	99 –
Dicamba	58 ***	3.8	69 ***
Ethephon	83	3.8	93
Halosulfuron	83	3.9	99
Oryzalin	81	4.1	101
Trifluralin	80	4.1	97
2,4-D	78	3.6	83 ***

[a] Crop oil concentrate (1% vol vol^{-1}) was included in all treatments.

[b] Treatments were applied at 2× registered use rates.

[c] Means followed by *** are statistically different from the control according to Dunnett's test ($\alpha = 0.05$).

CHAPTER 5

Susceptibility of Palmer Amaranth (*Amaranthus palmeri*) Accessions in North Carolina to Atrazine, Dicamba, *S*-metolachlor, and 2,4-D

(In the format appropriate for submission as a Brief to Crop, Forage & Turfgrass Management)

Susceptibility of Palmer Amaranth (*Amaranthus palmeri*) Accessions in North Carolina to Atrazine, Dicamba, *S*-metolachlor, and 2,4-D

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Core ideas

1) All of the 120 accessions of Palmer amaranth collected in the Coastal Plain of North Carolina were controlled by atrazine and dicamba applied at field use rates in the greenhouse.
2) Reduced sensitivity among accessions was noted when *S*-metolachlor and 2,4-D were applied to Palmer amaranth at field use rates in the greenhouse.
3) Additional research is needed to determine if reduced sensitivity of Palmer amaranth to *S*-metolachlor and 2,4-D is associated with evolved resistance.

Palmer amaranth (*Amaranthus palmeri* S. Watson) is the most troublesome weed in many crops in the United States (Van Wychen, 2019, 2020). Whitaker (2009) conducted a survey of 290 Palmer amaranth accessions collected across North Carolina in 2005 that indicated 17 and 18% of the accessions survived field use rates of glyphosate (0.75 lb a.e. acre^{-1}) and thifensulfuron-methyl (0.016 lb a.i. acre^{-1}), respectively. Poirier et al. (2014) reported at least 97% survival when these herbicides were applied to 134 accessions collected across North Carolina in 2010 with 93% of accessions surviving both herbicides. In the 2010 survey, glufosinate (0.4 lb a.i. acre^{-1}) and fomesafen (0.25 lb a.i. acre^{-1}) controlled all accessions. More recently, Mahoney et al. (2020) surveyed 110 accessions collected from the North Carolina Coastal Plain in 2016 and reported that at least 96% of the accessions survived glyphosate (0.75 lb acre^{-1}) and thifensulfuron-methyl (0.016 lb acre^{-1}). Fomesafen (0.25 lb acre^{-1}) and mesotrione (0.1 lb a.i. acre^{-1}) controlled these accessions 98% and 90%, respectively, while no accessions survived glufosinate (0.4 lb acre^{-1}). Since Mahoney et al. (2020) collected the Palmer amaranth accessions in 2016, evolved resistance to 2,4-D, dicamba, and *S*-metolachlor has been reported in the U.S. (Heap, 2021). Although Palmer amaranth with resistance to atrazine was first confirmed in the U.S. in 1995, resistance to this herbicide has not been reported in populations of this weed in North Carolina (Heap, 2021). Therefore, studies were conducted to further evaluate sensitivity of Palmer amaranth accessions collected by Mahoney et al. (2020) to atrazine, dicamba, *S*-metolachlor, and 2,4-D.

Materials and Methods

To determine Palmer amaranth susceptibility to atrazine, dicamba, and 2,4-D, seeds from 120 accessions (Figure 5.1) collected by Mahoney et al. (2020) were planted in 2020 and 2021 in a greenhouse (35.788°N, 78.694°W) having 85/78°F day/night and supplemental lighting for a 16 h photoperiod. Irrigation was applied overhead to maintain field capacity. Experimental units consisted of seeds sown into 10 continuous cells in a 50-cell tray (50 square cell Plug Flats, Greenhouse Megastore, Danville, IL) containing potting soil mix (SunGro Fafard 4P Mix, Agawam, MA), and thinned to one plant per cell for a total of 10 plants per experimental unit. Atrazine, dicamba, and 2,4-D were applied to Palmer amaranth (4 to 6 leaves, 2 to 4 inches tall) in separate studies. Herbicide rates are provided in Table 5.1 with a non-treated control included for comparison.

To determine Palmer amaranth susceptibility to *S*-metolachlor, fifty seeds for each accession were separately sown approximately 0.25 inches deep into 4 × 4 × 3.5 inch square pots (Square Injection Molded Pots, Greenhouse Megastore, Danville, IL) containing steam sterilized soil (loamy-sand; 84% sand, 12% clay, 4% silt) with a 6.0 pH and 0.6% organic material. Seeds were placed at least 0.5 inches from the edges of the pots. Immediately after seeding, pots were treated with *S*-metolachlor (Table 5.1) followed by 0.25 inches of overhead sprinkler irrigation within 1 hour of herbicide application. The rate of *S*-metolachlor used is the standard for applications in sweetpotato [*Ipomoea batatas* (L.) Lam.], a major crop in North Carolina. This rate (0.7 lb a.i. acre^{-1}) is lower than the conventional rate for row crops (0.95 lb a.i. acre^{-1}). Three non-treated control plots were used for every accession to establish expected germination. The design in both experiments was a randomized complete block with four or five replications.

Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with two flat-fan nozzles (8003VS, TeeJet Technologies, Springfield, IL) spaced 20 inches apart and calibrated to deliver 20 gal acre^{-1} aqueous solution at 20 psi. Each study was conducted twice. Plants with green leaves and apical meristems 3 weeks after herbicide application were considered survivors. Percent survival was calculated for each experimental unit as the number of plants surviving divided by the total number of plants. Data were subjected to ANOVA using PROC MIXED in SAS (version 9.4, Cary, NC) separately for each herbicide. Accessions with 0% survival were excluded from analysis because of a lack of variance. Accession and run of the experiment were treated as fixed effects, and replication nested within experiments was considered a random effect. Accessions with a 95% confidence interval not containing 0% were considered to have reduced sensitivity.

Results and Discussion

Interactions between experimental runs were not present ($P > 0.05$); thus, the data were combined (Figure 5.2). Differences in Palmer amaranth survival were observed for *S*-metolachlor ($P < 0.0001$) and 2,4-D ($P < 0.0001$) when comparing across accessions. However, no differences in survival were noted for atrazine ($P = 0.9528$) or dicamba ($P = 0.3591$). Survival from *S*-metolachlor (22%) and 2,4-D (47%) differed from 0% survival according to 95% confidence intervals. Of these accessions, 18 survived both *S*-metolachlor and 2,4-D. Our results along with those of Mahoney et al. (2020) provide a baseline point for the North Carolina Coastal Plain relative to evolved resistance to atrazine, dicamba, fomesafen, and glufosinate given Palmer amaranth was controlled by field use rates of these herbicides. Widespread resistance to glyphosate and thifensulfuron-methyl was confirmed in 2010 accessions (Poirier et al., 2014) and more recently in the accessions used in our experiment (Mahoney et al., 2020). Evolved resistance to mesotrione was also confirmed in the accessions we evaluated (Mahoney et al., 2020). Additional research is needed to confirm possible resistance to 2,4-D and *S*-metolachlor in the accessions expressing reduced sensitivity at field use rates under greenhouse conditions. Irrespective of confirmation of evolved resistance, our results can be used to encourage growers and their advisors to incorporate multiple tactics to manage Palmer amaranth in an attempt to prevent further selection for biotypes resistant to these herbicides.

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Table 5.1 Herbicides and growth regulator trade names, use rates, and manufacturers.[a]

Active ingredient	Trade name	Rate	Timing	Manufacturer	City, State	Website
		lb a.i. or a.e. acre^{-1}				
Atrazine[b]	AAtrex 4L	1	POST	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta-us.com
Dicamba	Xtendimax	0.5	POST	Bayer CropScience	St. Louis, MO	www.cropscience.bayer.us
S-metolachlor	Dual Magnum	0.7	PRE	Syngenta Crop Protection, LLC	Greensboro, NC	www.syngenta-us.com
2,4-D	Enlist One	0.5	POST	Corteva Agriscience	Wilmington, DE	www.Corteva.com

[a] Abbreviations: POST, post-emergent; PRE, pre-emergent.

[b] Crop oil concentrate included at 1% (v/v).

Figure 5.1 Seed from 120 Palmer amaranth accessions were collected from 22 North Carolina counties: 12 from cotton (*Gossypium hirsutum* L.), 31 from peanut (*Arachis hypogaea* L.), 56 from soybean [*Glycine max* (L.) Merr.], and 21 from sweetpotato [*Ipomoea batatas* (L.) Lam.].

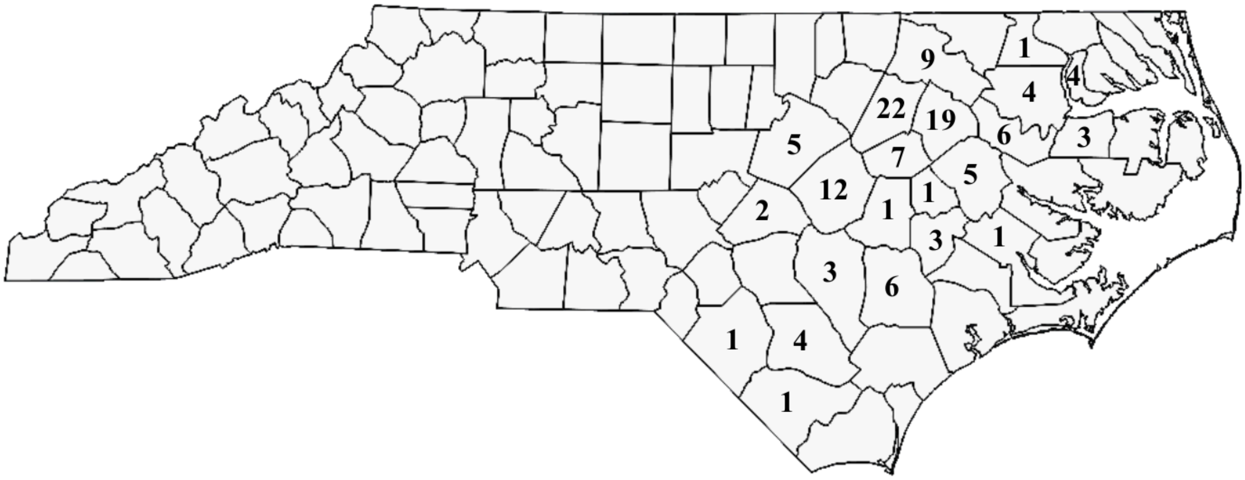

Figure 5.2 Survival 3 weeks after application for 120 accessions of Palmer amaranth collected from the North Carolina Coastal Plain for atrazine (1 lb a.i. acre^{-1}) post-emergent, dicamba (0.5 lb a.e. acre^{-1}) post-emergent, 2,4-D (0.5 lb a.e. acre^{-1}) post-emergent, and *S*-metolachlor (0.7 lb a.i. acre^{-1}) pre-emergent. Accessions with a 95% confidence interval not containing 0% were considered to have reduced sensitivity.