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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.

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Palmer amaranth is the most common and troublesome weed in sweetpotato (Webster 2010; Smith and Moore, unpublished data) due to many factors, including large and vigorous growth and high fecundity.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

Table 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 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.

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 Research Project-4 (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). 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 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 (TeeJet 8003; TeeJet Technologies) 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, 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, Faison, NC (35.149°N, 78.204°W) (Fais18WF) and 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 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 ($P \le 0.05$). 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.

Table 3. Effect of herbicide treatment on sweetpotato foliar injury and stunting.[a,b]

	Foliar injury[d]		Stunting	
Herbicide[c]	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 ($P \le 0.05$).

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

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

[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.

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 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). 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 3).

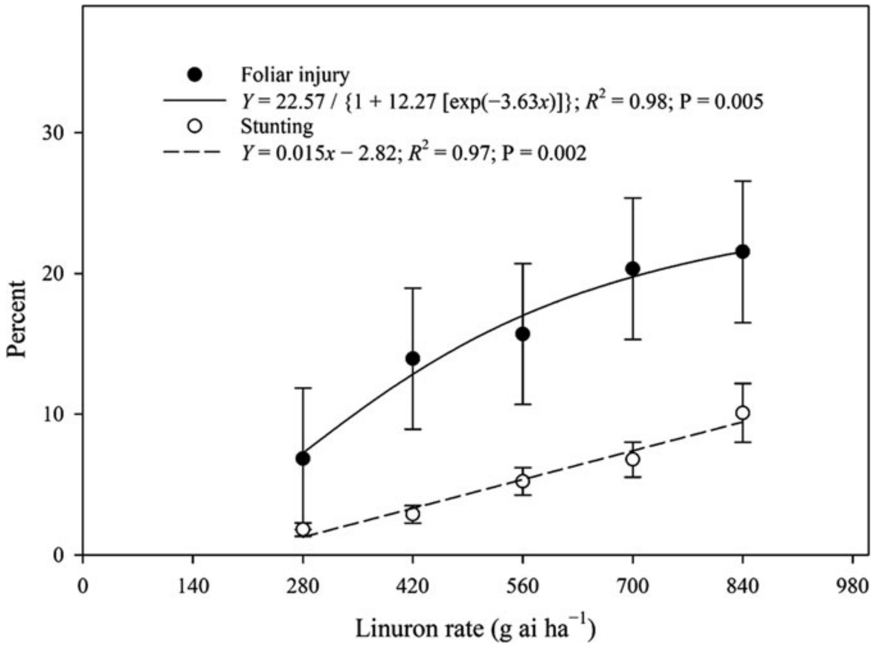

Figure 1. The influence of linuron rate on sweetpotato foliar injury and stunting pooled across studies and herbicide combinations. Visual foliar injury and stunting were rated on a scale of 0% (no treatment effect) to 100% (crop death). Points represent means and vertical bars represent means ± SE.

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 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). 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 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 posttransplant 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 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 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 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

Table 4. Palmer amaranth and goosegrass control as affected by herbicide treatment.[a]

	Palmer amaranth control[c]						Goosegrass control[c]	
	2 WAPT[d]		4 WAPT		8 WAPT		3 WAPT	
Herbicide[b]	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.

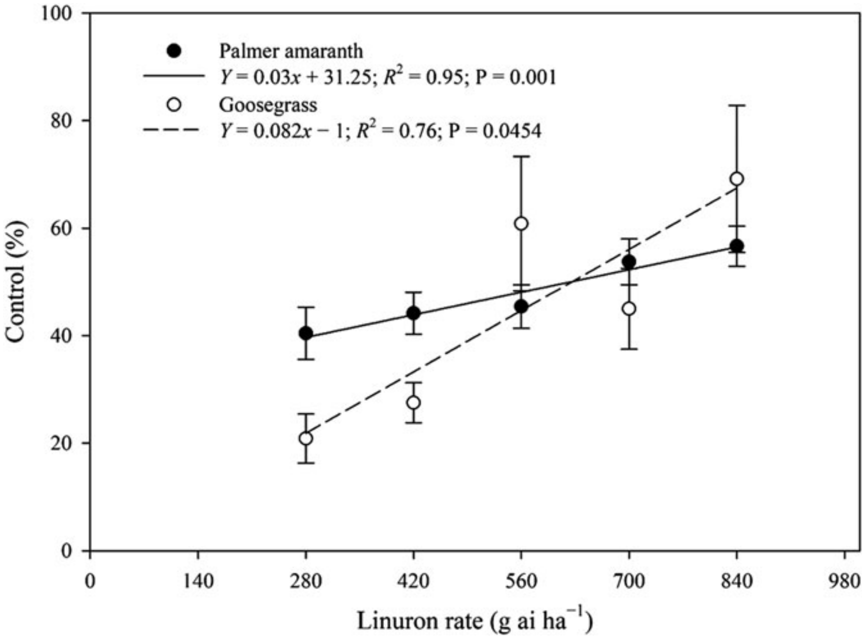

Figure 2. Palmer amaranth control 2 wk after post-transplant treatment (WAPT) and goosegrass control 3 WAPT in the weedy Clinton, NC, site in 2018 as affected by linuron rate. Palmer amaranth control data are pooled across herbicide combination, and goosegrass control are pooled across linuron alone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

(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 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 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.

Table 5. Sweetpotato storage root yield as affected by herbicide treatment.[a,b]

Herbicide[c,d]	Canner[e]				No. 1				Jumbo				Marketable[f]			
	Clin18WD[g]	Fais18WF	Bow18WF	Clin19WD	Clin18WD	Fais18WF	Bow18WF	Clin19WD	Clin18WD	Fais18WF	Bow18WF	Clin19WD	Clin18WD	Fais18WF	Bow18WF	Clin19WD
	1,000kg 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 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.

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 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; DJ Mahoney, personal communication; 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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