Peanut Response to Flumioxazin and *S*-Metolachlor Under High Moisture Conditions

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ABSTRACT

Georgia produces nearly 51% of the United States peanut (*Arachis hypogaea* L.) crop. To combat and prevent weed infestations, herbicide programs containing flumioxazin and *S*-metolachlor are often applied preemergence (PRE). Despite herbicide effectiveness for weed control, peanut injury following heavy rainfall can be problematic. The objective of this study was to evaluate the impact of injury from flumioxazin and *S*-metolachlor after simulated heavy rainfall events on peanut growth and yield. Plots were planted at the University of Georgia Ponder Research Farm located near Ty Ty, Georgia using conventional tillage practices and twin-row spacing. Treatments included PRE applications of flumioxazin at 0, 0.11 and 0.22 kg ai/ha alone or in combination with *S*-metolachlor at 0, 1.07, 1.40, 2.80 kg ai/ha and were applied using a CO_2-pressurized backpack sprayer. Irrigation and rainfall were $\geq$20 cm in the 30 days after planting (DAP) to simulate heavy rainfalls. Flumioxazin at 0.22 kg ai/ha caused the greatest visual injury (>60%) and most whole-plant fresh weight/m reductions at 21 DAP compared to other treatments. Peanut density was not impacted by flumioxazin or *S*-metolachlor. Neither flumioxazin nor *S*-metolachlor affected J-rooting. Yield was not reduced by any rate of flumioxazin. However, *S*-metolachlor at 2.80 kg/ha, (2.6X field rate), reduced yields by 8.9% compared to plots where no *S*-metolachlor or recommended field rates were applied.

Key Words: J-rooting, peanut biomass, peanut injury, rainfall

The United States produced $1.28 billion worth of peanuts in 2019 of which Georgia produced 51% of the total production (USDA-NASS 2021). Peanut is susceptible to weed competition due to slow canopy establishment, prostrate growth habit, and wide critical period for weed control from 3 to 8 weeks after planting (Burke *et al*. 2007; Everman *et al*. 2008). Georgia-06G is the dominant peanut cultivar planted in the southeast and in 2020, 87% of the acres grown for certified peanut seed available for sale to growers was Georgia-06G (Anonymous, 2020a). Peanut is commonly grown in rotation with cotton in the region and therefore, similar weed issues between these systems persist. This includes Palmer amaranth (*Amaranthus palmeri* S. Watson) which has been documented to be resistant to multiple herbicide modes of action making its control difficult (Heap 2021). To minimize yield loss from weeds, preemergence (PRE) herbicides are frequently used in peanut to inhibit weed germination and provide residual weed control (Grichar *et al*. 2001). In response to resistance issues, producers have continued to integrate PRE herbicides into their herbicide programs to minimize weed emergence.

One commonly used PRE herbicide in peanut is flumioxazin, a WSSA Group 14 protoporphyrinogen oxidase (PPO) inhibitor. Flumioxazin provides long residual activity, a high level of efficacy, and an overall fit into weed management programs by expanding modes of action applied PRE in peanut (Askew *et al*. 1999; Clewis *et al*. 2002, Main *et al*. 2003). It has been shown to provide > 85% control in peanut of various problematic weeds without affecting pod grade or disease incidence. Furthermore, flumioxazin applied PRE controlled 99% of Palmer amaranth that had resistance to POST applied PPO inhibitors, further emphasizing its importance to peanut production systems where Palmer amaranth is problematic (Umphres *et al*. 2018; Wilcut *et al*. 2001).

Metolachlor, a 50/50 mixture of *R*/*S* stereoisomers, was first registered for use in peanut in 1980 (H. McLean, pers. communication). In 1997, *S*-metolachlor, a 12:88 mixture of R/S stereoisomers was commercialized (H. McLean, pers. communication). Formulations with a greater concentration of *S*-stereoisomers are more active and can be applied at lower rates controlling annual grasses (*Digitaria, Setaria,* and *Panicum* spp.) and small-seeded broadleaf weeds (*Amaranthus* and *Solanum* spp.) (Anonymous 2020b; O'Connell *et al*. 1998). When applied at equivalent rates, no differences in

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performance between *S*-metolachlor and metolachlor have been observed in peanut (Grichar *et al.* 2001). In general, and when applied at labeled rates, peanut emergence can be delayed and plant stunting was observed following soil application of metolachlor. However, yields were not negatively impacted (Cardina and Swann, 1988; Johnson *et al.*1993, 1994; Wehtje *et al.* 1988). Others have suggested that including *S*-metolachlor in a peanut weed control program can result in a positive yield response (Clewis *et al.* 2007; Grichar *et al.* 2001).

Despite flumioxazin and S-metolachlor's utility in a peanut production system, peanut injury after emergence has been variable, with injury ranging from minimal to >60% (Burke *et al.* 2002; Grey *et al.* 2005; Johnson *et al.* 2006; Main *et al.* 2003; Price *et al.* 2004; Wilcut *et al.* 2001). Previous publications have identified increases in injury as possibly relating to cold, wet conditions which slow plant metabolism, and increase herbicide availability for uptake (Askew *et al.* 1999; Burke *et al.* 2002; Grichar *et al.* 2004). During heavy rainfall, flumioxazin available in the soil water can splash onto the plant, allowing for foliar uptake and increasing peanut injury. In much of the southeastern US peanut-growing regions, heavy rainfall can occur during peanut emergence. These rainfall events increase the potential for early-season injury, however, the impact of this early-season injury on peanut injury, growth, and end-of-season yields has not been determined.

Early research suggested that J-rooting is partially caused by soil applications of metolachlor (Cardina and Swann 1988). However, there has not been additional research to connect J-rooting directly to applications of metolachlor/*S*-metolachlor or any other herbicide. J-rooting is a phenomenon where peanut taproot does not continue to grow downward but instead growth has inverted geotropism. The taproot then grows up toward the soil surface resulting in a "J" shaped root. The cause of J-rooting is not well understood but the appearance of J-rooting is often associated with plants under stress. Historically, there have always been grower concerns about the use of soil-applied metolachlor/*S*-metolachlor in peanut as it has anecdotally been connected to J-rooting. While the effects of *S*-metolachlor on peanut grown and yield have been addressed, there has not been additional research conducted to connect J-rooting to applications of *S*-metolachlor or any other herbicide.

Both flumioxazin and S-metolachlor require activating rainfall when used PRE in peanut. However, heavy spring rains following applications of PRE herbicides can result in significant peanut injury. In the peanut-growing regions of Georgia, rainfall exceeding 15 cm during and following planting can occur (Georgia Weather Network, 2021). Coupling heavy rainfall and the prostrate growth habit of peanut, young plants often make contact with herbicide-treated soil or are exposed at the rooting zone from downward herbicide movement with rainfall. Therefore, the objective of this study was to evaluate the effect of simulated high rainfall on peanut injury, J-rooting, and yield after applications of PRE combinations of flumioxazin and S-metolachlor.

Table 1. Planting, application, and harvest dates for flumioxazin/*S*-metolachlor high moisture peanut tests in Georgia (2017-2019).

	Year		
	2017	2018	2019
Planting Date	28 Jun.	30 Apr.	1 May
Application Date	28 Jun.	2 May	3 May
Digging Date	-	17 Sep.	18 Sep.
Harvest Date	-	20 Sep.	23 Sep.

Materials and Methods

Small plot field trials were conducted in 2017 through 2019 at the University of Georgia Ponder Research Farm located near Ty Ty, Georgia (31.507654°N, -83.658395°W). The soil type was a Fuquay sand with 96% sand, 0% silt, 4% clay, 0.57% organic matter, and a pH of 6.0. Conventional tillage practices were used and peanut was planted using a vacuum planter calibrated to deliver 18 peanut seed/m at a depth of 5 cm (Monosem Precision Planters, 1001 Blake St., Edwardsville, KS). Peanut (cv. GA-06G) was planted in a twin-row pattern (90 cm X 22 cm spacing) with a plot size of 7.6 m X 0.9 m. Planting, application, and harvest dates are presented in Table 1. Rainfall and supplemental irrigation totals for the first 30 days after planting (DAP) are presented in Table 2. These 30 DAP moisture totals ranged between 19.9 and 28.4 cm.

Treatments were arranged in a randomized complete block design with a 3 (flumioxazin rates) by 4 (*S*-metolachlor rates) factorial arrangement. Flumioxazin rates were 0, 0.11 and 0.22 kg ai/ha. *S*-metolachlor rates were 0, 1.07, 1.40, and 2.80 kg ai/ha. Normal use rates of these herbicides in peanut production are 0.11 and 1.07 kg ai/ha for flumioxazin and S-metolachlor, respectively (Anonymous 2016, Anonymous 2020b). Herbicide treatments were replicated 3 to 4 times and were applied using a CO_2 – pressurized backpack

Table 2. Rainfall and irrigation data (cm) for first 30 days after planting for flumioxazin/*S*-metolachlor high moisture peanut tests in Georgia (2017-2019).

Time (DAP[a])	2017			2018			2019		
	Rain	Irrigation	Total	Rain	Irrigation	Total	Rain	Irrigation	Total
0-7	1.3	9.4	10.7	0.0	13.5	13.4	0.4	7.5	7.9
8-14	1.0	0.0	1.0	2.7	0.0	2.7	3.0	5.8	8.8
15-21	3.1	1.3	4.4	3.9	0.0	3.9	1.6	1.3	2.9
22-30	1.3	2.5	3.8	8.4	0.0	8.4	0.0	1.3	1.3
Total	6.7	13.2	19.9	15.0	13.5	28.4	5.0	15.9	20.9

[a]DAP = days after planting.

sprayer calibrated to deliver 140 L/ha at 4.8 km/hr. Plots were maintained weed-free throughout the season using a combination of herbicides (pendimethalin, diclosulam, imazapic, and 2,4-DB) and hand-weeding. Peanut density, whole-plant (above + below ground) fresh weight biomass, and J-rooting was determined by hand-harvesting entire peanut plants from a 1 m section of row at 21 DAP. Visual estimates of peanut injury were made using a scale from 0 (no injury) to 100% (complete plant death) and collected 10 days after treatment (DAT) and 50 DAT. Peanut yield data were obtained by mechanical harvesting at maturity. Yield data were not collected in 2017 due to a very late planting date.

Data were subjected to ANOVA using PROC GLIMMIX in SAS, version 9.4 (SAS Institute, Cary, NC) to determine if year, flumioxazin rate, and *S*-metolachlor rate influenced peanut injury, stand density, whole-plant fresh biomass, J-rooting, and yield. Peanut injury, density, biomass, J-rooting, and yield were set as the response variables with year and replication within year included in the model as random factors. Year was not significant so all data were combined over years. Flumioxazin rate by *S*-metolachlor rate interactions were only significant for peanut density and whole-plant fresh weight biomass, therefore other response variables were analyzed by the main factor of herbicide. All P-values for tests of differences between least-squares means were compared and separated using the Tukey-Kramer method ($P<0.10$).

Results & Discussion

Peanut injury. At all rates, flumioxazin and S-metolachlor did not affect peanut emergence across all years (Table 3). Peanut plants were stunted, as indicated by reduced fresh weights in herbicide-treated plots at 21 DAP when compared to the untreated check. Fresh weights of peanut subjected to normal rates of flumioxazin (0.11 kg ai/ha) and S-metolachlor (1.07 kg ai/ha) were similar to the untreated check (Table 3). When the highest rate of both flumioxazin and S-metolachlor were applied to peanut, fresh weights were reduced by 49%. Peanut injury was transient in all years with the greatest injury occurring at 10 DAT. Injury increased with increasing herbicide rate for both flumioxazin and S-metolachlor (Tables 4 and 5). By 50 DAT, injury was less than 20% for all treatments. Despite increased moisture in this study, injury ratings did not exceed those reported in other studies for flumioxazin and S-metolachlor (Askew *et al*. 1999; Burke *et al*. 2002; Cardina and Swann 1988). Increasing injury with increasing flumioxazin rate has been noted in other studies (Askew *et al*. 1999; Burke *et al*. 2002; Jordan *et al*. 2009). In these studies, peanut injury was transient, even with increased injury occurring. For S-metolachlor, injury responses increased with increasing herbicide rate but fell below 20% for all

Table 3. The influence of flumioxazin and *S*-metolachlor, on peanut density and whole-plant fresh weight biomass under high moisture conditions in Georgia (2017-2019)[a,b].

Flumioxazin	*S*-metolachlor	Peanut density	Peanut Fresh Weight
kg ai/ha	kg ai/ha	plants/m	g/m
0	0	16 a[c]	104 a
	1.07	15 a	80 bcd
	1.40	15 a	78 bcd
	2.80	16 a	75 bcd
0.11	0	15 a	85 bc
	1.07	16 a	87 ab
	1.40	15 a	69 b-e
	2.80	16 a	70 bcd
0.22	0	15 a	71 bcd
	1.07	15 a	65 de
	1.40	16 a	67 cde
	2.80	14 a	51 e

[a]Averaged over three years (2017, 2018, and 2019).
[b]Data collected 21 days after planting.
[c]Means in the same column with the same letter are not significantly different according to Tukey-Kramer method ($P<0.10$).

Table 4. The effect of flumioxazin on peanut injury, J-rooting, and yield under high moisture conditions in Georgia (2017-2019)[a].

Flumioxazin Rate	Peanut Injury (%)		Peanut J-Rooting	Yield
kg ai/ha	10 DAT[b]	50 DAT	%[c]	kg/ha
0[a]	14 c[d]	8 b	46 a	6550 a
0.11	31 b	9 b	48 a	6580 a
0.22	51 a	16 a	50 a	6530 a

[a]Averaged over three years (2017, 2018, and 2019) and four *S*-metolachlor rates (0, 1.07, 1.40, and 2.80 kg ai/ha).
[b]DAT = days after treatment.
[c]Data collected 21 days after planting.
[d]Means in the same column with the same letter are not significantly different according to Tukey-Kramer method (P<0.10).

Table 5. The effect of *S*-metolachlor on peanut injury, J-rooting, and yield under high moisture conditions in Georgia (2017-2019)[a].

S-metolachlor Rate	Peanut Injury (%)		Peanut J-Rooting	Yield
kg ai/ha	10 DAT[b]	50 DAT	%[c]	kg/ha
0	23 c[d]	5 c	48 a	6830 a
1.07	30 bc	9 bc	45 a	6630 a
1.40	33 b	10 b	49 a	6540 ab
2.80	42 a	19 a	51 a	6220 b

[a]Averaged over three years (2017, 2018, and 2019) and three flumioxazin rates (0, 0.11, and 0.22 kg ai/ha).
[b]DAT = days after treatment.
[c]Data collected 21 days after planting.
[d]Means in the same column with the same letter are not significantly different according to Tukey-Kramer method (P<0.10).

rates by 50 DAT. Injury for *S*-metolachlor was also noted in previous studies (Cardina and Swann 1988), however, rates used in that study were greater than those used in this study and exceed labeled rates for application of this product (Anonymous, 2020b)

J-rooting. J-rooting was not affected by any herbicide. At the time of plant harvest (21 DAP), J-rooting was present in all plots including the untreated check at rates >45%. A previous study connected the J-rooting phenomenon to the use of *S*-metolachlor (Cardina and Swann 1988). However, the herbicide rate of 6.7 kg ai/ha used in the present study is far above rates that are typically used in production fields. Although studies have noted root malformations with the use of *S*-metolachlor in other below-ground crops (Abukari *et al*. 2015; Meyers *et al*. 2012), this three-year study had J-rooting at the same level in plots treated with *S*-metolachlor and flumioxazin as the untreated check. The present study indicates that J-rooting is not caused by typical field use rates of *S*-metolachlor or flumioxazin, even under high moisture conditions that could move these herbicides into the root zone. Therefore, this phenomenon may be influenced by other seed, environmental, or edaphic conditions.

Peanut yield. Despite rates causing up to 51% injury at 10 DAT, flumioxazin did not affect yield (Table 4). This result is similar to previous literature, indicating that flumioxazin does not negatively impact yield even when high levels of early-season injury occurred (Askew *et al*. 1999; Burke *et al*. 2002; Main *et al*. 2003). However, yields were significantly reduced by the 2.80 kg ai/ha rate of S-metolachlor. This rate exceeds current labeled rates by 2.6X (Anonymous, 2020b). Negative yield impacts from metolachlor at labeled rates were not observed and are supported by previous literature (Cardina and Swann 1988; Johnson *et al*. 1993, 1994; Wehjte *et al*. 1988). The results of one study suggested that tank-mixing *S*-metolachlor and flumioxazin PRE improved peanut yield over *S*-metolachlor alone (Clewis *et al*. 2007). In another study, *S*-metolachlor increased yields due to eliminating competition from yellow nutsedge (*Cyperus esculentus*) (Grichar *et al*. 2001).

Summary and Conclusions

Results from this study support the continued use of labeled rates of flumioxazin and *S*-metolachlor to combat weeds in peanut. Flumioxazin and *S*-metolachlor both caused early-season injury in peanut, and injury for both herbicides was directly related to the application rate. The early-season injury from flumioxazin did not have a negative impact on yield, while yield was negatively impacted by S-metolachlor at rates above the recommended labeled rates were applied. As "Georgia-06G" is grown throughout much of the peanut growing regions of the US, injury caused by these products can be tolerated by growers when heavy rainfall does occur. Furthermore, during all three years of this study, J-rooting was not increased by the application of S-metolachlor or flumioxazin. This indicates that J-rooting is caused by other factors. Additional research into the causes J-rooting should be investigated to include other biotic or abiotic factors.

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