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Interaction of Seedling Germination, Planting Date, and Flumioxazin on Peanut Physiology under Irrigated Conditions

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Abstract

Diclosulam and flumioxazin applied preemergent (PRE) results in direct peanut exposure to these herbicides prior to seedling emergence. Flumioxazin has been reported to induce injury in adverse weather (*i.e.* cool-wet soil conditions) at crop emergence. Research at Ty Ty and Plains, Georgia evaluated the physiological effects of PRE herbicides to emerging peanut in 2018 and 2019. Peanut seed with variable germination and different planting dates were evaluated as additional factors. Peanut plant physiological measurements included electron transport (ETR), net assimilation rate (A_{net}), quantum yield of PSII (Φ_{PSII}), and stomatal conductance to water vapor (GSW). Data were obtained from V3 to R1 peanut growth stages using a LiCOR 6800, along with stand counts and plant width measures. In 2018, diclosulam reduced peanut ETR when measured across multiple growing degree days (GDD) after planting, compared to the nontreated control (NTC). Flumioxazin reduced peanut ETR compared to the NTC, at several sample timings for each planting date. In 2018 and 2019 at both locations, flumioxazin impacted A_{net} less than ETR, but was consistently similar to/or greater than the NTC. Peanut Φ_{PSII} responded similarly as A_{net} at each location and yr. GSW was variable in both years; however flumioxazin treated plants had higher GSW rates than other treated plants. Peanut stand counts, plant widths, and pod yields noted few differences compared to the physiological measures. Though some peanut plant physiological differences were noted when measured at varying GDD's after planting with the different PRE treatments, planting date, and seed vigor, no specific trends were observed. Growers will often observe peanut injury from flumioxazin early in the season. However, it is transient and does not affect yield.

Keywords

Diclosulam, Flumioxazin, Peanut, *Arachis hypogaea* L., Photosynthesis,

Electron Transport

1. Introduction

In 2019, 85% of US peanut (*Arachis hypogea* L.) hectares were planted in the southeastern states of Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Virginia [1]. Georgia leads the nation with 47% of production [2]. In order to maintain this profitability, peanut growers need to be able to start the growing season with high quality seed, establish an adequate population, under weed free conditions. Planting peanut at the optimal timing is critical in order to establish adequate populations. Factors such as soil temperature, air temperature, and soil moisture play an important role in acceptable stand establishment. Kvien *et al.* [3] indicated that adequate peanut germination will occur when soil temperatures are in the range of 20˚C to 35˚C at a depth of 10 cm for 3 consecutive days.

Peanut emerges from soil within 6 to 11 days after planting, depending upon soil and air temperatures [4]. Research has indicated optimal growing conditions occur between air temperatures of 27˚C to 32˚C [5]. These optimal germinating conditions typically occur between late April and May for southern Georgia, yet some varieties allow for early planting due to a resistance to Tomato spotted wilt virus (TSWV) (Family: Bunyaviridae Genus: *Tospovirus*) transmitted by the western flower thrip (*Frankliniella occidentalis* Pergande) and tobacco thrips (*Frankliniella fusca* Hinds) [6] [7] [8]. Prasad *et al.* [8] reported that cooler soil temperatures resulted in smaller seedlings and lower plant populations in peanut. These sub-optimal soil temperature conditions may also impact physiological factors in early season peanut growth.

Peanuts are very susceptible to competition from weeds as canopy closure occurs 8 to 10 weeks after planting, or not at all [9]. Optimal weed management includes beginning the peanut growing season weed-free using herbicides that allow the crop to become established without competition. Maintaining a weed free peanut crop from weeks 3 to 8 after planting is essential, allowing peanut to achieve a maximum yield [10]. Peanut growers typically apply PRE herbicides including pendimethalin, *S*-metolachlor, and flumioxazin [2]. In Georgia, PRE herbicides diclosulam and flumioxazin are often recommended [11]. Diclosulam, an ALS herbicide, has been used as a PRE herbicide in peanut since 2000 [12]. It has demonstrated excellent crop safety in Georgia [13] and has a POST label for Benghal dayflower (*Commelina benghalensis* L.) control. However, it has limited uses in some states due to peanut injury concerns [14] [15].

Since 2001, growers have been able to use flumioxazin herbicide for peanut weed control [16]. Flumioxazin is an *N*-phenylphthalimide and is classified as a PPO-inhibitor [17]. In a normal functioning chloroplast, protoporphyrinogen IX oxidase will oxidize protoporphyrinogen IX (PPGIX) into protoporphyrin IX

(PPIX) to eventually become chlorophyll or cytochromes. Once a PPO-inhibiting herbicide is absorbed, the oxidation process will not occur, thus resulting in a buildup of PPGIX that will undergo extraplastidic oxidation [18]. After oxidation, the newly formed PPIX will begin absorbing light, resulting in the formation of radical singlet oxygen that will cause cell membrane and pigment destruction, tissue decay, and eventual plant death. Numerous studies have established that cotton (*Gossypium hirsutum* L.) and peanut may sustain injury after emergence from flumioxazin applications [19] [20] [21] [22] [23]. Berger *et al.* [19] indicated that flumioxazin applied 15-day PRE cotton planting at 30 and 60 $g \cdot ha^{-1}$ resulted in significant stand loss compared to the nontreated control at one location. Stand counts were reduced up to 71% compared to the nontreated control due to a higher rainfall amounts at that location. Johnson *et al.* [22] reported peanut injury symptomology included overall stunting, necrotic lesions, and discolored petioles in peanut. The investigators applied flumioxazin up to 10 days after planting (DAP) and noted visual injury 26 DAP was up to 59%. Wilcut *et al.* [23] noted similar injury as Johnson *et al.* [22], in that flumioxazin symptomology included stunting and necrotic foliage, and also included delayed emergence. The investigators tested 8 Virginia type peanut cultivars and indicated that 7 were injured up to 28%, and one 45%. These investigators supported the claim by Berger *et al.* [19] that rainfall is a significant factor in crop injury.

In addition to large amounts of rainfall, cooler temperatures reduced plant metabolism, therefore intensifying crop injury [24]. English *et al.* [25] reported that as flumioxazin contacted the hypocotyl of developing peanut plants, lesions formed, which often prevented the cotyledon from opening, stunting seedling development, or becoming lethal to the plant. Though flumioxazin provides excellent early season weed control, under certain environmental conditions, flumioxazin will cause crop injury.

Though injury observed is transient and should not affect yield, physiological injury has not been measured in peanut. The purpose of this study is to quantify flumioxazin interactions in emergence, stand establishment, and measure photosynthetic efficiency analytically in leaves of peanut seedlings.

2. Materials and Methods

Peanut field experiments. Irrigated peanut field trials were conducted at the University of Georgia Ponder Farm near Ty Ty, GA (31.51 N, 83.65 W) and the Southwest Georgia Research and Education Center in Plains, GA (32.04 N, 84.38 W) in 2018 and 2019. Soil properties near Ty Ty consisted of 100% Tifton loamy sand (Fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 25% clay, 67% sand, 9% silt, and 0.3% organic matter in the 2018 location. The 2019 location consisted of Dothan loamy sand (Fine-loamy, kaolinitic, thermic Plinthic Kandiudults) and Fuquay loamy sand (Loamy, Kaolinitic, thermic Arenic Plinthic Kandiudults) for a soil composition of 22% clay, 70% sand, 8% silt, and 0.4% organic matter. The 2018 Plains location consisted of Faceville sandy loam (Fine, kaolinitic, thermic Typic Kandiudults), Ochlockonee local alluvium (Coarse-loamy, siliceous, acid, thermic Typic Udifluvents), and Tifton sandy loam (Fine-loamy, kaolinitic, thermic Plinthic Kandiudults) for a soil composition of 26% clay, 62% sand, 12% silt, and 0.4% organic matter. The 2019 location consisted of a Greenville sandy loam (clayey, kaolinitic, thermic Rhodic Kandiudults) and Tifton sandy loam (Fine-loamy kaolinitic, thermic Plinthic Kandiudults) for a composition of 35% clay, 57% sand, 8% silt, and 0.2% organic matter.

Experimental design was a split-split-plot with 4 replications. Main plots were PD to simulate one early planting and 2 on-time plantings. One subplot component was two different seed lots of Georgia 16HO peanut [26] with 75 (Low) and 90% (High) germination rates (Georgia Seed Development Association, Athens GA), each yr. The second subplot component was herbicide treatments of flumioxazin at 107 g·ai·ha^{-1} [27], diclosulam at 27 g·ai·ha^{-1} [28] and a nontreated control (NTC). Herbicide treatments were applied immediately after planting using TeeJet (TeeJet, Wheaton, IL) AIXR 11002 nozzles at 187 L/ha at 207 kPa. Herbicides were irrigated within 3 d of application to ensure proper herbicide movement into the soil if no rainfall had occurred. Planting dates in Ty Ty were April 9th, April 25th, May 8th; and April 12th, April 25th, May 9th, respectively for 2018 and 2019. Planting dates for Plains were April 20th, May 3rd, May 14th; and April 17th, May 1st, May 14th, respectively for 2018 and 2019. Weather data for each location across the entire study are in **Table 1**. The Plains location was planted in a single-row manner at 18 seed m^{-1} of row while Ty Ty was planted at 18 seed m^{-1} in a twin row pattern [11]. All experiments received a blanket application of pendimethalin PRE applied at 1067 g·ai·ha^{-1}. Plots at Ty Ty received an application of phorate insecticide applied at 2945 g·ha^{-1} both years. The Plains location received a POST treatment of dicrotophos insecticide at 140 g·ha^{-1}. All plots were maintained weed-free and under University of Georgia agronomic recommendations [10].

Numerous steps of photosynthesis were measured using the infrared gas analyzer LiCOR 6800 (LiCOR Biosciences, Lincoln, NE). These included the physiological parameters of net photosynthesis assimilation (A_{net}), electron transport efficiency (ETR), quantum yield of PSII (Φ_{PSII}), and stomatal conductance to water vapor, all of which were collected in this study. The LiCOR compares the mass flow per time of these gases and determines the net assimilation rate:

$$A_{\text{net}} = \frac{\mu_0 \left[c_0 - c_a \left(\frac{1-\omega_0}{1-\omega_a} \right) \right]}{s} \tag{1}$$

where A_{net} represents net carbon assimilation, μ_0 is the flow rate entering the leaf chamber, c_0 is the CO_2 concentration entering the chamber, ω_0 is H_2O entering the chamber, μ_a is the flow rate of air leaving the chamber, c_a is the CO_2 concentration leaving the chamber, ω_a is the H_2O leaving the chamber, and s represents the leaf area [29]. Quantum yield of PSII can be described by:

$$\Phi_{\text{PSII}} = \frac{F'_m - F_s}{F'_m} \tag{2}$$

Table 1. Plains and Ty Ty, GA weather data for peanut research grown in 2018 and 2019.

Location	Year	Month	Temperature[a]		Rainfall
			Maximum	Minimum	
			C		cm
Plains	2018	April[b]	22.9[c]	11.2	7.2
		May	29.2	17.9	20.2
		June	31.8	20.7	12.5
		July	32	21.6	14.1
		August	31.4	20.9	10
		September	32.7	21.1	8.1
		October	28.4	16.7	16.9
	2019	April	26.6	11.5	3.5
		May	31.4	18.4	4.0
		June	32.7	20.9	3.7
		July	33	21.5	18.5
		August	33	21.9	10.2
		September	33.8	19.9	0.1
		October	28	15.8	12.1
Ty Ty	2018	May	30.4	18.7	34.1
		June	32.8	21.6	33
		July	32.5	22.3	52.2
		August	32.4	21.9	36.1
		September	33.1	21.8	3.7
		October	31.3	19.9	0
	2019	May	31.9	19.1	4.4
		June	32.2	21.2	14.7
		July	33.3	21.8	8.8
		August	33.3	22.5	21.5
		September	33.3	20.1	0.4
		October	34.3	20.1	0

[a]Temperature is averaged across the entire month and rainfall is total amount. [b]Data collection began at 1st planting date and terminated on final harvest. [c]Weather data from University of Georgia Weather Network.

where F_m' represents the maximum fluorescence yield of PSII and F_s represents the minimum fluorescence yield of PSII [29]. ETR is determined by:

$$\text{ETR} : \Phi_{\text{PSII}} f Q \alpha_{\text{leaf}} \tag{3}$$

where Φ_{PSII} represents the quantum yield of PSII, f is the fraction of photons going to PSII, and α_{leaf} represents absorption at measurement wavelengths [29]. Finally, the stomatal conductance to water vapor is represented as GSW and is calculated by:

$$\frac{2}{\left(\frac{1}{g_{tw}}-\frac{1}{g_{bw}}\right)+\sqrt{\left(\frac{1}{g_{tw}}-\frac{1}{g_{bw}}\right)^2+\frac{4K}{(K+1)^2}\left(2\frac{1}{g_{tw}}-\frac{1}{g_{bw}}\right)\frac{1}{g_{bw}}}} \quad (4)$$

where g_{tw} is the total conductance to water vapor, g_{bw} is the boundary layer conductance to water vapor, and K is the stomatal ratio [29].

The gas analyzer was equipped with a MultiPhase Flash™ Fluorometer set to control the flow rate to leaf chamber at 400 μmol·s^{-1}, temperature set at leaf temperature, and set to measure 2 cm^2 of the clamped leaf. Readings were taken within 2 hours of solar noon in full sun conditions, between growth stages of V3 to R1 in 2018, and V3 to V6 in 2019 [30]. This measurement timing was chosen as ETR rates are at maximum rate and stability [31]. Physiological data collection readings were collected 2 minutes after leaf chamber was clamped onto the outermost, fully expanded top leaf, or after measured parameters were stabilized (**Table 2**). Stand counts from 1 of row were taken twice in 2018 and three times

Table 2. Physiological data collection timings in 2018 and 2019 for peanut at Plains and Ty Ty, GA.

Location	Year	Measurement[a]	Planting date 1[b]		Planting date 2		Planting date 3	
			Date	GDD[c]	Date	GDD	Date	GDD
Plains	2018	1	5/11	375	5/14	282	6/1	493
		2	5/12	404	5/17	356	6/5	599
		3	5/14	456	5/19	410	6/7	654
		4	5/17	530	6/1	750	6/24	1159
		5	6/1	868	6/5	857	6/25	1192
	2019	1	5/1	252	5/14	329	5/24	284
		2	5/6	372	5/15	346	5/28	422
		3	5/7	395	5/16	367	5/29	455
		4	5/14	556	5/21	507	6/3	614
Ty Ty	2018	1	5/4	389	5/16	490	5/19	332
		2	5/5	413	5/18	544	5/20	357
		3	5/7	459	5/19	575	5/22	409
		4	5/10	537	5/22	653	5/25	494
		5	5/16	704	5/25	738	5/30	631
	2019	1	4/27	251	5/6	271	5/22	361
		2	4/28	267	5/7	295	5/23	390
		3	4/29	306	5/8	322	5/24	420
		4	5/6	487	5/15	485	5/30	624

[a]Gas exchange and fluorescence measurements recorded using the LI-6800 infrared gas analyzer. [b]Planting dates for Plains were April 20th, May 3rd, May 14th; and April 17th, May 1st, May 14th, respectively for 2018 and 2019. Planting dates in Ty Ty were April 9th, April 25th, May 8th; and April 12th, April 25th, May 9th, respectively for 2018 and 2019. [c]Abbreviations: number of growing degree days, GDD.

in 2019. Plant width was collected by measuring the widest leaf-tip to leaf-tip of the plant, with 3 plants per plot. Inversion of each PD was determined by the Hull-Scrape Method described in Williams and Drexler [32]. Overall, there were 2208 to 2522 GDD accumulated across experimental planting dates and years. After several days of drying time, peanut pod yield was harvested using a small plot combine.

Data were subjected to analysis of variance (ANOVA) appropriate for the seed germination rate [2] by herbicides [3] by planting dates [3] in a factorial arrangement. ANOVA procedures were conducted using PROC GLIMMIX in SAS University Edition [33]. Means for the significant effects and interactions were separated using Tukey-Kramer HSD set at an $P < 0.05$. Data was analyzed by year, location, planting date (PD), and measurement GDD's for seed germination rate, herbicide treatments, and their interactions.

3. Results and Discussion

Significant herbicide by year interactions occurred, preventing the data from being analyzed across years. Therefore, data are presented across herbicide treatment and germination rate by GDD by PD for each year (**Figure 1** and **Figure 2**). A total of 4 (2019) or 5 (2018) measurements per PD were taken from growth stages V3 to R1 for each experiment.

Net Photosynthesis. Differences were first noted for PD 1 at 404 GDD in that flumioxazin treated plants had a higher A_{net} than the NTC, yet both were not different than the diclosulam treated plants in Plains (**Figure 1**). Differences were noted at the 456 GDD measurement in which flumioxazin treated plants from low germinating seed had a lower photosynthetic rate compared to the flumioxazin treated and diclosulam treated high germination seed plants. The remaining combinations were not different. Next, PD 3 only had differences at 465 GDD in that the flumioxazin treated plants noted a higher A_{net} than the other herbicides. This was also noted in herbicide by germination interactions. The flumioxazin treated plants from low germinating seed were higher than the diclosulam treated plants from high germinating seed and the NTC low germinating seed plants. All remaining treatments were not different.

Differences were noted at 459 GDD of PD 1 in that the flumioxazin treated plants were higher than the diclosulam treated plants, yet the NTC was not different from either herbicide treatment. This was also noted in the herbicide by germination interactions in which the flumioxazin treated high germination seed plants noted a higher A_{net} compared to the diclosulam treated plants with high germination, while both treatments were not different from any other combination. Additional A_{net} differences for the 2018 season in Ty TY were noted at 357 GDD of PD 3 in which the diclosulam treated plants were lower than the flumioxazin treated plants, while the NTC was not different from either herbicide treatment.

Finally, in 2019, PD 1 noted differences at 252 GDD in that the NTC plants had a higher A_{net} than the diclosulam treated plants, while the flumioxazin

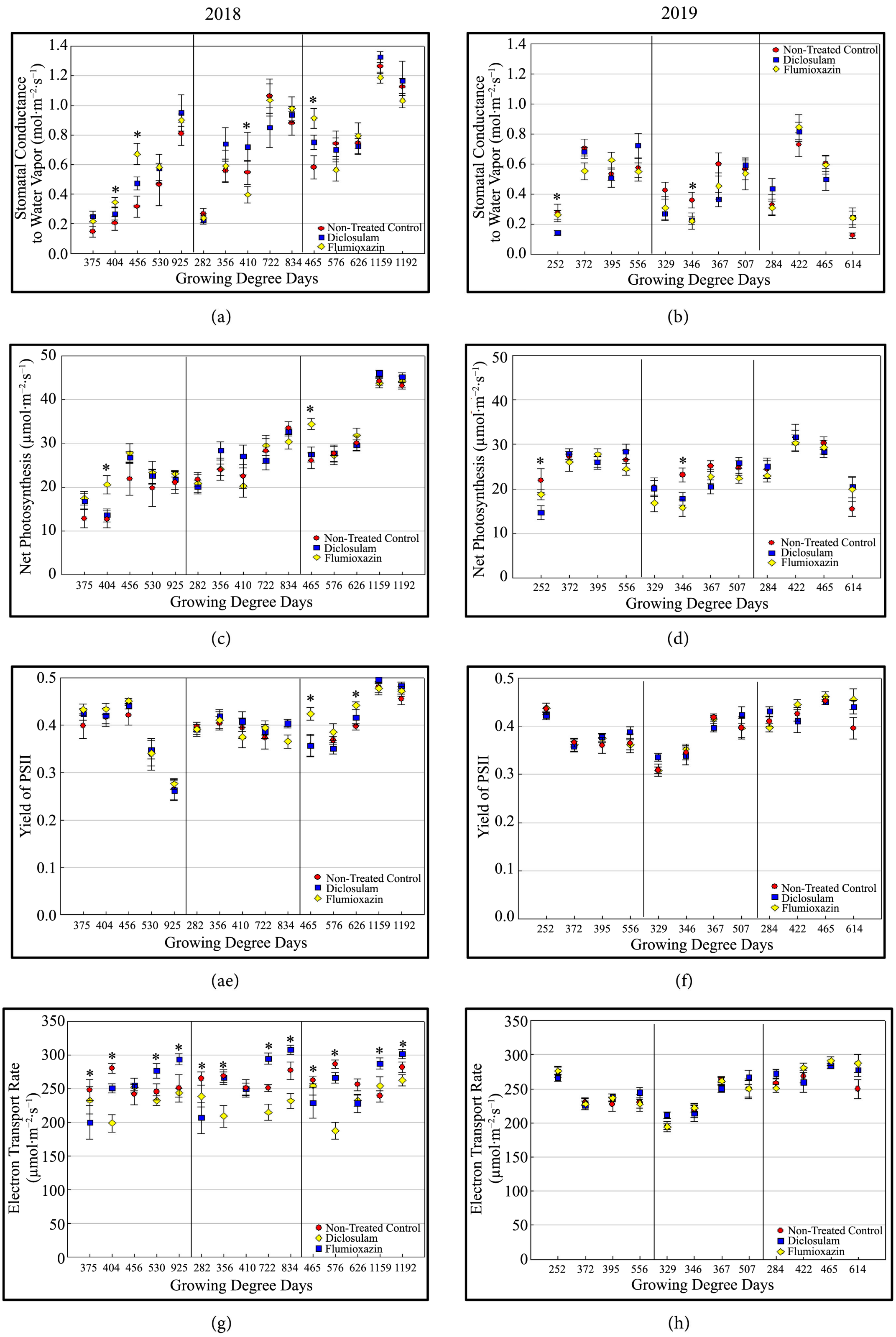

Figure 1. The response of stomatal conductance to water vapor (g_s), net photosynthesis (A_{net}), quantum yield of photosystem II (Φ_{PSII}), and electron transport rate (ETR) during the 2018 and 2019 growing season in Plains, GA. The asterisk indicates significant differences between the treatments at an alpha of 0.05 according to Tukey's HSD. The solid lines indicate each respective planting date with the first being on the left, second PD being in the middle, and the third planting date on the right.

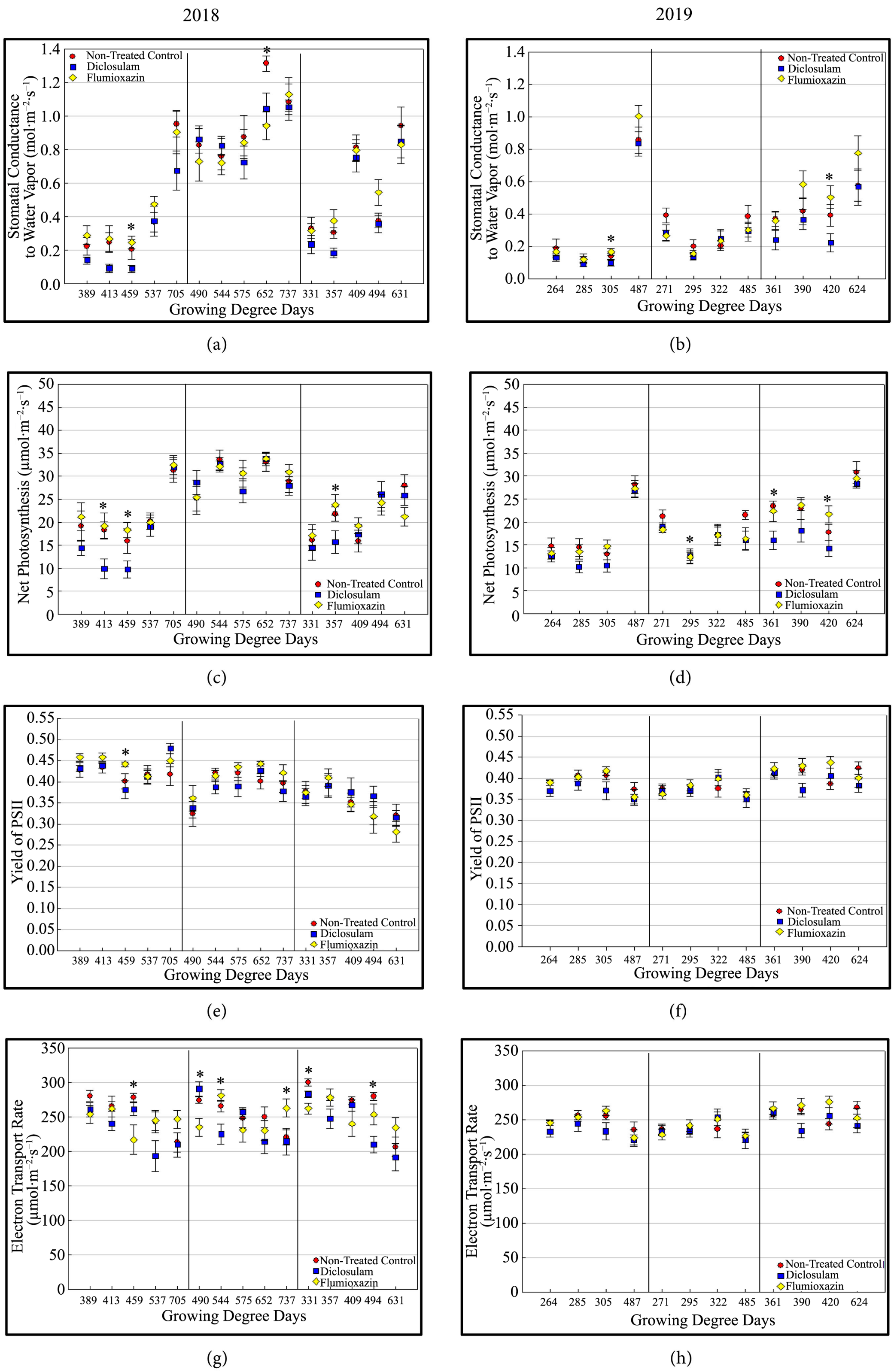

Figure 2. The response of stomatal conductance to water vapor (g_s), net photosynthesis (A_{net}), quantum yield of photosystem II (Φ_{PSII}), and electron transport rate (ETR) during the 2018 and 2019 growing season in Ty Ty, GA. The asterisk indicates significant differences between the treatments at an alpha of 0.05 according to Tukey's HSD. The solid lines indicate each respective planting date with the first being on the left, second PD being in the middle, and the third planting date on the right.

treated plants were not different from either in Plains (**Figure 2**). Differences were also noted at 372 GDD in that the high germination plants noted a higher photosynthetic rate compared to the low germination plants. Plant date 2 at 346 GDD indicated differences in the NTC plants had a higher A_{net} compared to the flumioxazin treated plants, while the diclosulam treated plants were not different from either.

At Ty Ty, for PD 2, after 271 GDD's there were differences in herbicide treatment, germination, and their interactions during the 2019 growing season (**Figure 1**). First, the NTC plants were higher than the flumioxazin treated plants, while the diclosulam treated plants were not different from either. The high germinating seed plants had a higher A_{net} compared to the low germinating seed plants. The interaction difference noted was NTC on high germinating plants were higher than all other treatment combinations. The final A_{net} difference was noted with the flumioxazin treated plants were higher than the diclosulam treated plants, while the NTC were not different from either at 420 GDD of PD 3.

Quantum Yield of Photosystem II. In 2018, quantum yield of PSII was affected at 456 GDD of PD 1 in which both germination and herbicide by germination differences were indicated at the Plains location (**Figure 1**). The flumioxazin treated and NTC low germination plants had a significantly higher PSII rate when compared to the NTC high vigor plants, while other germination by herbicides were not different (P = 0.028 and 0.046, respectively). Germination differences were noted at 925 GDD in which the plants from lower germinating seed indicated a higher PSII yield than the lower germination plants. During PD 3, the 626 GDD measurement indicated the flumioxazin treated plants had a higher PSII yield compared to the NTC, yet both herbicide treatments were not different than the diclosulam treated plants.

In 2018, differences in quantum yield of PSII were noted for PD 1 at 413 GDD in that the high germinating seed plants were higher than plants from low germinating seed, while indicating herbicide by germination differences as well in Ty Ty (**Figure 2**). High germinating seed plants treated with flumioxazin indicated a higher yield of PSII compared to the NTC low germinating seed plants, while all other combinations were not different from each other. Differences at 459 GDD were also noted with the flumioxazin treated plants being higher in PSII yield compared to the diclosulam treated plants, while the NTC plants were not different from either herbicide.

During the Plains 2019 growing season, differences were noted at the 395 GDD in which the flumioxazin treated high germinating seed plants, along with the NTC and diclosulam low germinating seed plants, had a higher PSII yield compared to the NTC high germinating seed plants (**Figure 1**). The diclosulam treated plants from high germinating seed and flumioxazin treated plants from low germinating seed were not different from any treatment. In 2019, differences were only noted at 487 GDD of PD 1, in that the high germination seed plants indicated a higher PSII yield compared to the low germination seed plants in Ty

Ty (**Figure 2**).

Electron Transport Rate. In 2018, the ETR rates in PD 1 at 375 GDD were different in that the plants from low germinating seed had a higher ETR compared to the high germinating seed plant rates for Plains (**Figure 1**). This translated into germination by herbicide interactions in that the high germinating seed plants treated with diclosulam had a lower ETR from all other treatment combinations and germination rates, except for the flumioxazin treated plants from low germinating seed. Differences were also recorded at 404 GDD of PD 1 with herbicide treatment differences. The flumioxazin treated plants indicated a lower ETR than the other herbicide treatments. This also translated into germination by herbicide interactions, which is described in **Table 3**. Finally, at 925 GDD, differences were noted with herbicides, germination rates, and interactions. As with the 530 GDD measurement, the diclosulam treated plants were higher than the other herbicide treatments. In addition, the high germination plants had a higher ETR than the plants from lower germination seed. The herbicide by germination interactions are noted in **Table 3**. The ETR at Plains for PD 2 showed treatment differences in that the NTC plants had a higher ETR than the diclosulam treated plants, yet both were not different than the flumioxazin treated plants at 282 GDD. Herbicide treatment by germination rate interactions is indicated in **Table 3**. At 356 GDD of PD 2, treatment and treatment by germination interactions were noted in that NTC and diclosulam treated plants had a higher ETR compared to the flumioxazin treated plants. Flumioxazin treated plants had a lower ETR compared to the other herbicide and germination interactions. Differences were noted for all herbicides, germination rates, and interactions at 722 GDD of PD 2 in Plains. All herbicide treatments were different from, while the plants from low germinating seed had a higher ETR than the plants from high germinating seed. The diclosulam treated plants with low germination were different from all treatment and germination rates except for the diclosulam treated plants form high germinating seed. Diclosulam treated plants from both germination rates were significantly higher than the flumioxazin treated plants from high germination seed. Finally, at 834 GDD of PD 2, all treatments were different from each other, with the flumioxazin treated plants indicating a lower ETR than the other herbicide treated plants. At the 576 GDD measurement of plant date 3, the flumioxazin treated plants recorded a lower ETR than all other treated plants. Herbicide by germination interactions were significant in that the flumioxazin treated plants from low germinating seed were different from all combinations, except for the flumioxazin treated plants from the high germinating seed. The flumioxazin treated plants from high germination seed were also not different from the diclosulam treated high germinating seed plants, while being different from the remaining herbicide and germination combinations. Finally, at the 1192 GDD measurement of PD 3, the diclosulam treated plants had a higher ETR compared to the flumioxazin treated plants, yet both were not different from the NTC plants. Herbicide by germination rate interactions indicated that the flumioxazin treated high germinating

Table 3. The effects on electron transport rate (μmol·m^{-2}·s^{-1}) and stomatal conductance to water vapor (mol·m^{-2}·s^{-1}) for seedlings established from variable quality GA-16HO seed and treated with different herbicides at Plains, GA for the 2018 growing season.

Plant Date[a]	GDD[b]	Treatment	Seed Germination	Estimate[c]	
				(μmol·m^{-2}·s^{-1})	
1	404	NTC	Low	288	a
ETR		NTC	High	273	a
		Diclosulam	Low	254	ab
		Diclosulam	High	247	abc
		Flumioxazin	High	205	bc
		Flumioxazin	Low	193	c
1	925	Diclosulam	High	304	a
ETR		NTC	High	290	ab
		Diclosulam	Low	284	ab
		Flumioxazin	Low	249	ab
		Flumioxazin	High	239	bc
		NTC	Low	212	c
2	282	Flumioxazin	High	277	a
ETR		NTC	High	275	a
		Diclosulam	Low	259	ab
		NTC	Low	255	ab
		Flumioxazin	Low	201	bc
		Diclosulam	High	154	c
				mol·m^{-2}·s^{-1}	
1	456	Flumioxazin	High	0.757	a
GSW		Flumioxazin	Low	0.587	ab
		Diclosulam	Low	0.574	ab
		NTC	Low	0.429	abc
		Diclosulam	High	0.372	bc
		NTC	High	0.198	c

[a]Planting dates for Plains wereApril 17th (1), May 1st (2), May 14th(3) in 2018. [b]Abbreviations. Growing degree days, GDD; Electron transport rate, ETR;stomatal conductance to water vapor, GSW; nontreated control, NTC. [c]Means with the same letter are not significantly different according to Tukey HSD set at alpha 0.05.

plants were different from the diclosulam treated plants of both germination rates and the NTC plants from high germinating seed. The other combinations were not different from each other.

Differences were also reported at 490 GDD of PD 2, in which the flumioxazin treated plants were lower than the other two herbicide treatments. These treatment differences did indicate treatment by germination interactions which are described in **Table 4**. During Ty Ty's PD 3, differences were indicated at 331 GDD as the flumioxazin treated plants had a lower ETR than the other 2 herbicide treatments. This was also noted in the herbicide by germination interactions in which the flumioxazin treated low germinating plants were different from all combinations, except the flumioxazin treated plants from high germinating seed. The flumioxazin treated high germination plants were not different from any herbicide and germination rate combination. No ETR differences were noted in Plains during the 2019 growing season (**Figure 1**). The only differences noted in Ty Ty during the 2019 growing season were PD 1 at 487 GDD in which the high germinating plants noted a higher ETR compared to the lower germination plants (**Figure 2**).

Stomatal Conductance to Water Vapor: During the 2018 growing season, Stomatal conductance to water vapor differences were noted at 404 GDD of Plains PD 1, with the flumioxazin treated plants having a higher GSW than the NTC, yet the diclosulam treated plants were not different from either treatment (**Figure 1**). These differences were also noted at 456 GDD of PD 1, but the differences translated into herbicide by germination differences also. These differences are described in **Table 3**. The Plains PD 3 measurement at 465 GDD noted herbicide and herbicide by germination interactions. The flumioxazin treated plants noted a higher GSW than the NTC plants, yet the diclosulam treated plants were not different from either. The flumioxazin treated plants from low germinating seed had a higher GSW rate than the NTC from high germinating seed. All other treatment and germination combinations were not different from each other.

Furthermore, differences were reported for Ty Ty's GSW at PD 1 at 459 GDD in that the flumioxazin treated plants had a higher rate than the diclosulam treated plants, while the NTC plants were not different from either for the 2018 growing season (**Figure 2**). Interaction differences indicated the diclosulam treated plants from high germinating seed were lower than the flumioxazin treated plants from high germinating seed, yet both were not different from all

Table 4. Herbicide treatment by seedling germination interactions of Ty Ty, Georgia planting date 2 at 490 GDD[a] for ETR of the 2018 growing season.

Treatment	Seed germination	Estimate ($\mu mol \cdot m^{-2} \cdot s^{-1}$)
Diclosulam	High	313[ab]
NTC	Low	281[ab]
Diclosulam	Low	269[abc]
NTC	High	268[abc]
Flumioxazin	Low	249[bc]
Flumioxazin	High	221[c]

[a]Abbreviations. Growing degree days, GDD; nontreated control, NTC. [b]Means with the same letter are not significantly different according to Tukey HSDset at alpha 0.05.

other herbicide and germination combinations. Herbicide differences were also noted at 357 GDD of PD 3 in which the flumioxazin treated plants were higher than the diclosulam treated plants, while the NTC plants were not different from either. The Plains 2019 growing season noted differences at 252 GDD of PD 1 in which the NTC and flumioxazin treated plants indicated a higher GSW than the diclosulam treated plants (**Figure 1**).

In Ty Ty during the 2019 growing season, GSW differences were noted at 305 GDD of PD 1 as the flumioxazin treated plants were higher than the diclosulam treated plants, yet the NTC were not different from either (**Figure 2**). This was also noted in the herbicide by germination interactions in which the flumioxazin treated plants from low germinating seed were higher than the diclosulam treated plants of both germination rates. The final differences were at 420 GDD of PD 3, in which the flumioxazin treated plants noted a higher GSW compared to the diclosulam treated plants, while the NTC plants were not different from either.

Stand Counts and Yield: Stand counts, plant width, and crop yield were also recorded and analyzed. Plant width in Plains for PD 3 in 2019 noted a difference as the NTC plants were wider than the flumioxazin treatment, with the diclosulam treated plants were not different from either herbicide treated plants. In 2018 and 2019, stand count and yield had no differences noted. Yield for the 2018 and 2019 growing seasons are described in **Table 5**. Though physiological differences were noted throughout both seasons, no trend was noted, and injury was transient.

In 2019, stand counts were unaffected by herbicide treatments at the Ty Ty location. Plant widths in 2019 were affected in PD 2 and 3. For plant date 2, flumioxazin was different than the remaining treatments by causing some stunting. Plant date 3 recorded that only the NTC was higher than flumioxazin, as both diclosulam and flumioxazin caused stunting. Yields for each PD noted no differences for both years, indicating that though some injury may be seen early in the growing season, the injury is transient. These data may differ from peanut grown under non-irrigated conditions, warranting to further this study under non-irrigated conditions to collect data for Georgia growers who may not use irrigation.

Physiological measurements at multiple planting times have been studied by Virk *et al.* [34] and noted A_{net} to be within 15 and 25 $\mu mol \cdot m^{-2} \cdot s^{-1}$ while ETR was within 97 and 267 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for peanut. Peanut physiological measurements recorded were within or near Virk *et al.* [34] findings validating each parameter. Photosynthesis is a process utilized by plants to grow and produce glucose and oxygen from water and carbon dioxide [35], driven by photosynthetically active radiation (PAR). PAR are light wavelengths between 400 and 700 nm [36]. Virk *et al.* [34] determined the physiological effects of multiple planting dates on peanut photosynthetic efficiency of first true leaves. The investigators noted that net peanut plant photosynthesis was unaffected by PD for any cultivar tested, though numerous photosynthetic reactions were affected. Planting date affected

Table 5. Peanut seed pod yield from 2018 and 2019 growing seasons in Ty Ty and Plains Georgia.

Location	Year	Treatment[a]	Seed Germination	Planting Date 1[b]	Planting Date 2	Planting Date 3
					kg/ha	
Plains	2018	Diclosulam	High	6136	6285	5743
		Diclosulam	Low	6281	5164	5343
		Flumioxazin	High	6715	6396	6221
		Flumioxazin	Low	6130	5003	6208
		NTC	High	6376	5510	5938
		NTC	Low	6270	5523	6250
	2019	Diclosulam	High	3936	5545	2432
		Diclosulam	Low	4107	5878	2437
		Flumioxazin	High	4303	5551	2450
		Flumioxazin	Low	4283	6140	2223
		NTC	High	3340	5866	2193
		NTC	Low	3598	5247	2450
Ty Ty	2018	Diclosulam	High	6449	6971	7026
		Diclosulam	Low	6473	6826	6423
		Flumioxazin	High	7083	7424	6813
		Flumioxazin	Low	6709	6401	6415
		NTC	High	7473	6948	7449
		NTC	Low	6831	6749	7140
	2019	Diclosulam	High	6483	6808	6141
		Diclosulam	Low	6172	7008	6398
		Flumioxazin	High	6265	6979	6356
		Flumioxazin	Low	6211	6708	6310
		NTC	High	6112	6949	5646
		NTC	Low	6242	6786	5660

[a]Abbreviations. Growing degree days, GDD; nontreated control, NTC; [b]Planting dates for Plains were April 20th (1), May 3rd (2), May 14th (3); and April 17th (1), May 1st (2), May 14th (3), respectively for 2018 and 2019. Planting dates in Ty Ty were April 9th (1), April 25th (2), May 8th (3); and April 12th (1), April 25th (2), May 9th (3), respectively for 2018 and 2019.

parameters such as electron transport rate and stomatal conductance to water vapor due to the plant being at different growth stages as temperatures fluctuated.

During both growing seasons, rainfall events occurred during, or shortly after peanut emergence. As the rain impacted the ground, splash bounced onto green leaf matter, while also carrying flumioxazin. The flumioxazin would then cause necrotic and chlorotic injury on the leaves. This injury was noted periodically to occur on the measured leaf, partially causing a reduction in photosynthesis. This is supported by Garry *et al.* [37] in which the investigators noted a reduction in photosynthesis as necrosis was noted on pea (*Pisum sativum* L.) leaves. It was not directly proportional to injury, though, in that photosynthesis was not noted to decrease as necrotic injury increased. Bigot *et al.* [38] indicated that as stomatal closure occurred from flumioxazin, photosynthesis was reduced, as well as plant transpiration. The investigators also noted that Φ_{PSII} was significantly reduced in grapevine leaves, due to alterations of other photochemicals, causing a higher number of closed PSII reaction centers. Though numerous physiological injuries occur, this injury was noted to not cause yield loss or reduced fiber quality in cotton [23]. This supports the findings of this study in that peanut yield for all treatments, with respect to planting dates and locations, were not different in each yr.

Other crops have shown sensitivity to POST flumioxazin applications. Wilcut *et al.* [23] reported rainfall splash bouncing up to 15 cm reaching green plant matter, did not cause yield loss or fiber quality reduction in cotton. Bigot *et al.* [38] performed a study measuring the physiological response of grapevine (*Vitis vinifera* L.) to flumioxazin applications. The investigators noted that net photosynthesis rate was significantly decreased when applied beginning at only one d after soil application, including plant death. Other PPO herbicides have been shown to cause injury when plants are subjected to adverse conditions during emergence. Miller *et al.* [39] reported that soybean sustained injury from saflufenacil when emerging during cold, wet conditions. These types of injury are common among crops that have had flumioxazin applied to them.

The 2018 and 2019 growing seasons had drastically different weather events which may have contributed to the varying measurements between yr. The increased rainfall during emergence in 2018 played a role in causing increased injury in the 2018 season, and not in the 2019 season as previously discussed. Though numerous differences were noted, no season long trend of injury was noted. The physiological injury noted during the measurements was transient and did not impact yield (data not shown). Though growers may see early season injury from flumioxazin in adverse weather conditions, this injury will likely not cause yield reductions.

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Conflicts of Interest

The authors declare no conflict of interest.

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