New Herbicide Strategies for Weed Management in Pumpkin and Soybean and Potato Vine Desiccation

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Abstract

Weed control and desiccation are routinely executed with herbicides. Potato vine desiccation facilitates harvest, improves skin set, and regulates tuber size. Saflufenacil, glufosinate, saflufenacil plus glufosinate, and carfentrazone plus glufosinate were compared to diquat applied at 43, 31, and 17% B potatoes; similar vine desiccation (14 days after treatment), skin set, and yield were noted amongst treatments. Residual herbicides are routinely used for weed control in pumpkin. Fluridone and acetochlor formulations applied preemergence were evaluated in direct-seeded pumpkin compared to other labeled herbicides. Fluridone resulted in total crop loss following heavy rainfall immediately after planting; less rainfall resulted in transient injury. Acetochlor formulations resulted in significant pumpkin injury (34 to 39%) 14 days after planting. *S*-metolachlor controlled weeds similar to acetochlor without significant injury. Palmer amaranth has developed resistance to six different herbicide modes of action. The weed grows rapidly and is best controlled $\leq$10 cm in height. To control glyphosate and ALS-resistant biotypes, fomesafen plus dicamba were applied at first postemergence (POST) to small Palmer amaranth (<5 cm, 0 d) and at simulated delays of 7, 14, 21, and 28 d. All plots received lactofen plus dicamba 14 days after first POST. Palmer amaranth control 14 days after first POST was 100% when delayed 0 or 7 d and 62% at the 28 day delay; control increased to 88% following lactofen plus dicamba applied second POST. Yield was significantly reduced when first POST was delayed 28 days at one location.

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General Audience Abstract

Herbicides effectively control weeds by either applying them to the soil prior to emergence or applying them to foliage. Herbicides are used for desiccation of potato vines to facilitate harvest, improve skin set, and regulate tuber size. Potatoes with tougher skin have a longer shelf life and are more resistant to disease. Potato grade classifications include size chef, A, and B potatoes. Size B potatoes hold the greatest value for red-skinned potatoes. Experiments were conducted in Virginia to evaluate saflufenacil, glufosinate, saflufenacil plus glufosinate, and carfentrazone plus glufosinate as desiccants compared to diquat applied at 43, 31, and 17% B potatoes. All desiccants resulted in similar vine desiccation 14 days after treatment, skin set, and yield. This research demonstrates that glufosinate and saflufenacil are effective alternatives to diquat for potato vine desiccation; however, further research is needed to evaluate the safety of saflufenacil applied to potatoes prior to harvest.

Soil applied herbicides are commonly used in pumpkin production. Fluridone and two acetochlor formulations, herbicides that effectively control troublesome weeds in other crops, were evaluated for pumpkin production in addition to fomesafen, ethalfluralin, clomazone, halosulfuron, and *S*-metolachlor. Fluridone and acetochlor formulations resulted in significant pumpkin injury early in the growing season and total crop loss was observed by fluridone in 2018. Fomesafen significantly reduced pumpkin

stand and yield. *S*-metolachlor, a member of the same chemical family as acetochlor, provided similar weed control without significant pumpkin injury. This research demonstrates that fluridone and acetochlor formulations are poor candidates for pumpkin production.

Palmer amaranth is a troublesome weed in soybean that grows rapidly and is resistant to many herbicides. Palmer amaranth is best controlled at a height of 10 cm or less, but timely applications are not always feasible. Fomesafen plus dicamba were applied to small Palmer amaranth (<5 cm, 0 day) and at simulated delays of 7, 14, 21, and 28 days. All treatments received lactofen plus dicamba 14 days after the initial postemergence. Palmer amaranth control 14 days after first postemergence was 100% when application was delayed 0 or 7 day whereas Palmer amaranth control was 62% when first postemergence was delayed 28 days. Lactofen plus dicamba applied second postemergence increased control to 88% when the first postemergence was delayed 28 days. Compared to nontreated plots, Palmer amaranth biomass was reduced 99% by all treatments. This research demonstrates that fomesafen plus dicamba followed by lacofen plus dicamba can be effective for rescue control of Palmer amaranth.

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Comparison of Diquat, Glufosinate, and Saflufenacil for Vine Desiccation of Dark Red Norland Potato

Abstract

Chemical desiccants are commonly used to regulate tuber size, strengthen skin, and facilitate harvest for potato production. Carfentrazone is labeled for potato vine desiccation; however, limited data are available. Saflufenacil, a PPO-inhibiting herbicide, is an effective desiccant in other crops. Field research was conducted in Virginia to evaluate carfentrazone and saflufenacil as a desiccant applied to Dark Red Norland potatoes. Desiccants consisted of diquat, glufosinate, saflufenacil, glufosinate plus carfentrazone, and glufosinate plus saflufenacil applied at 3 timings (DESIC-1, DESIC2, and DESIC-3) when size B potatoes averaged 43, 31, and 17%. Potato vine desiccation was more difficult at DESIC-1 and DESIC-2 due to immature vines. Diquat was the fastest vine desiccant across timings, 88% at DESIC-1 7 days after treatment (DAT). Glufosinate alone desiccated potatoes vines 65% at DESIC-1 7 DAT; however, glufosinate plus carfentrazone and glufosinate plus saflufenacil increased vine desiccation 8 and 16%, respectively. Vine desiccation by all treatments ranged 99 to 100% 14 DAT. Skin set by all desiccants and timings ranged between 21.2 and 22.6 Ncm. No significant differences in yield were noted amongst desiccants. When no desiccant was applied, tuber size increased at harvest, resulting in increased amounts of Chef and Size A potatoes and consequently a decrease in Size B potatoes which hold the greatest value. This research indicates that glufosinate and saflufenacil are suitable alternatives to diquat for potato vine desiccation; however, more research is needed to determine the safety of saflufenacil applied to potatoes prior to harvest for consumers.

Potato (*Solanum tuberosum* L.) acreage in the U.S during 2017 totaled 365,156 ha; producing over 20.3 billion kg of potatoes (USDA 2018). Red potato production represented 7% of the total U.S. potato production (Richardson 2017). Potato cultivar 'Red Norland' is produced more than any other type of red skin potato on the Canadian prairies (Waterer et al. 2011). The cultivar is also popular in the mid-Atlantic region, where it is produced for fresh market use (Kuhar et al. 2018).

Vine desiccation prior to potato harvest is a common practice in the U.S, giving producers the ability to regulate tuber growth and skin set, prevent spread of diseases, and facilitate more efficient harvest due to reduced vegetation. Vine kill may be executed via mechanical destruction or chemical desiccation (Boydston et al. 2018; Murphy 1968). However, chemical desiccation is the preferred method to regulate tuber size and skin strength (Kuhar et al. 2018; Murphy 1968). Vine desiccation timing is based on tuber size at desiccation and desired potato grade at harvest (Boydston et al. 2018). Furthermore, effective vine desiccation depends on vine maturity; mature vines are easier to desiccate than immature vines (Haderlie et al. 1989). Potato size, determined by diameter or weight, receive designations from smallest to largest of: Creamer, B, A, and Chef potatoes (USDA 2011). Producers of red skinned potatoes rely on vine desiccation to regulate tuber size with the overall goal to maximize B potato yield, which has the greatest economic value of all potato grades (Richardson 2017, Strange and Blackmore 1990; USDA 2011).

Skin set is the physiological process that occurs during the end of periderm maturation when tuber growth has ceased (Lulai and Orr 1993; Nolte and Olsen 2005). The periderm, or skin, prevents moisture loss and degradation by diseases and other pests (Nolte and Olsen 2005). In comparison to the periderm of the 'Russet Burbank' potato, the periderm of many potato cultivars, including the ‘Red Norland’, matures much slower (Lulai and Orr 1993). Sabba and Bussan (2012) evaluated skin set of Red Norland potatoes across multiple soil types and found no consistent relationship between skin set and soil type. However, relative humidity (RH) has been demonstated to influence skin set. Post-harvest skin set evaluations of ‘Norchip’ and ‘Norland’ cultivars at 50 and 95% RH (and constant temperature) demonstrated that a phenotypic increase in skin set could only be achieved at 50% RH (Lulai and Orr 1993). Time between vine desiccation and harvest also influences skin set. In a Washington study, ‘Bintje’ and ‘Ciklamen’ potato cultivars harvested 2 weeks after vine desiccation were injured 55% compared to 5.1% when harvest was delayed 4 weeks (Boydston et al. 2018).

Sulfuric acid is the most effective potato vine desiccant when compared with dinoseb, diquat, endothal, glufosinate, and pyraflufen ethyl; however, sulfuric acid is a highly corrosive substance that requires specialized equipment and extreme precaution (Boydston et al. 2018; Haderlie et al. 1989). Prior to 1986, dinoseb, a dinitrophenol compound, accounted for 70% of the herbicides used for vine desiccation in potatoes due to its effectiveness when applied in warm weather (Haderlie et al. 1989; Murphy 1968; Mutch et al. 1984). After dinoseb was removed from the market for health concerns in 1986, diquat became the standard potato vine desiccant (Haderlie et al. 1989; Pavlista 2001). Diquat and dinoseb desiccated potato vines 17 and 19%, respectively, one day after treatment (DAT) and 80 and 85%, respectively, 2 weeks after treatment (WAT) (Haderlie et al. 1989). Diquat, a member of the bypyridylium herbicide family, is a WSSA group 22 photosystem I electron diverter that is used as a desiccant in potato, oilseeds, and legumes (Anonymous 2015b). To improve efficacy of diquat by increasing spray coverage in dense foliage, at least 1100 L of water ha^{-1} is suggested (Anonymous 2015b). Diquat can result in incomplete stem and leaf desiccation, generally a result of incomplete spray coverage, which can result in tuber regrowth (Boydston et al. 2018; Misener and Everett 1981; Pavlista 2001). Diquat should never be applied to drought stressed potatoes and if a second application is required, a 5 day (d) waiting period between applications is recommended for improved vine coverage (Anonymous 2015b; Kuhar et al. 2018). Paraquat, also a member of the bypryidylium family of herbicides, has been shown to effectively desiccate potato vines; however, paraquat facilitates potato deterioration during storage and therefore is rarely used (Anonymous 2011).

Alternatives to diquat for vine desiccation include glufosinate, carfentrazone, and pyraflufen-ethyl (Kuhar et al. 2018). Glufosinate, a group 10 herbicide, is non-selective and controls many broadleaf and grass weeds. As a potato vine desiccant, harvest is legally required to be delayed at least 9 d following glufosinate application. Glufosinate is not labeled for potatoes harvested for seed production (Anonymous 2016a). Research comparing potato vine desiccation by glufosinate and diquat indicated glufosinate was not as effective as diquat at 3 and 7 DAT (Ivany and Sanderson 2001). However, at 14 DAT, vine desiccation by glufosinate was similar to diquat (Boydston et al. 2018). In another study comparing potato vine desiccants, glufosinate, diquat, sulfuric acid, carfentrazone, and pyraflufen-ethyl were evaluated. Glufosinate plus pyraflufen-ethyl more effectively desiccated potato vines than glufosinate alone. Harvest 2 WAT resulted in similar tuber skin injury among all treatments except glufosinate, which significantly reduced skinning injury. However, it is important to note that glufosinate treatments were applied several days prior to all other desiccatns to account for a slower vine death (Boydston et al. 2018). Glufosinate applied as a desiccant also resulted in a 6% increase of potatoes with a diameter of 35 to 70mm, which is categorized as a B potato. Glufosinate consequently reduced the number of potatoes >70mm, which are categorized as A potatoes and hold less economic value (Gonnella et al. 2009; USDA 2011).

Carfentrazone-ethyl and saflufenacil are both group 14, protoporphyrinogen oxidase (PPO) inhibiting herbicides (Anonymous 2015a; Anonymous 2016b). Carfentrazone is labeled for potato vine desiccation and requires complete coverage of the targeted plant to ensure successful desiccation; if a second application is required, 7 to 14 d must separate applications (Anonymous 2015a). Limited data exists for carfentrazone used as a potato vine desiccant (Kuhar et al. 2018). Saflufenacil is used as a harvest aid in cotton, oilseeds, and small grains and can be applied as a single application or sequential applications (Anonymous 2016b). Saflufenacil evaluated as a potential harvest aid in edible bean desiccated leaf, pod, and stem 87, 80, and 62%, respectively, desiccation was similar or greater than carfentrazone, diquat, and glufosinate 8 DAT (Soltani 2013). While saflufenacil is not currently labeled for potato vine desiccation and no published research exists, saflufencacil's history as a harvest aid has peaked interest in utilizing the herbicide for potato vine desiccation. While alternatives to diquat exist for potato vine desiccation, research on these alternatives is limited. The primary objective of this research was to compare potato vine desiccation by diquat to glufosinate and saflufenacil. The secondary objective was to evaluate the relationship between desiccant and timing and their collective effects on yield, grade, and skin set of red skinned potato.

Materials and Methods

Experiments were conducted at the Eastern Shore Agricultural Research and Extension Center near Painter, VA (37.58939 N, -75.82375 W) during 2017 and 2018. The soil type for both years included a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludults) with 1% organic matter and pH 6.4.

In both years, potato cultivar 'Dark Red Norland' was planted into fields prepared with one pass by a moldboard plow followed by a disc harrow followed by a field cultivator. Potatoes were planted on March 13, 2017 and March 30, 2018 on adjacent fields for a total of two site-years. The experimental design was a randomized complete block with treatments replicated three times. Plots consisted of 2 rows by 9 m, with rows spaced 91 cm apart.

Treatments consisted of a factorial arrangement of three vine desiccation timings by five herbicide treatments. Vine desiccation timings were initiated when percent B potatoes (kg B potatoes/kg total potatoes x 100) averaged 43 (DESIC-1), 31 (DESIC-2), or 17% (DESIC-3). Herbicide treatments consisted of diquat, glufosinate, saflufenacil, glufosinate plus carfentrazone, glufosinate plus saflufenacil, and no herbicide. Adjuvants tank mixed with treatments included diquat plus nonionic surfactant, glufosinate plus ammonium sulfate (AMS), saflufenacil plus methylated seed oil (MSO) and AMS, glufosinate with carfentrazone plus AMS, and glufosinate with saflufenacil plus MSO and AMS. All plots received paraquat plus *S*-metolachlor plus metribuzin following drag-off. Herbicide desiccation applications were made on June 1, 8, and 15 in 2017 and on June 7, 14, and 21 in 2018. Herbicide application rates and sources are for all herbicides listed in Table 1. All herbicides were applied using a propane-pressurized backpack sprayer equipped with flat-fan nozzles (XR11003 TeeJet Extended Range Flat spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 190L ha^{-1} at 165kPa.

Visible estimates of potato stem and leaf desiccation were evaluated on a 0 to 100% scale (Haderlie et al. 1989) and collected at 4, 7, and 14 DAT. Prior to harvest, potatoes from each plot were collected for a skin set evaluation. Evaluations were conducted via a torque meter measuring tuber skin set in newton-centimeters (Ncm). Plots were mechanically harvested at the conclusion of the season to determine potato yield. Following harvest, potatoes were graded into size categories: Chef, A, and B (USDA 2011). To determine total yield, Chef, A, and B potatoes from each plot were combined.

Data for vine desiccation, tuber skin set, and potato yield were subjected to ANOVA using the Fit Model procedure in JMP PRO 13 software (SAS Institute Inc., Cary, NC). Desiccation timing, desiccant treatment, and site-year were considered fixed effects, whereas replications were treated as random. Treatment means were separated using Fisher's protected LSD (P = 0.05) when appropriate.

Results and Discussion

The three-way interactions of year by desiccant by desiccation timing were not significant for any parameter recorded. Likewise, the two-way interactions of year by desiccant and year by desiccation timing were not significant for any parameter recorded. However, the two-way interaction of desiccant by desiccation timing was significant for potato vine desiccation. Therefore, all data are presented pooled over years and desiccation timings except for potato vine desiccation.

Potato vine desiccation. Potato vine desiccation was less successful earlier in the season at DESIC-1 and DESIC-2 when size B potatoes averaged 43 and 31%, respectively, compared to DESIC-3 when size B potatoes averaged 17% (Table 3). At the first two desiccation timings, 4 DAT, diquat was generally more effective than glufosinate alone and saflufenacil alone. Diquat works much faster than glufosinate; therefore, observation soon after application often favor diquat (Ivany and Sanderson 2001; Soltani et al. 2013) as was the case for this experiment. Diquat applied at DESIC-1 and DESIC-2 desiccated potato vines 80 and 81% 4 DAT, respectively; potato vine desiccation by glufosinate alone and saflufenacil alone was <71%. This trend remained 7 DAT. Potato vine desiccation by diquat applied at DESIC-1 and DESIC-2 desiccated potato vines 88 to 93% 7 DAT. Activity of glufosinate alone and saflufenacil alone 7 DAT was no better than 80%. However, by 14 d after DESIC-1 and DESIC-2 potato vine desiccation by all treatments ranged 99 to 100%. Later in the season, diquat applied at DESIC-3 continued to be more effective than glufosinate 4 DAT. However, potato vine desiccation by diquat and saflufenacil at this time was similar. Moreover, 7 and 14 d after DESIC-3, all treatments similarly desiccated potato vines 98 to 100%. Immature vines result in slower desiccation than mature vines that have begun to naturally deteriorate (Haderlie et al. 1989), which may explain treatment similarities later in the season when potato vines were more mature.

In general, saflufenacil improved initial potato vine desiccation by glufosinate. Glufosinate applied DESIC-1 desiccated potato vines 37 and 65% 4 and 7 DAT, respectively. At this same timing, saflufenacil added to glufosinate increased vine desiccation 35% 4 DAT and 16% 7 DAT. Similarly, glufosinate plus saflufenacil was more effective than glufosinate 7 d after DESIC-2 and 4 d after DESIC-3. It should be noted that glufosinate plus saflufenacil was equally effective as diquat at all rating intervals when applied at DESIC-1, DESIC-2, or DESIC-3. Similarly to saflufenacil, carfentrazone added to glufosinate improved initial potato vine desiccation by glufosinate alone, especially 4 d after DESIC-1 and 4 days after DESIC-3.

Potato leaf desiccation. Data analysis for potato leaf desiccation allowed for pooling across year and desiccation timing; therefore, data are presented by desiccant. Potato leaf desiccation was more uniform and complete than stem desiccation across timings and desiccants, similar to findings by Pavlista (2001). Furthermore, leaf desiccation efficacy was not dependent on vine maturity. Leaf desiccation by all treatments ranged 93 to 96% 4 DAT (Table 4).

Similarly, at 7 and 14 DAT all desiccants desiccated potato leaf 96% or greater. All treatments desiccated potato leaf 100% 14 DAT.

Skin set. Data for skin set allowed for pooling across year and desiccation timing; therefore, data are presented by desiccant. Similar to results for leaf desiccation, no differences in skin set were noted among desiccant treatments (Table 5). Skin set for all desiccants ranged 21.2 to 22.6 Ncm. Adequate rainfall resulted in appropriate soil moisture before and after vine desiccation to allow for effective skin set. Approximately 60% soil moisture at vine desiccation is required for adequate skin set (Nolte and Olsen 2005). At least 18 d separated vine desiccation and harvest, sufficient time for effective skin set. At shorter harvest intervals, differences in skin set may be observed (Boydston et al. 2018; Nolte and Olsen 2005). The extended harvest delay may also explain why the nontreated control yielded similar skin set to treated plots, as the vines were able to naturally senesce (Haderlie et al. 1989).

Yield. Data for potato yield and grade allowed for pooling across year and desiccation timing; therefore, data are presented by desiccant. Although, potato yield and grade for all desiccant treatments were statistically similar (Table 6), numerical trends were evident, especially between plots receiving a desiccant and plots not receiving a desiccant. In the absence of a desiccant, potatoes tended to be larger. Chef and Size A potato were 302 and 19654 kg ha^{-1}, respectively, compared to 112 to 266 kg ha^{-1} Chef and 17266 to 18547 kg ha^{-1} Size A in treated plots. Furthermore, % Chef potatoes in nontreated plots was greater than all desiccant treatments, except saflufenacil (Table 7). Similarly, % Size A potatoes in nontreated plots was approximately 71% compared to 67 to 69% in treated plots. Despite treatment differences between Chef and Size A potatoes, little differences were observed when comparing desiccants for Size B yield. Size B potatoes hold the greatest value amongst potato grades (Richardson

2017). Gonnella and others (2009) found that environmental conditions have a much greater impact on potato yield than desiccants. Rainfall for April, May, and June totaled 6, 22, and 6 cm, respectively, in 2017 and 5, 13, and 12 cm, respectively, in 2018. Overall, rainfall was adequate for the growing season and neither year experienced absence of rainfall >10 d. This may explain why differences in potato yield and grade were minimal. However, it should be noted that despite differences in yield and grade, desiccants can facilitate harvest and skin set when the harvest interval is short (Murphy 1968).

Diquat is the primary potato vine desiccant in the United States and research on alternatives is limited (Kuhar et al. 2018; Pavlista 2001). This research indicates that glufosinate and saflufenacil are suitable alternatives to diquat for potato vine desiccation. Although these products had slower desiccation activity, ultimately, vine and leaf desiccation and subsequent effects on skin set, potato yield and grade were similar to diquat. It should also be noted that saflufenacil improved initial potato vine desiccation by glufosinate. Saflufenacil, like other PPO-inhibiting herbicides, is a good candidate as a tank mix partner for glufosinate used for potato vine desiccation (Boydston et al. 2018; Soltani et al. 2013). However, more information on saflufenacil as a potato vine desiccant is needed, especially residue studies to determine mammalian safety of the herbicide applied prior to harvesting potato.

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Table 1. Herbicides and adjuvants used in experiments in Virginia, 2017 and 2018.[a]

Herbicides and adjuvants[b]	Trade names	Formulation Concentration	Application time	Application rate	Manufacturer
diquat	Reglone®	240 g ai L^{-1}	POST	561 g ai ha^{-1}	Syngenta Crop Protection
nonionic surfactant	Scanner®	100%	PRE and POST	0.25% (v v^{-1})	Loveland Products, Inc.
glufosinate-ammonium	Rely® 280	281g ai L^{-1}	POST	431 g ai ha^{-1}	Bayer CropScience
ammonium sulfate	Actamaster® Soluble Crystal Spray Adjuvant	100%	POST	10, 18 g L^{-1}	Loveland Products, Inc.
saflufenacil	Sharpen®	342 g ai L^{-1}	POST	50, 25 g ai ha^{-1}	BASF Chemical Co.
methylated seed oil	MSO® Concentrate with Leci-Tech®	100%	POST	1% (v v^{-1})	Loveland Products, Inc.
carfentrazone	Aim® EC	240 g ai L^{-1}	POST	56 g ai ha^{-1}	FMC Corp.
S-metolachlor		630 g ai L^{-1}			
metribuzin	Boundary® 6.5 EC	150 g ai L^{-1}	POST	1,367 g ai ha^{-1}	Syngenta Crop Protection
metribuzin	TriCor® DF	75%	POST	105 g ai ha^{-1}	United Phosphorus, Inc.
paraquat	Gramoxone® SL 2.0	240 g ai L^{-1}	PRE	561 g ai ha^{-1}	Syngenta Crop Protection

[a] Specimen labels for each product and mailing addresses and website addresses of each manufacturer can be found at http://www.cdms.net

[b] Ammonium sulfate applied at 10 g L^{-1} when applied with saflufenacil alone and 18 g L^{-1} when applied with glufosinate. Nonionic surfactant applied with paraquat and diquat.

Table 2. Planting and desiccation application dates for experiments.

Year	Planting date	PRE	DESIC-1[a]	DESIC-2	DESIC-3
2017	March 13	April 5	June 1	June 8	June 15
2018	March 30	April 23	June 7	June 14	June 21

[a] Size B potatoes averaged 43, 31, and 17% at DESIC-1, DESIC-2, and DESIC-3, respectively.

Table 3. Potato vine desiccation 4, 7, and 14 days after treatment (DAT) in Virginia in 2017 and 2018.[a,b,c]

	Desiccation timing																	
	DESIC-1[d]						DESIC-2						DESIC-3					
Desiccant[e]	4 DAT		7 DAT		14 DAT		4 DAT		7 DAT		14 DAT		4 DAT		7 DAT		14 DAT	
	%																	
Diquat	80	a	88	a	99	a	81	a	93	a	100	a	94	a	100	a	100	a
Glufosinate	37	c	65	cd	100	a	67	b	80	cd	100	a	76	b	98	a	100	a
Saflufenacil	62	b	63	d	99	a	71	b	76	d	100	a	93	a	99	a	100	a
Glufosinate + Carfentrazone	63	b	73	bc	100	a	73	ab	85	bc	100	a	89	a	99	a	100	a
Glufosinate + Saflufenacil	72	ab	81	ab	99	a	75	ab	88	ab	100	a	93	a	100	a	100	a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD at $P = 0.05$.
[b] Application dates are listed in Table 2.
[c] Data pooled over years.
[d] Size B potatoes averaged 43, 31, and 17% at DESIC-1, DESIC-2, and DESIC-3, respectively.
[e] Diquat, glufosinate, and carfentrazone were applied at 561, 431, and 56 g ai ha^{-1}, respectively. Saflufenacil was applied at 50 g ai ha^{-1} alone and 25 g ai ha^{-1} when mixed with glufosinate.

Table 4. Potato leaf desiccation 4, 7, and 14 days after treatment (DAT) in Virginia in 2017 and 2018.[a,b,c]

Desiccant[d]	4 DAT[d]	7 DAT	14 DAT
	———	%	———
Diquat	96 a	99 a	100 a
Glufosinate	94 a	99 a	100 a
Saflufenacil	93 a	96 b	100 a
Glufosinate + Carfentrazone	95 a	99 a	100 a
Glufosinate + Saflufenacil	96 a	99 a	100 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD at P = 0.05.
[b] Application dates are listed in Table 2. Size B potatoes averaged 43, 31, and 17% at DESIC-1, DESIC-2, and DESIC-3, respectively.
[c] Data pooled over years and across desiccation timings.
[d] Diquat, glufosinate, and carfentrazone were applied at 561, 431, and 56 g ai ha^{-1}, respectively. Saflufenacil was applied at 50 g ai ha^{-1} alone and 25 g ai ha^{-1} when mixed with glufosinate.

Table 5. Potato skin set in response to desiccant averaged over desiccation timing in Virginia in 2017 and 2018.[a,b,c]

Desiccant[d]	Skin Set	
	Ncm	
Diquat	22.4	a
Glufosinate	21.6	a
Saflufenacil	22.6	a
Glufosinate + Carfentrazone	21.2	a
Glufosinate + Saflufenacil	22.4	a
No desiccant	21.7	a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD at P = 0.05.

[b] Application dates listed in Table 2.

[c] Data pooled over years.

[d] Diquat, glufosinate, and carfentrazone were applied at 561, 431, and 56 g ai ha^{-1}, respectively. Saflufenacil was applied at 50 g ai ha^{-1} alone and 25 g ai ha^{-1} when tank mixed with glufosinate.

Table 6. Potato yield and grade in response to desiccant averaged across desiccation timing in Virginia in 2017 and 2018.[a,b,c]

Desiccant[d]	Chef[e]		Size A		Size B		Total	
	kg ha^{-1}							
Diquat	123	a	17885	a	7729	a	24790	a
Glufosinate	168	a	17266	a	7005	a	23705	a
Saflufenacil	266	a	18547	a	6959	a	24871	a
Glufosinate + Carfentrazone	112	a	18275	a	6989	a	24389	a
Glufosinate + Saflufenacil	190	a	18053	a	6799	a	24146	a
No desiccant	302	a	19654	a	7309	a	27266	a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Application dates listed in Table 2.

[c] Data pooled over years.

[d] Diquat, glufosinate, and carfentrazone were applied at 561, 431, and 56 g ai ha^{-1}, respectively. Saflufenacil was applied at 50 g ai ha^{-1} alone and 25 g ai ha^{-1} when tank mixed with glufosinate.

[e] Potatoes were graded according to USDA standards for potato grades (USDA 2011).

Table 7. Percent Chef, Size A, and Size B potato grades of total yield in response to desiccant averaged across desiccation timing in Virginia in 2017 and 2018.[a,b,c]

Desiccant[d]	Chef[e]		Size A		Size B	
	—————————————————— % ——————————————————					
Diquat	0.4	a	66.6	a	33.1	a
Glufosinate	0.5	a	67.9	a	31.6	a
Saflufenacil	0.9	a	69.7	a	29.4	a
Glufosinate + Carfentrazone	0.3	a	69.1	a	30.5	a
Glufosinate + Saflufenacil	0.7	a	69.3	a	30.1	a
No desiccant	0.9	a	70.7	a	28.4	a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD at P = 0.05.
[b] Application dates listed in Table 2.
[c] Data pooled over years.
[d] Diquat, glufosinate, and carfentrazone were applied at 561, 431, and 56 g ai ha^{-1}, respectively. Saflufenacil was applied at 50 g ai ha^{-1} alone and 25 g ai ha^{-1} when tank mixed with glufosinate.
[e] Potatoes were graded according to USDA standards for potato grades.

Evaluation of Pumpkin tolerance to Fluridone and Two Acetochlor Formulations

Abstract

Residual herbicides are routinely relied upon to control troublesome weeds, such as morningglory and pigweed species, in pumpkin production. Fluridone and acetochlor, group 12 and 15 herbicides, respectively, provide broad spectrum weed control when applied preemergence. Field research was conducted in Virginia and New Jersey to evaluate pumpkin tolerance and weed control to preemergence herbicides. Treatments consisted of fomesafen at 2 rates, ethalfluralin, clomazone, halosulfuron, fluridone, *S*-metolachlor, acetochlor emulsifiable concentrate (EC), acetochlor microencapsulated (ME), and no herbicide. A separate study specifically evaluated fluridone applied preemergence at 42, 84, 126, 168, 252, 336, and 672 g ai ha^{-1}. Fluridone, acetochlor EC, acetochlor ME, and halosulfuron injured pumpkin 81, 39, 34, and 35% 14 days after planting (DAP) when 0.7 and 2.6 cm of rain fell 2 and 3 DAP compared to 40, 8, 19, and 33% when 1.5 cm of rain fell 4 DAP. Fluridone controlled ivyleaf morningglory and common ragweed 91 and 100% 28 days after planting, respectively. Acetochlor EC controlled redroot pigweed 100%. Pumpkin treated with *S*-metolachlor yielded the greatest (10764 fruit ha^{-1}) despite broadcasting over the planted row; labeling requires a directed application to row-middles. Fluridone resulted in pumpkin injury >95% at rates 168 g ai ha^{-1} and greater; significant yield loss were noted when the herbicide was applied at rates greater than 42 g ai ha^{-1}. This research demonstrated that fluridone and acetochlor formulations are unacceptable candidates for pumpkin production.

United States pumpkin (*Cucurbita pepo* L.) production totaled 26,710 ha, with an average yield of 26,992 kg ha^{-1} during 2016, and generated approximately $207.66 million dollars (USDA 2016). Traditionally, in the mid-Atlantic region, pumpkin are direct-seeded into fields prepared with conventional-tillage or no-till into a winter small grains cover crop. Transplanting pumpkin plants into a plasticulture system is less popular (Bratsch 2009). For both systems, irrigation is used to sustain pumpkin growth during hot and dry periods (Bratsch 2009; Kuhar et al. 2018).

A 2006 survey found pigweeds (*Amaranthus spp.*), nutsedges (*Cyperus spp.*), and morningglories (*Ipomoea spp.*) species to be common and troublesome weeds in the southern U.S. (Webster 2006). These weeds are also problematic in pumpkin and other cucurbit crop production (Friesen 1978). Morningglory species, common ragweed (*Ambrosia artemisiifolia* L.), and pigweed species, can reduce pumpkin and cucumber yield up to 79 and 100%, respectively (Trader et al. 2007). Particularly troublesome are biotypes of Palmer amaranth (*Amaranthus palmeri* S. Wats.) resistant to glyphosate and ALS-inhibiting herbicides (Cahoon et al. 2015a; Kuhar et al. 2018), which are widespread throughout the southern U.S. (Heap 2018).

Pumpkin producers have traditionally relied upon ethalfluralin and halosulfuron applied preemergence (PRE) to control pigweed species (Kuhar et al. 2018). Ethalfluralin applied preplant incorporated (PPI) and PRE resulted in similar control of annual grass species (Prostko et al. 2001). An additional study noted field bindweed control increased up to 48% when bioherbicide treatments were applied PPI instead of PRE (Vogelgsang et al. 1998). However, due to risk of crop injury, ethalfluralin product labels restrict incorporation of ethalfluralin prior to planting pumpkin and other cucurbits (Anonymous 2016; Kuhar et al. 2018). Furthermore, no-till pumpkin production is increasing in popularity, resulting in greater dependence on PRE herbicides. A pre-mixture of ethalfluralin plus clomazone is also a popular residual choice for pumpkin producers, but like other ethalfluralin containing products, it may not be incorporated (Anonymous 2011). Furthermore, clomazone does not effectively control pigweed species. Clomazone alone controlled redroot pigweed 7% 21 DAT (Brown and Masiunas 2002). Halosulfuron, an ALS-inhibiting herbicide, has long been used PRE and postemergence (POST) in pumpkin (Trader et al. 2007). Applied PRE, halosulfuron effectively controls pigweed species (Brandenberger et al. 2005; Shaner 2014). Halosulfuron plus clomazone plus ethalfluralin applied PRE controlled yellow nutsedge (*Cyperus esculentus* L.) 38 to 70% (Trader et al. 2008). Previous research demonstrated halosulfuron applied PRE and PPI controlled pigweed species 95 and 97%, respectively (Soltani et al. 2014). Despite its effectiveness against pigweed species, halosulfuron does not effectively control ALS-resistant biotypes of Palmer amaranth (Kuhar et al. 2018). *S*-metolachlor is also labelled for use in pumpkin and has residual herbicide activity against pigweed species, other small-seeded broadleaf weeds, and most annual grasses (Anonymous 2015; Kuhar et al. 2018; Shaner 2014). Despite effectiveness of *S*-metolachor, pumpkin producers are reluctant to use it due to potential crop injury. *S*-metolachlor product labels restrict applications to inter-row or inter-hill areas with 30.5 cm of nontreated area directly over the row or 15.2 cm to either side of a planted hill to avoid *S*-metolachlor contact with un-germinated pumpkin seed (Anonymous 2015; Kuhar et al. 2018). More recently, no-till pumpkin producers have turned to fomesafen applied PRE to control Palmer amaranth (Kuhar et al. 2018). Fomesafen is a PPO-inhibiting herbicide with residual and POST herbicide activity (Kuhar et al. 2018; Shaner 2014). Fomesafen injury is transitory in several cucurbit crops including some pumpkin and squash (*Cucurbita moschata* Duchesne) (Peachey et al. 2012). Weeds controlled 92 to 100% by residual activity of fomesafen include pigweed species, morningglory species, common lambsquarters (*Chenopodium album* L.), common purslane (*Portulaca oleraceae* L.), hairy nightshade (*Solanum villosum* L.), and velvetleaf (*Abutilon theophrasti* Medik.) (Peachey et al. 2012; Shaner 2014). However, biotypes of Palmer amaranth have developed PPO-resistance throughout much of the mid-south as well as in North Carolina (Heap 2018; Place 2018). Due to the aforementioned reasons, producers are interested in additional residual herbicides for Palmer amaranth control and other weeds in pumpkin.

Fluridone, a group 12 herbicide, is a phytoene desaturase-inhibitor that provides residual broadleaf weed and annual grass control (Goggin and Powles 2014; Shaner 2014; Waldrep and Taylor 1966).Fluridone and acetochlor effectively control troublesome weeds such as Palmer amaranth; fluridone controlled Palmer amaranth PRE 100% 38 DAT (Braswell et al. 2016). Fluridone has been primarily used as an aquatic herbicide to control Hydrilla (*Hydrilla verticillate* L.f.*)* (Netherland and Jones 2015). Due to its persistence in the soil, there is concern that fluridone may carryover to subsequent crops (Cahoon et al. 2015b; Hill et al. 2016). However, fluridone carryover evaluated for rotational injury to cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench.], peanut (*Arachis hypogaea* L.), and soybean [*Glycine max* (L.) Merr.] resulted in minimal transient injury and did not affect yield (Cahoon et al. 2015b).

Acetochlor, a group 15 herbicide, is in the chloroacetamide family and acts as a seedling shoot inhibitor (Anonymous 2012; Jhala et al. 2015; Shaner 2014). Acetochlor has a half-life of roughly 27 days in soil (Oliveira et al. 2013). The emulsifiable concentrated (EC) formulation of acetochlor is labeled for use in corn and non-food perennial bioenergy crops (Anonymous 2012). The microencapsulated (ME) formulation of acetochlor releases the active ingredient more slowly than the EC formulation, providing greater safety to various crops (Fishel 2010).

Microencapsulated acetochlor is labeled for use in field corn, cotton, grain sorghum, and soybean (Anonymous 2014). Acetochlor applied PRE effectively controls pigweed species, other small-seeded broadleaf weeds, and most annual grasses (Cahoon et al. 2015a; Shaner 2014). Microencapsulated acetochlor applied PRE in peanuts controlled Palmer amaranth and Texas millet [*Urochloa texana* (Buckley) R. Webster] 95 and 90%, respectively (Grichar et al. 2015). Cahoon and others (2015a) noted acetochlor ME applied PRE controlled glyphosate resistant (GR) Palmer amaranth 84% 3 weeks after PRE, while cotton injury was minimal.

Pumpkin tolerance to fluridone and acetochlor is unknown. Residual effectiveness of fluridone and acetochlor against many troublesome weeds coupled with improved crop safety of acetochlor ME make these herbicides candidates for pumpkin production. The primary objective of this research was to evaluate weed control and pumpkin tolerance to fluridone, acetochlor EC, and acetochlor ME applied PRE compared to commercial standard residual herbicides.

Materials and Methods

Herbicide Comparison Experiment.

Experiments were conducted at the Eastern Shore Agricultural Research and Extension Center (ESAREC) near Painter, VA (37.58956 N, -75.82321 W) and a farm near Virginia Beach, VA (36.66752 N, -76.02975 W) during 2017. The experiment was conducted in two separate fields in Painter during 2018 and one location in New Jersey (40.20361 N, -74.55867 W). Soil descriptions for each location are listed in Table 8.

During 2017 pumpkin cultivar ‘Kratos’ (*Cucurbita maxima* Duchesne) (Syngenta Crop Protection, Greensboro, NC) was planted on June 13 at Painter and July 6 at Virginia Beach. During 2018 pumpkin cultivar ‘Cougar’ (*Cucurbita pepo* L.) (Hollmes Seed Co, Canton, OH) was planted on June 8 in both fields near Painter and pumpkin cultivar ‘Kratos’ was planted on

June 26 in New Jersey. Pumpkins were direct-seeded into fields prepared with one pass by a moldboard plow followed by a disc harrow followed by a field cultivator. The experimental design was a randomized complete block with treatments replicated four times. Pumpkin were planted 1 seed 0.9 m^{-1} in New Jersey and 1 seed 1.2 m^{-1} at all other sites. Plots were 1 row by 9 m, with rows spaced 229 and 183 cm at Painter and New Jersey, respectively, and 1 row by 8 m, with rows spaced 183 cm at Virginia Beach.

Treatments included fomesafen applied at two rates, ethalfluralin, clomazone, halosulfuron, fluridone, *S*-metolachlor, acetochlor EC, acetochlor ME, applied PRE immediately after planting. A nontreated check was included in each study for comparison. Herbicide rates and sources are listed in Table 9. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TTI 110015 Turbo TeeJet Induction flat spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 220 kPa in Virginia and (XR8004VS TeeJet Extended Range Flat spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 138 kPa in New Jersey.

Pumpkin stand was determined 14 days after planting (DAP) by counting all emerged pumpkin plants in each plot. Visible estimates of weed control, 0 to 100%, and pumpkin injury (growth reduction, chlorosis, and necrosis recorded separately plus a composite total injury rating) were collected according to (Frans et al.1986) 14, 28, 42, 56, and 90 DAP. During 2017, ivyleaf morningglory (*Ipomoea hederacea* Jacq.) and spurred anoda [*Anoda cristata* (L.) Schltdl.] were evaluated in Painter and pitted morningglory (*Ipomoea lacunosa* L.) was evaluated in Virginia Beach. During 2018, ivyleaf morningglory and yellow nutsedge were evaluated at field 1 in Painter, ivyleaf morningglory and spurred anoda were evaluated at field 2 in Painter, and common ragweed, redroot pigweed, and common lambsquarters were evaluated in New Jersey. Pumpkins were hand harvested, counted, and weighed to determine total fruit number, average fruit size, and total yield. Due to prolific late season rainfall and disease during 2017, the Virginia Beach site experienced nearly complete crop loss; therefore, yield was not collected at this location. Inadequate rainfall throughout the growing season during 2018 significantly reduced pumpkin growth in New Jersey; therefore, yield was not collected at this location either.

Data for weed control, pumpkin injury, and pumpkin yield were subjected to ANOVA using JMP PRO 13 software (SAS Institute Inc., Cary, NC). Treatment and location were considered fixed effects, whereas replications were treated as random. When treatment by location interaction was significant, data are presented by location. If the interaction was not significant, data are analyzed and presented pooled across locations. Treatment means were separated using Fisher's protected LSD ($P = 0.05$) when appropriate.

Fluridone rate study.

A separate study was conducted evaluating various fluridone rates on pumpkin tolerance. The experiments were conducted in two separate fields at Painter during 2018 and in New Jersey. Soil descriptions for each location are listed in Table 18.

During 2018 pumpkin cultivar 'Cougar' was planted on June 8 in both fields near Painter and pumpkin cultivar 'Kratos' was planted on June 26 in New Jersey. Pumpkins were direct-seeded into fields prepared with one pass by a moldboard plow followed by a disc harrow followed by a field cultivator. All plots were kept weed free throughout the season. The experimental design was a randomized complete block with treatments replicated four times. Plots were 1 row by 9 m, with rows spaced 229 and 183 cm at Painter and New Jersey, respectively.

Treatments included fluridone applied PRE immediately after planting at 42, 84, 126, 168, 252, 336, and 672 g ai ha^{-1}. A nontreated, weed-free check was included in each study for comparison through hand weeding and clethodim plus nonionic surfactant applied 13 DAP. Herbicide rates and sources are listed in Table 2. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TTI 110015 Turbo TeeJet Induction flat spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 220 kPa in Virginia and (XR8004VS TeeJet Extended Range Flat spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 138 kPa in New Jersey.

Pumpkin stand was determined 14 and 28 DAP by counting all emerged pumpkin plants in each plot. Visible estimates of pumpkin injury were collected as previously decribed 14, 28, 42, 56 DAP. Pumpkins were hand harvested as previously described.

Data for pumpkin stand, injury and yield were subjected to ANOVA using JMP PRO 13 software (SAS Institute Inc., Cary, NC). Treatment and location were considered fixed effects, whereas replications were treated as random. When treatment by location interaction was significant, data are presented by location. If the interaction was not significant, data were analyzed and presented pooled across locations. Quadratic regression of treatment means for all dependent variables was conducted.

Results and Discussion

Herbicide comparison experiment.

The two-way interactions of treatment by environment (site by year) were significant for pumpkin stand and yield; therefore, data for these parameters was presented by environment. Likewise, the two-way interactions of treatment by environment was significant for pumpkin injury; however, the three Painter environments responded similarly. As a result, data for pumpkin injury is presented pooled across Painter environments with data for Virginia Beach and New Jersey environments presented separately. Treatment by environment interactions for weed control were not significant, thus data for weed control was pooled across locations with corresponding weed species.

Pumpkin Response. Pumpkin injury varied across environments. Overall, pumpkin injury was greatest at Painter environments (Table 10). At Painter, fluridone, halosulfuron, acetochlor EC, and acetochlor ME were most injurious 14 DAP, injuring pumpkin 81, 35, 39, and 34%, respectively. Injury by all other treatments was less, ranging 6 to 14%. Injury by all treatments decreased 28 DAP, but a similar trend for injury was observed. At Painter, fluridone injured pumpkin 73% 28 DAP whereas halosulfuron injured pumpkin 19%, similarly to both formulations of acetochlor (9 to 15%). Pumpkin injury in response to fomesafen LR, fomesafen HR, ethalfluralin, clomazone, and *S*-metolachlor ranged 3 to 6% and was less than injury caused by fluridone and halosulfuron. Halosulfuron is capable of injuring cucurbit crops, especially on coarse textured soils with little organic matter (Trader et al. 2007), as was the case at Painter. However, halosulfuron injury is normally transitory and does not result in yield loss. Likewise, Trader and others (2008) reported halosulfuron applied PRE injured squash 42%, but injury was transient and did not result in squash yield loss. Rainfall shortly after planting may also explain increased injury observed at Painter. In 2018, Painter received 0.7 and 2.6 cm of rainfall 2 and 3 DAP, respectively, compared to 1.5 cm 4 DAP in 2017; New Jersey received 0.2 cm 2 DAP.

At Virginia Beach, acetochlor EC (53%) injured pumpkin greater than acetochlor ME (33%) 14 DAP. Similar to acetochlor ME, fluridone caused 26% pumpkin injury. At this location, pumpkin injury caused by all other treatments was minimal (0 to 2%). Pumpkin injury 28 DAP, alike to injury 14 DAP, was greatest in plots treated with acetochlor EC (26%). Again, acetochlor ME (14%) and fluridone (8%) were less injurious than acetochlor EC and injury by all other treatments was negligible (5% or less). Pumpkin injury by all treatments at New Jersey were statistically similar at 14 and 28 DAP. Injury ranged 8 to 40% and 11 to 27% at 14 and 28 DAP, respectively.

Despite being broadcast over the planted row, *S*-metolachlor resulted in a maximum pumpkin injury of 16% 14 DAP and 18% 28 DAP. Labels for *S*-metolachlor containing products require a 30 cm zone of nontreated soil directly over the row or 15 cm to each side of a planted hill or emerged pumpkins to avoid potential stand loss and pumpkin injury (Anonymous 2015; Kuhar et al. 2018). Results of this experiment confirm *S*-metolachlor is a useful tool for pumpkin weed management with minimal risk for crop injury.

Pumpkin stand in nontreated plots ranged 6 to 10 plants 9 m row^{-1} depending on environment (Table 11). At all three Painter environments, both rates of fomesafen reduced pumpkin stand 20 to 75%. Despite early season injury, Peachey and others (2012) reported fomesafen applied at 350 and 700 g ai ha^{-1} did not significantly reduce pumpkin yield. The only other treatments to reduce pumpkin stand compared to nontreated checks included halosulfuron at Painter, 2017 and fluridone at both Painter fields in 2018. More alarming, fluridone caused complete stand loss at Painter Field 1 and Field 2 during 2018. Similar to exaggerated injury observed at Painter environments compared to Virginia Beach and New Jersey, an initially heavy rainfall shortly after planting is the likely culprit for significant pumpkin stand loss caused by fluridone. At Virginia Beach (6 to 7 plants 9 m row^{-1}) and New Jersey (4 to 6 plants 9 m row^{-1}), no treatments reduced pumpkin stand relative to the nontreated. Moreover, no treatment difference were observed at these environments.

*Weed Control***.** Ivyleaf morningglory, spurred anoda, and yellow nutsedge were present in 4, 3, and 2 environments, respectively. Despite severe pumpkin injury, fluridone controlled ivyleaf morningglory well, 91% 28 DAP and 73% 42 DAP (Table 12). In a previous study, fluridone at 336 g ai ha^{-1} controlled pitted morningglory 86% 12 WAP (Hill et al. 2017). No other treatment controlled ivyleaf morningglory greater than 52 or 33% at 28 or 42 DAP, respectively. Morningglory species are particularly troublesome in cucurbit crops and no viable chemical options currently exist (Friesen 1978). Likewise, fluridone controlled spurred anoda 93% 28 and 42 DAP. Clomazone also controlled spurred anoda well, providing 92% control 28 DAP and 96% 42 DAP. Comparatively, spurred anoda control by fomesafen, ethalfluralin, halosulfuron, *S*-metolachlor, and acetochlor was 37% or less. Little information is available on the efficacy of fluridone for spurred anoda control. York (2018) reported fluridone + fomesafen controlled spurred anoda 80% or greater. Halosulfuron controlled yellow nutsedge 79 and 63% 28 and 42 DAP, respectively. Similar to yellow nutsedge control by halosulfuron, fomesafen HR, *S*-metolachlor, and acetochlor EC controlled the weed 62 to 70% 28 DAP and 56 to 69% 42 DAP. Yellow nutsedge is a common weed to vegetable production; therefore, control of this weed is more understood (Trader et al. 2008). Halosulfuron, fomesafen, and *S*-metolachlor have all been reported to provide >70% residual control of yellow nutsedge (Meyers 2017; Reed et al. 2016; Trader et al. 2008)

Common ragweed, redroot pigweed, and common lambsquarters infested only the New Jersey, 2018 environment. At this location, fluridone controlled common ragweed 100% 28 DAP and 83% 42 DAP (Table 13). At 28 DAP, fomesafen, halosulfuron, and acetochlor EC controlled common ragweed similarly to fluridone (64 to 100%) whereas all other treatment resulted in 0 to 15%. Similar trends for common ragweed control 42 DAP were observed with the exception of halosulfuron, which resulted in less control (38%) compared to fluridone. Cahoon and others (2017) reported similar common ragweed control by fluridone (93%) and fomesafen (82%) 8 weeks after PRE applications to cotton. In contrast to common ragweed control, redroot pigweed was controlled well by *S*-metolachlor, acetochlor, halosulfuron, and fomesafen, where 80 to 100% and 75 to 100% control was observed 28 and 42 DAP, respectively. Fluridone was only marginally effective against redroot pigweed, controlling the weed 63% 28 DAP and 58% 42 DAP. Braswell and others (2016) reported Palmer amaranth (also a member of the *Amaranthus* genus) control by fluridone to be good, 100% control 38 DAT. However, these researchers used 280 g ai ha^{-1} fluridone compared to 168 g ai ha^{-1} used in this experiment. Other researchers recommend 336 g ai ha^{-1} fluridone to effectively control Palmer amaranth when applied alone (York 2018). Furthermore, for more consistent Palmer amaranth control, labels for fluridone containing products require a tank mix partner when fluridone is applied at 221 g ai ha^{-1} or less (Anonymous 2018). Rates used in this experiment may explain why fluridone was not more effective controlling redroot pigweed. Clomazone controlled redroot pigweed poorly and confirms previous reports of inadequate Amaranthus spp. control by clomazone (Desmond and Brown 2002; Brown and Masiunas 2002). Fluridone controlled common lambsquarters 99 to 100%. At 28 DAP, clomazone (90%) and halosulfuron (98%) provided similar common lambsquarters control to fluridone. At 42 DAP, fluridone, controlled common lambsquarters 100%, compared to 69% by clomazone and halosulfuron.

Yield. Pumpkin yield was not collected at Virginia Beach due to severe disease nor at New Jersey due to lack of rainfall. During 2017, at Painter, pumpkin fruit and total yield ranged 6578 to 8970 fruit ha^{-1} and 47781 to 81445 kg ha^{-1}, respectively (Table 14). At this location, fruit and yield in all plots were similar, regardless of herbicide treatment. At both Painter environments during 2018, fluridone prohibited fruit production and therefore diminished pumpkin yield to 0 kg ha^{-1}. At Field 1, plots treated with *S*-metolachlor produced the greatest number of fruit (10764 fruit ha^{-1}) and yield (68302 kg ha^{-1}). Pumpkin yield response to acetochlor was variable. Only plots treated with acetochlor ME yielded similarly to *S*-metolachlor treated plots. All other plots, including those treated with acetochlor EC, produced less fruit (5023 to 8013 fruit ha^{-1}) and therefore less yield (30874 to 50215 kg ha^{-1}) than plots treated with *S*-metolachlor. At Field 2, all herbicide treatments resulted in 8372 to 10046 fruit ha^{-1} and 46339 to 62628 kg ha^{-1}, except halosulfuron and fluridone, which produced fewer fruit and less yield. As mentioned previously, fluridone resulted in complete yield loss at this environment. Comparatively, halosulfuron treated plots generated only 5382 fruit ha^{-1} and 32646 kg ha^{-1}. Trader and others (2007) noted that halosulfuron at 27 g ai ha^{-1} improved yield compared to nontreated pumpkin.

Fluridone rate study.

The two-way interaction of fluridone rate and environment was not significant for pumpkin stand and total injury, therefore data for these parameters was pooled across environments. Due to a significant fluridone rate by environment interaction for yield, data for yield is presented by environment.

Crop Response. Pumpkin stand and total injury were inversely related with fluridone rate. Pumpkin stand in nontreated check plots averaged 7 plants 9 m row^{-1} 14 DAP (Figure 1). The two lowest rates of fluridone had no effect on pumpkin stand. However, fluridone rates at or greater than 126 g ai ha^{-1} reduced pumpkin stand by as many as 6 plants 9 m row^{-1}. Total pumpkin injury followed a similar trend as pumpkin stand, fluridone rates $>$ 126 g ai ha^{-1} resulted in 100% injury (Figure 2). Although, less injury was observed 28 DAP, the same general trend for pumpkin response to fluridone rate existed.

Yield. Correspondingly with early season stand loss and pumpkin injury, pumpkin fruit and yield generally decreased as fluridone rate increased. Nontreated plots at New Jersey yielded 4903 fruit ha^{-1} (Figure 3). Only plots treated with 84 g ai ha^{-1} produced a similar amount of fruit. All other rates of fluridone reduced fruit 983 to 4093 fruit ha^{-1} compared to the nontreated check. Despite a lesser effect on fruit set, total pumpkin yield in New Jersey was reduced approximately 48 to 100% for fluridone rates > 126 g ai ha^{-1} (Figure 4). At Painter, nontreated plots resulted in 12857 fruit ha^{-1} and 84573 kg ha^{-1}. Only plots treated with 42 g ai ha^{-1} fluridone generated a similar number of fruit (12199 fruit ha^{-1}) and yield (76332 kg ha^{-1}) as nontreated plots. All other fluridone rates significantly decreased fruit set and total yield. Moreover, fluridone rates 168 g ai ha^{-1} or greater caused complete or near complete fruit and yield loss.

Surprisingly, fruit size (total yield/number of fruit) did not seemed to be influenced by fluridone rate. Fruit size at New Jersey averaged 5.8 kg $fruit^{-1}$ in nontreated plots whereas fruit in fluridone treated plots, except for the highest rate, ranged 3.5 to 6.9 kg $fruit^{-1}$ (data not shown). A similar trend was observed in Painter. In treated plots with surviving pumpkins, average fruit weight was 6.2 to 6.4 kg $fruit^{-1}$ compared to 6.6 kg $fruit^{-1}$ for pumpkins in nontreated plots. From this, it can be concluded fluridone reduces pumpkin yield primarily by interfering with fruit set. This is likely in response to severe early season growth reduction and chlorosis from which pumpkins were unable to recover.

Despite excellent weed control by fluridone, most notably ivyleaf morningglory, these data indicate pumpkin injury by fluridone is unacceptable. Fluridone rates greater than 42 g ai ha^{-1} resulted in significant yield loss. Moreover, fluridone rates needed to achieve consistent weed control (>221 g ai ha^{-1}) reduced pumpkin yield 75 to 100%. Acetochlor EC and acetochlor ME did not injure pumpkins to the extent of flurdione. However, early season injury caused by acetochlor, regardless of formulation, was observed. *S*-metolachlor, also a member of the chloroacetamide family of herbicides and currently labeled for pumpkin, was much safer than acetochlor. In addition, *S*-metolachlor and acetochlor control a similar spectrum of weeds. For these reasons, like fluridone, acetochlor EC nor acetochlor ME are not recommended for pumpkin production.

Acknowledgments

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Table 8. Soil descriptions for experiment sites in New Jersey and Virginia, 2017 and 2018.[a,b,c]

Location	Years	Soil Series	Soil texture	OM[d]	pH
				%	
Herbicide comparison experiment					
Painter	2017	Bojac[a]	Sandy loam	1	6.4
Virginia Beach	2017	Munden[b]	Sandy loam	2	6.5
Painter, Field 1	2018	Bojac	Sandy loam	1	6
Painter, Field 2	2018	Bojac	Sandy loam	1	6
New Jersey	2018	Othello[c]	Silt loam	1.8	6
Fluridone rate study					
Painter, Field 1	2018	Bojac	Sandy loam	1	6
Painter, Field 2	2018	Bojac	Sandy loam	1	6
New Jersey	2018	Othello[c]	Silt loam	1.8	6

[a] Coarse-loamy, mixed, semiactive, thermic Typic Hapludults.
[b] Coarse-loamy, mixed, semiactive, thermic Aquic Hapludults.
[c] Fine-silty, mixed, active, mesic Typic Endoaquults.
[d] Organic matter.

Table 9. Herbicides used in experiments in New Jersey and Virginia, 2017 and 2018.[a]

Herbicides	Trade names	Formulation concentration	Application time	Application rate	Manufacturer
Fomesafen	Reflex®	240 g ai L^{-1}	PRE	210 (low rate; LR) or 280 (high rate; HR) g ai h^{-1}	Syngenta Crop Protection
Ethalfluralin	Curbit® EC	360 g ai L^{-1}	PRE	631 g ai ha^{-1}	Loveland Products Inc.
Clomazone	Command® 3ME	360 g ai L^{-1}	PRE	289 g ai ha^{-1}	FMC Corp.
Halosulfuron	Sandea®	75% w/w	PRE	39 g ai ha^{-1}	Gowan Co.
Fluridone[b]	SP1182	144 g ai L^{-1}	PRE	various rates	SePRO Corp.
S-metolachlor	Dual Magnum®	914 g ai L^{-1}	PRE	1,068 g ai ha^{-1}	Syngenta Crop Protection
Acetochlor, emulsifiable concentrate (EM)	Harness®	839 g ai L^{-1}	PRE	1,264 g ai ha^{-1}	Monsanto Co.
Acetochlor, microencapsulated (ME)	Warrant®	359 g ai L^{-1}	PRE	1,262 g ai ha^{-1}	Monsanto Co.
Clethodim	Select Max®	116 g ai L^{-1}	POST	136 g ai ha^{-1}	Valent U.S.A LLC
Nonionic Surfactant	Scanner®	100%	POST	0.25% v v^{-1}	Loveland Products, Inc.

[a] Specimen labels for each product, mailing addresses, and website addresses of each manufacturer can be found at http://www.cdms.net.

[b] Fluridone applied at 168 g ai ha^{-1} for herbicide comparison experiments and at 42, 84, 126, 168, 252, 336, and 672 g ai ha^{-1} for fluridone rate study.

Table 10. Pumpkin visible injury 14 and 28 days after planting (DAP) in New Jersey and Virginia for herbicide comparison experiment, 2017 and 2018.[a,b]

	Painter[c]		Virginia Beach		New Jersey	
Herbicides	14 DAP	28 DAP	14 DAP	28 DAP	14 DAP	28 DAP
	———————————	———————	———————	%	———————	———————
Fomesafen LR[d]	8 c	4 c	0 c	0 c	20 a	15 a
Fomesafen HR[d]	14 c	6 c	0 c	0 c	25 a	21 a
Ethalfluralin	7 c	3 c	1 c	0 c	26 a	17 a
Clomazone	7 c	5 c	1 c	0 c	32 a	22 a
Halosulfuron	35 b	19 b	2 c	5 c	33 a	27 a
Fluridone	81 a	73 a	26 b	8 bc	40 a	17 a
S-metolachlor	6 c	3 c	2 c	0 c	16 a	18 a
Acetochlor EC[d]	39 b	15 bc	53 a	26 a	8 a	12 a
Acetochlor ME[d]	34 b	9 bc	33 b	14 b	19 a	11 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b]Application rates listed in Table 9.

[c] Pumpkin injury pooled across experiment sites in Painter.

[d] Abbreviations: LR, low rate; HR, high rate; EC, emulsifiable concentrate; ME, microencapsulated.

Table 11. Pumpkin stand 14 days after planting (DAP) in New Jersey and Virginia for herbicide comparison experiment, in Virginia and New Jersey in 2017 and 2018. [a,b]

	2017				2018					
Herbicides	Painter		Virginia Beach		Painter, Field 1		Painter, Field 2		New Jersey	
	Plants 9 m row^{-1}									
Fomesafen LR[c]	8	b	7	a	4	c	5	c	5	a
Fomesafen HR[c]	8	b	6	a	2	d	3	d	6	a
Ethalfluralin	10	a	6	a	8	ab	7	b	5	a
Clomazone	10	a	7	a	8	ab	7	b	6	a
Halosulfuron	8	b	6	a	9	a	9	a	6	a
Fluridone	9	ab	6	a	0	e	0	e	4	a
S-metolachlor	11	a	6	a	8	ab	7	b	5	a
Acetochlor EC[c]	9	ab	6	a	7	b	8	ab	5	a
Acetochlor ME[c]	10	a	6	a	9	a	8	ab	6	a
Nontreated check	10	a	6	a	8	ab	8	ab	6	a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at $P = 0.05$.
[b]Application rates listed in Table 9.
[c] Abbreviations: LR, low rate; HR, high rate; EC, emulsifiable concentrate; ME, microencapsulated.

Table 12. Ivyleaf morningglory, spurred anoda, and yellow nutsedge control by herbicides applied preemergence (PRE) for herbicide comparison experiment, 2017 and 2018. [a,b,c]

Herbicides	Ivyleaf morningglory 28 DAP		Ivyleaf morningglory 42 DAP		Spurred anoda 28 DAP		Spurred anoda 42 DAP		Yellow nutsedge 14 DAP		Yellow nutsedge 28 DAP	
	%											
Fomesafen LR[d]	37	bc	6	d	37	b	15	b	21	cd	20	c
Fomesafen HR[d]	47	bc	29	bc	21	b	6	b	62	ab	56	ab
Ethalfluralin	38	bc	22	bcd	31	b	18	b	21	cd	19	c
Clomazone	16	d	11	cd	92	a	96	a	29	cd	13	c
Halosulfuron	52	b	25	bcd	36	b	14	b	79	a	63	a
Fluridone	91	a	73	a	93	a	93	a	4	d	0	c
S-metolachlor	30	cd	33	b	29	b	6	b	68	ab	66	a
Acetochlor EC[d]	41	bc	23	bcd	31	b	20	b	70	ab	69	a
Acetochlor ME[d]	28	cd	18	bcd	34	b	20	b	44	bc	29	bc

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Application rates listed in Table 9.

[c] Data pooled across experiment sites where weeds were present. Ivyleaf morningglory control pooled across all experiment sites in NJ and Painter. Spurred anoda control pooled across Painter, 2017 and Painter field 2, 2018. Yellow nutsedge control pooled across experiment site in NJ and Painter field 1, 2018.

[d] Abbreviations: LR, low rate; HR, high rate; EC, emulsifiable concentrate; ME, microencapsulated.

Table 13. Weed control 14 and 28 DAP by herbicides applied preemergence (PRE) in New Jersey for a herbicide comparison experiment in 2018.[a,b]

Herbicides	Common ragweed 28 DAP		Common ragweed 42 DAP		Redroot pigweed 28 DAP		Redroot pigweed 42 DAP		Common lambsquarters 28 DAP		Common lambsquarters 42 DAP	
	%											
Fomesafen	64	a	45	ab	80	ab	75	a	23	cd	13	d
Fomesafen	65	a	56	ab	95	ab	95	a	31	cd	60	abc
Ethalfluralin	5	b	4	d	55	b	50	ab	38	cd	23	cd
Clomazone	15	b	10	cd	8	c	0	b	90	ab	69	ab
Halosulfuron	75	a	38	bcd	98	a	95	a	98	a	69	ab
Fluridone	100	a	83	a	63	ab	58	a	99	a	100	a
S-metolachlor	0	b	0	d	100	a	75	a	10	d	5	d
Acetochlor EC	80	a	55	ab	100	a	100	a	51	bc	43	bcd
Acetochlor ME	8	b	0	d	85	ab	75	a	38	cd	24	bcd

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b]Application rates listed in Table 9.

Table 14. Pumpkin yield in Virginia for a herbicide comparison experiment in 2017 and 2018.[a,b]

Herbicides	Painter, 2017				Painter, Field 1, 2018				Painter, Field 2, 2018			
	fruit ha^{-1}		kg ha^{-1}		fruit ha^{-1}		kg ha^{-1}		fruit ha^{-1}		kg ha^{-1}	
Fomesafen	6937	a	62622	a	5621	cd	35749	cd	8420	a	49168	a
Fomesafen	7774	a	72577	a	5023	d	30874	d	8372	a	47951	ab
Ethalfluralin	8970	a	81445	a	8013	bc	47499	bcd	10046	a	62628	a
Clomazone	8610	a	78006	a	6339	bcd	41867	bcd	7814	ab	46339	ab
Halosulfuron	8133	a	76920	a	7654	bc	41441	bcd	5382	b	32646	b
Fluridone	8491	a	80359	a	0	e	0	e	0	c	0	c
S-metolachlor	7415	a	59365	a	10764	a	68302	a	9089	a	56276	a
Acetochlor EC	7176	a	58279	a	7893	bc	50215	bc	10046	a	58094	a
Acetochlor ME	6578	a	47781	a	8611	ab	53599	ab	9089	a	56621	a
No herbicide	7654	a	53211	a	6937	bcd	41054	bcd	9089	a	51846	a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.
[b]Application rates listed in Table 9.

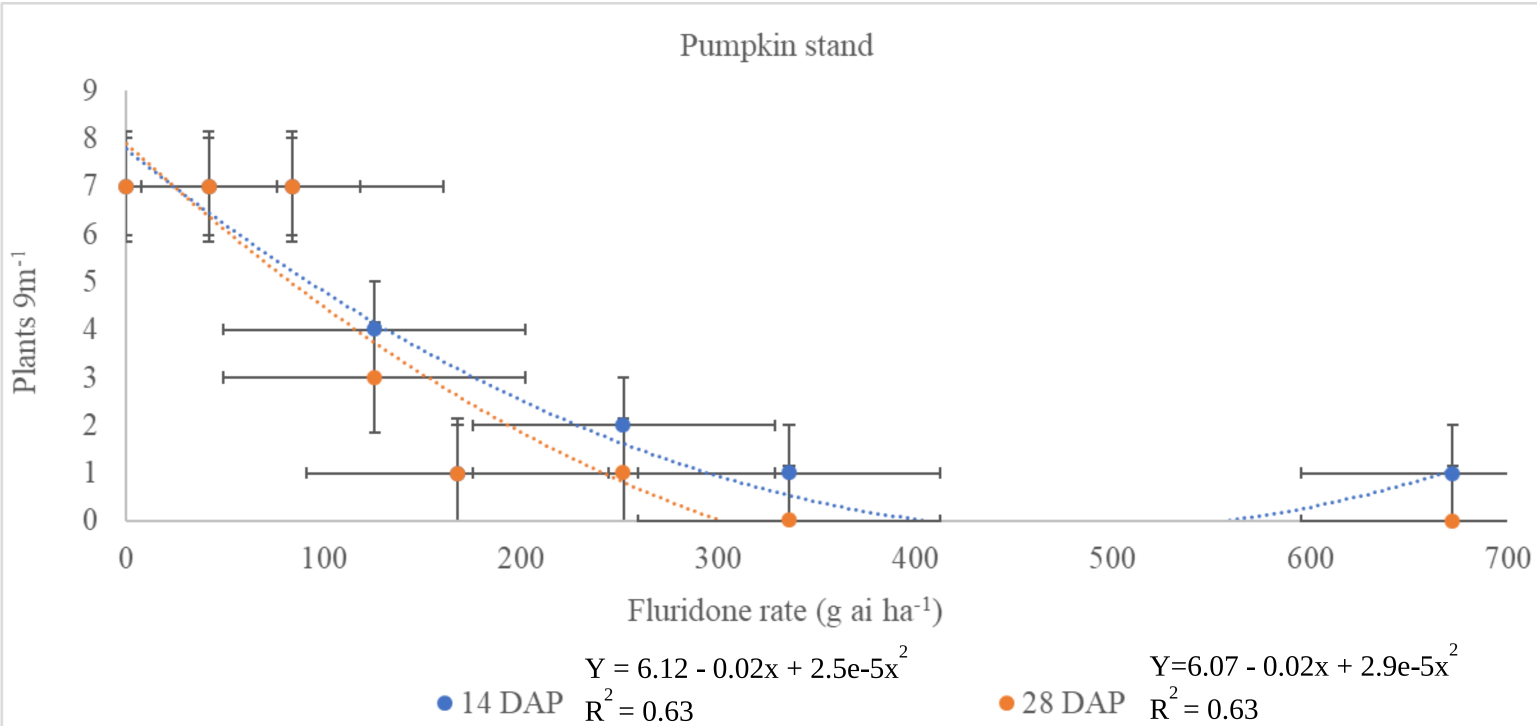

Figure 1. Pumpkin stand 14 and 28 days after planting (DAP) for fluridone rate experiment in New Jersey and Virginia. Application rates listed in Table 9. Pumpkin stand pooled across all experiment sites.

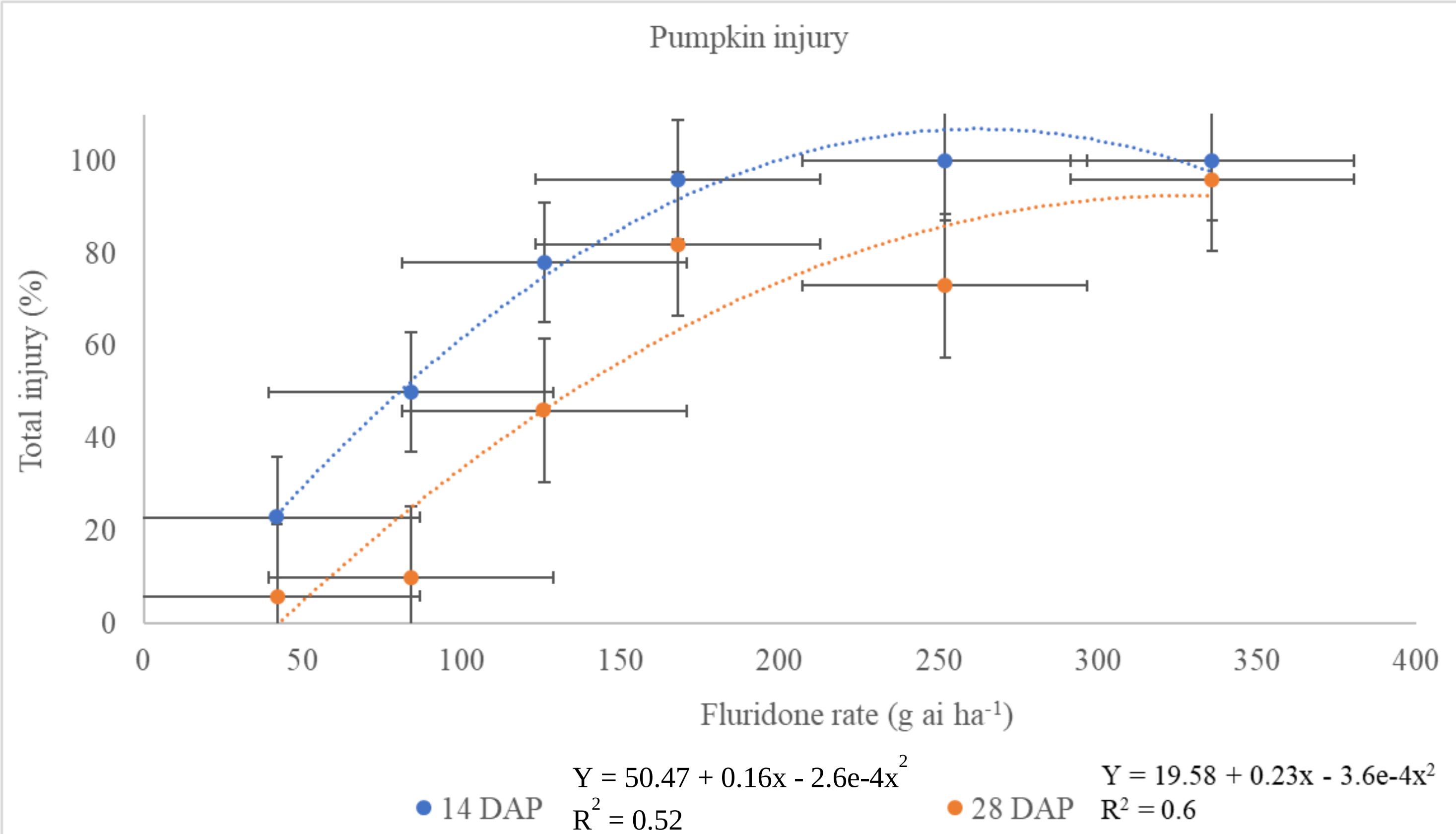

Figure 2. Pumpkin injury 14 and 28 days after planting (DAP) for fluridone rate experiment in New Jersey and Virginia. Application rates listed in Table 9. Pumpkin injury pooled across all experiment sites.

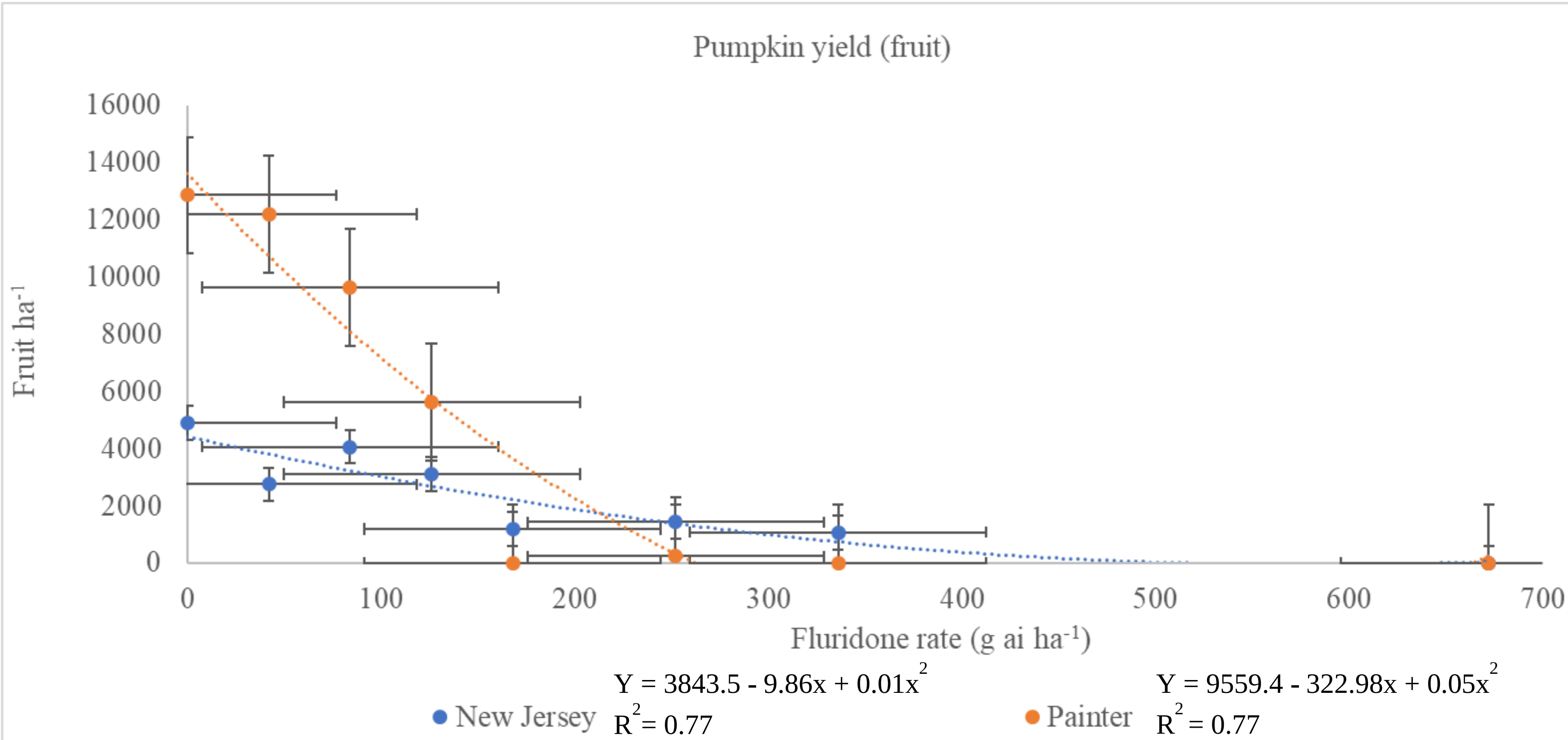

Figure 3. Pumpkin yield (fruit) for fluridone rate experiment in New Jersey and Virginia. Application rates listed in Table 9. Pumpkin yield (fruit) pooled across all experiment sites in Painter.

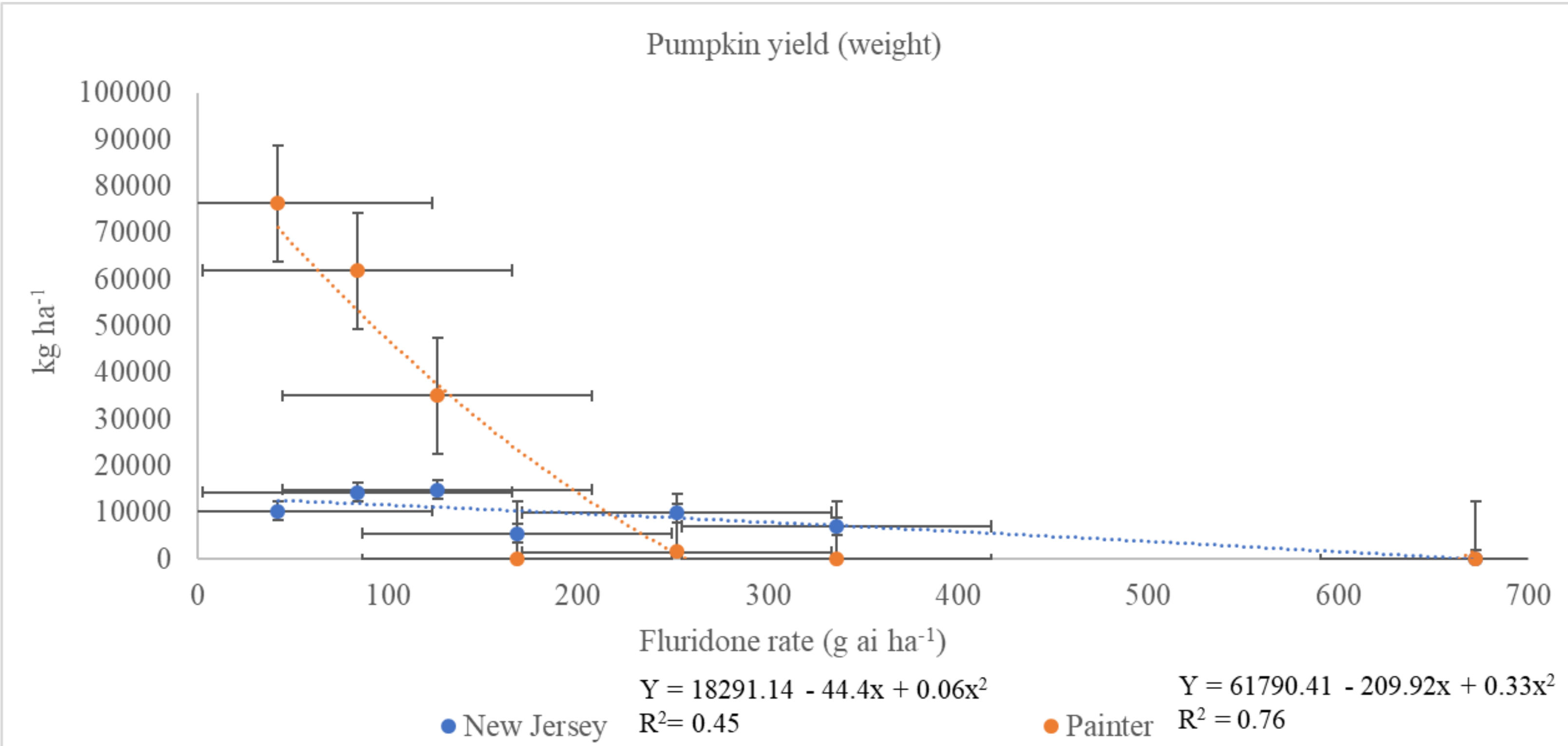

Figure 4. Pumpkin yield (weight) for fluridone rate experiment in New Jersey and Virginia. Application rates listed in Table 9. Pumpkin yield (fruit) pooled across all experiment sites in Painter.

Effect of Delayed Dicamba Plus Protoporphyrinogen Oxidase Inhibiting Herbicides on Palmer Amaranth (*Amaranthus palmeri*) Control and Soybean Yield

Abstract

Palmer amaranth is one of the most economically damaging weeds in the southern United States. Palmer amaranth control from PPO-inhibiting herbicides is most consistent when the weed is 10 cm or less in height; however, timely control is not always feasible. Field research was conducted to evaluate Palmer amaranth control by dicamba plus PPO-inhibiting herbicides when applied timely and when spray application is delayed. Treatments consisted of fomesafen at 423 g ai ha^{-1} plus dicamba at 561 g ae ha^{-1} applied timely to small Palmer amaranth (<5 cm; 0 d) and at simulated delays of 7, 14, 21, and 28 d after initial application. All treatments received lactofen at 219 g ai ha^{-1} plus dicamba at 561 g ae ha^{-1} 14 days after the first postemergence. *S*-metolachlor at 1,069 g ai ha^{-1} was applied to all treated plots 28 days after planting to prevent late Palmer amaranth emergence. When spray application was delayed 28 d, Palmer amaranth height averaged 55 cm. Palmer amaranth control 14 days after first postemergence was 100% when spray application was delayed 0 and 7 days. When first postemergence was delayed 14, 21, and 28 days Palmer amaranth control decreased to 86, 68, and 62%, respectively. Following lactofen plus dicamba applied second postemergence, Palmer amaranth was controlled 95, 91, and 88% late in the season, respectively. Soybean yield was significantly reduced 23% when first postemergence application was delayed 28 days for one location but no yield loss was observed at all other locations. This research demonstrates that fomesafen plus dicamba followed by lactofen plus dicamba can effectively control Palmer amaranth in rescue situations; however, every effort should be made for timely control to delay herbicide resistance.

Palmer amaranth *(Amaranthus palmeri* S. Wat.*)* is one of the most common, troublesome, and economically damaging agronomic weeds in the southern United States (Beckie 2011; Ward et al. 2013). Palmer amaranth, a herbaceous summer annual, can grow to a height of 2 meters and effectively competes with surrounding plants in hot and dry conditions (Keeley et al. 1987; Ward et al 2013). As a diaheliotropic plant, Palmer amaranth leaves track the sun, maximizing photosynthesis and increasing its competitiveness (Ehleringer and Forseth 1980). Palmer amaranth is also a prolific seed producer. Planted between March and June in monthly intervals, Palmer amaranth produced between 200,000 and 600,000 seeds per plant. (Keeley et al. 1987). Seed production from one herbicide resistant (HR) female Palmer amaranth could result in a predominantly resistant population within 2 years if sustained selection pressure is maintained on the species, emphasizing the need for a "zero-tolerance threshold" (Norsworthy et al. 2014). Soybean [*Glycine max* (L.) Merr.] yield is highly correlated with Palmer amaranth density and biomass. Klingaman and Oliver (1994) reported, soybean yield loss up to 68% at 10 Palmer amaranth plants per 1 m row.

Herbicides have been the primary weed control strategy in developed countries over the last half century (Davis and Frisvold 2017). Soybean cultivars were genetically modified with resistance to glyphosate and released in 1996 (Dill et al. 2007). Following commercialization of glyphosate-resistant (GR) soybean and their rapid adoption, glyphosate use exponentially increased due to convenience, effectiveness, and affordability it provided producers (Bonny 2016; Dill et al. 2007). Prior to GR Palmer amaranth confirmation in Georgia during 2004, glyphosate controlled Palmer amaranth well (Bond et al. 2006; Culpepper et al. 2006). Overdependence and repeated use of glyphosate resulted in GR Palmer amaranth biotypes in 28 states (Heap 2018). Continued selection pressure led to the development of Palmer amaranth biotypes with resistance to multiple modes of action, of which biotypes resistant to glyphosate and ALS-inhibiting herbicides are most widespread (Powles and Gaines 2016).

To control glyphosate and ALS-resistant Palmer amaranth, protoporphyrinogen oxidase (PPO) inhibiting herbicides are heavily relied upon (Braswell et al. 2016). Several PPO-inhibiting herbicides are registered for use in soybean (Flessner and Cahoon 2018). Some PPO-inhibiting herbicides may be applied as preemergence (PRE), postemergence (POST), or both PRE and POST (Umphres et al. 2018). Fomesafen, a PPO-inhibiting herbicide, provides consistent control of Palmer amaranth resistant to glyphosate and ALS herbicides (Cahoon et al. 2014; Flessner and Cahoon 2018). Salas-Perez and others (2007) reported fomesafen provided 97 to 100% control of 8 cm tall Palmer amaranth. Fomesafen can injure soybean when applied POST; however, injury is transient and does not result in yield loss (Beam et al. 2018; Belfry et al. 2016). Lactofen, another PPO-inhibiting herbicide labelled for use in soybeans, results in greater crop injury than fomesafen POST, but effectively controls small Palmer amaranth and other pigweed species (Harris et al. 1991). Lactofen controlled common waterhemp (*Amaranthus tuberculatas* Moq.*)* 86% 21 days after POST compared to 77% control by fomesafen (Hager et al. 2003). Sequential applications of lactofen can improve control of troublesome weeds. Sperry and others (2017) reported two applications of lactofen separated by 15 days controlled ALS-resistant Palmer amaranth 96%. To mitigate soybean injury and prevent yield loss from PPO-inhibiting herbicides, tolerant soybeans cultivars should be selected (Belfry et al. 2016).

Thirteen weed species world-wide have developed resistance to PPO-inhibiting herbicides. In the U.S., biotypes of tall waterhemp and common ragweed (*Ambrosia artemisiifolia* L.) have also developed resistance to PPO-inhibiting herbicides (Heap 2018). Palmer amaranth resistant to PPO-inhibiting herbicides was first confirmed in Arkansas (Salas et al. 2016) and has since been confirmed throughout much of the mid-South, including North Carolina (Heap 2018; Place 2018). The Gly-210 deletion mutation is responsible for PPO-resistance in Palmer amaranth. Cross resistance to all foliar applied PPO-inhibiting herbicides except saflufencacil is likely (Salas-Perez et al. 2017). In addition to glyphosate-, ALS-, and PPO-resistance, Palmer amaranth has also developed resistance to three other herbicide modes of action including, microtubule inhibitors, photosystem II inhibitors, and HPPD-inhibitors (Heap 2018; Ward et al. 2013). Alternative herbicide or other weed management techniques are required to control these HR weed biotypes.

Glufosinate resistant crops, coupled with glufosinate applied POST, has become a popular choice to control HR Palmer amaranth (Aulakh and Jhala 2015). To achieve optimal control of HR Palmer amaranth, timely glufosinate applications that achieve adequate spray coverage are required while the weed is small (10 cm in height or less) (Anonymous 2016; Whitaker et al. 2011). Unfavorable weather conditions and rapid growth of Palmer amaranth can make timely control difficult for producers (Crow et al. 2016).

Soybean cultivars introduced in 2017 have been genetically modified with resistance to both glyphosate and dicamba (Anonymous 2017; Flessner and Cahoon 2018). Dicamba plus glyphosate applied POST improved GR Palmer amaranth and GR horseweed control 60 to 100% and 85 to 98%, respectively, compared to glyphosate alone (Johnson et al. 2010). Corn producers have long used dicamba to control Palmer amaranth and other troublesome weeds. Crow and others (2016) reported dicamba plus diflufenzopyr POST provided >87% control of large (>20 cm) GR Palmer amaranth in corn (Crow et al. 2016). Additional research has revealed that sequential applications of dicamba plus glufosinate controls large (<71 cm) GR Palmer amaranth at least 87% in cotton (Vann et al. 2017a); however, this is not a legal tank mix nor is it currently an option in soybean production as soybeans with resistance to both dicamba and glufosinate are not commercially available (Anonymous 2017). However, tank mixtures of PPO-inhibiting herbicides plus dicamba are allowed on dicamba-resistant soybean (Budd et al. 2016). These tank mixtures will alleviate selection pressure for both PPO- and dicamba-resistance (Crow et al. 2016; Sosnoskie and Culpepper 2014). Furthermore, PPO-inhibiting herbicides plus dicamba may offer broader spectrum weed control and greater flexibility in POST timing to Palmer amaranth, similar to tank mixtures of glufosinate plus dicamba reported by Vann and others (2017b).

Considering the importance of controlling HR Palmer amaranth in soybeans, the threat of PPO-resistance, and the rapid growth of Palmer amaranth that can result in large weeds that are more difficult to control, research is necessary to identify methods of controlling large HR Palmer amaranth in soybean. The primary objective of this research was to evaluate Palmer amaranth control by dicamba plus a PPO-inhibiting herbicide when POST spray application is delayed. A secondary objective was to evaluate soybean yield response when initial POST timing is delayed and Palmer amaranth is allowed to compete with soybean early in the season.

Materials and Methods

Experiments were conducted at the Eastern Shore Agricultural Research and Extension Center near Painter, VA (37.59105 N, -75.82477 W) during 2017 and two separate fields during 2018 and at the Tidewater Agricultural Research and Extension Center near Suffolk, VA (36.68205 N, -76.75760 W) during 2017. Soil descriptions for each location are listed in Table 16.

During 2017, Roundup Ready 2 Xtend® soybean cultivars ‘AG48X7’ (Monsanto Company, St. Louis, MO) and ‘AG49X6' were planted at Suffolk and Painter, respectively. Planting dates are listed in Table 17. Soybean were planted into fields prepared by strip-tillage at Suffolk and with one pass by a moldboard plow followed by a disc harrow followed by a field cultivator at Painter. Soybean rows were spaced 76 cm with a seeding rate of 28 seeds m^{-1}. Artificial populations of Palmer amaranth were established at each location by sowing herbicide susceptible Palmer amaranth seed at an approximate rate of 3.2 million seed ha^{-1}on the soil surface immediately after planting. The experimental design was a randomized complete block with treatments replicated four times. Plot sizes were 4 rows by 6 m long, with 91 cm row spacing at Suffolk and 4 rows by 6 m long, with 76 cm row spacing at Painter.

Treatments consisted of fomesafen plus dicamba (POST 1) applied timely (0 d delay) to small Palmer amaranth (<2.5 cm) and at simulated spray delays of 7, 14, 21, and 28 days after the initial, 0 d delay application. All treatments received lactofen plus dicamba POST 2 14 d after POST 1. A nontreated check was included for comparison. All plots received *S*-metolachlor approximately 43 days after planting (DAP) to ensure no Palmer amaranth emerged later in the season. Clethodim was applied midseason to control annual grasses and reduce grass competition with soybean and Palmer amaranth. Herbicide application dates are listed in Table 17, and herbicide rates and sources are listed in Table 18. All herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TTI 110015 Turbo TeeJet Induction flat spray nozzles, TeeJet Technologies, Wheaton, IL) delivering 140L ha^{-1} at 220 kPa.

Visible estimates of Palmer amaranth control and soybean injury (growth reduction, chlorosis, and necrosis recorded separately) were collected according to Frans and others (1986) 7 and 14 days after first POST and 7 and 14 days after second POST. Soybean heights were collected 65 to 73 DAP. Soybean heights were also collected before harvest 140 to 184 DAP. Palmer amaranth fresh weights were also collected late in the season 88 to 127 DAP by collecting above ground biomass from 1 m^2 in nontreated check plots and from 3 row middles in all other plots. Plots were mechanically harvested and weighed using a small plot combine (Almaco SPC20, Almaco, Nevada, IA) to determine soybean yield. Harvest was unfeasible for all nontreated check plots due to weeds and yields were considered zero. Field 1 in Painter was not harvested due to significant deer herbivory.

Data for Palmer amaranth control, Palmer amaranth fresh weight, soybean injury, soybean height, and soybean yield were subjected to ANOVA using JMP PRO 13 software (SAS Institute Inc., Cary, NC). Data for nontreated checks were excluded from analysis, except in a separate analysis for which Dunnett's procedure (Dunnett 1955) was used to compare Palmer amaranth biomass in the nontreated checks to all other treatments. Treatment and location were considered fixed effects, whereas replications were treated as random. When treatment by location interaction was significant, data are presented by location. If the interaction was not significant, data are presented pooled across locations. Treatment means were separated using Fisher's protected LSD ($P = 0.05$) when appropriate.

Results and Discussion

Two-way interactions of herbicide treatment by environment (site year) were significant for soybean growth reduction, total injury and yield; therefore, data for these parameters are presented by environment. However, the two-way interactions of herbicide treatment by environment were not significant for soybean necrosis, soybean height, Palmer amaranth control, and Palmer amaranth biomass. Data for these parameters are presented pooled across environments.

Soybean response. Soybean growth reduction varied by environment and application timing. With the exception of Painter, Field 1 during 2018, fomesafen plus dicamba, regardless of first POST application delay, reduced soybean growth similarly 14 DA POST 1 (Table 19). At these environments, soybean growth reduction ranged 5 to 16% 14 DA POST 1. However, fomesafen plus dicamba applied at the initial POST (0 d first POST delay) reduced soybean growth 55% at Painter, Field 1 whereas the combination applied at all other timings caused 19 to 25% growth reduction 14 DA POST 1. Soybean response to fomesafen can be exacerbated by environmental conditions and soybean size at application (Belfry et al. 2016). Soybean stage averaged 1 trifoliate at the initial POST. This coupled with hot and humid conditions (96% relative humidity) at time of initial POST increased soybean response to fomesafen plus dicamba at Painter, Field 1. In general, fomesafen plus dicamba followed by (fb) lactofen plus dicamba applied earlier in the season reduced soybean growth greater than when POST applications were delayed, except Painter 2017. At Suffolk, two applications of a PPO-inhibiting herbicide plus dicamba when initial POST was delayed 0, 7, or 14 d reduced soybean growth 19 to 21% 14 DA POST 2. In comparison, initial POST delays of 21 and 28 d decreased soybean growth 10 to 13%, respectively. At Painter, Field 1, fomesafen plus dicamba fb lactofen plus dicamba caused 50 and 39% growth reduction when initial POST was delayed 0 and 7 d, respectively, whereas all other treatments reduced soybean growth 16 to 21%.

Soybean necrosis 14 DA POST 1 and 14 DA POST 2 was marginal (<13%) (Table 20). Fomesafen plus dicamba caused 7 to 10% necrosis regardless of timing. Similarly, fomesafen plus dicamba POST 1 fb lactofen plus dicamba POST 2 caused 6 to 13% necrosis 14 DA POST. Similar results were reported by Belfry and others (2016).

Ratings for total injury were a composite rating of growth reduction and necrosis. Trends for total soybean injury matched closely with trends for growth reduction and necrosis (Table 21). Similar to soybean growth reduction, fomesafen plus dicamba applied at 0 d first POST delay injured soybean 40% 14 DA POST 1; fomesafen plus dicamba fb lactofen plus dicamba injured soybean 33 and 29% 14 DA POST 2 when initial POST was delayed 0 and 7 d, respectively.

Visible difference in growth reduction, necrosis, and total injury observed earlier in the season did not influence soybean height 56 DAP or just prior to harvest. Soybean height ranged 67 to 72 and 81 to 87 cm 56 DAP and just prior to harvest, respectively, with no differences observed between treatments at either evaluation (Table 22). It is well documented that soybean recover from early season injury from PPO-inhibiting herbicides and yield is unaffected (Beam et al. 2018; Belfry et al. 2016).

Palmer Amaranth Control. Palmer amaranth control was similar across environment, allowing data to be presented pooled over environments. Palmer amaranth is more easily controlled by PPO-inhibiting herbicides when the weed is 10 cm or less in height (Harris et al. 1991; Salas-Perez et al. 2007; Sperry et al. 2017). Palmer amaranth height averaged 3, 10, 16, 46, and 55 cm when first POST was delayed 0, 7, 14, 21, and 28 d, respectively (Table 18). As expected, fomesafen plus dicamba applied at 0 and 7 d first POST delay controlled small (≤10 cm in height) Palmer amaranth well 14 DA POST 1 (Table 23). At these timings, fomesafen plus dicamba controlled Palmer amaranth 100%. Fomesafen plus dicamba was less effective controlling Palmer amaranth 14 cm or greater; the combination controlled Palmer amaranth 86, 68, and 62% when first POST was delayed 14, 21, and 28 d, respectively. Palmer amaranth grows rapidly (Horak and Loughin 2000) and can be difficult to control with contact herbicides when >10 cm in height (Anonymous 2016; Horak and Loughin 2000; Vann et al. 2017a; Whitaker et al. 2011). Glufosinate controlled Palmer amaranth >10 cm less than 70% 28 d after treatment (Crow et al. 2016). Vann and others (2017b) reported similar results when evaluating delayed glufosinate plus dicamba applications for Palmer amaranth control. In their study, glufosinate plus dicamba controlled 4 cm tall Palmer amaranth 99% 14 DA first POST. Comparatively, delays in first POST application of 14, 21, and 28 d resulted in approximately 87, 80, and 74% Palmer amaranth control, respectively. Moreover, dicamba can improve large Palmer amaranth control by contact herbicides (Vann et al. 2017a).

Comparable to Palmer amaranth control earlier in the season, fomesafen plus dicamba applied at 0 and 7 d delays fb lactofen plus dicamba 14 d later controlled 10 cm or less Palmer amaranth 100% 14 DA POST 2. Despite a second application of a PPO-inhibiting herbicide plus dicamba, Palmer amaranth control 14 DA POST 2 when first POST was delayed 0 or 7 d remained greater than when first POST was delayed 14, 21, or 28 d. However, when first POST was delayed 14, 21, or 28 d, lactofen plus dicamba applied 14 d later improved Palmer amaranth control. Lactofen plus dicamba improved initial Palmer amaranth control by fomesafen plus dicamba 9 to 26% 14 DA POST 2. Again, Vann and others (2017b) observed similar results; glufosinate plus dicamba applied after an earlier combination of the same herbicides increased Palmer amaranth control 12 to 15% when first POST was delayed 14 to 28 d. Furthermore, research conducted in North Carolina reported glufosinate plus dicamba fb glufosinate plus dicamba 14 d later was more effective controlling 16 to 23 cm Palmer amaranth than glufosinate fb glufosinate or dicamba fb dicamba (Vann et al. 2017a).

Trends in late season Palmer amaranth biomass mirrored visible estimates of Palmer amaranth control. Late season Palmer amaranth biomass in nontreated checks totaled 28413 kg ha^{-1} (Table 24). All treatments reduced Palmer amaranth biomass at least 99% compared to the nontreated check. When comparing treatments, Palmer amaranth biomass in plots where first POST was delayed 0 to 21 d was 0 to 17 kg ha^{-1} and significantly less than Palmer amaranth biomass produced when first POST was delayed 28 d (106 kg ha^{-1}). All treatments prevented Palmer amaranth seed production.

Yield. Despite early- and mid-season Palmer amaranth interference, yield loss was not always observed. Soybean yields were excellent and is reflective of plentiful rainfall during 2017 and 2018. Sixty-three and 68 cm of rainfall were observed at Suffolk and Painter, during the 2017 and 2018 growing season, respectively and is likely why yield response to early season Palmer amaranth interference was not as strong as previous research. In previous studies, 10 Palmer amaranth plants 1 m row^{-1} reduced soybean yield 68% (Klingaman and Oliver 1994). Soybean yield loss was observed at Painter during 2017. Soybean yielded 4069 to 4388 kg ha^{-1} when first POST was delayed 0, 7, 14, or 21 d. However, when first POST was delayed 28 d, soybean yield was reduced 19 to 24% compared to plots receiving the first POST earlier in the season. This environment had the greatest density of Palmer amaranth which may explain yield loss compared to other environments. At Suffolk and Painter, Field 2, soybean yield totaled 3869 to 4300 and 2908 to 3250 kg ha^{-1} and no difference among treatments were observed. Soybean yield results, especially at Painter during 2017, affirm the need to for timely Palmer amaranth control.

This research clearly shows combinations of fomesfen plus dicamba effectively controls small and marginally (10 to 16 cm) sized Palmer amaranth. It also demonstrates that fomesafen plus dicamba fb lactofen plus dicamba can be successful for rescue Palmer amaranth control when initial POST application is delayed from weather, equipment failures, or other setbacks. Furthermore, using two herbicide modes of actions with overlapping spectrums of weed control is an effective resistance management strategy (Diggle et al. 2003; Norsworthy et al. 2012; Powles et al. 1997) and will help delay resistance to PPO-inhibiting herbicides and dicamba. However, all efforts should be made to control weeds at appropriate sizes, which is also critical for delaying herbicide resistance and avoiding soybean yield loss (Neve and Powles 2005a; Neve and Powles 2005b; Norsworthy 2012; Norsworthy et al. 2012).

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Table 15. Soil descriptions for experiment sites in Virginia, 2017 and 2018.[a,b,c]

Location	Year	Soil series	Soil texture	OM[c]	pH
				%	
Painter	2017	Bojac[a]	Sandy loam	1	6.4
Suffolk	2017	Suffolk[b]	Loamy sand	0.9	6.3
Painter, Field 1	2018	Bojac	Sandy loam	1	6.4
Painter, Field 2	2018	Bojac	Sandy loam	1	6.4

[a] Coarse-loamy, mixed, semiactive, thermic Typic Hapludults.

[b] Fine-loamy, siliceous, semiactive, thermic Typic Hapludults.

[c]Organic matter

Table 16. Soybean planting, herbicide application, and soybean harvest dates in Virginia, 2017 and 2018.

Location	Year	Planting	Timely initial POST[a]	Soybean harvest
Painter	2017	June 12	June 28	November 16
Suffolk	2017	May 17	May 26	November 28
Painter, Field 1	2018	May 14	May 29	October 24
Painter, Field 2	2018	June 6	June 19	October 24

[a]Palmer amaranth height <5 cm for timely initial POST.

Table 17. Herbicides and adjuvants used in experiments in Virginia, 2017 and 2018.[a]

Herbicides and adjuvants	Trade names	Formulation Concentration	Application time	Application rate	Manufacturer
Dicamba	Clarity®	480 g ae L^{-1}	POST-1 and POST-2	561 g ae ha^{-1}	BASF Chemical Co.
Fomesafen	Flexstar®	226 g ai L^{-1}	POST-1	423 g ai ha^{-1}	Syngenta Crop Protection
Lactofen	Cobra®	240 g ai L^{-1}	POST-2	219 g ai ha^{-1}	Valent Corp.
Methylated seed oil	MSO® Concentrate with Leci-Tech®	100%	POST-1 and POST-2	1% v/v 140 g ai ha^{-1}	Loveland Products, Inc.
Clethodim	Select Max®	116 g ai L^{-1}	POST	136 g ai ha^{-1}	Valent Corp.
S-metolachlor	Dual MAGNUM®	914 g ai L^{-1}	POST	1,069g ai ha^{-1}	Syngenta Crop Protection

[a] Specimen labels for each product, mailing addresses, and website addresses of each manufacturer can be found at http://www. cdms.net.

Table 18. Soybean growth stage and Palmer amaranth heights at first POST application in Virginia, 2017 and 2018.[a]

First POST delay	Soybean growth stage	Palmer amaranth height	
		Maximum	Average
day	Number of trifoliate leaves	———cm———	
0	1	10	3
7	2	18	10
14	4	44	16
21	5	77	46
28	7	107	55

[a] Soybean growth stage and Palmer amaranth height averaged across experiment sites.

Table 19. Soybean growth reduction 14 days after (DA) POST 1 and 14 DA POST 2.[a,b]

First POST delay[c]	Painter, 2017		Suffolk, 2017		Painter, Field 1, 2018		Painter, Field 2, 2018	
	14 DA POST 1	14 DA POST 2	14 DA POST 1	14 DA POST 2	14 DA POST 1	14 DA POST 2	14 DA POST 1	14 DA POST 2
day	———	———	———	———	%	———	———	———
0	6 a	5 b	10 a	19 ab	55 a	50 a	14 a	12 a
7	5 a	8 b	5 a	21 a	20 b	39 a	14 a	12 a
14	8 a	10 b	16 a	20 a	25 b	22 b	11 a	6 a
21	14 a	6 b	13 a	13 bc	24 b	21 b	11 a	6 a
28	15 a	24 a	16 a	10 c	19 b	16 b	5 a	1 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.
[b] Application dates listed in Table 17. Soybean growth stages at application are listed in Table 19.
[c] Dicamba (561 g ae ha^{-1}) plus fomesafen (423 g ai ha^{-1}) were applied POST 1 followed by dicamba plus lactofen (219 g ai ha^{-1}) 14 days later (POST 2). All treated plots received *S*-metolachor (1069 g ai ha^{-1}) 28 days after planting for residual control of Palmer amaranth.

Table 20. Soybean necrosis 14 days after (DA) POST 1 and 14 DA POST 2.[a,b,c]

First POST delay[d]	14 DA POST 1		14 DA POST 2	
day	———————%———————			
0	7	a	8	b
7	10	a	13	a
14	9	a	9	b
21	9	a	8	b
28	8	a	6	b

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Application dates listed in Table 17. Soybean growth stages at application are listed in Table 19.

[c] Soybean necrosis data pooled across all experiment sites.

[d] Dicamba (561 g ae ha^{-1}) plus fomesafen (423 g ai ha^{-1}) were applied POST 1 followed by dicamba plus lactofen (219 g ai ha^{-1}) 14 days later (POST 2). All treated plots received *S*-metolachor (1069 g ai ha^{-1}) 28 days after planting for residual control of Palmer amaranth.

Table 21. Total soybean injury 14 days after (DA) POST 1 and 14 DA POST 2.[a,b]

	Painter, 2017		Suffolk, 2017		Painter, Field 1, 2018		Painter, Field 2, 2018	
First POST delay[c]	14 DA POST 1	14 DA POST 2	14 DA POST 1	14 DA POST 2	14 DA POST 1	14 DA POST 2	14 DA POST 1	14 DA POST 2
day	———	———	———	———	%	———	———	———
0	10 b	7 b	8 a	20 ab	40 a	33 a	11 ab	11 b
7	16 b	12 b	13 a	24 a	19 b	29 a	16 a	19 a
14	11 b	12 b	17 a	23 ab	22 b	18 b	12 ab	7 b
21	14 b	7 b	15 a	18 b	18 b	19 b	11 ab	7 b
28	30 a	19 a	18 a	9 c	15 b	14 b	4 b	4 b

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.
[b] Application dates listed in Table 17. Soybean growth stages at application are listed in Table 19.
[c] Dicamba (561 g ae ha^{-1}) plus fomesafen (423 g ai ha^{-1}) were applied POST 1 followed by dicamba plus lactofen (219 g ai ha^{-1}) 14 days later (POST 2). All treated plots received *S*-metolachor (1069 g ai ha^{-1}) 28 days after planting for residual control of Palmer amaranth.

Table 22. Soybean height 56 days after planting (DAP) and prior to harvest in Virginia, 2017 and 2018.[a,b,c]

First POST delay[d]	56 DAP	Harvest
day	cm	
0	72 a	83 a
7	68 a	87 a
14	69 a	87 a
21	71 a	82 a
28	67 a	81 a

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Application dates listed in Table 17. Soybean growth stages at application are listed in Table 19.

[c] Soybean height pooled across experiment sites 56 DAP and just prior to harvest.

[d] Dicamba (561 g ae ha^{-1}) plus fomesafen (423 g ai ha^{-1}) were applied POST 1 followed by dicamba plus lactofen (219 g ai ha^{-1}) 14 days later (POST 2). All treated plots received *S*-metolachor (1069 g ai ha^{-1}) 28 days after planting for residual control of Palmer amaranth.

Table 23. Palmer amaranth control 14 days after (DA) POST 1 and 14 DA POST 2 in Virginia, 2017 and 2018.[a,b,c]

First POST delay[d]	14 DA POST 1		14 DA POST 2	
day	——%		——	
0	100	a	100	a
7	100	a	100	a
14	86	b	95	bc
21	68	c	91	cd
28	62	d	88	d

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Application dates listed in Table 17. Palmer amaranth sizes at application are listed in Table 19.

[c] Palmer amaranth control pooled across experiment sites.

[d] Dicamba (561 g ae ha^{-1}) plus fomesafen (423 g ai ha^{-1}) were applied POST 1 followed by dicamba plus lactofen (219 g ai ha^{-1}) 14 days later (POST 2). All treated plots received *S*-metolachor (1069 g ai ha^{-1}) 28 days after planting for residual control of Palmer amaranth.

Table 24. Palmer amaranth biomass and soybean yield in Virginia, 2017 and 2018.[a,b]

First POST delay[c]	Palmer amaranth biomass		Yield					
			Painter, 2017		Suffolk, 2017		Painter, Field 2, 2018	
day	kg ha^{-1}							
0	0	b	4294	a	3938	a	3250	a
7	1	b	4246	a	4222	a	3054	a
14	12	b	4388	a	3869	a	2981	a
21	17	b	4069	a	4016	a	3339	a
28	106	a	3315	b	4300	a	2908	a
nontreated	28413[d]		--		--		--	

[a] Means within a column followed by the same letter are not different according to Fisher's Protected LSD test at P = 0.05.

[b] Application dates listed in Table 17. Palmer amaranth sizes at application are listed in Table 19.

[c] Dicamba (561 g ae ha^{-1}) plus fomesafen (423 g ai ha^{-1}) were applied POST 1 followed by dicamba plus lactofen (219 g ai ha^{-1}) 14 days later (POST 2). All treated plots received *S*-metolachor (1069 g ai ha^{-1}) 28 days after planting for residual control of Palmer amaranth.

[d] Palmer amaranth biomass pooled across experiment sites. Means within column followed by * are not different from nontreated check according to Dunnett's procedure at P = 0.05.