Dose-response of two Jack O'Lantern pumpkin cultivars to fomesafen applied preemergence

Authors: Arana, Jeanine, Meyers, Stephen L., Johnson, William G., and Guan, Wenjing

Source: Weed Technology, 36(4) : 537-543

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wet.2022.49

Weed Technology

www.cambridge.org/wet

Dose-response of two Jack O'Lantern pumpkin cultivars to fomesafen applied preemergence

Jeanine Arana[1], Stephen L. Meyers[2], William G. Johnson[3] and Wenjing Guan[4]

[1]Graduate Research Assistant, Department of Horticulture and Landscape Architecture, Purdue University, West Lafayette, IN, USA; [2]Assistant Professor, Department of Horticulture and Landscape Architecture, Purdue University, West Lafayette, IN, USA; [3]Professor, Department of Botany and Plant Pathology, Purdue University, West Lafayette, IN, USA and [4]Clinical Engagement Associate Professor, Department of Horticulture and Landscape Architecture, Purdue University, Vincennes, IN, USA

Research Article

Cite this article: Arana J, Meyers SL, Johnson WG, Guan W (2022) Dose-response of two Jack O'Lantern pumpkin cultivars to fomesafen applied preemergence. Weed Technol. **36**: 537–543. doi: 10.1017/wet.2022.49

Received: 12 April 2022
Revised: 6 June 2022
Accepted: 21 June 2022
First published online: 4 July 2022

Associate Editor:
Darren Robinson, University of Guelph

Nomenclature:
Fomesafen; pumpkin 'Bayhorse Gold' and 'Carbonado Gold'; *Cucurbita pepo* L.

Keywords:
Dose-response; emergence; injury; protoporphyrinogen oxidase; yield

Author for correspondence:
Jeanine Arana, Graduate Research Assistant, Department of Horticulture and Landscape Architecture, Purdue University, 625 Agriculture Mall Drive, West Lafayette, IN 47907.
E-mail: jcordone@purdue.edu

Abstract

Three dose-response trials were performed in 2020 and 2021 to determine the tolerance of two Jack O'Lantern pumpkin cultivars to fomesafen applied preemergence at two Indiana locations: the Southwest Purdue Agricultural Center (SWPAC) and the Pinney Purdue Agricultural Center (PPAC). The experiment was a split-plot arrangement in which the main plot was the fomesafen rate of application (0, 280, 560, 840, and 1,220 g ai ha^{-1}), and the subplot was the pumpkin cultivar ('Bayhorse Gold' and 'Carbonado Gold'). As the fomesafen rate increased from 280 to 1,120 g ha^{-1}, the predicted pumpkin emergence decreased from 85% to 25% of the nontreated control at SWPAC-2020, but only from 99% to 74% at both locations in 2021. The severe impact on emergence at SWPAC-2020 was attributed to rainfall. Visible injury included bleaching and chlorosis due to the herbicide splashing from the soil surface onto the leaves and included stunting, but injury was transient. As the fomesafen rate increased from 280 to 1,120 g ha^{-1}, the predicted marketable orange pumpkin yield decreased from 95% to 24% of the nontreated control at SWPAC-2020 and 98% to 74% at PPAC-2021. Similarly, the predicted marketable orange pumpkin fruit number decreased from 94% to 21% at SWPAC-2020 and 98% to 74% at PPAC-2021. Fomesafen rate did not affect marketable orange pumpkin yield and fruit number at SWPAC-2021 and marketable orange pumpkin fruit weight at any location-year. Overall, the fomesafen rate of 280 g ha^{-1} was safe for use preemergence in the pumpkin cultivars 'Bayhorse Gold' and 'Carbonado Gold' within one day after planting, but there is a risk of increased crop injury with increasing rainfall.

Introduction

The United States is ranked fifth among countries producing pumpkin, squash, and gourds (FAO 2022). In 2020, pumpkin production in the United States totaled $194 million; Indiana ranked fifth among the top pumpkin-producing states, with 2,428 ha valued at approximately $16 million (USDA NASS 2021). Although production practices can vary widely, pumpkins are usually direct-seeded into bare-ground rows placed 1.2 to 1.8 m apart. Pumpkins can be bushy or vining. In-row seed spacing is determined based on this distinction and ranges from 46 to 240 cm (Phillips 2021). The wide row and plant spacing required for this crop's growth allows weeds to establish easily.

Weeds can reduce pumpkin yield by as much as 67% (Walters and Young 2010). Common, difficult-to-control weeds in Midwestern cucurbit production are Eastern black nightshade (*Solanum ptychanthum* Dunal), horseweed (*Erigeron canadensis* L.), morningglory spp. (*Ipomoea* spp. L.), pigweeds (*Amaranthus* spp. L.), giant ragweed (*Ambrosia trifida* L.), wild buckwheat [*Fallopia convolvulus* (L.) Á. Löve], Canada thistle [*Cirsium arvense* (L.) Scop.], dandelion (*Taraxacum officinale* F.H. Wigg.), field bindweed (*Convolvulus arvensis* L.), Johnsongrass [*Sorghum halepense* (L.) Pers.], and yellow nutsedge (*Cyperus esculentus* L.) (IPMdata 2005). Weed management in conventional pumpkin production generally includes chemical control. Preemergence herbicides combined with shielded postemergence row-middle application of nonselective herbicides are those most often used by pumpkin producers (Phillips 2021).

Herbicides can significantly reduce production costs by helping farmers overcome labor scarcity and elevated costs associated with other weed management practices. It has been estimated that US crop production would decrease by 20% without herbicides (Gianessi and Reigner 2007). Farmers can only use state-registered herbicides for tolerant crops. In Indiana, few herbicides have been registered for use in pumpkin production (Phillips 2021), so farmers have to rely on the same herbicides year after year, a practice that can contribute to herbicide resistance (Evans et al. 2016; Gressel 1991).

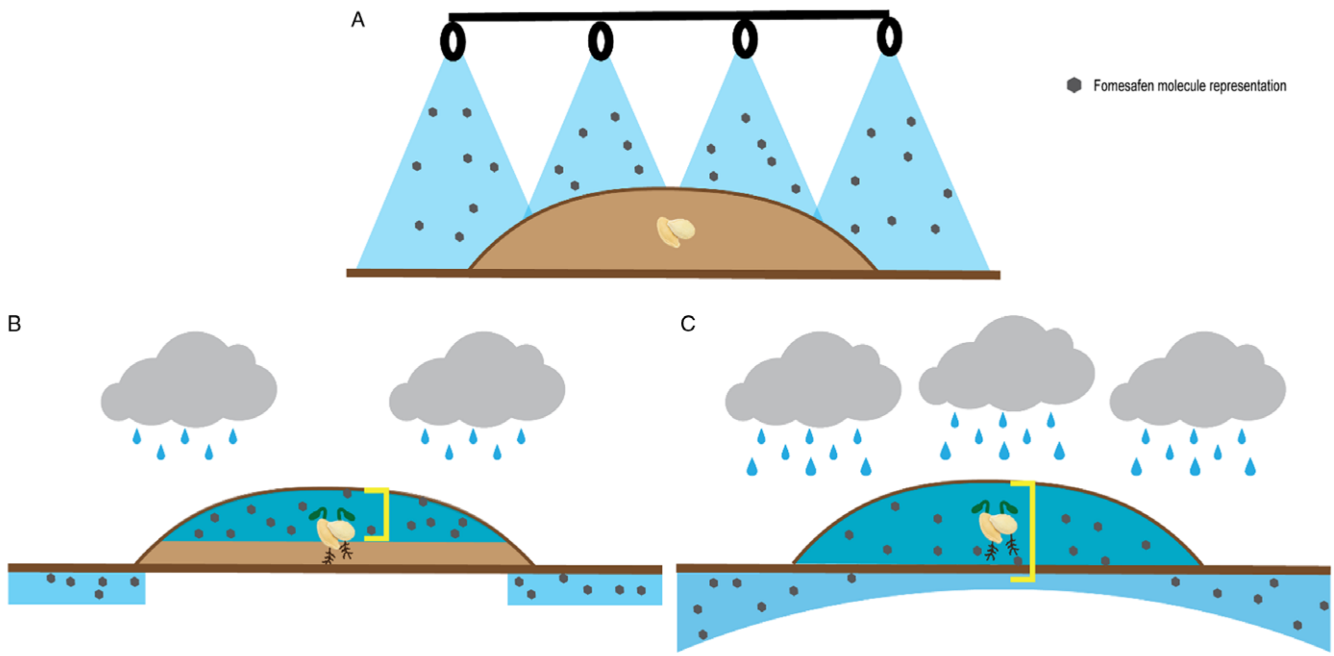

Figure 1. Preemergence herbicide application (A) and the effect of rain on the herbicide zone distribution (B and C). (B) A scenario where low to moderate rain shortly after planting moves the herbicide to the weeds' grow zone but not the crop's root zone. (C) A scenario where excessive rain shortly after planting moves the herbicide to the crop's root zone, increasing the risk of crop uptake.

Fomesafen is a Group 14 herbicide that inhibits protoporphyrinogen oxidase. It is registered with 24C Special Local Need labels for use preemergence after pumpkin seeding but before crop emergence in Illinois, Kansas, Michigan, Minnesota, and Ohio, where it successfully controls several of the problematic weeds found in pumpkin production. However, it is not registered in Indiana (Phillips 2021). Farmers have noted this inconsistency in extension meetings and want fomesafen to be registered in Indiana as well. In-state tolerance data are desirable for an herbicide to be registered with a 24C label. A crop is considered tolerant when the applied herbicide does not cause any toxicity (Pitty 1995) or when it shows some injury but completely recovers by the end of its growing cycle (Seefeldt et al. 1995).

Dose-response studies can be used to derive a model from the biological effect of an herbicide, or multiple herbicides on a crop, or multiple crops (Streibig 1980). Dose-response curves are often sigmoidal and constrained by an upper and a lower limit. The upper and lower limits are defined by the response from nontreated plants (control) and the highest dose applied (Knezevic et al. 2007). Our objective was to fit fomesafen dose-response curves to evaluate the biological response of two pumpkin cultivars. With this, we can determine possible outcomes regarding crop tolerance at other fomesafen rates within the range of rates used in our study.

Materials and Methods

Fomesafen dose-response field trials were conducted in 2020 and 2021 at the Southwest Purdue Agricultural Center (SWPAC), Vincennes, IN (38.73°N, 87.48°W) and in 2021 at the Pinney Purdue Agricultural Center (PPAC), Wanatah, IN (41.44°N, 86.93°W). At SWPAC, soil types were a Conotton gravelly loam (loamy-skeletal, mixed, active, mesic Typic Hapludalfs, 65% sand) with 0.8% organic matter (OM) and pH 6.6 in 2020, and a mixture of Lomax loam (coarse-loamy, mixed, superactive, mesic Cumulic Hapludalfs, 32% sand) and Lyles sandy loam (coarse-loamy, mixed superactive, mesic Typic Endoaquolls, 67% sand) with 0.9% OM and pH 6.4 in 2021. At PPAC, the soil type was a mixture of Tracy sandy loam (coarse-loamy, mixed, active, mesic Ultic Hapludalfs, 59% sand) and Bourbon sandy loam (coarse-loamy, mixed, active, mesic Aquultic Hapludalfs, 56% sand) with 1.7% OM and pH 6.8.

Fields were prepared with tillage prior to the formation of raised beds. Raised beds with subsurface drip tape were prepared on June 17, 2020 and June 15, 2021 at SWPAC and June 2, 2021, at PPAC. The experimental design was a randomized complete block design with a split-plot treatment arrangement and four replications. The main plots consisted of the fomesafen rate and the subplots of the pumpkin cultivar randomly placed within each main plot. Subplots were 27 m^2 and contained three 4.9-m-long rows, 1.8 m apart. Fomesafen (Reflex®; Syngenta Crop Protection, LLC, Greensboro, NC) rates were 0, 280, 560, 840, and 1,120 g ai ha^{-1}, where 0 g ai ha^{-1} was the nontreated control. Pumpkin cultivars were 'Bayhorse Gold' and 'Carbonado Gold' (Rupp Seeds, Inc., Wauseon, OH). Crop fertilization, irrigation, and diseases and insect management followed recommendations by Phillips (2021).

In each 27-m^2 subplot, two pumpkin seeds were hand-planted into the same hole 1.2 m apart in-row, totaling 24 seeds per subplot, on June 18, 2020 and June 16, 2021 at SWPAC, and on June 2, 2021 at PPAC. Two pumpkin seeds were planted per planting hole in the event that one seed failed to germinate. Subplots were thinned to one plant per hole 2 to 4 wk after planting. Fomesafen was broadcast-applied on top of the bed and respective row middles (Figure 1A) within 1 d of planting. To help manage weeds, *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, LLC, Greensboro, NC) at 1,070 g ai ha^{-1} was broadcast-applied in a separate application across all plots within 1 d after applying fomesafen. At SWPAC, both herbicides were applied using a tractor-mounted PTO-driven Hypro 7560 C roller pump with four TeeJet XR 8003 VS nozzles (Spraying Systems Co., Wheaton, IL) calibrated to deliver 187 L ha^{-1} at 207 kPa. At PPAC, fomesafen was applied using a CO_2-pressurized backpack sprayer equipped with four TeeJet XR 11004 VS nozzles calibrated to deliver 187 L ha^{-1} at 165 kPa and *S*-metolachlor was applied using PTO-driven Hypro model 6500 C roller pump with four TeeJet XR 8003 VS nozzles calibrated to deliver 187 L ha^{-1} at 138 pKa.

Data collection included counting the number of emerged pumpkin plants out of the 24 seeds that were planted 2 wk after treatment (WAT). Visible crop injury was rated using a scale of 0 (no injury) to 100% (crop death) at 2, 4, 6, and 8 WAT. Weed control was rated 4 WAT on a scale of 0 (no control) to 100% (complete control) relative to the 0 g ha^{-1} fomesafen treatment. After the 4-WAT weed control rating, weeds were removed either by hand or with hoes or cultivators to maintain plots weed-free and avoid yield loss due to weed interference. Pumpkin harvest was performed on September 12, 2020 [86 d after planting (DAP)] and September 17, 2021 (93 DAP) at SWPAC, and on September 1, 2021 (91 DAP) at PPAC. All fruits were harvested from each plot, individually weighed, and the color of each fruit recorded. A fruit was classified as marketable if it weighed ≥1.5 kg. Marketable fruits were categorized as orange (≥50% of the surface area was orange), green (<50% of the surface area was orange), and immature (green, tender rind). Individual marketable fruit weight average was calculated by dividing the marketable yield by the marketable fruit number of each category.

Emergence and marketable orange pumpkin yield and fruit number data were converted to a percent of the nontreated control using Equation 1:

$$Percent\ control = \frac{B}{M} \times 100 \qquad [1]$$

where *M* was the average of the nontreated control variable value pooled across the four repetitions within a location-year for each pumpkin cultivar and *B* was the variable value of each data point for each location-year.

Data were subjected to statistical analysis using R software (RStudio®; PBC, Boston, MA). Data were first analyzed for each location-year with a linear model and subjected to ANOVA to determine if the models were statistically significant for each trial. If models were significant, data were combined across all three or only two location-years to check if the normality of the data was affected and determine if statistically interactions ($P \leq 0.05$) existed between fomesafen rate, pumpkin cultivar, and location-year for each response variable. If data normality was affected or interactions between the explanatory variables existed, data are presented separately. Response variables were emergence as a percent of the nontreated control, visible pumpkin injury at 2, 4, and 6 WAT, weed control 4 WAT, marketable orange pumpkin yield and fruit number as a percent of the nontreated control, and marketable pumpkin yield (kg 27 m^{-2}), fruit number, and average individual fruit weight (kg $fruit^{-1}$) for the green and immature fruits. Visible pumpkin injury and weed control data were arcsin-squareroot transformed for analysis and are presented as back-transformed data. Data from the nontreated check were excluded from the visible pumpkin injury and weed control data analysis due to zero variance.

Significant response variables' models were then subjected to nonlinear regression analyses using the package *drc* in R software and fit to either a three-parameter log-logistic model using Equation 2:

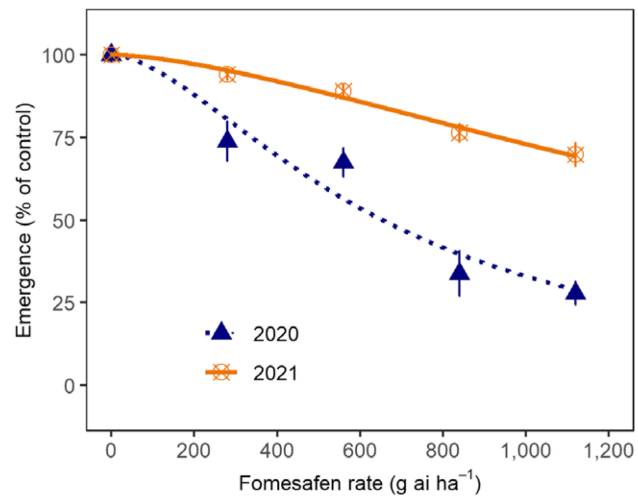

Figure 2. Effect of fomesafen rate on Jack O'Lantern pumpkin emergence as a percent of the nontreated control pooled across cultivars at the Southwest Purdue Agricultural Center (SWPAC) in 2020 and across cultivars and locations (SWPAC and the Pinney Purdue Agricultural Center) in 2021 described with a three-parameter log-logistic model [*d*/(1 + Exp[*b*(log *x* – log *e*)]. Parameters for 2020: *b* = 2, *d* = 100, and *e* = 654; lack-of-fit P = 0.056. Parameters for 2021: *b* = 2, *d* = 100, and *e* = 1875; lack-of-fit P = 0.710.

$$3P\ log-logistic = \frac{d}{1 + Exp\ [b(log\ x - log\ e)]} \qquad [2]$$

where *d* is the upper limit, *b* is the growth rate, *e* is the inflection point, and *x* is the fomesafen rate in g ai ha^{-1}, or a three-parameter logistic model using Equation 3:

$$3P\ logistic = \frac{d}{1 + Exp\ [b\ (x - e)]} \qquad [3]$$

where *d* is the upper limit, *b* is the relative slope, *e* is the inflection point, and *x* is the fomesafen rate in g ai ha^{-1}. Nonlinear models fit were analyzed with a lack-of-fit test, where a $P > 0.05$ indicates that the nonlinear model provides adequate description of the data. If data did not fit a model, a Tukey's HSD means separation test was performed at a $P \leq 0.05$ significance level.

Results and Discussion

Pumpkin Emergence

The SWPAC-2020 emergence as a percent of the nontreated control data was separated from the 2021 data because there was significant fomesafen rate-by-location-year interaction ($F_{8,\ 89} = 7.32$, $P = 1.98 \times 10^{-7}$) when pooled across all three location-years. However, emergence data from both locations in 2021 were pooled. Data were pooled across cultivars because there were no significant fomesafen rate-by-cultivar interactions. A three-parameter log-logistic model (Equation 2) was fit to the SWPAC-2020 and the pooled 2021 data. At SWPAC-2020, as fomesafen rate increased from 280 to 1,120 g ha^{-1}, predicted emergence decreased from 85% to 25% of the nontreated control at SWPAC-2020, but only from 99% to 74% in 2021 at both locations (Figure 2). After thinning the subplots to one plant per planting hole, the nontreated subplots had 11 (SWPAC-2020) or 12 (SWPAC and PPAC-2021) plants per subplot. At SWPAC-2020, as the fomesafen rate increased from 280 to 1,120 g ha^{-1}, the

Table 1. Biweekly rainfall accumulation for the first 8 wk after treatment (WAT) with fomesafen at the Southwest Purdue Agricultural Center (SWPAC) in 2020 and 2021 and the Pinney Purdue Agricultural Center (PPAC) in 2021.

			Cumulative rainfall[a]			
Location-year	Planting date	Date of the first rain	0 to 2 WAT	2 to 4 WAT	4 to 6 WAT	6 to 8 WAT
			mm			
SWPAC-2020	June 18	June 21	120	23	70	117
SWPAC-2021	June 16	June 19	44	135	13	91
PPAC-2021	June 2	June 7	17	157	69	69

[a]Data from the Midwest Regional Climate Center, West Lafayette, IN.

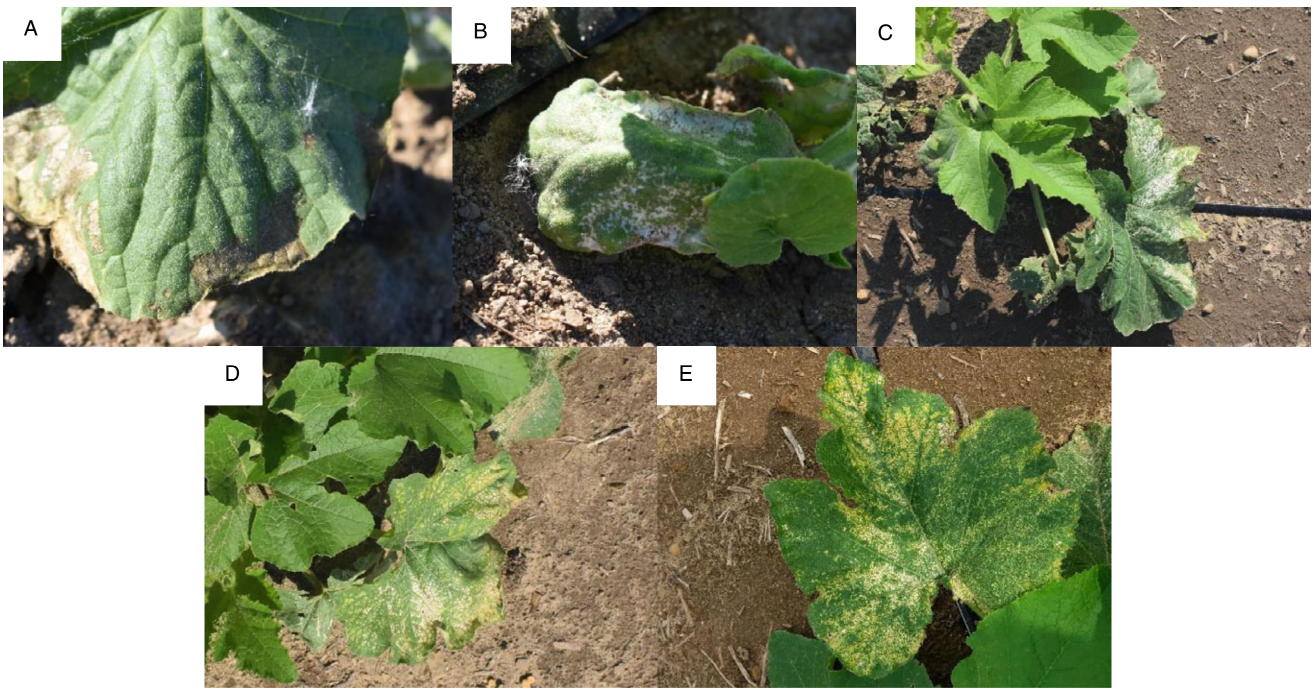

Figure 3. Jack O'Lantern pumpkin injury symptoms at a fomesafen rate of 1,120 g ha^{-1}. Necrosis 2 wk after treatment (WAT) (A), small white and brown spots at 2 (B) and 4 WAT (C), and chlorosis at 4 (D) and 6 WAT (E) at the Pinney Purdue Agricultural Center in 2021.

pumpkin density decreased to 8 (280 and 560 g ha^{-1}), 4 (840 g ha^{-1}), and 3 (1,120 g ha^{-1}) plants per subplot. At the other two location-years, subplots treated with fomesafen averaged 11 plants per subplot.

We attributed the reduction in emergence to excessive rainfall. Cumulative rainfall within 2 WAT in 2020 was 120 mm, but in 2021 it rained only 44 mm at SWPAC and 17 mm at PPAC (Table 1). Soil-applied herbicide uptake happens mainly in the root for dicotyledonous plants via diffusion, interception, or mass flow. Herbicide uptake via mass flow, the process where the herbicide moves due to the hydrostatic gradient, accounts for the majority of the herbicide uptake (Menendez et al. 2014). Rain is necessary to incorporate preemergence herbicides into the soil profile (Figure 1B). However, excessive rain moves the herbicide deeper in the soil profile into the crop's root zone (Figure 1C), enhancing the hydrostatic gradient, thus increasing herbicide absorption. Fomesafen is highly mobile under water-saturated soil conditions, especially in soils with low OM content, high pH, and a high proportion of sand content (Guo et al. 2003; Li et al. 2019; Weber et al.1993, 2004). Low soil OM content and the excessive rain through the first 2 wk at SWPAC-2020 increased fomesafen available for uptake in the crop root zone in an early, vulnerable stage, thus reducing emergence.

Peachey et al. (2012) reported that fomesafen at 560 g ha^{-1} reduced the emergence of 'Eureka' cucumber (*Cucumis sativus* L.), 'Golden Delicious' Hubbard squash (*Cucurbita maxima* Duchesne), 'Dickinson' pumpkin, and 'Ultra' butternut winter squash (*Cucurbita moschata* Duchesne ex. Poir.), and 'Elite' zucchini, 'Yellow Crookneck' summer squash, and 'Small Sugar' pumpkin (*C. pepo* L.) on average from 2.8 to 2.1 plants m^{-1} (25% reduction). However, the pumpkin cultivar 'Small Sugar' emergence was not affected by the fomesafen rate of 280 g ha^{-1} and was reduced only by 8% at the fomesafen rate of 560 g ha^{-1}. Our results differ from their result in that we found a somewhat wide range of emergence reduction (5% to 21%) even at the lowest fomesafen rate of 280 g ha^{-1}, presumably because of the soils' OM content. Peachey et al. (2012) reported OM content ≥2.1% for all soil types, which could have increased fomesafen sorption to the soil. Also, other environmental conditions like rainfall must be taken into consideration. Similar to our results, Ferebee (2018) reported that fomesafen at 280 g ha^{-1} reduced the plant stand of 'Kratos' (*C. moschata*) and 'Cougar' (*C. pepo* L.) pumpkin by

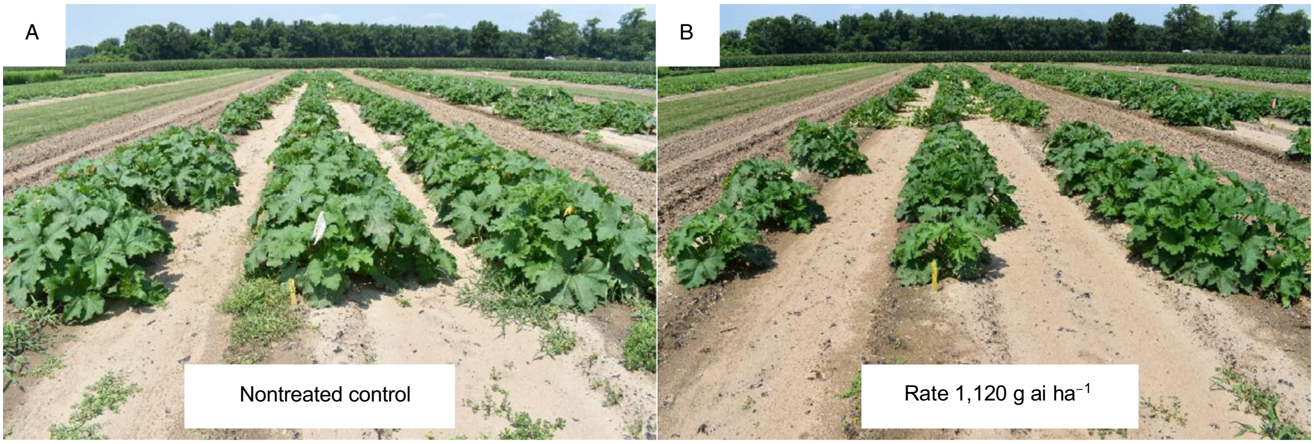

Figure 4. Nontreated control (A, 0 g ha^{-1}) vs. highest fomesafen rate (B, 1,120 g ha^{-1}) treatment to represent Jack O'Lantern pumpkin stunting at 6 wk after transplanting at the Southwest Purdue Agricultural Center in 2021.

20% and 63% to 75%, respectively. These trials were also conducted in soils with low OM content (1%). Likewise, they attributed the reduction in plant stand to rainfall (7 to 26 mm) shortly after planting (2 to 3 DAP).

Pumpkin Injury

We observed necrosis (Figure 3A), small white and brown spots (Figure 3B, C), chlorosis (Figure 3D, E), and stunting injury (Figure 4). Injury data were analyzed separately by location-year because of a significant fomesafen rate-by-location-year interaction. Injury was pooled across both cultivars in each location-year because of a nonsignificant fomesafen rate-by-cultivar interaction. Injury data 4 WAT at SWPAC-2020 and PPAC-2021 were fit a three-parameter logistic model (Equation 3; Figure 5). All other injury data were subjected to a Tukey's HSD mean comparison test (Table 2). At 2 WAT, as the fomesafen rate increased from 280 to 1,120 g ha^{-1}, injury increased from 6% to 28% at SWPAC-2021 and 5% to 36% at PPAC-2021 (Table 2). At 4 WAT, predicted injury increased from 7% to 26% (SWPAC-2020) and 4% to 50% (PPAC-2021) (Figure 5), and observed injury data at SWPAC-2021 increased from 0 to 13% (Table 2). At 6 WAT, injury ranged from 1% to 11% at SWPAC-2020 and 2021 and from 1% to 21% at PPAC-2021 (Table 2). Injury 8 WAT increased from 0 to 4% at SWPAC-2021 and 5% to 33% at PPAC-2021 (Table 2). With the exception of PPAC-2021, injury decreased from 2 to 8 WAT.

Heavy rainfall events increase the chance of injury due to the splashing of fomesafen from the soil onto the leaves (Peachey et al. 2012). This could explain the necrosis and chlorosis scattered patterns on cotyledons and leaves lying close to the ground. Injury 8 WAT was mainly stunting. Lingenfelter and VanGessel (2016) also mentioned stunting up to 8 WAT with fomesafen applied at 175 and 350 g ha^{-1} to five pumpkin cultivars (*C. pepo* and *C. maxima*). As mentioned before, fomesafen persistence in the soil varies with OM, sand content, and pH. For this reason, fomesafen half-life values in diverse soil types ranged variably from 4 to 66 d (Li et al. 2019; Mueller et al. 2014). Pumpkin injury inconsistency across trials was possibly due to its variable persistence depending on soil characteristics and other environmental factors such as microbial degradation (Feng et al. 2012; Mielke et al. 2022) and rainfall pattern. PPAC-2021 had the most prolonged injury (Table 2), probably because there could have been more available

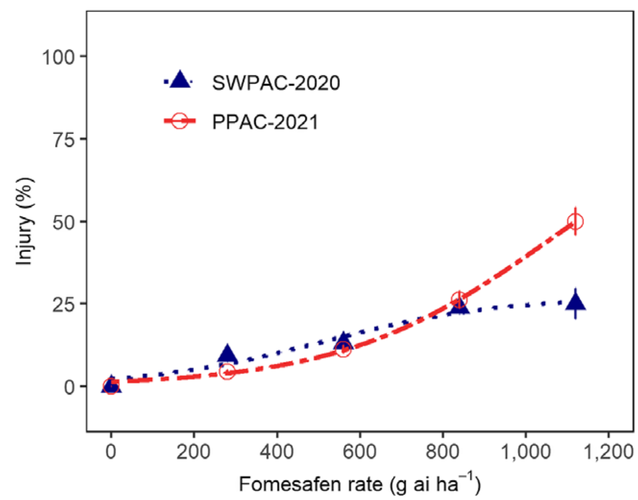

Figure 5. Effect of fomesafen rate on Jack O'Lantern pumpkin injury at 4 wk after treatment at the Southwest Purdue Agricultural Center in 2020 (SWPAC-2020) and the Pinney Purdue Agricultural Center in 2021 (PPAC-2021), described with a three-parameter logistic model [$d/(1 + \text{Exp})[b(x - e)]$]. Parameters for SWPAC-2020: $b = -0.005$, $d = 27$, and $e = 509$; lack-of-fit P = 0.275. Parameters for PPAC-2021: $b = -0.004$, $d = 89$, and $e = 1{,}060$; lack-of-fit P = 0.819.

herbicide as a result of less leaching. Herbicide was probably less likely to leach at PPAC-2021 because of a higher OM content (1.7%) than the other two location-years and less rainfall within the first 8 WAT (Table 1).

Weed Control

Weed control data were analyzed separately by location and year. Increasing fomesafen rates did not affect weed control at SWPAC-2021 ($F_{7,21} = 2.01$, $P = 0.102$). Relative to the 0 g ha^{-1} fomesafen rate treatment that only received *S*-metolachlor, weed control was above 90% for all fomesafen rates in all three location-years 4 WAT (Table 3). Fomesafen controlled carpetweed (*Mollugo verticillata* L.), common ragweed (*Ambrosia artemisiifolia* L.), morningglory spp., pigweeds, and prickly sida (*Sida spinosa* L.), and grass species at SWPAC-2020; carpetweed, common purslane (*Portulaca oleracea* L.), and grass species at SWPAC-2021; and carpetweed, common lambsquarters (*Chenopodium album* L.),

Table 2. Jack O'Lantern pumpkin injury and standard error (SE) at 2, 4, 6, and 8 wk after treatment (WAT) with fomesafen at the Southwest Purdue Agricultural Center (SWPAC) in 2020 and 2021 and the Pinney Purdue Agricultural Center (PPAC) in 2021 pooled across pumpkin cultivars 'Bayhorse Gold' and 'Carbonado Gold'.

	Pumpkin injury[a]							
	2 WAT		4 WAT[b]	6 WAT			8 WAT	
Rate	SWPAC 2021	PPAC 2021	SWPAC 2021	SWPAC 2020	SWPAC 2021	PPAC 2021	SWPAC 2021	PPAC 2021
g ha^{-1}	%							
280	6 (2) a[c]	5 (1) a	0 (0) a	1 (1) a	1 (1)	1 (1) a	0 (0) a	5 (2) a
560	9 (1) ab	14 (2) b	2 (1) ab	1(1) a	5 (2)	4 (2) a	1 (1) a	6 (3) a
840	15 (3) bc	28 (4) c	6 (2) b	11 (1) b	1 (1)	13 (3) b	0 (0) a	16 (3) ab
1,120	28 (5) c	36 (4) c	13 (2) c	7 (3) ab	11 (4)	21 (3) b	4 (1) b	33 (5) b

[a]Injury was arcsin transformed for analysis and back-transformed for the table. Scale: 0% = no injury, 100% = crop death.
[b]Data for SWPAC-2020 and PPAC-2021 at 4 WAT were fit a three-parameter logistic model (Figure 5).
[c]Means separation using Tukey's HSD test P ≤ 0.05. Means followed by the same letter are not significantly different. Lack of letters indicates that the F statistic was not significant at a α = 0.05.

Table 3. Effect of fomesafen rate on weed control and standard error (SE) 4 wk after treatment at the Southwest Purdue Agricultural Center (SWPAC) in 2020 and 2021 and the Pinney Purdue Agricultural Center (PPAC) in 2021.

	Weed control[a]		
Rate	SWPAC-2020	SWPAC-2021	PPAC 2021
g ha^{-1}	%		
280	95 (1) c[b]	90 (3.3)	92 (2.1) b
560	98 (0.8) bc	98 (1.1)	94 (1.7) b
840	99 (0.2) ab	97 (1.4)	99 (0.6) a
1,120	100 (0) a	99 (0.8)	99 (0.6) a

[a]Weed control was arcsin transformed for analysis and back-transformed for the table. Scale: 0% = no weed control, 100% = complete weed control.
[b]Means separation using Tukey's HSD test P ≤ 0.05. Means followed by the same letter are not significantly different. Lack of letters indicates that the F statistic was not significant at a α = 0.05.

giant ragweed, morningglory spp., velvetleaf (*Abutilon theophrasti* Medik.), volunteer soybean [*Glycine max* (L.) Merr.], and grass species at PPAC-2021. Weed control during the first 4 wk after emergence is ideal in pumpkin production because of its critical weed-free period of 4 to 6 wk (Dittmar and Boyd 2019; Schonbeck 2015). Because plots were maintained weed-free after 4 WAT, we cannot determine from this study how fomesafen rate-related weed control would have affected crop growth and yield.

Pumpkin Yield

Because there was a significant fomesafen rate-by-location-year interaction, marketable orange pumpkin yield ($F_{8,\ 88}$= 4.78, $P = 6.67 \times 10^{-5}$) and fruit number ($F_{8,\ 89}$ = 5.32, $P = 1.81 \times 10^{-5}$) as a percent of the nontreated control data were analyzed separately by location-year. There were no differences in yield, nor fruit number among treatments at SWPAC-2021, where the average marketable orange pumpkin yield was 109 kg 27 m^{-2} and fruit number was 16 fruits 27 m^{-2} pooled across all treatments (data not shown). Marketable orange pumpkin yield data as a percent of the nontreated control at SWPAC-2020 and PPAC-2021 fit a three-parameter log-logistic model (Equation 2, Figure 6A). As the fomesafen rate increased from 280 to 1,120 g ha^{-1}, marketable orange pumpkin yield decreased from 95% to 24% of the nontreated control (102 kg 27 m^{-2}) at SWPAC-2020 and 99% to 66% of the nontreated control (119 kg 27 m^{-2}) at PPAC-2021 (Figure 6A). Marketable orange pumpkin fruit number as a percent of the nontreated control fit a three-parameter log-logistic model at SWPAC-2020 (Equation 2) and a three-parameter logistic model at PPAC-2021 (Equation 3) (Figure 6B). As the fomesafen rate increased from 280 to 1,120 g ha^{-1}, the marketable orange pumpkin fruit number decreased from 94% to 21% of the nontreated control (15 fruits 27 m^{-2}) at SWPAC-2020 and 98% to 74% of the nontreated control (17 fruits 27 m^{-2}) at PPAC-2021 (Figure 6B).

Fomesafen rate did not significantly influence the individual marketable orange pumpkin fruit weight nor the marketable green and immature pumpkin yield, fruit number, and individual fruit weight (data not shown).

Although predicted pumpkin marketable orange pumpkin yield and fruit number decreased as the fomesafen rate increased from 280 to 1,120 g ha^{-1}, the values for the lowest fomesafen rate used were not statistically different from the nontreated control. These results confirm the results of Lingenfelter and VanGessel (2016) and Peachey et al. (2012), who reported that pumpkin yield was not affected by fomesafen rates of 175 and 350 g ha^{-1}, and 280 and 560 g ha^{-1}, respectively. Lingenfelter and VanGessel (2016) noted no effect on individual fruit weight as well. Because the individual marketable orange pumpkin fruit weight average was not affected by any fomesafen rate, marketable yield loss at high fomesafen rates was attributed only to the reduced plant stand.

Overall, the recommended, labeled fomesafen rate for use preemergence in other Midwestern states of 280 g ha^{-1} was safe for use preemergence in Jack O'Lantern pumpkin cultivars 'Bayhorse Gold' and 'Carbonado Gold' at SWPAC and PPAC. Despite the impact on emergence at SWPAC-2020, the pumpkins recovered, and predicted yield loss was only 5%, and visible injury was less than 7% in all the ratings at all locations. Also, adding this fomesafen rate to a blanket application of *S*-metolachlor improved weed control (>90% compared to the nontreated control). However, in soils with a low OM content and a high portion of sand, heavy rainfall events shortly after planting are expected to move the herbicide to the crop root zone and affect emergence. Consequently, it is necessary to plan its application carefully. If emergence reduction happens, significant yield loss due to reduced plant stand is expected only at fomesafen rates higher than 280 g ha^{-1}. When considering its use, Indiana pumpkin growers must also consider that fomesafen can only be applied in alternate years and has a maximum total use rate of 343 g ha^{-1} year^{-1} in all areas north of Interstate 70 and at 410 g ha^{-1} year^{-1} in all areas south of of Interstate 70 in Indiana.

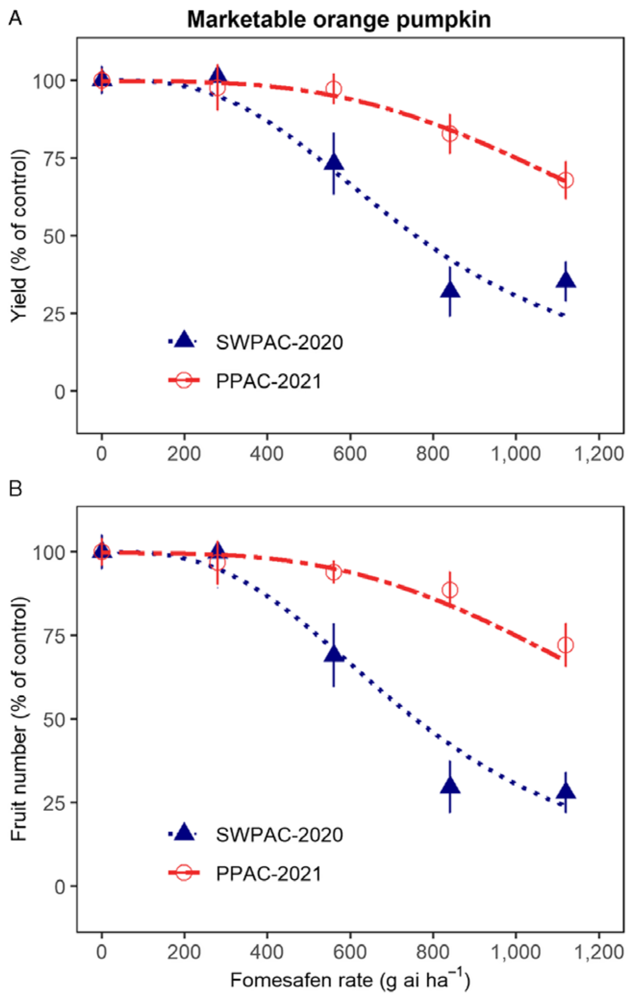

Figure 6. Effect of fomesafen rate on marketable Jack O'Lantern pumpkin yield (A) and fruit number (B) as a percent of the nontreated control at the Southwest Purdue Agricultural Center in 2020 (SWPAC-2020) and at the Pinney Purdue Agricultural Center in 2021 (PPAC-2021). Marketable pumpkin yield at both location-year and fruit number at SWPAC-2020 described with a three-parameter log-logistic model $[d/(1+Exp[b(logx-loge)])]$. Parameters for (A) SWPAC-2020: $b=3$, $d=100$, and $e=757$; lack-of-fit P = 0.241. Parameters for (A) PPAC-2021: $b=3$, $d=100$, and $e=1{,}402$; lack-of-fit P = 0.869. Parameters for (B) SWPAC-2020: $b=3$, $d=100$, and $e=713$; lack-of-fit P = 0.500 Fruit number at PPAC-2021 described with a three-parameter logistic model $[d/(1+E[b(x-e)])]$. Parameters for (B) PPAC-2021: $b=0.004$, $d=99$, and $e=1{,}387$; lack-of-fit P = 0.930.

Acknowledgments. We thank the following individuals for assistance with this research: Dennis Nowaskie, Bill Davis, Ange Thompson, Tristand Tucker, Paul Howard, Jacob Imbus, Jessica Conner, Brandi Woolam, Nathaly Vargas, Laura Rodríguez, and Luz Cardona. We thank Syngenta Crop Protection, LLC for supplying herbicides used in this study, and Rupp Seeds, Inc. for supplying pumpkin seeds used in the study. This project was funded by the Indiana State Department of Agriculture through grant A337-19-SCBG-19-003. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the ISDA. This work is supported by the US Department of Agriculture–National Institute of Food and Agriculture Hatch project 7000862. No conflicts of interest have been declared.

References

Dittmar PJ, Boyd NS (2019) Weed management in cucurbit crops (muskmelon, cucumber, squash, and watermelon). Gainsville, FL: IFAS Extension, University of Florida. 5 p

Evans JA, Tranel PJ, Hager AG, Schutte B, Wu C, Chatham LA, Davis AS (2016) Managing the evolution of herbicide resistance. Pest Manage Sci 72:74–80

[FAO] Food and Agriculture Organization of the United Nations (2022) FAOSTAT statistical database. https://www.fao.org/faostat/en/#rankings/countries_by_commodity. Accessed: February 24, 2022

Feng Z, Li Q, Zhang J, Zhang J, Huang X, Lu P, Li S (2012) Microbial degradation of fomesafen by a newly isolated strain *Pseudomonas zeshuii* BY-1 and the biochemical degradation pathway. J Agric Food Chem 60:7104–7110

Ferebee JH (2018) New herbicide strategies for weed management in pumpkin and soybean and potato vine desiccation. Masters dissertation. Suffolk, VA: Virginia Polytechnic Institute and State University. 87 p

Gianessi LP, Reigner NP (2007) The value of herbicides in US crop production. Weed Technol 21:559–566

Gressel J (1991) Why get resistance? It can be prevented or delayed. Pages 1–25 *in* Casley JC, Cussans GW, Atkin RK, eds. Herbicide Resistance in Weeds and Crops. Oxford: Butterworth-Heinemann

Guo J, Zhu G, Shi J, Sun J (2003) Adsorption, desorption and mobility of fomesafen in chinese soils. Water Air Soil Poll 148:77–85

[IPMdata] USDA North Central IPM Center (2005) Midwest pest management strategic plan for processing and Jack-o-lantern pumpkins. Washington, DC: US Department of Agriculture. 109 p

Knezevic SZ, Streibig JC, Ritz C (2007) Utilizing R software package for dose-response studies: the concept and data analysis. Weed Technol 21:840–848

Li X, Grey T, Price K, Vencill W, Webster T (2019) Adsorption, desorption and persistence of fomesafen in soil. Pest Manage Sci 75:270–278

Lingenfelter D, VanGessel MJ (2016) Reflex for pumpkins: does it have a fit?. Richfield, PA: Pennsylvania Vegetable Marketing and Research Program. 5 p

Menendez J, Rojano-Delgado MA, De Prado R (2014) Differences in herbicide uptake, translocation, and distribution as sources of herbicide resistance in weeds. Pages 141–157 *in* ACS Symposium Series. Washington, DC: American Chemical Society

Mielke KC, Mendes KF, de Sousa RN, Medeiros BAP (2022) Degradation process of herbicides in biochar-amended soils: impact on persistence and remediation. IntechOpen. 23 p

Mueller TC, Boswell BW, Mueller SS, Steckel LE (2014) Dissipation of fomesafen, saflufenacil, sulfentrazone, and flumioxazin from a Tennessee soil under field conditions. Weed Sci 62:664–671

Peachey E, Doohan D, Koch T (2012) Selectivity of fomesafen based systems for preemergence weed control in cucurbit crops. Crop Prot 40:91–97

Phillips B, ed. (2021) Midwest Vegetable Production Guide for Commercial Growers. West Lafayette, IN: Purdue University Extension. 299 p

Pitty A (1995) Introducción a la biología, ecología y manejo de malezas. [Introduction to the Biology, Ecology and Management of Weeds]. Tegucigalpa, Honduras: Escuela Agrícola Panamericana. 300 p

Schonbeck M (2015) Weed management strategies for organic cucurbit crops in the southern United States. eOrganic. https://eorganic.org/node/4573#:~:text=Under%20favorable%20conditions%2C%20cucurbits%20kept,weed%20growth%20through%20canopy%20closure.&text=Late%2Demerging%20weeds%20can%20set,squash%2C%20pumpkin%2C%20and%20watermelon. Accessed: February 15, 2022

Seefeldt SS, Jensen JE, Fuerst EP (1995) Log-logistic analysis of herbicide dose-response relationships. Weed Technol 9:218–227

Streibig JC (1980) Models for curve-fitting herbicide dose response data. Acta Agric Scand Sect B 1:59–64

[USDA NASS] US Department of Agriculture–National Agricultural Statistics Service (2021) Vegetables 2020 summary February 2021. Washington, DC: US Department of Agriculture. 99 p

Walters SA, Young BG (2010) Effect of herbicide and cover crop on weed control in no-tillage Jack-o-lantern pumpkin (*Cucurbita pepo* L.) production. Crop Prot 29:30–33

Weber JB, Strek HJ, Sartori JL (1993) Mobility of fomesafen and atrazine in soil columns under saturated- and unsaturated-flow conditions. Pestic Sci 39:39–46

Weber JB, Wilkerson GG, Reinhardt CF (2004) Calculating pesticide sorption coefficients (K_d) using selected soil properties. Chemosphere 55: 157–166