Weed Technology

www.cambridge.org/wet

Grain sorghum response to simulated fomesafen and terbacil carryover from watermelon in Georgia

Nicholas J. Shay[1] and Eric P. Prostko[2]

[1]Graduate Research Assistant, Department of Crop and Soil Sciences, University of Georgia, Tifton, GA, USA and [2]Professor and Extension Weed Specialist, Department of Crop and Soil Sciences, University of Georgia, Tifton, GA, USA

Research Article

Cite this article: Shay NJ and Prostko EP (2024) Grain sorghum response to simulated fomesafen and terbacil carryover from watermelon in Georgia. Weed Technol. **38**(e65), 1–6. doi: 10.1017/wet.2024.36

Received: 4 March 2024
Revised: 28 March 2024
Accepted: 12 May 2024

Associate Editor:
Lawrence E. Steckel, University of Tennessee

Nomenclature:
Fomesafen; terbacil; grain sorghum; *Sorghum bicolor* (L.) Moench; watermelon; *Citrullus lanatus* (Thunb.) Matsum. & Nakai

Keywords:
Crop rotation; degradation; double-cropping; herbicides

Corresponding author:
Nicholas J. Shay;
Email: nicholas.shay@uga.edu

Abstract

Georgia growers can benefit from double-cropping grain sorghum following watermelon to maximize land use and add economic value to their operations. However, capitalizing on the economic advantages of harvesting two crops within a single season must account for potential herbicide injury to rotational crops. An integrated weed management strategy that includes a preplant application of fomesafen and terbacil is recommended for weed control in watermelon production systems. However, currently labeled plant-back restrictions for grain sorghum require a minimum of 10 and 24 mo for fomesafen and terbacil, respectively. Therefore this research aimed to determine the tolerance of grain sorghum to fomesafen and terbacil following soil applications applied 90 to 100 d before planting (DBP). Experiments were conducted at the University of Georgia Ponder Research Farm from 2019 to 2023. The experimental design was a randomized complete block with four replicates. Five rates of fomesafen (35, 70, 140, 210, and 280 g ai ha^{-1}), four rates of terbacil (3.5, 7.0, 10.5, and 14.0 g ai ha^{-1}), and a nontreated control were evaluated. In 2019, fomesafen caused significant sorghum leaf necrosis, plant density reductions, height reductions, and yield reductions of at least 16%, especially when applied at rates $\geq$ 210 g ai ha^{-1}. Terbacil had little to no effect on sorghum injury, density, height, or yield in any year. These results suggest that sorghum has sufficient tolerance to terbacil when applied 90 to 100 DBP. In four of five years, sorghum had an acceptable tolerance to fomesafen when applied 90 to 100 DBP. However, yield losses observed in 2019 suggest that caution should be taken when fomesafen is applied 90 to 100 DBP grain sorghum at $\geq$ 210 g ai ha^{-1}.

Introduction

Grain sorghum is a hardy, warm-season annual crop and one of the most important cereal grains in the world (Ottman and Olsen 2009). Commonly used throughout the United States in double-cropping systems, sorghum displays many attributes highly sought after when compared to other fall rotational crops, including quick establishment, drought tolerance, water-use efficiency, and minimal production inputs (Bennett et al. 1990; Peerzada et al. 2017; Sanford et al. 1973). For analogous reasons, producers in the Coastal Plains region of southern Georgia often double-crop sorghum following watermelon. This is a novel method for increasing production per unit of land within one growing season (Brandenberger et al. 2007; Crabtree et al. 1990; Lewis and Phillips 1976). Sorghum is well documented to tolerate a wide range of harsh environments, making it a suitable option to handle the midsummer planting after watermelon harvest, when extreme temperatures and intermittent drought can otherwise limit production (Saballos 2008; Stahlman and Wicks 2000). However, residual herbicides commonly used in watermelon production systems have the potential to influence sorghum growth and yield negatively (Cobucci et al. 1998; Kratky and Warren 1973; Tweedy et al. 1971).

Watermelon is considered one of the primary specialty crops in Georgia, with 6,799 ha planted in 2023 (USDA 2024). Weeds that emerge in watermelon within the first 4 to 5 wk can significantly reduce yield from unwanted competition (Stall 2009). Thus critical components for maximizing weed control and yield include crop rotations, tillage, and a robust herbicide program (Culpepper and Vance 2020). One of the current recommended weed control strategies is a preplant or preemergence (PRE) application of fomesafen (Reflex® 2SL, Syngenta, Greensboro, NC, USA) and terbacil (Sinbar® 80WG, Tessenderlo Kerley, Phoenix, AZ, USA) utilized in transplant bare ground, seeded bare ground, and most used transplant small-bed polyethylene (plastic) mulch production systems (University of Georgia 2024). Fomesafen (210 g ai ha^{-1}) and terbacil (14 g ai ha^{-1}) at the current recommended labeled rates can be applied either before plastic mulch installation or over the top before punching transplant holes (Culpepper and Vance 2020).

Fomesafen is an effective tool by providing extended residual control of problematic small-seeded broadleaf weeds, such as Palmer amaranth (*Amaranthus palmeri* S. Watson), in watermelon and other agronomic crops (University of Georgia 2024). Fomesafen could also be considered a favorable option for limiting nontarget herbicide exposure with its relatively low off-site movement. As a weak acid (pKa = 2.7), this diphenyl ether and protoporphyrinogen oxidase inhibitor (PPO) exhibits strong adsorption potential with half-life values (DT_{50}) ranging between 80 and 128 d in sandy soils of the Coastal Plains region of Georgia (Li et al. 2018; Potter et al. 2016; Silva et al. 2013). Soil characteristics, such as pH and organic matter (OM), are significant factors that can influence the behavior of fomesafen in the soil profile and cause differential retention (sorption potential) (Li et al. 2018; Silva et al. 2013). Similar adsorption characteristics were observed for terbacil, which also displays lengthy residual activity with a DT_{50} value of 120 to 180 d in a silt loam soil (Jensen and Kimball 1982; Rahman 1977). As a photosystem II inhibitor in the uracil family, terbacil can have an average phytotoxic residue of 18 to 24 mo (Jensen and Kimball 1982; Rahman 1977). Both fomesafen and terbacil exhibit not only high levels of persistence but also relatively high water solubility, which leads to increased suspension in the soil solution (Kratky and Warren 1973; Silva et al. 2013). In terms of weed management, such circumstances are most often desirable. However, elevated mobility of fomesafen and terbacil and resuspension into the soil solution can increase successive crop injury, including to grain sorghum.

Previous research has reported that significant injury to grain sorghum can occur from carryover of fomesafen and terbacil, leading to reductions in grain yield (Cobucci et al. 1998; Kratky and Warren 1973; Tweedy et al. 1971), although studies concluded that sorghum yield losses can be avoided if planting is delayed 100 to 179 d after a fomesafen application at a rate of 250 g ai ha^{-1} (Cobucci et al. 1998). Similar research for terbacil has not been explored. This recommendation coincides with typical sorghum planting intervals immediately following watermelon harvest ~100 d. However, this falls outside the labeled plant-back interval for fomesafen and terbacil at 10 and 24 mo, respectively (Anonymous 2019, 2022).

Mitigating losses in grain sorghum from herbicide carryover is critical. No studies have directly investigated the effects of fomesafen and terbacil carryover on grain sorghum in Georgia. Reviewing sorghum's tolerances with 10,117 planted ha valued at US$12 million will provide valuable information for sorghum management decisions when implemented into watermelon double-cropping systems (USDA 2024). Therefore this research aims to determine the tolerance of grain sorghum to simulated carryover of fomesafen and terbacil.

Materials and Methods

Description of Research Site

This research was conducted at the University of Georgia Ponder Farm near Ty Ty, GA (31.85°N, 84.1°W, 105 m elevation) from 2019 through 2023. The experimental site was nearly level (<2% slope) and primarily composed of Tifton loamy sand with 96% sand, 2% silt, 2% clay, 1.2% OM, and an average soil pH of 6.0 (USDA 2023).

Experimental Design and Treatments

The experimental site consisted of plots arranged in a randomized complete block design with four replicates. Treatments were randomly assigned to 2 × 7.62 m plots. The experimental site began in March of each year by utilizing both conventional tillage and a combination of burndown herbicides commonly used in agronomic systems to maintain plots weed-free. Following typical production patterns for watermelon in the Coastal Plains region of Georgia, applications of fomesafen (Reflex® 2SL) and terbacil (Sinbar® 80WG) were made in April to bare soil. Rates included terbacil at 3.5, 7, 10.5, and 14 g ai ha^{-1} and fomesafen at 35, 70, 140, 210, and 280 g ai ha^{-1}. A nontreated control (NTC) was also included for comparison. Treatments were applied utilizing a CO_2-pressurized backpack sprayer and TeeJet® AIXR11002 nozzles (TeeJet® Technologies, Glendale Heights, IL, USA) calibrated to deliver 140 L ha^{-1}. Immediately following application, overhead irrigation was administered at 12.7 mm to activate these herbicide treatments, which is a standard practice in watermelon production (University of Georgia 2024). The experimental field was maintained weed-free up until sorghum planting with multiple applications of glyphosate, glufosinate, or paraquat, as needed.

Grain sorghum ('Dekalb DKS 36-07' in 2019 and 'Dekalb DKS 40-76' in 2020 to 2023), treated with fluxofenim (Concep® III, Syngenta), was planted in July of each year using a Monosem two-row planter, 91-cm row spacing, 4 cm deep at a rate of 214,890 seeds ha^{-1}. Plots were maintained weed-free using a PRE application of paraquat at 774 g ai ha^{-1} (Gramoxone® 2SL, Syngenta) and *s*-metolachlor at 1,402 g ai ha^{-1} (Dual Magnum® 7.62EC, Syngenta) at planting. Atrazine at 1,121 g ai ha^{-1} (Aatrex® 4L, Syngenta) and *s*-metolachlor at 1,402 g ai ha^{-1} were applied postemergence (POST) approximately 15 d after planting (DAP). Management decisions for all other fertility, insect, and disease considerations were made according to University of Georgia Extension recommendations (University of Georgia 2024).

A complete listing of herbicide application dates, sorghum planting dates, and rainfall totals from application to planting is presented in Table 1.

Data Collection

Visual estimates of sorghum injury in the form of leaf necrosis were obtained 14 DAP using a scale of 0 indicating no injury to 100 indicating complete plant death. Aboveground fresh-weight biomass data were collected 14 DAP by hand-harvesting and weighing the number of plants 0.9 m^{-1}. Sorghum density data were collected 21 DAP by counting the number of plants 0.9 m^{-1}. Sorghum height data were collected 21 and 60 DAP. Yield data were obtained using a small-plot combine with grain moisture adjusted to 13%.

Statistical Analyses

Data were subjected to PROC GLIMMIX in SAS 9.4 (SAS Institute, Cary, NC, USA) (Littell et al. 2006). Conditional residuals for control were used for checking assumptions of normality, independence of errors, homogeneity, and multiple covariance structures. Fixed effects included year and herbicide treatments. Trials and replicates represented random effects. Means were compared using the LSMEANS procedure with a Fisher's protected least significant difference test for pairwise comparison ($P \leq 0.1$). The $P < 0.1$ value was chosen prior to trial initiation because it has been the authors' experience that biologically or practically significant differences in data are often overlooked when $P < 0.05$. The authors also feel that growers, the ultimate end users of these data, are willing to accept a slightly less stringent P

https://doi.org/10.1017/wet.2024.36 Published online by Cambridge University Press

Table 1. Herbicide application dates, planting dates, and rainfall totals for fomesafen and terbacil grain sorghum field trials, University of Georgia Ponder Farm near Ty Ty, GA, 2019 to 2023.[a]

Year	Variety	Herbicide application date	Grain sorghum planting date	Rainfall (from application to planting)	Long-term average
				mm	
2019	DKS 37-07	10 Apr	9 Jul	287	271
2020	DKC 40-76	17 Apr	20 Jul	382	294
2021	DKC 40-76	17 Apr	12 Jul	434	292
2022	DKC 40-76	4 Apr	6 Jul	188	278
2023	DKC 40-76	13 Apr	5 Jul	374	278

[a]Long-term historical (1981–2016) average. Data were obtained from the Georgia Weather Network (http://www.georgiaweather.net/).

Table 2. Leaf necrosis 14 d after planting following fomesafen and terbacil applied 90 to 100 d before planting, near Ty Ty, GA, 2019 to 2023.[a]

Herbicide	Rate	Necrosis				
		2019	2020	2021	2022	2023
	g ai ha^{-1}	%				
Nontreated control	—	0 c	0 b	0 c	0 c	0 c
Fomesafen	35	0 c	1 b	0 c	0 c	0 c
	70	4 c	1 b	0 c	0 c	0 c
	140	28 b	0 b	0 c	1 bc	1 bc
	210	38 a	1 b	5 b	5 b	3 b
	280	40 a	4 a	15 a	10 a	8 a
Terbacil	3.5	0 c	0 b	0 c	1 bc	0 c
	7.0	0 c	0 b	0 c	0 c	0 c
	10.5	0 c	0 b	0 c	0 c	0 c
	14	0 c	0 b	0 c	1 bc	0 c

[a]Means in the same column with the same letter are not significantly different according to Fisher's protected least significant difference test ($P \leq 0.1$).

value to capture real-world differences that could result in greater economic returns at the farm level.

Results and Discussion

Grain Sorghum Leaf Necrosis

There was a Year × Treatment interaction for leaf necrosis; thus data are presented by year ($P < 0.1$) (Table 2). In all years, terbacil did not affect sorghum leaf necrosis. However, leaf necrosis from applications of fomesafen varied by year, with the greatest injury observed in 2019. In 2019, fomesafen at the three highest rates (140, 210, and 280 g ai ha^{-1}) caused significant necrosis compared to the NTC. In subsequent years (2020 to 2023), leaf necrosis never exceeded 15% with any rate of fomesafen.

Grain Sorghum Aboveground Biomass

A significant Year × Treatment interaction was observed for grain sorghum aboveground biomass 14 DAP. Therefore years (2019) with treatment effects were separated, and the remaining were combined across years ($P < 0.01$) (Table 3). In 2019, aboveground biomass ranged from 17 to 56 g 0.9 m^{-1} across all treatments. Fomesafen at rates ≥ 140 g ai ha^{-1} reduced aboveground biomass by 40% to 64% compared to the NTC. However, fomesafen did not affect biomass from 2020 to 2023. Terbacil did not affect sorghum aboveground biomass when compared with the NTC. However, in 2019, differences were observed between rates of terbacil at 7.0 and 10.5 g ai ha^{-1}, with 56 and 38 g 0.9 m^{-1}, respectively. Overall, aboveground biomass was greater in 2019 than it was in 2020 to 2023, which could be a result of the differences in variety or other environmental factors, including differences in degree days.

Grain Sorghum Density

A significant Year × Treatment interaction was observed for grain sorghum density 21 DAP; therefore years were separated ($P < 0.1$) (Table 4). In 2019, fomesafen applied at 280 g ai ha^{-1} reduced sorghum density 16% when compared with the NTC (18 plants 0.9 m^{-1}). Results in 2020 and 2022 indicated no differences in density between treatments ($P > 0.1$). In 2023, sorghum density was reduced by 3.5 g ai ha^{-1} of terbacil compared with the NTC with 14 and 16 plants 0.9 m^{-1}, respectively.

Grain Sorghum Height

There was a significant Year × Treatment interaction for grain sorghum heights 21 DAP; therefore years with treatment interactions were separated, and the remaining were combined across years ($P < 0.01$) (Table 5). In 2019, sorghum heights followed similar trends to leaf necrosis whereby fomesafen at the three highest rates caused significant height reductions relative to the NTC (Table 5). However, no other height reductions were observed from fomesafen at 21 d or 60 d. Terbacil did not reduce sorghum plant heights at any time when compared with the NTC; however, differences were observed between 3.5 and 7.0 g ai ha^{-1} with 16 and 14 cm, respectively.

Grain Sorghum Yield

A significant Year × Treatment interaction was observed with respect to yield. Yield data for 2019 are presented separately from pooled 2020 to 2023 yield data (Table 6). In 2019, grain sorghum yield ranged from 3,657 to 4,781 kg ha^{-1}. Fomesafen applied at the labeled rate for watermelons (210 g ai ha^{-1}) and the highest rate

https://doi.org/10.1017/wet.2024.36 Published online by Cambridge University Press

Table 3. Grain sorghum aboveground fresh-weight biomass 14 d after planting following fomesafen and terbacil applied 90 to 100 d before planting, near Ty Ty, GA, 2019 to 2023.[a,b]

Herbicide	Rate	Biomass	
		2019	2020–2023
	g ai ha^{-1}	g 0.9 m^{-1}	
Nontreated control	—	47 ab	13 a
Fomesafen	35	35 bc	12 a
	70	38 bc	11 a
	140	28 cd	13 a
	210	18 d	14 a
	280	17 d	11 a
Terbacil	3.5	47 ab	11 a
	7.0	56 a	12 a
	10.5	38 bc	13 a
	14	44 ab	12 a

[a]Means in the same column with the same letter are not significantly different according to Fisher's protected least significant difference test ($P \leq 0.1$).
[b]A significant Treatment × Year interaction was observed; therefore 2019 data were isolated from combined data for 2020 to 2023.

Table 4. Grain sorghum density 21 d after planting following fomesafen and terbacil applied 90 to 100 d before planting, near Ty Ty, GA, 2019 to 2023.[a,b]

Herbicide	Rate	Density			
		2019	2020	2022	2023
	g ai ha^{-1}	0.9 m^{-1}			
Nontreated control	—	18 ab	17 a	16 bc	16 bc
Fomesafen	35	19 ab	16 a	17 bc	15 cd
	70	20 a	15 a	18 a	16 bc
	140	17 b	17 a	16 bc	17 a
	210	18 ab	15 a	16 bc	17 ab
	280	15 c	14 a	17 bc	16 bc
Terbacil	3.5	19 ab	17 a	15 c	14 d
	7.0	18 ab	17 a	17 ab	17 ab
	10.5	19 ab	18 a	18 a	17 ab
	14	19 ab	18 a	16 c	17 a

[a]Means in the same column with the same letter are not significantly different according to Fisher's protected least significant difference test ($P \leq 0.1$).
[b]Density data were not captured for 2021.

(280 g ai ha^{-1}) caused significant yield reductions when compared with the NTC (4,642 kg ha^{-1} compared to 3,897 and 3,657 kg ha^{-1}, respectively; Table 6). Yields from other treatments did not differ from the NTC. In 2020 to 2023, there were no treatment differences regardless of herbicide and rate, with yields ranging from 2,874 to 3,450 kg ha^{-1} (Table 6).

Overall, grain sorghum exhibited varied responses and was dependent on herbicide, rate, and year. Regardless of application rate, terbacil did not negatively impact vegetative growth or final yield in any year. These results were in contrast to previous studies in which sorghum plants were severely injured from soil treated with terbacil, although at much higher rates (1.12 kg ha^{-1}) (Tweedy et al. 1971). Terbacil exhibits a high level of persistence in the soil profile, with a DT_{50} concentration of 5 to 7 mo in sandy loam soils (Marriage et al. 1977; Rahman 1977). However, terbacil is considered a highly mobile herbicide in soils with low OM (<0.7%), regularly exceeding depths > 30 cm (Gardiner et al. 1969; Marriage et al. 1977; Rhodes et al. 1970; Skroch et al. 1971; Swan 1972). During the course of this experiment, rainfall accumulation between treatment application and planting (~100 d) totaled 188 to 434 mm over 2019 to 2023 (Table 1). Therefore leaching below the grain sorghum rooting zone is a probable cause of nonsignificant responses from terbacil treatments, as approximately 86% of total root biomass is in the upper 30 cm of the soil profile (Mayaki et al. 1976; Rhodes et al. 1970).

In contrast to terbacil treatments, grain sorghum exhibited negative responses to fomesafen applications but was dependent on rate and year. In 2019, both the labeled rate of fomesafen for watermelon (210 g ai ha^{-1}) and the highest rate (280 g ai ha^{-1}) resulted in sustained injury throughout the growing season, reducing density, aboveground biomass, height, and yield. This supports previous work in which sorghum injury from fomesafen (250 g ai ha^{-1}) was likely when planting < 100 DAA (Cobucci et al. 1998). Under aerobic conditions in a laboratory setting, Potter et al. (2016) reported a DT_{50} of fomesafen of 100 ± 20 d. Field observations would support these findings as well, with common PPO symptomology identified throughout the growing season, including tissue bronzing, streaking, chlorosis, and significant leaf necrosis (Table 2) (Ahrens 1994). However, grain sorghum response to fomesafen in subsequent years (2020 to 2023) indicated no substantial negative responses when compared with the NTC ($P > 0.1$).

One hypothesis leading to the differences in fomesafen response between 2019 and 2020 to 2023 could be variety sensitivity (Abit et al. 2009). This is a plausible hypothesis but would require further investigation. Other contributing factors seem more likely to be the physiochemical properties of fomesafen and the environmental conditions at application and thereafter until planting (Costa et al. 2014; Ying and Williams 2000). Across all site years, rainfall totals from herbicide application until sorghum planting were never below the long-term average (Table 1). Studies have indicated that soil characteristics like OM, pH, and sand, silt, and clay content are significant contributors to adsorption, water solubility, and leaching (Costa et al. 2014; Guo et al. 2003; Li et al. 2018). Li et al. (2018) reported that when fomesafen was applied at 280 to 560 g ai ha^{-1} to a Tifton loamy sand, DT_{50} values were 4 to 6 d, on average, and residuals were not detected > 26 d after treatment. Because the experimental site consisted of similar sandy loam soil with low OM (<0.1%), coupled with consistent rainfall, the moderate mobility of fomesafen most likely led to leaching through the soil profile.

Other environmental variables that account for the absence of distinctions between fomesafen treatments and the NTC for the years 2020 to 2023, during grain sorghum planting around 100 DAA, involve swift herbicidal breakdown via photolysis and microbial degradation (Li et al. 2018). Previous studies suggest that these mechanisms notably diminish concentrations and mitigate crop response (Li et al. 2018). Nonetheless, they fail to elucidate the variances between 2019 and 2020 to 2023, except for potential disparities in hybrids or other unidentified factors.

This research concentrated on a simulated watermelon production system in an open-field environment. However, it is noteworthy to acknowledge that many farmers opt for polyethylene plastic mulch (Li et al. 2018; University of Georgia 2024). Growers employ both small- and large-bed plastic mulch for watermelon cultivation. In such cases, fomesafen application can occur post–bed formation but before plastic mulch installation (AS Culpepper, personal communication, March 7, 2023). The persistence of fomesafen in the field has been shown to remain elevated when applied beneath plastic mulch before planting, as the mulch hinders photolysis, volatilization, and runoff from rain (Li et al. 2018; Reed et al. 2018). Consequently, it is plausible to

https://doi.org/10.1017/wet.2024.36 Published online by Cambridge University Press

Table 5. Grain sorghum plant height 21 and 60 d after planting following fomesafen and terbacil applied 90 to 100 d before planting, near Ty Ty, GA, 2019 to 2023.[a,b,c]

Herbicide	Rate	Height at 21 d			Height at 60 d (2020; 2022–2023)
		2019	2020	2021–2023	
	g ai ha^{-1}	cm			
Nontreated control	—	26 ab	13 bc	23 a	93 a
Fomesafen	35	27 ab	14 ab	23 a	98 a
	70	23 ab	15 a	22 a	100 a
	140	20 c	15 a	22 a	99 a
	210	20 c	16 a	23 a	100 a
	280	13 d	14 ab	21 a	98 a
Terbacil	3.5	27 ab	14 ab	23 a	96 a
	7.0	28 a	12 c	23 a	94 a
	10.5	26 ab	13 bc	23 a	97 a
	14	28 a	13 bc	23 a	96 a

[a]Means in the same column with the same letter are not significantly different according to Fisher's protected least significant difference test ($P \leq 0.1$).
[b]For 21 d after planting (DAP), a significant Year × Treatment interaction was observed; therefore 2019 and 2020 data were isolated from combined data for 2021 to 2023.
[c]Height data for 60 DAP were not collected in 2019 and 2021.

Table 6. Grain sorghum yield response following fomesafen and terbacil applied 90 to 100 d before planting, near Ty Ty, GA, 2019 to 2023.[a,b,c]

Herbicide	Rate	Grain yield	
		2019	2020–2023
	g ai ha^{-1}	kg ha^{-1}	
Nontreated control	—	4,642 a	3,061 a
Fomesafen	35	4,417 ab	3,385 a
	70	4,363 ab	2,936 a
	140	4,736 a	3,450 a
	210	3,897 bc	3,305 a
	280	3,657 c	3,268 a
Terbacil	3.5	4,751 a	2,972 a
	7.0	4,781 a	3,007 a
	10.5	4,518 a	2,950 a
	14	4,596 a	2,874 a

[a]Means in the same column with the same letter are not significantly different according to Fisher's protected least significant difference test ($P \leq 0.1$).
[b]A significant Year × Treatment interaction was observed. Therefore 2019 data were isolated from combined data for 2020 to 2023.
[c]Final moisture was adjusted to 13%.

speculate that the residual harm to grain sorghum around 100 DAA may be more pronounced in large-bed plastic mulch systems where fomesafen is applied to the bed before mulch installation. Hence further exploration is warranted to assess fomesafen degradation and grain sorghum reaction under these conditions.

Practical Implications

The combination of fomesafen and terbacil plays a crucial role in weed management within watermelon production systems. Commonly known for their lengthy residual and soil persistence, these PRE herbicides are effective at limiting the most troublesome weeds for much of the growing season. As a result, growers who intend to pursue these niche integrated production systems should be mindful of the risks. Double-cropping grain sorghum will most likely continue to be a method utilized in Georgia to optimize land use during the summer growing season. Therefore this research will help growers implement their weed management strategies and limit any potential negative responses from herbicide carryover.

While terbacil applied to bare ground at 14 g ai ha^{-1} poses minimal risk to grain sorghum planted 90 to 100 days after application, fomesafen applied at rates ≥ 210 g ai ha^{-1} has demonstrated the potential to induce notable sorghum injury and yield reduction. Injury caused by fomesafen to double-cropped grain sorghum applied 90 to 100 DBP at rates ≥ 210 g ai ha^{-1} could vary depending on variety. Nevertheless, adverse environmental conditions are likely the most influential factor impeding herbicide degradation. It is also important to note once again that this research was conducted on bare ground. A common practice in watermelon production systems is to utilize some level of polyethylene mulching in addition to herbicides for weed suppression. As a natural consequence of reduced exposure to environmental factors under these mulching conditions, differences in herbicide persistence would be expected that could increase injury. For this reason, future research would require investigating grain sorghum response to fomesafen and terbacil in mulch production systems.

Acknowledgments. This research could not have been conducted without the technical support of Dewayne Dales, Charlie Hilton, and Tim Richards.

Competing interests. The authors declare no conflicts of interest.

References

Abit MJ, Al-Khatib K, Regehr DL, Tuinstra MR, Claassen TM, Geier PW, Stahlman PW, Gordon BW, Currie RS (2009) Differential responses of grain sorghum hybrids to foliar-applied mesotrione. Weed Technol 23:28–33

Ahrens WH, ed (1994) Herbicide Handbook. 7th ed. Champaign, IL: Weed Science Society of America. 352 p

Anonymous (2019) Reflex® herbicide product label. Wilmington, DE: Syngenta. 8 p

Anonymous (2022) Sinbar® herbicide product label. Phoenix, AZ: Tessenderlo Kerley. 12 p

Bennett WF, Tucker BB, Maunder AB (1990) Modern Grain Sorghum Production. Ames, IA: Iowa State University Press. 178 p

Brandenberger LP, Shrefler JW, Webber CL, Talbert RE, Payton ME, Wells LK, McClelland M (2007) Injury potential from carryover of watermelon herbicide residues. Weed Technol 21:473–476

Cobucci T, Prates HT, Falcao CLM, Rezende MMV (1998) Effect of imazamox, fomesafen, and acifluorfen soil residue on rotational crops. Weed Sci 46: 258–263

Costa AIG, Queiroz MELR, Neves AA, de Assis RC, dos Soares CES, da Silva AA, D'Antonino L, de Oliveira AF, Bellato CR (2014) Mobility and persistence of the herbicide fomesafen in soils cultivated with bean plants using SLE/LTP and HPLC/DAD. Environ Sci Pollut Res 22:3457–3466

Crabtree R, Prater J, Mbolda P (1990) Long-term wheat, soybean, and grain sorghum double-cropping under rainfed conditions. J Agron 82:683–686

Culpepper AS, Vance JC (2020) 2020 Watermelon weed control program. University of Georgia Extension. https://site.extension.uga.edu/tiftcoag/2020/02/2020-watermelon-weed-control-programs/. Accessed: November 30, 2023

Gardiner JA, Rhodes RC, Adams JB, Soboczenski EJ (1969) Synthesis and studies with labeled bromacil 2-C14 and terbacil. J Agric Food Chem 17: 980–986

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

Jensen KIN, Kimball ER (1982) The comparative behavior of simazine and terbacil in soils. Weed Res 22:7–12

Kratky BA, Warren GF (1973) Water–soil–plant interactions with terbacil. Weed Sci 21:451–454

Lewis WM, Phillips JA (1976) Double cropping in the eastern United States. Mult Cropping 27:41–50

Li X, Grey T, Price K, Vencill W, Webster T (2018) Adsorption, desorption and persistence of fomesafen in soil. Pest Manag Sci 75:270–278

Littell R, Milliken G, Stroup W, Wolfinger R, Schabenberger O (2006) SAS for Mixed Models. 2nd ed. Cary, NC: SAS Institute. 828 p

Marriage PB, Khan SU, Saidak WJ (1977) Persistence and movement of terbacil in peach orchard soil after repeated annual applications. Weed Res 17: 219–225

Mayaki WC, Stone LR, Teare ID (1976) Irrigated and non-irrigated soybean, corn, and grain sorghum root systems. J Agron 68:532–534

Ottman M, Olsen M (2009) Growing Grain Sorghum in Arizona. Tucson, AZ: Arizona Cooperative Extension, University of Arizona College of Agriculture, Life, and Environmental Sciences. 3 p

Peerzada AM, Ali HH, Chauhan BS (2017) Weed management in sorghum [*Sorghum bicolor* (L.) Moench] using crop competition: A review. Crop Protect 95:74–80

Potter TL, Bosch DD, Strickland TC (2016) Field and laboratory dissipation of the herbicide fomesafen in the Southern Atlantic Coastal Plain (USA). J Agr Food Chem 65:5156–5163

Rahman A (1977) Persistence of terbacil and trifluralin under different soil and climatic conditions. Weed Res 17:145–152

Reed TV, Boyd NS, Wilson C, Ditmar PJ (2018) Effect of plastic mulch type on fomesafen dissipation in Florida vegetable production systems. Weed Sci 66:142–148

Rhodes RC, Belasco IJ, Pease HL (1970) Determination of mobility and adsorption of agrochemicals on soils. J Agric Food Chem 18:524–528

Saballos A (2008) Development and Utilization of Sorghum as a Bioenergy Crop. Spring, NY: Genetic Improvement of Bioenergy Crops. 211–248 pp

Sanford JO, Myhre DL, Merwine NC (1973) Double cropping systems involving no-tillage and conventional tillage. J Agron 65:978–982

Silva GR, D'Antonino L, Faustino LA, Silva AA, Ferreira FA, Texeira CC (2013) Sorption of fomesafen in Brazilian soils. Planta Daninha 31:971–977

Skroch WA, Sheets TJ, Smith JW (1971) Herbicide effectiveness, soil residues, and phytotoxicity to peach trees. Weed Sci 19:257–260

Stahlman PW, Wicks GA (2000) Weeds and their control in grain sorghum. Pages 535–582 *in* Smith CW, Federikson RA, eds. Sorghum: Origin, History, Technology, and Production. New York, NY: John Wiley

Stall WM (2009) Weed control in cucurbit crops (muskmelon, cucumber, squash, and watermelon). HS190/WG029, rev. 4/2009. Gainesville, FL: University of Florida IFAS Extension. 1–6 pp

Swan DG (1972) Effect of herbicides on alfalfa and subsequent crops. Weed Sci 20:335–337

Tweedy JA, Kern AD, Kapusta G, Millis DE (1971) Yield and nitrogen content of wheat and sorghum treated with different rates of nitrogen fertilizer and herbicides. J Agron 63:216–218

University of Georgia (2024) Georgia Pest Management Handbook: Commercial Edition 2024. Athens, GA: University of Georgia Extension. https://ipm.uga.edu/georgia-pest-management-handbook/. Accessed: March 1, 2024

[USDA] U.S. Department of Agriculture (2023) Web Soil Survey. Natural Resources Conservation Service. http://websoilsurvey.sc.egov.usda.gov/. Accessed: November 27, 2023

[USDA] U.S. Department of Agriculture (2024) Georgia agricultural statistics 2024. https://www.nass.usda.gov/Statistics_by_State/Georgia/index.php. Accessed: November, 30, 2023

Ying G, Williams B (2000) Dissipation of herbicides in soil and grapes in a south Australian vineyard. Agric Ecos Environ 78:283–289