Weed Technology

www.cambridge.org/wet

Tomato tolerance and purple nutsedge control with sulfuryl fluoride mixes

Jialin Yu[1], Joshua H. Freeman[2] and Nathan S. Boyd[3]

[1]Former Postdoctoral Research Associate, University of Florida Gulf Coast Research and Education Center, Wimauma, FL, USA; current: Professor, Co-Innovation Center for Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing, Jiangsu, China; [2]Associate Professor, University of Florida North Florida Research and Education Center, Quincy, FL, USA and [3]Professor, University of Florida Gulf Coast Research and Education Center, Wimauma, FL, USA

Research Article

Cite this article: Yu J, Freeman JH, Boyd NS (2021) Tomato tolerance and purple nutsedge control with sulfuryl fluoride mixes. Weed Technol. **35**: 950–956. doi: 10.1017/wet.2021.56

Received: 21 April 2021
Revised: 9 June 2021
Accepted: 29 June 2021
First published online: 12 July 2021

Associate Editor:
Darren Robinson, University of Guelph

Nomenclature:
1,3-dichloropropene; chloropicrin; sulfuryl fluoride; metam potassium; purple nutsedge; *Cyperus rotundus* L.; tomato; *Solanum lycopersicum* L.

Keywords:
Chloropicrin; fumigant combination; vegetable; nutsedge control; weeds

Author for Correspondence: Nathan Boyd, University of Florida Gulf Coast Research and Education Center, Balm, FL 33578.
Email: nsboyd@ufl.edu

Abstract

Sulfuryl fluoride (SF) is currently used as a fumigant for control of drywood termites and insects in building structures, vehicles, wood products, postharvest commodities, and food processing facilities. This research investigated the feasibility of using SF as a preplant soil fumigant for purple nutsedge control in plastic-mulched tomato production. SF treatments included SF injected through drip tapes or SF injected through drip tapes a few hours following shank injection of chloropicrin (Pic). Results revealed that SF alone at 224, 336, or 448 kg ha^{-1} was generally less effective compared with when it was applied in conjunction with Pic at 168 kg ha^{-1}. SF alone provided inconsistent control of purple nutsedge. In contrast, SF + Pic was as efficacious or more efficacious on purple nutsedge than the industry standards, including 1,3-dichloropropene (1,3-D) plus Pic and metam potassium. None of the fumigant treatments visually injured tomato plants, stunted growth, or adversely affected tomato yield. In one of the four tomato seasons, tomato plants growing in plots fumigated with SF + Pic resulted in taller tomato plants and higher markable yields. Results indicate that soil fumigation with SF + Pic is safe on plastic-mulched tomato and effectively controls purple nutsedge.

Introduction

Purple and yellow nutsedge (*Cyperus esculentus* L.) are some of the most problematic weed species in fruiting vegetable crops in Florida (Webster 2010). These two weed species are often found in mixed stands, but purple nutsedge is more likely to establish on well-drained soils, whereas yellow nutsedge is more likely to establish on wet soils (Holm et al. 1977; Wills 1987). The use of polyethylene mulch can effectively suppress broadleaf and grass weeds but not *Cyperus* spp. due to their pointed leaf tip and sturdy midrib that allow them to pierce the plastic film (Igbokwe 1996; Patterson 1998). Previous studies indicate that competition from *Cyperus* spp. can result in 73%, 85%, 51%, and 94% yield loss in bell pepper (*Capsicum annum* L.; Gilreath et al. 2005), cucumber (*Cucumis sativus* L.; Johnson and Mullinix 1999), tomato (*Solanum lycopersicum* L; Morales-Payan et al. 1997), and watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai; Buker et al. 2003], respectively.

Weed management in small fruiting vegetable crops is difficult because a limited number of registered herbicides are available to control them (Besançon et al. 2020; Castro et al. 2020; Randell et al. 2020; Yu and Boyd 2017). For example, only halosulfuron is registered for postemergence control of *Cyperus* spp. in tomato and no herbicides are registered for control of *Cyperus* spp. in strawberry (*Fragaria* × *ananassa* Duch.). Growers traditionally relied on the use of plastic mulch and soil fumigation with methyl bromide (MB) for preplant control of soilborne pathogens and weeds. However, the use of MB in agriculture has been discontinued because it was listed as an ozone-depleting substance (USEPA 2019). At present, 1,3-dichloropropene (1,3-D), chloropicrin (Pic), dimethyl disulfide (DMDS), and isothiocyanate generators such metam sodium are used as MB alternatives (Eure and Culpepper 2017; Guo et al. 2018; Hutchinson et al. 2003; McDonald et al. 2021; Ren et al. 2018; Yu et al. 2018; Yu and Boyd 2021). Unfortunately, it is evident that none of these alternatives provide as broad-spectrum pest control as MB (Eure and Culpepper 2017; Hanson and Shrestha 2006; Yu et al. 2018, 2019). For this reason, a weed management system comprising two or more weed management tactics, such as fumigants, herbicides, and fallow cover crops, has been recommended (Creamer et al. 1997; Eure and Culpepper 2017; Snapp et al. 2005; Yu et al. 2019).

Sulfuryl fluoride (SF, SO_2F_2) is presently used as a fumigant for control of drywood termites, weed-infesting beetles, and other insects in building structures, vehicles, and wood products (Derrick et al. 1990; Kenaga 1957). It is also used as a fumigant gas for pest control in post-harvest commodities and food processing facilities (Aung et al. 2001; Derrick et al. 1990; Rajendran et al. 2008; Zettler and Arthur 2000). At present, all soil fumigants registered in the United States have higher boiling points and lower vapor pressures than MB. As a result, they move less readily through the soil profile, which can contribute to reduced efficacy or inconsistent pest control. SF (boiling point = −55 °C at 760 mm Hg; vapor pressure = 1.16×10^4 mm Hg at 20 C) has a lower boiling point, but higher vapor pressure compared to MB (boiling point = 3.5 C; vapor pressure = 1.42×10^3 mm Hg at 20 C). The lower boiling point of SF indicates that it can be applied during cool seasons (Meister 1992), whereas the higher vapor pressure of SF indicates that it can be quickly distributed in the soil profile. In addition, during the fumigation, SF has lower emissions compared to MB (Cao et al. 2014). These physical properties give SF significant advantages compared to the existing MB alternatives as a preplant soil fumigant (Cao et al. 2014). Previous research showed that SF exhibited control activities against *Fusarium* spp., root-knot nematodes (*Meloidogyne* spp.), and weeds including large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and velvetleaf (*Abutilon theophrasti* Medik.; Cao et al. 2014). The use of SF as a preplant soil fumigant for control of *Cyperus* spp. has not been previously studied. There remains a need to understand its efficacy on weeds in plastic-mulched vegetables.

Previous studies have shown that Pic alone is inadequate for control of *Cyperus* spp. (Santos et al. 2006); however, adding Pic to 1,3-D, DMDS, propargyl bromide, MB, methyl iodide, or metam-sodium significantly enhanced the control of *Cyperus* spp. (Hutchinson et al., 2003; Yu et al. 2018; Yu and Boyd 2021). The efficacy of Pic used in conjunction with SF for weed control is unknown. Therefore, the objectives of this research were to 1) determine the efficacy of SF used alone or in conjunction with Pic against purple nutsedge and their impact on tomato growth and yield, and 2) compare the efficacy of SF and several other soil fumigant treatments (1,3-D + Pic and 1,3-D + Pic + metam potassium) on purple nutsedge in tomato.

Materials and Methods

Experiment Description

Field experiments were carried out in Balm, FL (Trial I, fall 2017; Trial II, spring 2018; GPS coordinates 27.76°N, 82.22°W) and Quincy, FL (Trial III, spring 2018; Trial IV, fall 2018; GPS coordinates 30.58°N, 84.59°W). In Balm, FL, the field trials were established at the Gulf Coast Research and Education Center on a Myakka fine sand, pH 6.8 and 1% organic matter. In Quincy, FL, the field trials were established at the North Florida Research and Education Center on a Dothan-Fuquay complex sandy loam, pH 6.4 and 1% organic matter.

At both sites, raised beds (20 cm tall, 81 cm tall, and 71 cm wide at the bed top) were shaped using a bed-forming machine (Kennco Manufacturing, Ruskin, FL). Plot size was 27 m of a single raised bed with between-row spacing of 1.5 m. Two separate drip tapes (Jain Irrigation Inc., Haines City, FL) with emitters spacing at 30 cm and a flow rate of 0.95 L min^{-1} 30 m^{-1} were installed 2.5 cm underneath the bed top surface and positioned 20 cm apart.

All experiments were established as a randomized complete block design with four replications. Fumigant treatments consisted of 1) nonfumigated control, 2) 224 kg ha^{-1} SF (ProFume®), 3) 336 kg ha^{-1} SF, 4) 448 kg ha^{-1} SF, 5) 224 kg ha^{-1} SF +168 kg ha^{-1} Pic, 6) 336 kg ha^{-1} SF + 168 kg ha^{-1} Pic, 7) 448 kg ha^{-1} SF + 168 kg ha^{-1} Pic, 8) 159 kg ha^{-1} 1,3-D + 121 kg ha^{-1} Pic (Pic-Clor 60), 9) 159 kg ha^{-1} 1,3-D + 121 kg ha^{-1} Pic (Pic-Clor 60) + 260 kg ha^{-1} metam potassium (K-PAM® HL), 10) 168 kg ha^{-1} Pic (Tri-Pic 100). Pic alone at 168 kg ha^{-1} was not included in Trial I, whereas 1,3-D + Pic + metam potassium was not included in Trials III and IV. All fumigants, except SF, were applied during the bed-forming process. Pic or 1,3-D + Pic was applied 20 cm below the soil surface using a fumigation rig with three equally distributed fumigant shanks. Metam potassium was applied 10 cm beneath the soil surface with a fumigation rig with six shanks. Immediately following the shank fumigation, TIF plastic film (Berry Plastic Corp., Evansville, IN) was used to cover the raised beds. All SF treatments were injected through drip tapes within 24 h following the shank injection of Pic. The dates of bed formation and fumigation are presented in Table 1. The fumigant product and application method information are presented in Tables 2 and 3, respectively.

Tomato (c.v. Winter Heaven; approximately 10 cm tall) was transplanted on August 31, 2017, in Trial I and March 7, 2018, in Trial II, whereas tomatoes (c.v. Quincy) were transplanted on April 2, 2018, in Trial III and August 6, 2018, in Trial IV. Tomato plants were transplanted in the center of the bed with 60-cm spacing between plants. Tomato was fertilized, irrigated, and managed for foliar pest control as per industry standards in the region.

Control of Purple Nutsedge

Purple nutsedge shoots that penetrated through the TIF plastic film in the entire plot was recorded within each plot at 4, 13, and 17 wk after fumigation (WAF) in Trial I, 4, 11; at 13 WAF in Trial II; and 4, 9, and 13 WAF in Trials III and IV. These timings roughly correspond to crop transplant, mid-season, and at harvest.

Tomato Growth and Yield

Tomato damage, where 0 represents no injury and 100 represents entire foliage desiccation, was visually determined at 1, 2, and 3 wk after transplanting (WATP) in all trials. To evaluate the potential adverse effect of fumigant treatments on tomato growth, tomato height was measured at 7 WATP in Trial I and 3, 9, and 12 WATP in Trial II. Tomato vigor, where 0 represents plant death and 10 represents a highly vigorous plant, was visually evaluated at 1, 2, and 4 WATP in Trial III and 2 and 4 WATP in Trial IV. Fruits from 10 tomato plants were harvested in each plot by season end and each fruit was graded before weighing as medium (5.5 cm < diam < 6.5 cm), large (6.5 cm < diam < 7 cm), or extra-large (diam > 7 cm; USDA-AMS 1991).

Statistical Analysis

Data were subjected to one-way ANOVA using SAS software (version 9.4; SAS Institute, Cary, NC). All experiments were analyzed separately because they were performed as separate trials, and weather conditions and weed pressures varied between trials. Data were examined for homogeneity of equal variance. Data were square root transformed when needed to normalize the data. Back-transformed data are presented. Treatment means were separated using the Fisher's protected LSD test at $P = 0.05$.

Results and Discussion

Purple Nutsedge Control

Purple nutsedge shoot densities varied across Trials I, II, III, and IV with an average of 32, 0.61, 13, and 14 shoots m^{-2} at 4 WAF in the

https://doi.org/10.1017/wet.2021.56 Published online by Cambridge University Press

Table 1. Dates of bed formation, fumigation, tomato transplant, and harvest.

Experimental run	Study site	Bed formation and fumigant application	Transplant	Harvest
Trial I	Balm, FL	July 19, 2017	August 31, 2017	November 29, 2017; December 12, 2017
Trial II	Balm, FL	February 5, 2018	March 7, 2018	June 20, 2018
Trial III	Quincy, FL	March 8, 2018	April 2, 2018	June 25, 2018; July 2, 2018
Trial IV	Quincy, FL	July 10, 2018	August 6, 2018	October 18, 25, and 31, 2018

Table 2. Fumigant product and manufacturer information.

Common name	Trade name	Chemical company	Address
Sulfuryl fluoride	ProFume®	Douglas	1550 East old 210 Hwy, Liberty, MO
1,3-dichloropropene + chloropicrin	Pic-Clor 60	Cardinal	P.O. Box 782, Hollister, CA
Chloropicrin	Tri-Pic 100	TriEst Ag Group, Inc.	1101 Industrial Boulevard, Greenville, NC
Metam potassium	K-PAM® HL	AMVAC	4100 E. Washington Blvd, Los Angeles, CA

Table 3. Fumigant application rate and method.

Fumigant[a]	Rate	Fumigation method
	kg ha^{-1}	
Nonfumigated control		
SF	224	Injected as a gas through the drip tape
SF	336	Injected as a gas through the drip tape
SF	448	Injected as a gas through the drip tape
SF + Pic	224 + 168	SF was injected as a gas through the drip tape, while Pic was injected with three shanks at 20-cm depth
SF + Pic	336 + 168	SF was injected as a gas through the drip tape, while Pic was injected with three shanks at 20-cm depth
SF + Pic	448 + 168	SF was injected as a gas through the drip tape, while Pic was injected with three shanks at 20-cm depth
1,3-D + Pic	159 + 121	Injected with three shanks at 20 cm depth
1,3-D + Pic + metam potassium	159 + 121 + 260	1,3-D+Pic was applied at 20 cm with three shanks, while metam potassium was injected with six shanks at 10-cm depth
Pic	168	Injected with three shanks at 20 cm depth

[a]Abbreviations: SF, sulfuryl fluoride; 1,3-D,1,3-dichloropropene; Pic, chloropicrin.

nonfumigated control treatment (Table 4). In Trials III and IV, purple nutsedge shoots increased to 41 and 35 shoots m^{-2} at 13 WAF in the nonfumigated control treatment.

In Trial I, SF alone at 448 kg ha^{-1} reduced purple nutsedge shoot density compared to the nonfumigated control at 4 WAF, whereas lower rates at 224 and 336 kg ha^{-1} were ineffective on any date (Table 4). In Trial II, all SF-alone treatments did not differ in purple nutsedge control but reduced purple nutsedge shoot density compared to the nonfumigated control. In Trial III, all SF-alone treatments significantly reduced purple nutsedge shoot density compared to the nonfumigated control at 4, 9, and 13 WAF. The highest rate of SF at 448 kg ha^{-1} was more effective and resulted in significantly lower purple nutsedge shoot density compared to the lowest rate at 224 kg ha^{-1}. In Trial IV, none of the SF-alone treatments reduced purple nutsedge shoot density compared to the nonfumigated control. In Trial IV, SF applied at a rate of 336 or 448 kg ha^{-1} applied in conjunction with Pic significantly reduced purple nutsedge shoot density compared to the nonfumigated control at 4 WAF. However, soils fumigated with Pic alone had approximately 2-fold of purple nutsedge shoot density compared to the nonfumigated control in all rating dates. SF + Pic provided greater reduction of purple nutsedge shoot density than the nonfumigated control in three of four trials, whereas SF alone provided greater reduction of purple nutsedge shoot density than the nonfumigated control in two of four trials.

Although 1,3-D + Pic reduced purple nutsedge shoot density at all rating dates in Trials I and III, this fumigant treatment was ineffective and did not reduce purple nutsedge shoot density at any date in Trials II and IV (Table 4). 1,3-D + Pic + metam potassium reduced purple nutsedge density at all dates in Trial I, and at 11 and 13 WAF in Trial II. In addition, soils fumigated with 1,3-D + Pic + metam potassium had significantly less purple nutsedge shoot density compared to 1,3-D + Pic at 11 and 13 WAF in Trial II.

In Trial II, Pic alone at 168 kg ha^{-1} did not reduce purple nutsedge shoot density compared to the nonfumigated control at any date (Table 4). In Trial III, Pic alone reduced purple nutsedge shoot density compared to the nonfumigated control at 4 WAF but not at 9 and 13 WAF. In Trial IV, soils fumigated with Pic alone displayed significantly higher purple nutsedge density than the nonfumigated control at all dates. In general, Pic alone at 168 kg ha^{-1} was ineffective for purple nutsedge control and in some cases increased purple nutsedge density.

The current MB alternatives, including 1,3-D, DMDS, Pic, and methyl isothiocyanate generators such as metam sodium and metam potassium, are used by vegetable growers for weed management in plasticulture vegetables (Hanson and Shrestha 2006; Snapp et al. 2005; Yu et al. 2018, 2019). Inconsistent control of *Cyperus* spp. in plastic-mulched vegetable crops with these fumigants has been documented (Boyd et al. 2017; Hutchinson et al. 2003; Hanson and Shrestha 2006; Snapp et al. 2005; Stevens et al. 2016, 2019). For example, in previous research, Yu et al. (2019) reported that 131 kg ha^{-1} 1,3-D + 205 kg ha^{-1} Pic did not effectively control purple nutsedge at 12 WAF in plastic-mulched bell pepper. In another study, however,

https://doi.org/10.1017/wet.2021.56 Published online by Cambridge University Press

Table 4. *Cyperus rotundus* density following various fumigant programs in field experiments.[a]

Fumigant[b,d]	Rate	Trial I[c] 4 WAF	Trial I 13 WAF	Trial I 17 WAF	Trial II 4 WAF	Trial II 11 WAF	Trial II 13 WAF	Trial III 4 WAF	Trial III 9 WAF	Trial III 13 WAF	Trial IV 4 WAF	Trial IV 9 WAF	Trial IV 13 WAF
	$kg\ ha^{-1}$	shoot m^{-2}											
Nonfumigated control	–	32.6a	96.6a	49.6a	0.61	0.46a	0.41a	13.0a	28.1a	41.1a	14.0bc	31.4bc	34.6bc
SF	224	34.3a	96.0a	66.3a	0.26	0.03b	0.10b	7.5b	13.0b	21.6bc	5.4cd	17.3c	18.4c
SF	336	12.9a	70.9a	50.9a	0.05	0.00b	0.00b	4.3bc	8.6bc	17.3cd	3.2cd	10.8c	11.9c
SF	448	4.1b	52.1a	49.1a	0.03	0.00b	0.00b	1.0c	2.1c	4.3de	5.4cd	11.9c	13.0c
SF + Pic	224 + 168	1.4b	7.1b	6.8b	0.00	0.05b	0.08b	0.0c	0.0c	2.1e	3.2cd	6.5c	8.6c
SF + Pic	336 + 168	0.3b	2.5b	3.0b	0.33	0.00b	0.00b	0.0c	0.0c	0.0e	1.0d	6.5c	6.5c
SF + Pic	448 + 168	0.4b	0.1b	0.5b	0.00	0.00b	0.00b	0.0c	0.0c	1.0e	0.0d	2.1c	2.1c
1,3-D + Pic	159 + 121	0.0b	0.0b	0.1b	0.48	0.48a	0.31a	0.0c	1.0c	5.4de	19.5ab	58.5ab	63.9ab
1,3-D + Pic + metam potassium	159 + 121 + 260	0.4b	0.8b	1.4b	0.03	0.00b	0.00b	–	–	–	–	–	–
Pic	168	–^{2}	–	–	0.23	0.26a	0.26ab	6.5b	18.4ab	31.4ab	28.1a	67.1a	69.3a

[a]Values followed by the same letter in the same column do not differ according to the Fisher's protected LSD test at P = 0.05.
[b]Pic at 168 $kg\ ha^{-1}$ was not included in Trial I; 1,3-D + Pic + metam potassium was not included in Trials III and IV.
[c]Trials I and II were conducted in Balm, FL; Trials III and IV were conducted in Quincy, FL.
[d]Abbreviations: SF, sulfuryl fluoride; 1,3-D, 1,3-dichloropropene; Pic, chloropicrin; WAF, weeks after fumigation.

Stevens et al. (2019) reported that 109 $kg\ ha^{-1}$ 1,3-D + 171 $kg\ ha^{-1}$ Pic was effective and significantly reduced purple nutsedge populations at 90 d after fumigation in plastic-mulched tomato. Yu et al. (2018) noted that shank injection of 159 $kg\ ha^{-1}$ DMDS + 379 $kg\ ha^{-1}$ Pic effectively controlled purple nutsedge. However, Pic is currently not registered in many countries, which limits the use of this fumigant combination.

Substantial effort has been made to determine herbicides that can be applied on raised beds following soil fumigation for control of *Cyperus* in plastic-mulched vegetable crops. Alves et al. (2013) documented that fumigation with 1,3-D + Pic followed by postemergence halosulfluron effectively reduced purple nutsedge tuber count in plasticulture tomato. Eure and Culpepper (2017) noted that DMDS + Pic plus the herbicide napropamide applied as a preemergence herbicide prior to transplanting followed by *S*-metolachlor applied as postemergence herbicide is required to replace MB in plasticulture bell pepper. Recently, Yu et al. (2019) documented that *S*-metolachlor applied preemergence following the fumigation of 1,3-D + Pic or DMDS + Pic improved the control of purple nutsedge and various broadleaf and grass weeds. Our results show that SF + Pic treatments are highly efficacious for purple nutsedge control. The highest rate of SF at 448 $kg\ ha^{-1}$ applied in conjunction with Pic reduced purple nutsedge to ≤2.1 shoots m^{-2} by season end, suggesting that the supplemental herbicides for *Cyperus* spp. control may not be needed when this fumigation program is used.

In the present study, soils fumigated with Pic alone exhibited an approximately 2-fold increase in purple nutsedge shoot density than the nonfumigated control in Trial IV. Santos et al. (2006) performed a multiseason field research trial from 1999 to 2003 in Florida and found that Pic rates ranging from 119 to 206 $kg\ ha^{-1}$ significantly stimulated *Cyperus* spp. sprouting. Based on these findings, we postulated that SF might be more efficacious on sprouted purple nutsedge than dormant tubers. As a result, fumigation with Pic at 168 $kg\ ha^{-1}$ prior to injecting SF through drip tapes provided equivalent or better control of purple nutsedge than SF alone. SF was injected through drip tapes a few hours after shank injection of Pic. Additional study is needed to identify the best application interval between SF and Pic applications.

In this study, a significant rate response was observed in some cases when SF was applied alone. At some of the rating dates, the highest rate of SF alone (448 $kg\ ha^{-1}$) provided statistically better control of purple nutsedge compared to the lowest rate at 224 $kg\ ha^{-1}$. However, there was no rate response when SF was applied in conjunction with Pic because all SF + Pic treatments were highly effective. In addition, results revealed that the SF + Pic treatments were statistically equally effective compared to 1,3-D + Pic + metam potassium, but generally provided greater control of purple nutsedge than 1,3-D + Pic. In previous research, Cao et al. (2014) compared the efficacy of SF and MB against *Abutilon theophrasti* and *Digitaria sanguinalis* and found that SF alone was generally less effective than MB on these weed species. Further study is needed to assess SF + Pic for control of other weed species.

Tomato Growth and Yield

All fumigants were safe to tomato (data not shown). In Trial II, fumigant treatments containing Pic, including SF + Pic, 1,3-D + Pic, 1,3-D + Pic + metam potassium, and Pic alone, displayed a positive effect on tomato growth and resulted in taller tomato plants than the nonfumigated control at 9 WATP (Table 5). Tomato plants growing in plots treated with 336 $kg\ ha^{-1}$ SF were also taller than the nonfumigated control at 9 WATP in Trial II. None of the fumigants negatively affected tomato height in Trial I or tomato vigor in Trials III and IV.

In Trials I and IV, the evaluated fumigant treatments did not differ from the nonfumigated control for tomato fruit yield in various sizes (Table 6). In Trial II, tomato plants growing in plots treated with SF + Pic, 1,3-D + Pic, and 1,3-D + Pic + metam potassium resulted in higher total marketable yield than the nonfumigated control, whereas SF alone did not improve tomato yield in any size category except for extra-large harvested from plots fumigated with 336 $kg\ ha^{-1}$ SF (Table 6). In addition, yield for large or extra-large tomato in plots fumigated with SF + Pic had higher yield than the nonfumigated control. Tomato plants grown in plots fumigated with 1,3-D + Pic + metam potassium or Pic alone produced significantly higher fruit yield for large and extra-large grading categories than the nonfumigated control.

In Trial III, plots treated with 224 $kg\ ha^{-1}$ SF +168 $kg\ ha^{-1}$ Pic and 448 $kg\ ha^{-1}$ SF + 168 $kg\ ha^{-1}$ Pic resulted in significantly greater large-size tomato fruit yield compared to the nonfumigated control (Table 6). However, we did not observe any significant

https://doi.org/10.1017/wet.2021.56 Published online by Cambridge University Press

Table 5. Tomato height and vigor following various fumigant programs in field experiments in Florida.[a]

		Tomato height				Tomato vigor[b]				
		Trial I[d]	Trial II			Trial III			Trial IV	
Fumigant[c,e]	Rate	7 WATP	3 WATP	9 WATP	12 WATP	1 WATP	2 WATP	4 WATP	2 WATP	4 WATP
	kg ha^{-1}	cm								
Nonfumigated control	–	85	17	73e	95	5.0	5.5	7	4.5	5.5
SF	224	88	20	81c-e	73	5.0	5.7	7.0	5	7.2
SF	336	88	19	84b-d	96	4.5	5.2	7.0	5.7	7.5
SF	448	88	18	81de	104	4.7	6.0	7.0	5.5	7
SF + Pic	224 + 168	87	19	97a	109	4.5	5.2	7.0	5	6.2
SF + Pic	336 + 168	87	20	93ab	105	4.5	5.2	7.0	5.2	7
SF + Pic	448 + 168	86	20	96a	115	4.7	5.2	7.0	5.0	7.0
1,3-D + Pic	159 + 121	88	19	91a-c	107	4.2	5.2	7.0	5.5	7.7
1,3-D + Pic + metam potassium	159 + 121 + 260	81	19	89a-d	105	–	–	–	–	–
Pic	168	–	19	90a-d	102	4.7	6.0	7.0	5.2	7.5

[a]Values followed by the same letter in the same column do not differ according to the Fisher's protected LSD test at $P = 0.05$.
[b]Tomato vigor visually evaluated on a scale from 0 to 10 with 0 being plant death and 10 being highly vigorous plants.
[c]Pic at 168 kg ha^{-1} was not included in Trial I; 1,3-D + Pic + metam potassium was not included in Trial III and IV.
[d]Trials I and II were conducted in Balm, FL; Trials III and IV were conducted in Quincy, FL.
[e]Abbreviations: SF, sulfuryl fluoride; 1,3-D, 1,3-dichloropropene; Pic, chloropicrin; WATP, weeks after transplanting.

Table 6. Tomato yield following various fumigant programs in field experiments.[a]

Experimental run	Fumigant[b,e]	Rate	Medium[c]	Large	Extra-large	Total marketable fruit yield
			kg ha^{-1}			
Trial I[d]	Nonfumigated control	–	4560	8600	34390	4754
	SF	224	3520	8020	32720	44320
	SF	336	3640	8940	39000	5158
	SF	448	4380	7620	29950	41950
	SF + Pic	224 + 168	4500	9640	38140	52160
	SF + Pic	336 + 168	3520	7100	32770	43390
	SF + Pic	448 + 168	2830	8890	31160	42930
	1,3-D + Pic	159 + 121	3290	7900	39760	50830
	1,3-D + Pic + metam potassium	159 + 121 + 260	4270	8890	38370	51530
Trial II	Nonfumigated control	–	1150c	3460c	10390e	15000e
	SF	224	2880a-c	6920bc	18460b-e	28270b-e
	SF	336	2880a-c	6350bc	17310c-d	26540c-e
	SF	448	2310bc	3460c	15000de	20770de
	SF + Pic	224 + 168	3460a-c	12120ab	27120a-d	42700a-c
	SF + Pic	336 + 168	4620ab	10390ab	31160a-c	45580ab
	SF + Pic	448 + 168	4620a	11540ab	32890ab	48470a
	1,3-D + Pic	159 + 121	2310a-c	7500bc	25390a-d	35770a-d
	1,3-D + Pic + metam potassium	159 + 121 + 260	4620a	13850a	34040a	51930a
	Pic	168	4040ab	9809ab	32310ab	45580ab
Trial III	Nonfumigated control	–	5840b	13510cd	33050a	52400
	SF	224	5200b	12350d	37070a	54610
	SF	336	6360b	14700b-d	35330a	56390
	SF	448	4990b	14040cd	34410a	53430
	SF + Pic	224 + 168	8160b	20460a	26370ab	54990
	SF + Pic	336 + 168	7240b	17950a-c	28050ab	53230
	SF + Pic	448 + 168	7850b	18940ab	26110ab	52890
	1,3-D + Pic	159 + 121	11140a	20610a	19970b	51720
	Pic	168	8130b	19530ab	26530ab	54190
Trial IV	Nonfumigated control	–	2400	7060	19390	28850
	SF	224	2120	8500	26790	37420
	SF	336	2730	9880	26300	38910
	SF	448	2440	9300	29870	41610
	SF + Pic	224 + 168	2640	7540	22780	32960
	SF + Pic	336 + 168	2590	8310	25330	36230
	SF + Pic	448 + 168	3790	12010	30140	45950
	1,3-D + Pic	159 + 121	2730	9890	23440	36060
	Pic	168	3080	9920	23100	36100

[a]Values followed by the same letter in the same column do not differ according to the Fisher's Protected LSD test at $P = 0.05$.
[b]Pic at 168 kg ha^{-1} was not included in Trial I; 1,3-D + Pic + metam potassium was not included in Trial III and IV.
[c]Fruit was graded prior to weighing as medium (5.5 cm < diameter <6.5 cm), large (6.5 cm < diameter <7 cm) or extra-large (>7 cm).
[d]Trials I and II were conducted in Balm, FL, while Trials III and IV were conducted in Quincy, FL.
[e]Abbreviations: SF, sulfuryl fluoride; 1,3-D, 1,3-dichloropropene; Pic, chloropicrin.

https://doi.org/10.1017/wet.2021.56 Published online by Cambridge University Press

difference among the fumigant treatments and the nonfumigated control in terms of total marketable fruit yield. In addition, none of the SF-alone treatments differed from the nonfumigated control in terms of tomato fruit yield in various size categories.

Large and extra-large tomato fruits often command a premium price. In a few cases in Trials II and III, SF + Pic resulted in significantly more large, extra-large, and total marketable fruit yields than the nonfumigated control and SF alone. Previous studies have shown an increase in tomato height and markable yield when Pic is applied in conjunction with other soil fumigants (Boyd et al. 2017; Yu et al. 2018). Boyd et al. (2017) observed that tomato plants growing in soils fumigated with 1,3-D + Pic or DMDS + Pic were slightly taller than those fumigated with DMDS alone and nonfumigated control. Stevens et al. (2019) reported that shank injection of 1,3-D + Pic resulted in taller tomato plants and better tomato vigor than the nonfumigated control. In other vegetables, Miller et al. (2014) noted that bell pepper plants growing in plots treated with 1,3-D + Pic or DMDS + Pic were taller than the nonfumigated control.

In summary, at the rates tested, all SF + Pic treatments were efficacious and provided season-long control of purple nutsedge. However, the overall trend showed that SF alone was less effective than SF + Pic and provided inconsistent control of purple nutsedge. Results also revealed that 1,3-D + Pic + metam potassium was highly effective and provided comparable control of purple nutsedge when compared to SF + Pic, whereas 1,3-D + Pic provided inconsistent control of purple nutsedge. In addition, our results agree with those from previous research that found that Pic alone was ineffective for purple nutsedge control (Santos et al. 2006). Moreover, none of the fumigant treatments exhibited an adverse effect on tomato growth and marketable yield. In one of the four tomato seasons, SF + Pic programs resulted in significantly greater tomato plant height and total marketable fruit yields than the nonfumigated control. Overall, this research demonstrates that fumigation with SF in conjunction with Pic is an efficacious solution for control of purple nutsedge in plasticulture vegetables. Additional studies are needed to determine the efficacy of SF + Pic on other weed species and soilborne pathogens, along with optimum time interval between Pic and SF injection.

Acknowledgments. We acknowledge financial and technical support from Douglas Products and Tri-Est Ag. We also thank the farm crews at the Gulf Coast Research and Education Center and North Florida Research and Education Center for assistance with fumigation and crop management. No conflicts of interest have been declared.

References

Alves C, MacRae AW, Hunnicut CJ, Jacoby TP, MacDonald GE, Dittmar PJ (2013) Impact of fallow programs and fumigants on nutsedge (*Cyperus* spp.) management in plasticulture tomato. Weed Technol 27:323–330

Aung L, Leesch J, Jenner J, Grafton-Cardwell E (2001) Effects of carbonyl sulfide, methyl iodide, and sulfuryl fluoride on fruit phytotoxicity and insect mortality. Ann Appl Biol 139:93–100

Besançon T, Wasacz M, Carr B (2020) Weed control and crop tolerance with *S*-metolachlor in seeded summer squash and cucumber. Weed Technol 34:849–856

Boyd NS, Vallad G, Wu F, Noling J, Guan Z (2017) Placement of metam potassium in combination with dimethyl disulfide, chloropicrin, and 1, 3-dichloropropene for *Cyperus rotundus* L. and broadleaf weed control in tomato (*Solanum lycopersicum* L.). Crop Prot 100:45–50

Buker RS, Stall W, Olson S, Schilling D (2003) Season-long interference of yellow nutsedge (*Cyperus esculentus*) with direct-seeded and transplanted watermelon (*Citrullus lanatus*). Weed Technol 17:751–754

Cao A, Guo M, Yan D, Mao L, Wang Q, Li Y (2014) Evaluation of sulfuryl fluoride as a soil fumigant in China. Pest Manag Sci 70:219–227

Castro E, Pucci C, Duarte S, Burgos NR, Tseng TM (2020) Improved herbicide selectivity in tomato by safening action of benoxacor and fenclorim. Weed Technol 34:647–651

Creamer NG, Bennett MA, Stinner BR (1997) Evaluation of cover crop mixtures for use in vegetable production systems. HortScience 32:866–870

Derrick MR, Burgess HD, Baker MT, Binnie NE (1990) Sulfuryl fluoride (Vikane): A review of its use as a fumigant. J Am Inst Conserv 29:77–90

Eure PM, Culpepper AS (2017) Bell pepper and weed response to dimethyl disulfide plus chloropicrin and herbicide systems. Weed Technol 31:694–700

Gilreath JP, Motis TN, Santos BM (2005) *Cyperus* spp. control with reduced methyl bromide plus chloropicrin doses under virtually impermeable films in pepper. Crop Prot 24:285–287

Guo H, Zhao X, Rosskopf EN, Di Gioia F, Hong JC, McNear DH (2018) Impacts of anaerobic soil disinfestation and chemical fumigation on soil microbial communities in field tomato production system. Appl Soil Ecol 126:165–173

Hanson B, Shrestha A (2006) Weed control with methyl bromide alternatives. CAB Rev Perspect Agric Vet Sci Nutr Nat Resour 1:1–13

Holm LG, Plucknett DL, Pancho JV, Herberger JP (1977) The world's worst weeds. Distribution and biology. Honolulu: University Press of Hawaii

Hutchinson CM, McGiffen ME Jr, Sims J, Becker J (2003) Fumigant combinations for *Cyperus esculentum* L. control. Pest Manag Sci 60:369–374

Igbokwe PE (1996) Mulching for nutsedge control in field-grown peppers. J Veg Crop Prod 2:47–53

Johnson WC, Mullinix BG (1999) *Cyperus esculentus* interference in *Cucumis sativus*. Weed Sci 47:327–331

Kenaga E (1957) Some biological, chemical and physical properties of sulfuryl fluoride as an insecticidal fumigant. J Econ Entomol 50:1–6

McDonald MR, Collins B, duToit L, Adusei-Fosu K (2021) Soil amendments and fumigation for the management of Fusarium wilt of bunching spinach in Ontario, Canada. Crop Prot 145:15646

Meister RT (1992) Farm Chemicals Handbook. Willoughby, OH: Meister Publishing

Miller MR, Dittmar PJ, Vallad GE, Ferrell JA (2014) Nutsedge (*Cyperus* spp.) control in bell pepper (*Capsicum annuum*) using fallow-period weed management and fumigation for two years. Weed Technol 28:653–659

Morales-Payan JP, Santos BM, Stall WM, Bewick TA (1997) Effects of purple nutsedge (*Cyperus rotundus*) on tomato (*Lycopersicon esculentum*) and bell pepper (*Capsicum annuum*) vegetative growth and fruit yield. Weed Technol 19:672–676

Patterson DT (1998) Suppression of purple nutsedge (*Cyperus rotundus*) with polyethylene film mulch. Weed Technol 12:275–280

Rajendran S, Kumar VL, Sriranjini V (2008) Fumigation of grain stacks with sulfuryl fluoride. Inter Pest Control 50:192–195

Randell T, Vance J, Culpepper A (2020) Broccoli, cabbage, squash and watermelon response to halosulfuron preplant over plastic mulch. Weed Technol 34:202–207

Ren ZJ, Li Y, Fang WS, Yan DD, Huang B, Zhu J, Wang X, Wang X, Wang, Q, Guo MX, Cao A (2018) Evaluation of allyl isothiocyanate as a soil fumigant against soil-borne diseases in commercial tomato (*Lycopersicon esculentum* mill.) production in China. Pest Manag Sci 74:2146–2155

Santos BM, Gilreath JP, Motis TN (2006) Impact of chloropicrin on nutsedge emergence through polyethylene mulch. HortTechnol 16:30–32

Snapp S, Swinton S, Labarta R, Mutch D, Black J, Leep R (2005) Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron J 97:322–332

Stevens MC, Freeman JH, Boyd NS (2019) Impact of ethanedinitrile rates and application method on nutsedge species and tomato root galling. Crop Prot 116:1–6

Stevens MC, Freeman JH, Dittmar PJ (2016) Impact of totally impermeable film on the efficacy of 1,3-dichloropropene and chloropicrin mixtures for the control of nutsedge. Weed Technol 30:910–918

[USEPA] U.S. Environmental Protection Agency (2019) Methyl bromide. https://www.epa.gov/ods-phaseout/methyl-bromide. Accessed: April 5, 2020

[USDA-AMS] U.S. Department of Agriculture–Agricultural Marketing Service (1991) United States Standards for Grades of Fresh Tomatoes. https://www.ams.usda.gov/grades-standards/tomato-grades-and-standards. Accessed: June 6, 2021

Webster T (2010) Weed survey-southern states: vegetable, fruit, and nut crops subsection. Proc South Weed Sci Soc 63:246–253

Wills GD (1987) Description of purple and yellow nutsedge (*Cyperus rotundus* and C. *esculentus*). Weed Technol 1:2–9

Yu J, Boyd NS (2017) Weed control with and strawberry tolerance to herbicides applied through drip irrigation. Weed Technol 31:87–876

Yu J, Boyd NS (2021) Long-term effect of fumigation and a sorghum cover crop on broadleaf and grass weeds in plastic-mulched tomato. Pest Manag Sci 77:1806–1817

Yu J, Land CJ, Vallad GE, Boyd NS (2018) Tomato tolerance and pest control following fumigation with different ratios of dimethyl disulfide and chloropicrin. Pest Manag Sci 75:1416–1424

Yu J, Sharpe SM, Boyd NS (2019) Fumigants alone or in combination with herbicide for weed management in bell pepper (*Capsicum annuum*). Crop Prot 118:31–35

Zettler JL, Arthur FH (2000) Chemical control of stored product insects with fumigants and residual treatments. Crop Prot 19:577–582