Nutsedge Control with Drip-applied 1,3-Dichloropropene plus Chloropicrin in a Sandy Soil

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SUMMARY. An evaluation of the effect of bed width (24, 28, 32, and 36 inches) on the control of a mixed population of nutsedge [yellow nutsedge (*Cyperus esculentus*) and purple nutsedge (*C. rotundus*)] was conducted with an emulsifiable concentrate formulation of a 1,3-dichloropropene (1,3-D) and chloropicrin (CP) mixture (1,3-DCP) for application through drip irrigation systems. Beds were mulched with either 1.4-mil-thick virtually impermeable film (VIF) or 0.75-mil-thick high-density polyethylene (HDPE) and 1,3-DCP was applied at 35 gal/acre by surface chemigation or via subsurface chemigation 6 inches deep within the bed. HDPE was more permeable to gaseous 1,3-D than VIF so that 1 day after treatment (DAT), 1,3-D gas concentration at the bed centers under VIF was significantly higher than under HDPE. Dissipation of 1,3-D gas with HDPE occurred within 7 DAT, but dissipation with VIF took ~10 days. In bed centers, 1,3-D concentrations 1 DAT were in the range of 2.3 to 2.9 mg·L⁻¹ whereas in bed shoulders concentrations ranged from 0.1 to 0.55 mg·L⁻¹. In 2002 and 2003, 1,3-D concentration in shoulders of narrower beds was significantly higher than in the wider beds, but dissipated more rapidly than in wider beds. Lower initial 1,3-D concentrations were observed with HDPE film in shoulders than with VIF and the rate of dissipation was lower with VIF. At 14 DAT, nutsedge plants were densely distributed along bed shoulders (19 to 27 plants/m²) with little or no emergence in the centers of beds (fewer than 5 plants/m²), but with no response to bed width. Nutsedge density increased with time, but the nature of the increase differed with bed width. The most effective nutsedge suppression was achieved with 36-inch beds, which had densities of 11–13 plants/m² on bed centers and 53 plants/m² on bed shoulders by 90 DAT. Nutsedge suppression was initially more effective with VIF than with HDPE film, so that no nutsedge emerged in the centers of beds mulched with VIF compared with 2–7 plants/m² with HDPE by 14 DAT. On bed shoulders there were 2–7 plants/m² with VIF and 32–57 plants/m² with HDPE. Increase in nutsedge density with time was greater with VIF so that by 90 DAT nutsedge densities on bed centers and shoulders were greater than with HDPE in 2002 and the same as with HDPE in 2003. Subsurface chemigation did not consistently improve suppression of nutsedge when compared with surface chemigation. Concentrations of 1,3-D in bed shoulders irrespective of bed width were nonlethal. Initial superior nutsedge suppression with VIF did not persist. Nutsedge control in a sandy soil with 1,3-DCP chemigation is unsatisfactory with one drip-tape per bed.

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Chisel-applied volatile formulations of the soil fumigant mixture 1,3-DCP are among the more promising alternatives to methyl bromide for crop production (Locascio et al., 1997). 1,3-DCP is already registered for use in plasticulture production of vegetables and strawberry (*Fragaria × ananassa*) in Florida for the control of plant pathogenic nematodes and soilborne pathogens. Its effect on nutsedges is weak or inconsistent when compared with methyl bromide. Under some conditions, the resulting concentrations of the fumigant and duration of exposure appear to be sufficient to provide adequate control of nutsedge (Hochmuth et al., 2002). However, this is not always the case and these conditions are not well understood. Hence, one approach to controlling purple nutsedge has utilized fumigant/herbicide combinations (Gilreath and Santos, 2004a, 2004b, 2005; Gilreath et al., 2004). In laboratory studies the effective concentration of 1,3-D + 17% chloropicrin resulting in 50% mortality of imbibed yellow nutsedge tubers was 20 µM (Hutchinson et al., 2004); while in greenhouse studies, 99% mortality of imbibed yellow nutsedge tubers was obtained with 327 L·ha⁻¹ 1,3-D + 35% chloropicrin (Motis et al., 2002). We hypothesized that the failure to achieve consistent results on nutsedges with 1,3-D-containing fumigants in the field may be due to insufficient duration of exposure to lethal concentrations.

Drip fumigation is a relatively new concept and Ajwa et al. (2002) identified a number of areas in which more work is needed: minimizing application rates; selecting mulches that restrict emissions and maximize efficacy; and optimum soil conditions, carrier amounts, and combinations of chemicals. Benefits of applying soil fumigants by chemigation include limited worker exposure since installation of polyethylene film is done prior

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
0.0254	mil	mm	39.3701
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450

to the application and the capability of simultaneous or sequential application of fumigants (Desaeger et al., 2005). Sequential application would be applicable to Florida plasticulture systems in which growers plant multiple crops in sequence using the same beds and polyethylene film. A third benefit is that drip application of emulsifiable concentrate formulations of 1,3-DCP is generally considered less susceptible to off-gassing than shank application of volatile, liquid formulations. Wang et al. (2001) reported lower emissions of 1,3-D with drip fumigation than with shank fumigation. As a result, buffer zones between application sites and any occupied buildings for volatile, liquid formulations were initially three times that for drip-applied formulations.

Limiting emissions is desirable for reducing the possibility of human and animal exposure. Also, strategies that result in higher soil fumigant concentrations as a consequence of limiting emissions can enhance the effectiveness of the fumigation. Wang et al. (2001) advocated the following approaches to reduce 1,3-D emissions: improved containment with impermeable mulches, application at increased soil depth, and reduced application rates. Containment refers to achieving a fumigant dose and exposure time that deliver effective pest control (Yates et al., 2002). Measures that result in fumigant containment reduce emissions, and consequently require less fumigant to be applied for similar level of pest control (Santos et al., 2005). VIFs consist of an impermeable barrier layer of ethylene vinyl alcohol or polyamide sandwiched between polyethylene (Yates et al., 2002). VIF use resulted in improved containment and reduced emissions of methyl bromide (MB) and alternative fumigants in California, when the entire field (not just beds) was covered during fumigation (Wang et al., 1999). In addition, Nelson et al. (2000, 2001) found that VIF-mulched beds retained higher concentrations of 1,3-D and had significantly lower emissions than no mulch controls and beds mulched with low-density polyethylene film during the 3 d following application.

Florida's plasticulture production system involves fumigant application to pre-formed beds that are then covered with polyethylene film. The film serves as a fumigation tarp and is retained as a production mulch. VIF is not as effective

in reducing emissions when used only on beds (Wang and Yates, 1998) since fumigants may be lost through lateral movement into the unmulched furrows. However, application only to the beds reduces the amount of fumigant and film that must be used, since application rates are based on treated surface area.

Csinos et al. (2002) have described a method of using dye to visualize the wetting pattern produced by drip irrigation emitters in polyethylene-mulched beds. In the deep sands in Florida, growers typically use one drip tape per bed, placed in the center of the bed for crops planted in two rows and slightly off-center for crops planted in a single row. Depending on fumigant volatility and the concentrations of gas that can be achieved in zones of the bed that remain dry, it may be possible to achieve lethal concentrations with chemigation. However, pest control may be inadequate with less volatile fumigants if the entire bed is not wetted. The objective of this study was to evaluate the effect of bed width, drip tape placement, and mulch film type on 1,3-DCP soil distribution and nutsedge control in a sandy soil. We hypothesized that decreasing bed width and use of subsurface chemigation and VIF would result in more effective nutsedge control by concentrating the fumigant in a smaller soil volume and enhancing fumigant containment.

Materials and methods

Experiments were conducted at the North Florida Research and Education Center—Suwannee Valley, near Live Oak, on a Lakeland fine sand (thermic, coated Typic Quartzipsamments) in Fall 2002 and 2003. Plots were 70 ft long and were located in a field with a high purple nutsedge infestation. The soil fumigant 1,3-D (60.8%) plus chloropicrin (33.3%) (InLine; Dow Agrosciences, Indianapolis) was applied as a chemigation treatment to beds with a range of widths that encompass widths generally used for vegetable production in Florida: 24, 28, 32, and 36 inches. In 2002, soil was hilled into false beds prior to pressing with a bed-shaper equipped with an adjustable-width press pan (Kennco Manufacturing, Ruskin, Fla.). In 2003, a Kennco one bed bed-shaper with interchangeable fixed-width press pans was used. Beds were 6 inches high. A single drip-irrigation tape (Ro-Drip;

Roberts Irrigation Products, San Marcos, Calif.) with emitters spaced at 12-inch intervals and a flow rate of 24 gal/h per 100 ft at 12 psi was installed along the center of each bed either at the soil surface or buried 6 inches within the bed. Two white-on-black films with the white side up were used to mulch the beds: 1.4-mil-thick VIF (Hytibarrier, Klerks, Richburg, S.C.) and 0.75-mil-thick HDPE (Sonoco, Hartsville, S.C.).

The experimental design was a split plot with bed widths allocated to main plots in a randomized complete-block design with six replications. Four film type/drip-tape depth combinations were assigned to the subplots in a completely randomized manner: HDPE, 0 inch; HDPE, 6 inches; VIF, 0 inch; and VIF, 6 inches. 1,3-DCP was applied through the drip irrigation system at 35 gal/acre on 15 Aug. 2002 and 28 Aug. 2003. In accordance with U.S. Environmental Protection Agency requirements, the rate of drip-applied fumigants is based on the bed width. Therefore, the wider the bed the larger the amount of fumigant that must be applied and thus the longer the duration of application. Duration of application was 240, 280, 320, and 360 min for 24-, 28-, 32-, and 36-inch bed widths, respectively. Water-soluble blue dye (Terramark SPI High Concentrate; ProSource One, Memphis, Tenn.) was injected immediately prior to the soil fumigant to permit visualization of the extent of the wetting pattern of the fumigant (Csinos et al., 2002). In each block, two nontreated control plots were also included, one of which was mulched with VIF and the other with HDPE film.

Efficacy of soil fumigant application was evaluated by monitoring soil gas concentration until 15 d after treatment (DAT) and by monitoring the density of a mixed population of purple and yellow nutsedge 14, 28, 60, and 90 DAT. Soil air was sampled using Gastec trichloroethylene detector tubes (132HA; Zefon International, St. Petersburg, Fla.) and a gas tube pump (Sensidyne, Clearwater, Fla.) to detect 1,3-D at 10-cm depth at the center and the shoulder of each bed. Nutsedge plants that emerged through the mulch films were counted on 14, 28, 60, and 90 d after fumigant application. Counts were performed on a 10-ft-long section of each plot. Separate counts were performed for the

bed shoulders and bed centers. From prior experience in sandy soils, the wetted width of the bed is narrower than the width of the bed because of limited lateral movement away from the drip tape. It was anticipated that some of the plots would have nutsedge occurring only in the bed shoulders. Therefore, bed shoulders were held constant and defined as 6-inch-wide strips along the edges of the bed. The rest of the bed was considered the bed center and was 12, 16, 20, and 24 inches wide for the 24-, 28-, 32-, and 36-inch bed widths, respectively.

Data analysis was performed using the MIXED procedure of SAS (version 9.0; SAS Institute, Cary, N.C.). Repeated measures analysis was utilized for gas and nutsedge data, which were collected at multiple intervals. Linear and quadratic responses to changing bed width and over time were evaluated using orthogonal polynomials. PROC IML was used to generate coefficients for orthogonal polynomials for the unevenly spaced time intervals. Nutsedge counts were square-root transformed prior to data analysis. The DIFF option was used to obtain comparisons between pairs of least squared means. Untransformed least squared means were used in the tables for ease of interpretation. Regression of wetting pattern measurements was done using PROC REG.

Results and discussion

As can be expected, for both bed centers and bed shoulders, gaseous 1,3-D concentration was highest immediately after application and declined with time.

1,3-D CONCENTRATION IN BED CENTERS. In 2002, the main effect of bed width on 1,3-D in soil gas sampled at bed centers was nonsignificant. The concentrations of 1,3-D were 0.4, 0.403, 0.468, and 0.474 mg·L⁻¹ for 24-, 28-, 32-, and 36-inch-wide beds, respectively, and not statistically different (data not shown). At 1, 4, and 7 DAT, concentration of 1,3-D with VIF was higher at bed centers than with HDPE, indicating more rapid dissipation of the soil fumigant with HDPE (Fig. 1). By 1 DAT, 1,3-D concentration at the bed centers under VIF was ~2 mg·L⁻¹, twice the concentration under HDPE. By 7 DAT, 1,3-D was no longer detectable under HDPE film, whereas there was more gradual

dissipation with VIF until 10 DAT. There was no statistical difference in soil gas concentrations between surface and subsurface chemigation.

In 2003, the effect of film type and depth of chemigation differed with bed width ($P < 0.01$). Initial concentrations of gaseous 1,3-D in the soil 1 DAT measured at the center of the beds mulched with VIF were 2.3 to 2.9 mg·L⁻¹ and generally higher than with HDPE (Fig. 2). As for 2002, the rate of loss of 1,3-D gas from the soil occurred more rapidly with HDPE. Therefore, 1,3-D was completely dissipated by 7 DAT with HDPE compared with 8–10 DAT with VIF. With HDPE, subsurface chemigation resulted in higher concentrations of 1,3-D with 24-, 28-, and 32-inch beds 1 DAT ($P \leq 0.04$). Subsurface drip chemigation with VIF resulted in similar 1,3-D gas concentrations as surface chemigation except for 32-inch beds, which had lower 1,3-D gas concentration with subsurface chemigation ($P = 0.003$).

1,3-D CONCENTRATION IN BED SHOULDERS. The initial concentrations of 1,3-D in bed shoulders were five-fold lower than in the bed centers ranging from 0.1 to 0.55 mg·L⁻¹ (Fig. 3). The effect of bed width on soil gas concentration in bed shoulders varied with time. In both years, concentrations of 1,3-D gas at 1 DAT were

similar in 24- and 28-inch beds ($P > 0.05$). Also, the concentrations in the bed shoulders of these narrower beds were higher than in the wider beds ($P \leq 0.002$) in both years. This can be attributed to the shoulders of wider beds being further away from the drip-tape than in narrower beds. In 2002, initial 1,3-D concentrations in 32- and 36-inch beds were statistically similar ($P > 0.05$); however, in 2003 1,3-D concentration was higher in 32-inch beds than in 36-inch beds ($P = 0.03$). In both years, 1,3-D concentration declined in a quadratic manner with the narrower bed widths and linearly with the wider bed widths, with more rapid dissipation occurring with the narrower bed widths.

As for bed centers, HDPE film was more permeable to gaseous 1,3-D at bed shoulders than VIF (Fig. 4). Initial 1,3-D concentrations at bed shoulders with VIF 1 DAT were significantly higher than under HDPE ($P < 0.01$). Loss of 1,3-D was faster with HDPE so that complete dissipation had occurred by 7 DAT, whereas 0.2–0.3 mg·L⁻¹ could still be detected under VIF. Subsurface chemigation did not result in differences in 1,3-D concentration in bed shoulders in 2002. In 2003, subsurface chemigation with VIF resulted in lower levels of 1,3-D gas at 1 DAT than surface chemigation

Fig. 1. Concentration of 1,3-dichloropropene at bed center of a sandy soil as affected by film type and depth of chemigation in 2002. Data were averaged over bed width. HDPE and VIF are 0.75-mil high-density polyethylene film and 1.4-mil virtually impermeable film, respectively. Q** indicates a quadratic trend significant at $P < 0.01$. Solid and dashed lines indicate surface and subsurface chemigation, respectively; 1 mil = 0.0254 mm, 1 mg·L⁻¹ = 1 ppm, 1 inch = 2.54 cm.

Fig. 2. Concentration of 1,3-dichloropropene at bed center of a sandy soil as affected by film type and depth of chemigation in 2003. HDPE and VIF are 0.75-mil high-density polyethylene film and 1.4-mil virtually impermeable film, respectively. All responses had a significant quadratic trend $P < 0.01$ as determined by orthogonal polynomials; 1 mil = 0.0254 mm, 1 $\text{mg}\cdot\text{L}^{-1}$ = 1 ppm, 1 inch = 2.54 cm.

($P < 0.01$). 1,3-D gas concentration with surface chemigation and HDPE film was close to detection limits 1 DAT and was undetectable by 4 DAT. Sub-surface chemigation HDPE resulted in $\sim 0.15 \text{ mg}\cdot\text{L}^{-1}$ 1,3-D, with complete dissipation by 7 DAT. Our results indicate greater 1,3-D concentration with VIF than with HDPE film and greater concentrations of 1,3-D in the center of the beds than in bed shoulders. Similar results were obtained in previous studies (Ajwa et al., 2002; Papiernik et al., 2004).

NUTSEDGE CONTROL WITH 1,3-DCP AS AFFECTED BY BED WIDTH. In 2002, by 14 DAT fewer than 3 plants/ m^2 were observed in the centers of beds and nutsedge density did not differ with bed width (Table 1). At subsequent evaluation dates, nutsedge density in bed centers decreased linearly as bed width increased. The rate of increase in nutsedge density over time was greater in narrower beds (24 and 28 inches) than in the wider beds (32

and 36 inches). By 60 and 90 DAT nutsedge densities in bed centers were highest with 24-inch beds (32.5 and 42.7 plants/ m^2), intermediate with 28-inch beds (21.3 and 26.4 plants/ m^2), and lowest with the 32- (8.4 and 17.4 plants/ m^2) and 36-inch beds (6.3 and 10.8 plants/ m^2). Higher nutsedge infestation occurred in the bed shoulders than in the bed centers. By 14 DAT nutsedge densities in bed shoulders ranged from 19.2 to 29.2 plants/ m^2 , but with no significant difference due to bed width. As for the bed centers, there was a linear decrease in nutsedge density with increasing bed width at 28, 60, and 90 DAT. The rate of increase of nutsedge density was also greater in 24- and 28-inch beds than in 32- and 36-inch beds. By 90 DAT nutsedge density was highest on shoulders 24-inch beds (120 plants/ m^2), intermediate with 28-inch beds (104 plants/ m^2) and lowest with 32- and

Fig. 3. Effect of bed width on 1,3-dichloropropene concentration in bed shoulders of a sandy soil. L** and Q** indicate linear and quadratic responses significant at $P \leq 0.01$ as determined by orthogonal polynomials; 1 $\text{mg}\cdot\text{L}^{-1}$ = 1 ppm, 1 inch = 2.54 cm.

36-inch beds (94 and 53 plants/ m^2 , respectively).

In 2003, as for 2002, no differences in nutsedge density in response to bed width were apparent on the centers and shoulders of beds by 14 DAT (Table 1). However, whereas with bed centers at 28, 60, and 90 DAT nutsedge density decreased as bed width increased, significant suppression of nutsedge density on bed shoulders was only apparent at 60 and 90 DAT. Nutsedge density in bed centers increased in a quadratic manner over time with all bed widths, but the rate of increase was highest with 24-inch beds, intermediate with 28- and 32-inch beds, and lowest with 36-inch beds. Along bed shoulders nutsedge density also increased quadratically over time. However, the rate of increase was similar with 24-, 28-, and 32-inch beds, whereas nutsedge density increased at a lower rate with 36-inch beds.

Fig. 4. Effect of film type and depth of chemigation on 1,3-dichloropropene concentration in bed shoulders of a sandy soil. HDPE and VIF are 0.75-mil high-density polyethylene film and 1.4-mil virtually impermeable film, respectively. L and Q indicate linear and quadratic responses, respectively. ^{NS}, ^{*}, ^{**} Nonsignificant and significant at $P \leq 0.05$ and 0.01 , respectively. Solid and dashed lines indicate surface and subsurface chemigation, respectively; 1 mil = 0.0254 mm, $1 \text{ mg} \cdot \text{L}^{-1} = 1 \text{ ppm}$, 1 inch = 2.54 cm.

NUTSEDGE CONTROL WITH 1,3-DCP AS AFFECTED BY FILM MULCH AND DEPTH OF CHEMIGATION. Nontreated control treatments were conducted with HDPE film and VIF, but only at the 36-inch bed width. Therefore these data were compared only with 36-inch chemigated beds (Table 2). Counts taken on the controls in 2002 did not distinguish between shoulders and centers of beds and are not reported. In 2002, nutsedge density was higher with the VIF control than with the HDPE controls by 60 DAT. However, in 2003, nutsedge density was higher in the VIF controls only at 90 DAT. Compared with the HDPE control, surface chemigation with HDPE film in 2002 resulted in similar nutsedge density in bed centers, but nutsedge density was higher in bed shoulders at 28 and 90 DAT. Nutsedge suppression was somewhat better in bed centers when chemigation was conducted with VIF than with HDPE, so that lower nutsedge densities were obtained with VIF and chemigation than the VIF control at 28 DAT with both surface and subsurface application. However, by 60 DAT only subsurface-treated VIF beds still had a lower nutsedge density than the VIF control, and density with the surface chemigation treatment was no longer significantly different. As for HDPE chemigation in bed shoulders, nutsedge densities were higher with VIF and surface chemigation than with the VIF controls at 28 and 90 DAT,

Table 1. Nutsedge control in a sandy soil chemigated with 1,3-dichloropropene plus chloropicrin as affected by bed width and time.

Bed width (inches)	Nutsedge density (plants/m ²) ^a									
	2002					2003				
	14 DAT ^b	28 DAT	60 DAT	90 DAT	Significance ^c	14 DAT	28 DAT	60 DAT	90 DAT	Significance
<i>Centers^w</i>										
24	2.2	10.6	32.5	42.7	Q**	4.6	17.0	70.2	65.5	Q**
28	1.7	10.6	21.3	26.4	Q**	1.2	9.0	49.7	50.1	Q**
32	0.9	4.6	8.4	17.4	L**	1.6	7.4	42.0	50.8	Q**
36	0.8	4.1	6.3	10.8	L**	1.0	3.2	12.0	12.8	Q**
Significance	NS	L**	L**	L**		NS	L**	Q**	Q**	
<i>Shoulders^w</i>										
24	19.2	83.5	112.5	120.2	Q**	27.4	51.7	119.7	114.9	Q**
28	29.2	77.7	96.5	103.9	Q**	21.4	43.0	98.3	95.0	Q**
32	24.0	56.3	77.4	93.6	Q**	23.9	46.2	96.0	111.5	Q**
36	20.9	40.6	43.8	52.6	Q**	20.0	32.9	48.8	53.2	Q**
Significance	NS	L**	L**	L**		NS	NS	L**	Q**	

^a1 plant/m² = 0.0929 plant/ft².

^bDays after treatment.

^cResponses in columns and rows were evaluated using orthogonal polynomials. ^{NS}, ^{**} Nonsignificant or significant at $P < 0.01$, respectively. L and Q indicate linear and quadratic responses, respectively.

^wBed center widths were 12, 16, 20, and 24 inches for 24-, 28-, 32-, and 36-inch bed widths, respectively, and shoulder width was 6 inches; 1 inch = 2.54 cm.

Table 2. Comparison of nutsedge density on nontreated beds and beds chemigated with 1,3-dichloropropene plus chloropicrin.

		Nutsedge density (plants/m ²) ^z							
Film ^y	Chemigation ^x	2002				2003			
		14 DAT ^w	28 DAT	60 DAT	90 DAT	14 DAT	28 DAT	60 DAT	90 DAT
<i>Centers^v</i>									
HDPE	control	---	8.3 ab	4.8 c	6.3 b	15.1 a	16.0 ab	22.0 a	14.8 b
HDPE	surface	2.2 a	6.9 ab	6.8 bc	9.9 ab	2.8 b	7.3 bc	12.3 b	9.9 b
HDPE	subsurface	1.1 a	3.8 bc	4.2 c	5.8 b	1.3 bc	5.1 c	10.8 b	10.3 b
VIF	control	---	15.7 a	23.0 a	18.0 ab	13.4 a	19.2 a	35.3 a	27.6 a
VIF	surface	0 a	4.7 bc	10.2 ab	19.0 a	0 c	0.3 d	11.7 b	11.1 b
VIF	subsurface	0 a	1.2 c	4.0 c	8.6 b	0 c	0.3 d	13.2 b	20.5 b
<i>Shoulders^v</i>									
HDPE	control	---	17.2 b	20.5 c	13.2 c	36.2 a	57.9 a	64.2 ab	51.3 b
HDPE	surface	46.8 a	59.2 a	42.8 abc	43.4 b	48.2 a	52.3 a	63.3 ab	55.9 b
HDPE	subsurface	19.0 b	33.2 b	31.7 bc	29.8 bc	22.9 a	40.1 ab	48.6 b	42.1 b
VIF	control	---	31.6 b	44.2 ab	41.3 b	35.5 a	63.1 a	95.9 a	115.4 a
VIF	surface	11.5 b	50.1 a	74.3 a	95.0 a	3.4 b	22.2 bc	40.9 b	43.0 b
VIF	subsurface	6.5 b	19.9 b	26.2 bc	42.5 b	5.4 b	17.0 c	42.5 b	72.8 b

^z1 plant/m² = 0.0929 plant/ft².

^yHDPE and VIF are 0.75-mil high-density polyethylene film and 1.4-mil virtually impermeable film, respectively; 1 mil = 0.0254 mm.

^xSubsurface chemigation was done at a soil depth of 6 inches; 1 inch = 2.54 cm.

^wDays after treatment.

^vAll untreated beds were 36 inches wide and were compared with only 36-inch-wide chemigated beds. Bed center width was 24 inches and shoulder width was 6 inches. Means in columns followed by the same lowercase letter are not significantly different at $P \leq 0.05$.

and nutsedge densities with VIF and subsurface chemigation and the VIF control were similar.

Chemigation was more effective in 2003 than in 2002. In 2003, chemigation with VIF reduced nutsedge density in both centers and shoulders of beds to lower levels than the VIF control at all evaluation dates (Table 2). However, nutsedge density with chemigation and HDPE film was reduced only in centers until 60 DAT, and no suppression was obtained in shoulders. No difference due to drip tape location was observed with either film.

The effects of film and drip-tape location on nutsedge density averaged over all bed widths are presented in Table 3. In 2002, no nutsedge had emerged on centers of beds mulched with VIF by 14 DAT. Surface and subsurface chemigation with HDPE film resulted in nutsedge densities of 3.2 and 2.4 plants/m², which were not significantly different. However, by 28 DAT nutsedge on bed centers of HDPE with surface chemigation had increased to 12.2 plants/m² and was significantly higher than the 8.1 plants/m² obtained with HDPE and subsurface chemigation. Similarly nutsedge density on VIF with surface chemigation at 28 DAT (6.5 plants/m²) was higher than on VIF with subsurface chemigation (3.2 plants/m²).

However, rate of increase in nutsedge density was greater with VIF than with HDPE later in the season, so that by 90 DAT nutsedge densities were higher on beds mulched with VIF than with HDPE, and the effect of drip tape depth was no longer significant. Hochmuth et al. (2002) reported on only a single evaluation of nutsedge density at 4 weeks after treatment. Consistent with our results for the same time frame, they found greater suppression of nutsedge with VIF than with HDPE film.

On bed shoulders in 2002, at 14 DAT, nutsedge density with VIF film was significantly lower than with HDPE (Table 3). Subsequently, emergence of nutsedge increased through the VIF treatments so by 28 DAT, VIF with surface chemigation and HDPE with subsurface chemigation had similar nutsedge densities. Subsurface chemigation in combination with VIF suppressed nutsedge more effectively than VIF with surface chemigation at 28 DAT, but this difference was not apparent at the subsequent evaluations. Nutsedge density on VIF continued to increase with time so that by 90 DAT nutsedge densities were 116 and 114 plants/m² with VIF with surface and subsurface chemigation, respectively, significantly higher than the 74 and 66 plants/m² with HDPE and surface and subsurface chemigation.

In 2003, unlike 2002, initial suppression of nutsedge (14 DAT) with HDPE on centers and shoulders of beds was more effective with subsurface chemigation than with surface chemigation (Table 3). This difference persisted until 28 DAT on bed centers but not on bed shoulders. Initial infestation of bed centers and shoulders at 14 and 28 DAT was lower with VIF than with HDPE. As in 2002, the suppression did not persist; however, instead of exceeding infestations on HDPE by 90 DAT, in 2003 VIF and HDPE had similar levels of nutsedge infestation. This similarity of infestation levels at 90 DAT and the decline in nutsedge density between 60 and 90 DAT with HDPE may have been due to combination of earlier senescence and dieback due to a natural infestation with a rust (*Puccinia* sp.) in 2003. No difference in nutsedge infestation between surface and subsurface chemigation occurred with VIF in 2003.

Application of a liquid formulation of 1,3-DCP to a depth of 12 inches with chisels spaced 12 inches apart resulted in significant nutsedge suppression (Hochmuth et al., 2002). This suppression was more effective with VIF than with a low-density polyethylene film. This result suggests that subsurface application of 1,3-DCP via chemigation should

Table 3. Nutsedge control in a sandy soil chemigated with 1,3-dichloropropene plus chloropicrin as affected by film type, chemigation depth, and time.

		Nutsedge density (plants/m ²) ^z									
Film ^y	Chemigation ^x	2002					2003				
		14 DAT ^w	28 DAT	60 DAT	90 DAT	Significance ^v	14 DAT	28 DAT	60 DAT	90 DAT	Significance
<i>Centers^u</i>											
HDPE	surface	3.2 a	12.2 a	15.5 b	17.6 b	Q**	6.9 a	24.7 a	53.5 a	38.1 a	Q**
HDPE	subsurface	2.4 a	8.1 b	12.3 b	14.1 b	Q**	1.5 b	10.5 b	46.7 ab	41.8 a	Q**
VIF	surface	0.0 b	6.5 b	22.5 a	33.7 a	Q**	0.0 c	1.2 c	42.1 bc	51.9 a	Q**
VIF	subsurface	0.0 b	3.2 c	18.3 ab	31.9 a	Q**	0.1 c	0.2 c	31.5 c	47.3 a	Q**
<i>Shoulders^u</i>											
HDPE	surface	46.8 a	81.0 a	76.6 ab	74.4 b	Q**	56.5 a	81.0 a	118.4 a	89.2 a	Q**
HDPE	subsurface	35.5 a	73.9 ab	69.8 b	66.1 b	Q**	32.2 b	59.5 a	107.7 a	97.1 a	Q**
VIF	surface	7.0 b	60.0 b	97.8 a	115.9 a	Q**	1.7 c	19.6 b	76.1 b	92.8 a	Q**
VIF	subsurface	4.0 b	43.3 c	85.9 ab	113.9 a	Q**	2.3 c	13.7 b	61.6 b	95.6 a	Q**

^z1 plant/m² = 0.0929 plant/ft².

^yHDPE and VIF are 0.75-mil high-density polyethylene film and 1.4-mil virtually impermeable film, respectively; 1 mil = 0.0254 mm.

^xSubsurface chemigation was done at a soil depth of 6 inches; 1 inch = 2.54 cm.

^wDays after treatment.

^vResponses in rows were evaluated using orthogonal polynomials. NS, **Nonsignificant or significant at $P < 0.01$, respectively. Q indicates a quadratic response. Means in columns followed by the same lowercase letter are not significantly different at $P \leq 0.05$.

^uBed center widths were 12, 16, 20, and 24 inches for 24-, 28-, 32-, and 36-inch bed widths, respectively, and shoulder width was 6 inches.

provide effective suppression with more even distribution. The pattern of emergence of earliest and greatest infestation occurring on bed shoulders with more gradual infestation of bed centers suggests that the nutsedge tubers occurring in the wetted zone were killed by the 1,3-DCP application, but that the concentrations of gaseous 1,3-DCP and its persistence in the bed shoulders were insufficient to control tubers located there. More even distribution of fumigant can be obtained when two drip-tapes are used (Ajwa and Trout, 2004; Desaegeer and Csinos, 2005; Desaegeer et al., 2004; Fennimore et al., 2003). However, this configuration is more costly for the grower, requires appropriate placement of the two tapes to ensure delivery of a lethal rate to the entire bed, and the positioning of transplants of a double-row crop such as bell pepper (*Capsicum annuum*) requires greater skill.

Even a few nutsedge plants can have an adverse effect on yield, the extent depending on the competitive ability of the crop. As few as 25 purple nutsedge plants/m² were sufficient to decrease tomato (*Lycopersicon esculentum*) yield by 10%; whereas the same number of yellow nutsedge plants doubled the yield reduction to 20% (Morales-Payan, 1999). In less competitive crops such as bell pepper and watermelon (*Citrullus lanatus*), yield can be reduced by 10% by just

5 and 2 yellow nutsedge plants/m², respectively (Buker et al., 2003; Motis et al., 2003).

In summary, concentrations of 1,3-D gas in shoulders of beds mulched with HDPE were nonlethal to nutsedge tubers since nutsedge plants emerged within 14 DAT. Concentrations of 1,3-D gas tended to be higher with VIF than with HDPE; this may account for the delay in emergence of nutsedge observed with VIF compared with HDPE. However, even with VIF, in Florida's deep sandy soils, a single drip-tape apparently results in inadequate concentration and time of exposure of nutsedge tubers along bed shoulders. Therefore, the initial nutsedge suppression with VIF did not persist, so that by 90 DAT nutsedge densities with both film types were equivalent or greater with VIF. Narrow bed widths did not eliminate nutsedge emergence on bed shoulders; in fact, the best nutsedge control was obtained with 36-inch beds. However, with 20 plants/m² by 14 DAT and greater than 50 plants/m² by 90 DAT with 36-inch beds, nutsedge control with 1,3-DCP chemigation can be considered unsatisfactory. It is likely that adequate control of nutsedge can be achieved with 24-inch beds if 1,3-DCP were applied for the duration used for the 36-inch beds; however, this would result in an application that exceeds the current recommended rate.

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