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Rate Response of 1,3-Dichloropropene for Nematode Control in Spring Squash in Deep Sand Soils[1]

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Abstract: The soil fumigant 1,3-dichloropropene (1,3-D) formulated with chloropicrin is viewed as a likely alternative for replacing methyl bromide in Florida when the latter is phased out in 2005. Therefore, it behooves us to learn more about using 1,3-D in deep, sand soils. Two trials were conducted on spring squash to determine the most effective rate of 1,3-D for the control of *Meloidogyne* spp. Rates tested included 0, 56, 84, 112, and 168 liters/ha of 1,3-D applied broadcast with conventional chisels 30 cm deep. The chisel traces were sealed by disking immediately after fumigant application. *Cucurbita pepo* cv. Sunex 9602 was sown 7 days after fumigation. The population density of plant-parasitic nematodes in soil and root-knot nematode galling severity was determined at 34 and 65 days after planting (DAP), and the number of marketable fruit and yield were determined. The number of fruit and yield were higher in all plots that received 1,3-D than in untreated controls. The number of *Meloidogyne* spp. second-stage juveniles was lower in all fumigated plots in trial 1 at both 34 and 65 DAP, and in trial 2 at 65 DAP, than in the untreated control. The severity of root galling was decreased with all treatments in both trials, with broadcast rates of 84, 112, and 168 liters/ha providing the best control of root-knot nematodes in spring squash grown in sandy soil. Satisfactory management of root knot on squash grown in early spring months in north Florida can be achieved with low rates of 1,3-D.

Key words: Cucurbita pepo, 1,3-dichloropropene, efficacy, fumigation, management, *Meloidogyne arenaria, Meloidogyne incognita,* nematode, rate, root-knot nematode, squash.

The phase-out of methyl bromide creates a need for effective and reliable alternative chemicals for control of pests and pathogens of high-valued vegetables, nursery crops, some ornamentals, and turfgrass renovations or new installations. The soil fumigant, 1,3-dichloropropene (1,3-D) plus chloropicrin, is considered a strong candidate to replace methyl bromide for the vegetable industry in Florida. It is one of the few registered fumigants available for broad-spectrum management of nematodes and other soilborne pathogens.

1,3-Dichloropropene is toxic to plant-parasitic nematodes (Fletcher, 1956; Youngson and Goring, 1970) and is currently recommended in Florida for a variety of vegetable and agronomic crops (Dunn and Noling, 1995). Although the fumigant has been used successfully to control plant-parasitic nematodes on many crops (Dickson, 1985; Weingartner and Shumaker, 1990), its performance can vary (Dickson and Hewlett, 1988; Melton, 1996). Factors that may affect its efficacy in deep, sand soils include depth of placement, sealing after injection, soil moisture and temperature, and dosage.

Recommended application rates for field crops in Florida range from 56 to 112 liters/ha (Dunn and Noling, 1995), but there is a tendency among agriculturalists to lower rates to reduce crop production cost. The objective of this study was to evaluate the efficacy of four rates of 1,3-D for the management of root-knot nematodes in deep, sand soils of Florida.

Materials and Methods

Two experiments (trials 1 and 2) were conducted during 1999 in fields at the University of Florida Green Acres Agronomy Research Farm in Alachua County, Florida. The soil was an Arredondo fine sand (84% sand, 12% silt, 4% clay; 4% organic matter;

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pH 6.1). The sites were naturally infested with *Meloidogyne* spp., *Criconemoides* spp., *Pratylenchus brachyurus* (Godfrey) Filipjev and Stekhoven, and *Paratrichodorus minor* (Colbran) Siddiqi. Because root-knot nematode was patchy in distribution, both sites were infested in fall 1997 with *Meloidogyne arenaria* (Neal) Chitwood race 1 and *M. incognita* (Kofoid and White) Chitwood race 1, each cultured on tomato (*Lycopersicon esculentum* Mill. cv. Rutgers). Heavily galled, chopped tomato roots (ca. 600 g of galled roots/12.2 m row) were placed in 15-cm-deep open furrows spaced 90 cm apart. Hairy vetch (*Vicia villosa* Roth) was planted to both sites in fall 1997. Peanut (*Arachis hypogaea* L. cv. Sunrunner) was planted in summer 1998, and hairy vetch was again planted in the fall of the same year as a winter cover crop. The hairy vetch was plowed under 30 March 1999.

The experimental design was a randomized complete block with six replications. Plots were 12.2 m long with a row spacing of 90 cm, and a 2.4-m alley separated each block. An untreated fallow plot on either side of each treated plot served as a border. 1,3-D was broadcast-injected 13 April 1999 at 0, 56, 84, 112, or 168 liters/ha 30 cm deep with six conventional chisels (two forward and four rear inclined double-beveled blades) spaced 30 cm apart. The two outer chisels were forward-swept, and the four inner chisels were backward-swept. A 1.8-m-wide, two-gang disk was run through each plot immediately after fumigant injection, cutting the soil surface ca. 15 cm deep to form a surface seal and break the continuity of chisel traces (1 to 1.3-cm openings in the upper soil profile left by conventional chisels). Soil moisture at both sites at the time of fumigation was ca. 13%, and the soil temperature at 10 cm deep on the day of fumigation increased from a minimum of 25 °C to a maximum of 28 °C.

Twelve cores (2.5-cm-diam., 20-cm-deep) of soil from each plot were taken with a cone-shaped sampling tube at pretreatment (Pi) on 12 April, mid-season (Pm) on 16 May, and final harvest (Pf) on 23 June. Soil cores from each plot were combined and nematodes were extracted from a 100-cm^3 subsample by a centrifugal-flotation method (Jenkins, 1964). All plant-parasitic nematodes were counted.

Summer squash, *Cucurbita pepo* L. cv. Sunex 9602, was planted on 20 April 1999, 7 days after fumigation. Three weeks after planting, seedlings were thinned to one plant every 45 cm of row. The center 12 plants per plot were designated for yield. Preplant, 55 kg/ha of 10-10-10 fertilizer was applied broadcast and incorporated. Postplant, a total of 16.5 kg/ha of nitrogen in the form of NH_4NO_3 and 16.5 kg/ha of potassium in the form of K_2O was divided into six weekly applications applied by drip irrigation beginning 2 weeks after seedling emergence. Double-wall drip tubing (Chapin Twinwall, Watertown, NY), with emitters spaced 30 cm apart and a flow rate of 62 ml/minute/30.5 m, was placed 7.5 to 10 cm from the center of the bed for application of water, fertilizer, and calcium. Calcium (8.4% CaO) at a rate of 0.19 liters/ha was applied weekly beginning at flowering to reduce the incidence of blossom end rot. One hive of honey bees (*Apis mellifera* L.) per 2.5 ha was placed 50 m from the fields at the time of flowering to aid in pollination (Hochmuth et al., 1998).

Broadleaf weeds and foliar pathogens were managed with applications of naptalam and bensulide, and chlorothalonil and manzate, respectively (Hochmuth et al., 1998). Methomyl was applied to manage insect pests. The plots were cultivated on 19 May for weed control.

Squash was first harvested on 30 May 1999, and harvesting continued three times a week for 3 weeks. The number and weight of marketable squash per plot were recorded. Sixty-five days after planting an overall rating for plant growth was made for each plot based on a subjective scale of 1 to 10 (1 = stunted, chlorotic, or dead plants, 10 = full, lush, green growth). Root-knot nematode galling was determined on 23 June for all 12 plants in each plot based on an index scale of 0 to 10 (0 = no galls on roots and 10 = 100% of the root system galled) (Barker et al., 1986).

Reproductive factor for the *Meloidogyne* spp. was determined by Pm/Pi and Pf/Pi ratios, where Pi = initial population density, Pm = population density 34 days after planting, and Pf = population density 65 days after planting. The means for each treatment at the three sampling times (Pi, Pm, and Pf) were calculated and used for the proportion calculations.

Daily minimum and maximum soil temperatures between planting and harvest were obtained from the Agronomy Department climatological data collected from a NOAA-approved weather station located within 100 to 150 m of both trials. The mean daily soil temperature 10 cm deep was calculated by averaging the daily minimum and maximum temperatures. Degree days were calculated by temperature summations (Arnold, 1960) with the formula, degree day = $(T_{max} + T_{min})/2 - z$, where T_{max} was the maximum daily soil temperature, T_{min} was the minimum daily soil temperature, and z was the lower developmental threshold of 10 °C.

Quadratic regression analyses were used to estimate 1,3-D dosage responses (SAS Institute, Cary, NC). Orthogonal contrasts were performed on gall indices and rates of 1,3-D. All nematode data were transformed with $\log_e(x + 1)$ before analysis.

Results

The results for each trial are presented separately because of a significant trial × treatment interaction for most variables. The R^2 values were low for most models because of variability in estimates of *Meloidogyne* spp. population densities and fruit production, but the overall model effects were significant ($P \leq 0.1$), indicating trends in treatment means.

An increase in fruit production was observed in both trials when the plants were grown in soil fumigated with 1,3-D (Trial 1:$Y = 42.30 + 0.47X - 0.002X^2$, $R^2 = 0.28$, $P < 0.05$; Trial 2: $Y = 13.49 + 0.17X - 0.0006X^2$, $R^2 = 0.2$, $P < 0.1$). In trial 1, the mean number of fruit increased 52, 54, 78, and 66% compared to the untreated control for 56, 84, 112, and 168 liters of 1,3-D/ha, respectively. In trial 2, the mean number of fruit increased 48, 113, 64, and 96% compared to the untreated control for 56, 84, 112, and 168 liters of 1,3-D/ha, respectively.

Marketable yield of squash increased in soil fumigated with 1,3-D compared to plants grown in untreated soil (Fig. 1A). In trial 1, the greatest increase in yield (a 2.1-fold increase compared to the untreated control) was from plants grown in soil that

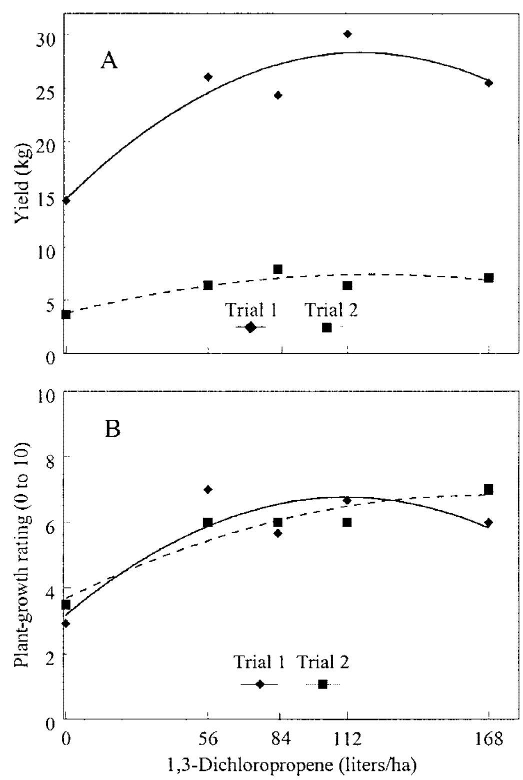

FIG. 1 A,B. Effects of rates of 1,3-dichloropropene for control of *Meloidogyne* spp. on the marketable yield and growth of squash produced in two trials conducted at the University of Florida Green Acres Agronomy Farm in 1999. Each data point is a mean of six replicates. A) Quadratic models indicated a positive response between squash yield and the rate of 1,3-dichloropropene applied in both trials. Trial 1: $Y = 14.54 + 0.24X - 0.001X^2$, $R^2 = 0.28$, $P < 0.05$; trial 2: $Y = 3.78 + 0.06X - 0.0002X^2$, $R^2 = 0.21$, $P < 0.05$. B) Effects of rates of 1,3-dichloropropene on the growth of squash 65 days after planting. The plants were rated on a scale of 1 to 10 (1 = stunted, chlorotic, or dead plants, 10 = full, green, lush growth). Quadratic models indicated a positive response between the growth of the plants and the rate of 1,3-dichloropropene applied in both trials. Trial 1: $Y = 3.17 + 0.06X - 0.0003X^2$, $R^2 = 0.28$, $P < 0.05$; trial 2: $Y = 3.68 + 0.04X - 0.0001X^2$, $R^2 = 0.24$, $P < 0.05$.

received 1,3-D at 112 liters/ha. In trial 2, the greatest yield increase was from plants grown in soil fumigated with 84 liters of 1,3-D/ha (Fig. 1A).

Overall plant growth in both trials was improved with fumigation (Fig. 1B), with nearly a 1.9-fold improvement in the growth ratings over the untreated control in fumigated plots. Plants from the untreated control were stunted, whereas plants in plots fumigated with 1,3-D had a growth rating of 6 to 7 (Fig. 1B).

Fumigation decreased the severity of root galling caused by *Meloidogyne* spp. in both trials (Fig. 2). The untreated control in trial 1 had a mean gall rating of 7.1 corresponding to 71% of the roots being galled, whereas in trial 2, the mean galling rating was 3.4. A decrease in the galling index was observed for all fumigated plots compared to the untreated control. The mean galling indices for the untreated control and fumigated plots were lower in trial 2 than in trial 1. Data from the galling indices of both trials combined indicated that fumigated plots had a lower mean gall index than the untreated control ($P \leq 0.0001$) (Table 1). More galls were produced on plants grown in soil fumigated with 56 liters of 1,3-D/ha in trial 2 compared with plots fumigated with 84, 112, and 168 liters/ha (Table 1).

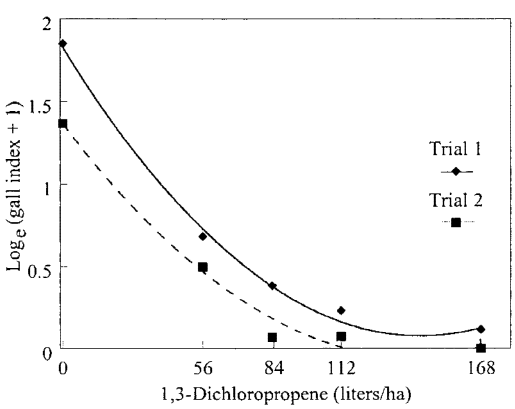

FIG. 2. Effects of rates of 1,3-dichloropropene on root galling of squash induced by *Meloidogyne* spp. 65 days after planting in two trials conducted at the University of Florida Green Acres Agronomy Farm in 1999. Each data point is a mean of six replicates. The data were transformed with $\log_e(x+1)$ before analysis. Trial 1: $Y = 1.84 - 0.02X + 0.00008X^2$, $R^2 = 0.53$, $P = 0.0001$; trial 2: $Y = 1.37 - 0.02X + 0.00007X^2$, $R^2 = 0.81$, $P = 0.0001$.

TABLE 1. Contrasts comparing root-knot nematode gall indices[a] on squash and rates of 1,3-dichloropropene in trials 1 and 2[b].

Contrast[c]	Mean	F value	P
	Trial 1		
Untreated	1.85	22.6	0.0001
Fumigated	0.35		
	Trial 2		
Untreated	1.37	91.1	0.0001
Fumigated	0.16		
56 Liters/ha	0.50		
vs. 84 Liters/ha	0.07	7.2	0.05
vs. 112 Liters/ha	0.07	7.0	0.05
vs. 168 Liters/ha	0	9.6	0.01

[a] Root galling was determined 65 days after planting based on a scale of 0 to 10 (0 = no galls and 10 = 100% of the root system galled) (Barker et al., 1986). The data were transformed with $\log_c(\chi + 1)$ before analysis.

[b] Two experiments (trials 1 and 2) were conducted during 1999 in fields of close proximity at the University of Florida Green Acres Agronomy Research Farm in Alachua County, Florida.

[c] 1,3-Dichloropropene was applied-broadcast at 0, 56, 84, 112, and 168 liters/ha. Data for the untreated control and each fumigant rate are means of six replications. Pooled data for the 1,3-dichloropropene fumigated plots are the means of 24 plots.

Meloidogyne spp. population densities at 34 DAP (Pm) in trial 1 and 65 DAP (Pf) in both trials were lower in plots fumigated with 1,3-D than in untreated plots (Figs. 3A,B). At 34 DAP in trial 1 (Fig. 3A), a mean of 35 J2/100 cm^3 of soil was detected in the untreated control compared to 0.3 J2/100 cm^3 of soil in plots fumigated with 84 liters of 1,3-D/ha. At 65 DAP, the untreated control had 77 J2/100 cm^3 of soil, whereas population densities remained low in fumigated plots. At this time in trial 2, the population density of J2 decreased with soil fumigation with 15, 23, 70, and 23-fold decreases in numbers of J2 compared with the control (Fig. 3B). The reproductive factor (Pm/Pi and Pf/Pi ratios) for the untreated control and all four 1,3-D rates in both trials were less than 1 (data not shown). The reproductive factor in the fumigated plots were lower than the untreated control.

The population densities of *Paratrichodorus minor, Pratylenchus brachyurus,* and *Criconemoides* spp. were low at 34 and 65 DAP in both trials; therefore, the results are not reported. The population density of *Cri-*

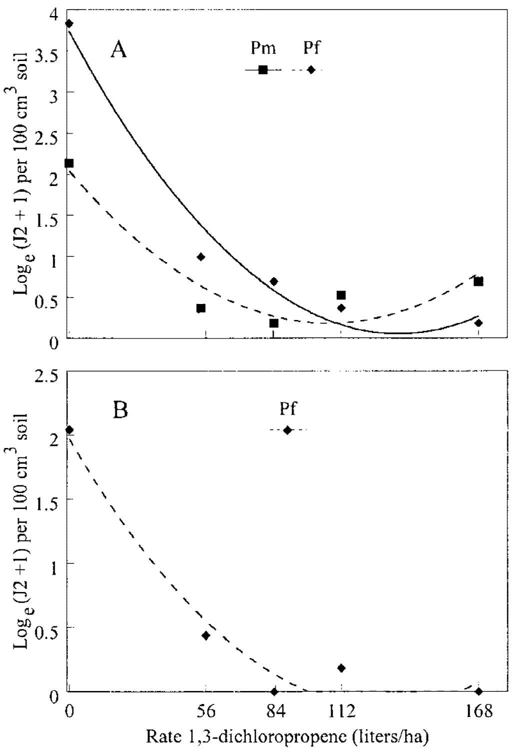

FIG. 3 A,B. Effects of rates of 1,3-dichloropropene on the density of *Meloidogyne* spp. second-stage juveniles (J2) per 100 cm^3 soil in two trials conducted at the University of Florida Green Acres Agronomy Farm in 1999. Sampling occurred at 34 (Pm) and 65 (Pf) days after planting. Each data point is a mean of six replicates. Data were transformed with $\log_e (x + 1)$ before analysis. A) Trial 1: $Y = 2.0 - 0.03X + 0.0002X^2$, $R^2 = 0.28$, $P < 0.05$ (Pm), and $Y = 3.74 - 0.05X + 0.0002X^2$, $R^2 = 0.67$, $P \leq 0.0001$ (Pf). B) Trial 2: $Y = 1.98 - 0.03X + 0.0001X^2$, $R^2 = 0.41$, $P < 0.01$ (Pf).

conemoides spp. at both sampling times in both trials decreased following fumigation. *Criconemoides* spp. at 34 DAP decreased with increasing rates of 1,3-D in trial 1, $Y = 3.7 - 0.007X - 0.00004X^2$ ($R^2 = 0.41$; $P = 0.001$), whereas at 65 DAP, their numbers were reduced from 156/100 cm^3 soil in the untreated control to 71, 37, 30, and 4/100 cm^3 of soil in plots fumigated with 56, 84, 112, and 168 liters of 1,3-D/ha, respectively. Transformed data fit the quadratic model $Y = 1.3 - 0.01X - 0.0004X^2$ ($R^2 = 0.24$; $P = 0.05$). The response of *Criconemoides* spp. to rates of 1,3-D in trial 2 were similar to those in trial 1 (data not shown) except that the number of *Criconemoides* spp. recovered from untreated plots and from plots that were fumigated with 56 liters of 1,3-D/ha was higher than from plots treated with 84 and 168 liters of 1,3-D/ha ($P \leq 0.05$).

The daily degree days from the day of planting until the completion of the study ranged from 11.9 to 19.7. The cumulative degree days from 20 April to 23 June 1999 was 1,098; therefore, it is estimated that there were sufficient heat units for development of at least one generation of root-knot nematodes during the interval of these two trials. Egg masses were observed on the squash roots at harvest.

DISCUSSION

The number and yield of squash increased when soil was fumigated with 1,3-D. The overall number of fruit and total fruit weight were greater in trial 1 than in trial 2, despite higher numbers of *Meloidogyne* spp. in the trial 2 site. Increases in yield following fumigation are commonly reported with many kinds of crops (Kinloch and Rich, 1998; Schenk, 1990; Weingartner et al., 1993). In these trials no phytotoxicity was observed in the squash seedlings at any of the rates of 1,3-D applied. Plants that were grown in fumigated soil were uniform in growth, consistent in plant stand, and larger than plants grown in untreated soil.

Fumigation with 1,3-D decreased the number of second-stage juveniles of *Meloidogyne* spp. in soil and the number of galls on squash roots. In trial 2, the higher rates (84, 112, and 168 liters of 1,3-D/ha) were more effective in reducing root-gall severity than the low rate of 56 liters/ha. However, only a low level of root galling was observed on roots from fumigated plots at final harvest with 15% of roots galled in trial 1 and 7% in trial 2. Squash, which is an excellent host for *Meloidogyne* spp., is a short-season crop (Robinson and Decker-Walters, 1997) that is normally planted in late winter and early spring (February to April) and late summer and early fall (August to September) in north Florida (Hochmuth et al., 1998). In the former case, soil temperature may remain relatively low, thereby slowing the rate of development of root-knot nematodes. Temperature influences the development of root-knot nematodes (Vrain and Barker, 1978; Wong and Mai, 1973), and degree days have been used as a means of measuring the rates of development of several nematode species including root-knot nematodes (Arnold, 1960). Tyler (1933) found that the minimum temperature for development of *Meloidogyne* spp. was between 9 °C and 10 °C and it took between 6,000 and 8,000 heat units for the nematode to develop from second-stage juveniles to egg-laying females in tomato roots. In the field, approximately 9,000 heat units were necessary for the development of *M. javanica* in tobacco roots (Milne and DuPlessis, 1964). Under the conditions of this study, the soil temperature remained below 20 °C at 10 cm deep. According to the relatively low number of heat units, accumulated root-knot nematodes would have just reached reproductive maturity at the conclusion of these trials. Unfortunately, we did not measure egg production; however, abundant root-knot nematode galls formed on roots, and egg masses were observed, especially in the untreated control. The extracted second-stage juveniles in soil at 34 and 65 DAP in both trials were lower than the initial population density estimations, and the rate of reproduction was below 1 and, in a few cases, the nematode reproductive rate was zero. Therefore, we conclude that only one generation of the nematode was produced during the period of these experiments.

For most crops planted in Florida, there is a relatively long growing season. Root-knot nematodes in soil, even at low densities, generally have sufficient heat units to complete three or more generations per year, thereby increasing the population densities substantially. For long-season crops such as peanut, 1,3-D applied-broadcast at low rates (28, 47, and 65 liters of 1,3-D/ha) provided only marginal control of *M. arenaria* race 1 (Dickson and Hewlett, 1988). However, for a short-season crop such as squash grown in early spring months in north Florida, low rates of 1,3-D may be all that is necessary for satisfactory management of root knot.

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