Journal of Nematology 40(3):210–216. 2008.

Effect of Fumigation on *Rotylenchulus reniformis* Population Density Through Subsurface Drip Irrigation Located Every Other Furrow

T. A. Wheeler,[1] D. O. Porter,[2] D. Archer,[1] B. G. Mullinix Jr.[1]

Abstract: Plots naturally infested with *Rotylenchulus reniformis* were sampled in the spring of 2006 and 2007 at depths of 15 and 30 cm in the bed, furrow over the drip tape, and "dry" furrow, and at approximately 40 to 45 cm depth in the bed and dry furrow. Then, 1,3-dichloropropene (Telone EC) was injected into the subsurface drip irrigation at 46 kg a.i./ha, and 3 to 4 weeks later the plots were resampled and assayed for nematodes. The transformed values for nematode population density (IvLRr) before fumigation were higher at 30 and 40 cm depths than at a 15 cm depth. IvLRr before fumigation was higher in the soil over the drip lines than in the bed or dry furrow and was higher in the bed than the dry furrow. IvLRr was higher in the plots to be fumigated than the plots that were not to be fumigated for all depths and locations except at a 15 cm depth over the drip lines, where the values were similar. However, after fumigation, IvLRr was lower over the drip lines at a 30 cm depth in plots that were fumigated compared to samples in a similar location and depth that were not fumigated. There were no other location/depth combinations where the fumigation reduced IvLRr below that in the nonfumigated plots. Yield in 2006, which was a very hot and dry year, was predicted adequately (R^2 = 0.67) by a linear model based on the preplant population density of *R. reniformis*, with a very steep slope (-2.8 kg lint/ha per *R. reniformis*/100 cm^3 soil). However, no relationship between nematode density and yield was seen in 2007, which had cooler weather for most of the season. Yield was not significantly improved by fumigation through the drip irrigation system in either year compared to plots treated only with aldicarb (0.84 kg a.i./ha), indicating that the level of control with fumigation did not kill enough *R. reniformis* to be successful.

Key words: chemigation, cotton, *Gossypium hirsutum*, reniform nematode

Nematodes can cause substantial losses in crops grown on subsurface drip irrigation (Apt and Caswell, 1988). Subsurface drip irrigation systems are a relatively expensive type of irrigation technology, and producers who invest in these systems typically have high yield expectations. Injection of fumigants through drip irrigation can be effective at nematode control (Roberts et al., 1988; Desaeger et al., 2004). However, these examples are all for drip irrigation systems placed within the bed. The application of fumigants through drip irrigation can be more difficult than shank application (Apt and Caswell, 1988). The more traditional fumigation methods were generally successful if the soil was not too wet and if a good seal could be applied to keep the fumigant in the ground. Fumigation with 1,3-dichloropropene (1,3-D) through subsurface drip irrigation systems is distributed through water rather than through air pores, and so an understanding of soil/water properties is critical to successful application (Apt and Caswell, 1988).

The southern High Plains of Texas is a semi-arid region that uses irrigation water primarily from the Ogallala aquifer (Colaizzi et al., 2006b; Allen et al., 2008). Subsurface drip irrigation (SDI) is a highly efficient method of irrigation that has proven to offer crop yield, quality and/or water-use efficiency advantages over other irrigation methods in many water-limited production systems (Segarra et al., 1999; Bordovsky and Porter, 2003; Colaizzi et al., 2006c). Adoption of SDI has expanded in the Texas Southern High Plains from an estimated 8,000 ha in 2000 to over 100,000 ha in 2007 (Bordovsky, 2007).

For many row crops such as cotton, drip laterals are commonly installed in alternate furrows, significantly lowering the initial capital cost as well as ongoing repair costs associated with mechanical damage to the tape (Colaizzi et al., 2006a). With the high capital costs and high-level management required for successful operation of an SDI system, commercial cotton producers using SDI tend to manage their crops more intensively and have higher yield expectations (Lamm et al., 2007).

While fumigation through drip irrigation can be effective when the drip lines are in the center of a bed, there is a question as to whether they can be effective when the drip lines are laid every other furrow. Fumigation distribution with 1,3-D has been examined within beds. In sandy soils, high concentrations of 1,3-D were found in the center of the bed, but declined at the bed shoulder (Desaeger et al., 2004). Wang and Yates (1999) found that a rate of 47 kg a.i./ha 1,3-D resulted in significant concentrations in the bed, whereas application of 112 kg a.i./ha 1,3-D with a shank application in the bed extended the effective concentrations of 1,3-D to the whole soil profile, including the furrows. The objective of this work was to determine the spatial range of control of *R. reniformis* with 1,3-D applied in drip irrigation lines that were spaced at 2-m intervals in the furrows.

Materials and Methods

The test was conducted in an Acuff loam (fine-loamy, mixed, thermic Aridic Paleustolls) (50% sand, 21% silt, 29% clay; pH 7.8). A SDI system was installed in the spring of 2005 at a depth of 35 cm from the bottom of the furrow on alternating furrows. The drip tape was Netafim Typhoon 875 with 2.2 cm diam., 61 cm emitter

Received for publication March 7, 2008.
[1]Texas AgriLife Research, Lubbock, TX 79403
[2]Texas Agrilife Extension and Texas AgriLife Research, Lubbock, TX 79403
The authors thank the Texas A&M University System and Dow Agrosciences for funding support for this project.
Email: ta-wheeler@tamu.edu
This paper was edited by Brent Sipes.

spacing and a 0.91 liter/hr flow rate. A cotton crop was grown in the test area and irrigated with the SDI system during 2005. The beds were originally formed in 2005, and then no further cultivation or bed shaping was conducted for the subsequent cropping seasons. The test was conducted during 2006 and 2007. Plots were 13.8 m long and two rows wide (1-m row spacing) with two rows of border between plots. The drip tape between the two rows of the plot was tied off at the end of each plot. The plots were connected by PVC pipe at the head of the plot (header line). Manually operated valves controlled flow into the plots, allowing each plot to be irrigated or fumigated separately as necessary for treatments.

Meteorological data were collected from a weather station located on site and were provided by the Texas High Plains Evapotranspiration Network (http://txhighplainset.tamu.edu) (Porter et al., 2005). Crop evapotranspiration data (ET_c), also provided by the Texas High Plains Evapotranspiration Network, were based upon the ASCE-EWRI Standardized Reference ETos (short, grass reference) equation (Allen, et al. 2005).

Soil samples were taken at depths of 15, 30 and 40-45 cm in the bed and dry furrow and 15 and 30 cm depths in the furrow with the drip tape. Each sample, taken before fumigation in April, consisted of four locations where the soil was removed to the desired depth, and then approximately 200 cm^3 was removed horizontally from that depth. In 2006, each location was assayed separately, and the results were averaged; in 2007, the soil from the four subsamples at location/depth combination was combined, and two assays were run from each composite sample and averaged. Samples were taken before fumigation and then again 3-4 wk after fumigation (before planting). Samples taken after fumigation consisted of three soil cores that were run similarly to the prefumigation samples. In 2006, prefumigation soil samples were taken on 19–21 April, and post-fumigation samples were taken on 19-21 May. There were 12 plots sampled in 2006. In 2007, prefumigation soil samples were taken 5-6 April, and post-fumigation samples were taken on 21-22 May. There were 14 plots sampled in 2007. Reniform nematodes were extracted from 200 cm^3 of soil using a pie-pan assay (Thistlethwayte, 1970).

Plots were fumigated with 1,3-D (Telone EC with 98% a.i.) at a rate of 46 kg a.i./ha through the SDI on 26 April and 18-19 April in 2006 and 2007, respectively. In 2006, conditions were dry before fumigation (23 mm of rain during the previous month), so the plots were irrigated until the wetting front was approximately 75% through the bed. In 2007, the soil was wet (96 mm of rain the previous month), so irrigation was only conducted for several hours the day before fumigation. The soil temperature at 15 cm averaged 20°C in 2006 and 14°C in 2007 on the days of fumigation. In 2006, a pump was used to move the combination of 1,3-D and water through the drip lines, and in 2007 a CO_2 pressurized system running at 75 kPa was used to move the fumigant and water through the SDI system. The fumigant for each plot (130 ml) was mixed into 75 liters of water in 2006 before injection and into 45 liters of water in 2007. The SDI system was run for 1 hr after fumigation had finished to clean the lines and push the product out further into the soil. The fumigated plots were not tarped. Four plots were fumigated in 2006, with treatments arranged in a randomized complete block design, and seven plots, chosen randomly, were fumigated in 2007.

In 2006, 12 plots were sampled intensively and divided into three treatments: fumigated, no treatment and aldicarb at 0.84 kg a.i./ha applied in the furrow at planting. The treatments were arranged in a randomized complete block design with four replications. In 2007, 14 plots were intensively sampled and divided into two treatments: fumigated + aldicarb (0.59 kg a.i./ha) applied in the furrow at planting and aldicarb at 0.84 kg a.i./ha applied in the furrow at planting. Aldicarb was added to the fumigated plots for thrips control. The treatments were randomly arranged with seven replications per treatment. The test area was planted with the cotton cultivar 'Fibermax (FM) 960B2R' on 22 May in 2006 and 'FM 9063B2RF' on 30 May in 2007. The SDI system was run as needed until a week before planting to achieve sufficient soil moisture for seed germination, and then the PVC pipe was disconnected from the drip tubing until approximately 1 mon after planting. This was done to allow tractors to move through the plot area for planting and weed and insect control for the first month after planting. The PVC pipe was then reattached and drip irrigation was used for the rest of the growing season as needed by the crop. In 2006, water (13 mm) was applied by overhead sprinklers after planting because the heat had caused the soil to dry out rapidly and again on 19 June (26 mm) to reduce the water stress on the plants. The SDI system was started after the second application of water from the overhead system. The plots were harvested with a John Deere 7445 cotton stripper modified to catch the stripped plots in a small basket mounted on load cells. A sample of the harvested plot was saved and ginned to determine the percent of the weight that was lint. The test area was harvested on 28 November and 21 November in 2006 and 2007, respectively.

The effect of fumigant vs. the plots that would be receiving aldicarb (nonfumigated) on *R. reniformis* density (both nontransformed and transformed) was analyzed using PROC MIXED in SAS (v9.1, Cary, NC). The design was a split-split-split plot, with treatment (fumigation or not) as the main plot, position of sample (drip line, bed or dry furrow) as the sub plot, and depth of sample as the sub sub plot). There was a wide range of nematode densities in April before fumigation, so nematode density was initially transformed by LOG_{10} (nematode density + 1)/100cm^3 soil, and when

this transformation was insufficient to handle the variability in nematode population density, then this value was transformed with the inverse variance transformation (Tinm and Mieczkowski, 1997) (((LOG$_{10}$(nematode density + 1))/standard deviation), where the standard deviation was from each treatment/location/depth combination. The prefumigation and post-fumigation transformed nematode densities are referred to as IvLRr$_{bf}$ and IvLRr$_{af}$, respectively.

The design was unbalanced since the 40-45 cm depth was sampled in the bed and dry furrow, but not in the drip line furrow (to avoid cutting the drip line). The data set was tested twice, once with all three locations (bed, drip furrow and dry furrow), but the 40-45 cm depth counts removed (only 15 and 30 cm depths were tested), and once when all the drip samples were removed (location = bed or dry furrow; depth = 15, 30 and 40 cm), so that all the treatment combinations for each model were balanced. The fixed effects were treatment (1,3-D vs. none), depth and location, and the model was tested with the Satterthwaite's option. The model statement included the main effects and all two-way and three-way interactions. The random statement contained year, year x treatment, and year x location (treatment), year x depth(treatment) and year x location x depth(treatment). The effect of the prefumigation nematode density on post-fumigation density was tested with correlation analysis (PROC CORR), and, if the relationship was significant at $P \leq 0.05$, then the prefumigation nematode density (without transformation) was included as a covariate in the analysis with the post-fumigation nematode density. If a fixed factor was significant at $P \leq 0.10$, then differences within treatments or interaction terms were examined for significance at $P \leq 0.05$ with the PDIFF option.

The effect of treatment (fumigant, none and aldicarb in 2006; fumigant + aldicarb and aldicarb only in 2007) on yield (kg of lint/ha) was analyzed for each year separately using analysis of variance with PROC GLM in SAS (v9.1, Cary, NC). This model also included a covariate for *R. reniformis* density in May which was calculated by averaging the eight location/depth combinations sampled in each plot and subtracting the average nematode density for all the samples from this value. Regression analysis was used to predict yield in each year with the plot average density for *R. reniformis* (averaged over the eight samples). Several models were compared including linear models with at-plant density of *R. reniformis* and LOG$_{10}$(density +1), as well as the quadratic model of nematode density. A model was considered significant if $P \leq 0.05$.

Results

The average *R. reniformis* density in April for location/depth/treatment combinations ranged from171 to 1,441 *R. reniformis*/100 cm^3 soil (Table 1). The plots that would be later fumigated ranged from 330 to 1,441 *R. reniformis*/100 cm^3 soil, and the plots that would not be fumigated ranged from 171 to 1,083 *R. reniformis*/100 cm^3 soil in April. Standard deviation of LOG$_{10}$ (prefumigation *R. reniformis* + 1/100 cm^3 soil) was generally higher for the prefumigation "none" treatment than the 1,3-D (before fumigation) treatment (Table 1). *Rotylenchulus reniformis* density in May ranged from 191 to 644/100 cm^3 soil in fumigated plots, and those not fumigated in May ranged from 217 to 1,042/100 cm^3 soil. So, the fumigated plots had a smaller range of *R. reniformis* density after fumigation than before, while the plots that were not fumigated had similar ranges of *R. reniformis* density in April and May. The standard deviation of LOG$_{10}$(*R. reniformis* +1)/100 cm^3 soil was smaller for the fumigated plots in May from samples taken in the bed as compared with other locations and compared to the standard deviations associated with the nonfumigated samples taken in May (Table 1).

The model fitted to IvLRr$_{bf}$ when the 40 to 45 cm depths were removed and drip furrow samples were included had a significant treatment x location x depth interaction. IvLRr$_{bf}$ was significantly higher for the plots that were going to be fumigated than those that were not going to be fumigated for all locations and depths, except the 15 cm depth over the drip furrow (Table 2). The choice of plots for fumigated vs. no fumigation was selected randomly, but was unfortunately biased towards higher *R. reniformis* density in the plots to be fumigated. IvLRr$_{bf}$, when averaged for both fumigated and nonfumigated plots in April, was

Table 1. Effect of fumigation (1,3-dichloropropene), sampling location and depth on average *Rotylenchulus reniformis* population density before and after fumigation, averaged over 2006 and 2007.

Treatment	Location	Depth (cm)	Rr$_{bf}$[a]	LRr$_{bf}$[b]	SD[c] LRr$_{bf}$	Rr$_{af}$[d]	LRr$_{af}$[e]	SD LRr$_{af}$
1,3-D	Bed	15	703	2.68	0.49	546	2.60	0.43
1,3-D	Bed	30	1,441	2.97	0.54	644	2.74	0.26
1,3-D	Bed	40	786	2.69	0.37	492	2.64	0.2
1,3-D	Drip Furrow	15	649	2.50	0.75	522	1.96	1.12
1,3-D	Drip Furrow	30	1,407	3.03	0.36	294	1.84	0.95
1,3-D	Dry Furrow	15	342	2.34	0.47	191	1.93	0.78
1,3-D	Dry Furrow	30	501	2.54	0.38	353	2.26	0.82
1,3-D	Dry Furrow	40	330	2.38	0.47	225	2.10	0.64
none	Bed	15	816	2.39	0.96	589	2.48	0.71
none	Bed	30	645	2.49	0.78	815	2.54	0.96
none	Bed	40	375	2.20	0.84	490	2.41	0.74
none	Drip Furrow	15	1,083	2.65	0.75	1,042	2.50	1.06
none	Drip Furrow	30	819	2.57	0.91	862	2.62	0.85
none	Dry Furrow	15	274	1.90	0.92	217	1.59	1.06
none	Dry Furrow	30	474	2.06	0.99	615	2.09	1.27
none	Dry Furrow	40	171	1.86	0.76	223	1.77	1.04

[a]Rr$_{bf}$ = average *R. reniformis*/100 cm^3 soil, before fumigation in April.
[b]LRr$_{bf}$ = LOG$_{10}$(Rr$_{bf}$ + 1).
[c]SD = standard deviation.
[d]Rr$_{af}$ = average *R. reniformis*/100 cm^3 soil, after some plots were fumigated in May.
[e]LRr$_{af}$ = LOG$_{10}$(Rr$_{af}$ + 1).

significantly higher for the soil over the drip furrow (4.37) than the bed (4.00) or dry furrow (3.79), and $IvLRr_{bf}$ was significantly higher in the bed than the dry furrow. $IvLRr_{bf}$ was significantly higher at the 30 cm depth (4.61) than at the 15 cm depth (3.50). When the nontransformed, prefumigation nematode densities were used instead of the transformed values, then the overall model was not significant at $P \leq 0.10$.

In May, after fumigation, $IvLRr_{af}$ (when 40 cm depth samples were removed, and drip line samples were included) was significantly affected by all factors, two-way and three-way interactions, and the covariate (*R. reniformis*/100 cm^3 soil, in April). The covariate predicted that $IvLRr_{af}$ would increase 0.000456 per *R. reniformis* found in 100 cm^3 soil. $IvLRr_{af}$ was lower in the drip furrow at the 30 cm depth than the equivalent location/depth for the nonfumigated plots (Table 2). For all other location/depth combinations, $IvLRr_{af}$ was always higher in May for the fumigated plots than the nonfumigated plots (Table 2). Since $IvLRr_{bf}$ was higher for the plots to be fumigated in April, it is difficult to tell if fumigation lowered $IvLRr_{af}$, except in the drip area at the 30 cm depth. In that case, the values were not only lowered, but changed from significantly higher before fumigation to significantly lower after fumigation than the nonfumigated plots. So, fumigation was successful over the drip furrow at 30 cm depth, but not in the bed or dry furrow at 30 or 15 cm depths.

When the samples from the drip furrows were removed and the 40 to 45 cm depth samples were included, then $IvLRr_{bf}$ was significantly affected by treatment, location, depth, location x depth and the three-way interaction. $IvLRr_{bf}$ was higher for the plots that were going to be fumigated than not fumigated for all locations and depths, as was seen previously (Table 3). In May, $IvLRr_{af}$ was significantly affected by treatment, location, all two-way and the three-way interactions and the covariate. $IvLRr_{af}$ was higher at all location/depth combinations for the fumigated plots, compared with the nonfumigated plots. So, with the drip samples removed, no success was identified with fumigation. The bed had a higher $IvLRr_{bf}$ (4.28) than the dry furrow (3.76). The highest $IvLRr_{bf}$ was found at the 30 cm (4.22) and 40 to 45 cm (4.22) depths, compared with the 15 cm (3.64) depth. After fumigation, the bed still had higher $IvLRr_{af}$ (6.03) than the dry furrow (2.24). In May, $IvLRr_{af}$ was higher for the 40 cm depth (4.91) than the 15 cm depth (3.35) and intermediate for the 30 cm depth (4.29). When the nontransformed, post-fumigation nematode densities were used in the analysis, then the overall model was not significant at $P \leq 0.10$.

In 2006, yield (kg lint per ha) was affected by treatment (none, aldicarb at 0.59 kg/ha and 1,3-D) only when the (density of *R. reniformis* – mean density) was included as a quadratic function. With yield adjusted by the quadratic function, plots treated with aldicarb yielded more (907 kg lint/ha) than nontreated plots (494 kg lint/ha). Plots treated with 1,3-D were intermediate (690 kg lint/ha). Yield in 2006 was significantly associated with reniform nematode preplant density. Yield could be described by a quadratic model based on the preplant average (post-fumigation) density in May ($R^2 = 0.73$) and linear models utilizing both LOG_{10} (density + 1) ($R^2 = 0.64$) and nontransformed density ($R^2 = 0.35$). A linear model was chosen to illustrate the relationship, where a single outlier density (1,584/100 cm^3 soil) was removed from the analysis ($R^2 = 0.67$) (Fig. 1). The loss in yield in 2006 was quite steep with increasing nematode density (Fig. 1). The weather in 2006 was unusually hot and dry (Fig. 2A), which resulted in early-season stress on the plants (Fig. 2A,B). Generally, irrigation and rainfall should maintain at least 75% of the crop evapotranspiration (ET_c) to minimize yield loss due to drought. Crop evapotranspiration (ET_c) is a meteorologically based estimate of crop water demand that uses a reference crop model and an appropriate crop coefficient function to take into account atmospheric conditions, crop species and growth stage

TABLE 2. Effect of fumigation (1,3-dichloropropene), sampling location and depth (15 and 30 cm) on average transformed[a] *Rotylenchulus reniformis* population density before and after fumigation, averaged over 2006 and 2007.

Location	Depth (cm)	$IvLRr_{bf}$[b] (nontransformed means of *R. reniformis*/100 cm^3 in parenthesis)		$IvLRr_{af}$[c] (nontransformed means of *R. reniformis*/100 cm^3 in parenthesis)	
		1,3-D	None	1,3-D	None
Bed	15	5.36 cy[d] (703)	2.34 cdz (816)	6.01 by (546)	3.44 az (588)
Bed	30	5.29 cdy (1,441)	3.03 abz (645)	10.34 ay (644)	2.67 abz (815)
Drip Furrow	15	3.19 ey (649)	3.37 ay (1,083)	1.77 dy (522)	2.17 bcy (1,042)
Drip Furrow	30	8.25 ay (1,407)	2.68 bcz (819)	1.60 dz (294)	3.01 aby (862)
Dry Furrow	15	4.81 dy (342)	1.92 dz (274)	2.63 cy (191)	1.64 cz (217)
Dry Furrow	30	6.49 by (501)	1.94 dz (474)	2.85 cy (353)	1.74 cz (615)

[a]An inverse variance transformation was used (LOG_{10}((*R. reniformis* +1)/100 cm^3 soil))/(standard deviation for that treatment combination).
[b]$IvRr_{bf}$ = the inverse variance transformation defined in (a) applied to the population density in April before any treatments were applied.
[c]$IvRr_{af}$ = the inverse variance transformation defined in (a) applied to the population density in May after fumigation had been applied to some plots.
[d]Within a column, the treatment combinations were separated by the PDIFF option in PROC MIXED in SAS (v 9.1, Cary, NC). The highest average transformed density started with an "a," and significantly different treatment combinations had different letters. A comparison was made between location/depth combinations treated with 1,3-D and no treatment at a given sampling time. The highest average transformed density started with a "y," and if the other treatment was significantly lower, then it had a "z" after the mean.

TABLE 3. Effect of fumigation (1,3-dichloropropene), sampling location (bed and dry furrow only) and depth on average transformed[a] *Rotylenchulus reniformis* population density before and after fumigation, averaged over 2006 and 2007.

Location	Depth (cm)	$IvLRr_{bf}$[b] (nontransformed means of *R. reniformis*/100 cm^3 in parenthesis)		$IvLRr_{af}$[c] (nontransformed means of *R. reniformis*/100 cm^3 in parenthesis)	
		1,3-D	None	1,3-D	None
Bed	15	5.39 by[d] (703)	2.37 az (816)	5.89 cy (546)	3.31 az (588)
Bed	30	5.32 by (1,441)	3.06 az (645)	10.10 by (644)	2.58 az (815)
Bed	40	7.08 ay (786)	2.49 az (375)	10.96 ay (492)	3.36 az (490)
Dry Furrow	15	4.84 by (342)	1.95 az (274)	2.59 dy (191)	1.64 bz (217)
Dry Furrow	30	6.52 ay (501)	1.97 az (474)	2.79 dy (353)	1.68 bz (615)
Dry Furrow	40	4.98 by (330)	2.31 az (171)	3.39 dy (225)	1.93 bz (223)

[a]An inverse variance transformation was used (LOG_{10}((*R. reniformis* +1)/100 cm^3 soil))/(standard deviation for that treatment combination).
[b]$IvRr_{bf}$ = the inverse variance transformation defined in (a) applied to the population density in April before any treatments were applied.
[c]$IvRr_{af}$ = the inverse variance transformation defined in (a) applied to the population density in May after fumigation had been applied to some plots.
[d]Within a column, the treatment combinations were separated by the PDIFF option in PROC MIXED in SAS (v 9.1, Cary, NC). The highest average transformed density started with an "a," and significantly different treatment combinations had different letters. A comparison was made between location/depth combinations treated with 1,3-D and no treatment at a given sampling time. The highest average transformed density started with a "y," and if the other treatment was significantly lower, then it had a "z" after the mean.

specific factors. ET_c expresses crop-specific water demand due to local atmospheric conditions, effectively relating combined effects of maximum and minimum air temperatures, humidity, wind and solar radiation. When presented in combination with rainfall (and irrigation), it can be used to relate relative risk of crop drought stress. In June 2006, the ratio of rain to ET_c was less than 75% for the second half of the month, while in 2007, this ratio was equal to or greater than 75% until early July (Fig. 2B).

In 2007, there was no effect of treatment on yield (aldicarb alone = 1,639 kg lint/ha and 1,3-D + aldicarb = 1,671 kg lint/ha), and preplant nematode density was not correlated with yield (Fig. 1). The weather in 2007 was much cooler and wetter during the first half of the growing season than in 2006 (Fig. 2A). The plots were in a water deficit situation in June 2006 because the drip system was not running and again in July because of the large amount of water that had to be added to replace water in the soil and keep up with the plant needs. However, crop management was sufficient to allow yields > 2,000 kg lint/ha when *R. reniformis* was < 10/100 cm^3 soil (Fig. 1, Table 4). During 2007, rainfall and a lower evapotranspiration rate (Fig. 2A) kept the plants in a stress-free water state in June (Fig. 2B), and the

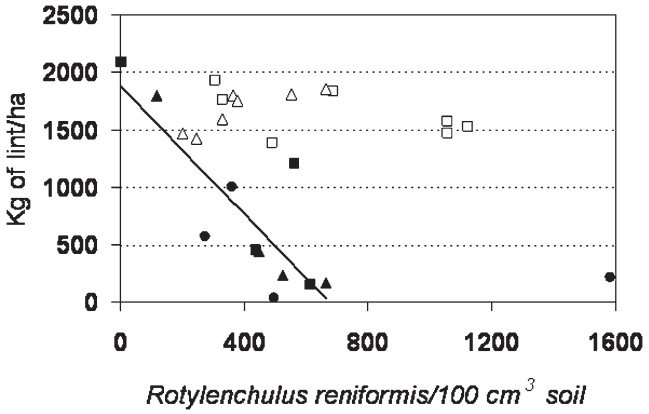

FIG. 1. Effect of preplant population density of *Rotylenchulus reniformis* on yield. Treatments in 2006 were none (●), aldicarb at 0.84 kg a.i./ha (■), and 1,3-dichloropropene (1,3-D) at 46 kg a.i./ha (▲), and predicted yield in 2006 (▬) was based on the equation: kg lint/ha = 1,876 – 2.77(*R. reniformis*/100 cm^3 soil), R^2 = 0.67. Treatments in 2007 were aldicarb at 0.84 kg a.i./ha (□) and 1,3-D at 46 kg a.i./ha + aldicarb at 0.50 kg a.i./ha (△).

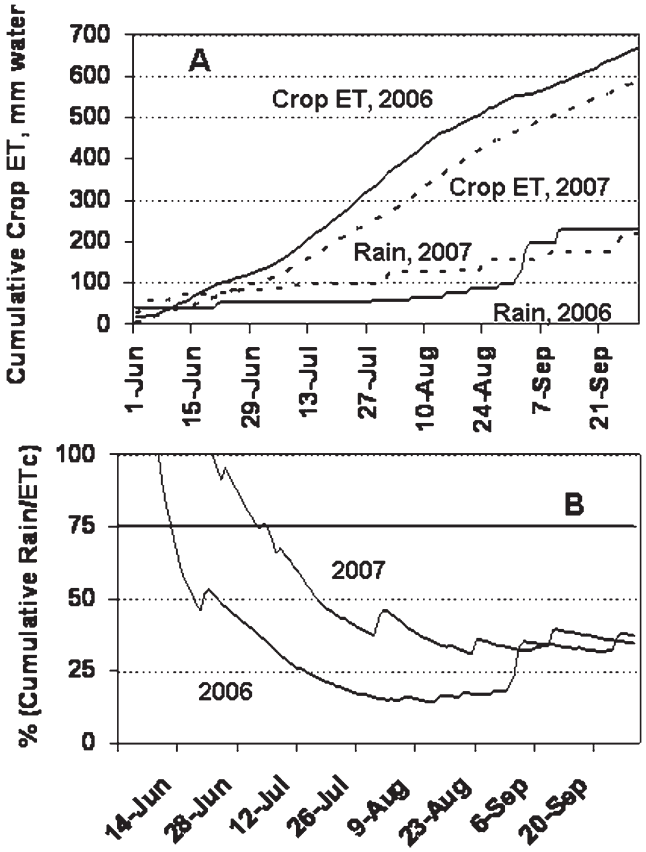

FIG. 2. A. Cumulative crop evapotranspiration (ET_c) for 2006 and 2007 and cumulative rainfall in 2006 and 2007. ET_c were based upon the ASCE-EWRI Standardized Reference ETos (short, grass reference) equation, which takes into account air temperature, humidity, solar radiation, wind, relative humidity and other factors. B. The ratio of (cumulative rain/cumulative ET_c) x 100.

TABLE 4. Relationship between *Rotylenchulus reniformis* at planting (averaged over three locations [bed, dry furrow and drip line furrow] and three depths [15, 30, and 40 cm] within each plot) and yield in 2006 and 2007.

Treatment in 2006	Average *R. reniformis*/100 cm^3 soil in 2006	Yield (kg of lint per ha) in 2006	Treatment In 2007	Average *R. reniformis*/100 cm^3 soil in 2007	Yield (kg of lint per ha) in 2007
Aldicarb	3	2,084	1,3-D + Aldicarb	202	1,467
1,3-D	117	1,801	1,3-D + Aldicarb	248	1,422
None	274	570	Aldicarb	305	1,932
None	363	999	Aldicarb	329	1,760
Aldicarb	437	454	1,3-D + Aldicarb	329	1,588
1,3-D	448	436	1,3-D + Aldicarb	366	1,799
None	497	37	1,3-D + Aldicarb	378	1,755
1,3-D	525	233	Aldicarb	491	1,384
Aldicarb	565	1,212	1,3-D + Aldicarb	553	1,810
Aldicarb	616	152	1,3-D + Aldicarb	664	1,854
1,3-D	663	167	Aldicarb	690	1,832
None	1,584	220	Aldicarb	1,056	1,472
			Aldicarb	1,058	1,572
			Aldicarb	1,123	1,522

irrigation system was able to maintain water in the soil profile during the rest of the season.

DISCUSSION

While the reduction in *R. reniformis* density by 1,3-D was statistically significant, it was trivial in practical terms, because of the low yields that still occurred in the treated test plots in 2006. Preplant fumigation through drip irrigation with 1,3-D was able to reduce the numbers of *R. reniformis*, but only in the area closest to the drip lines. The concentration of fumigant would be expected to be highest over the area of application (Wang and Yates, 1999). Others have observed that 1,3-D was able to affect nematodes and weeds beyond the wetting front (Desaeger et al., 2004; Chase et al., 2006). However, in these experiments, nematodes were not killed in sufficient numbers anywhere in the field and particularly not in the bed and dry furrow.

The Acuff loam in these experiments allowed good lateral water movement, compared with coarser textured soils. Wang et al. (2004) indicated that the most important factor in fumigation with 1,3-D in drip irrigation was soil type, but that the variability was higher in fine-textured soils compared with coarse-textured soils. Ou et al. (2005) found that fumigation with 1,3-D through drip was erratic, with more than 50% of the product found near the end of the drip tape in one experiment and a more uniform distribution in a second experiment.

The density of *R. reniformis* in this drip irrigated field was higher at the 30 and 40 cm depths than the 15 cm depth. *Rotylenchulus reniformis* is known to have a relatively high density at lower soil depths. In 15 of 17 fields sampled, more than 50% of *R. reniformis* population density was found below 30.5 cm (Robinson et al., 2005). Any type of fumigation when the target population is that deep will be challenging.

The strong inverse relationship between nematode preplant density and yield in 2006 and the absence of any relationship in 2007 is one reason that nematode assay services may be hesitant to make recommendations. The reniform nematode is highly variable in its year-to-year damage. The maximum yield in this test field was 2,084 kg lint/ha, so in one year there was an average loss of 67%, and in the next year the average loss was 19%. The yield-loss relationship may not always look as bad as 2006, but management options must realistically reduce population densities to low levels and do so in soils that have a wide range of textures (Robinson et al., 1987). Producers who use SDI systems face two challenges in regards to managing *R. reniformis*: the nematode is a very deep parasite, and SDI is not typically deeper than 30 cm; and soil textures can be less favorable for uniform fumigant distribution since the nematode is found in a wide range of soil textures. It may be impossible to adequately control this nematode with fumigation through SDI, particularly at wide tape spacing. Having SDI in the field also makes traditional shank fumigation riskier, since the application can tear up existing drip tape, particularly if the beds have shifted over time with respect to the location of the drip tape. In conclusion, fumigation with 1,3-D (at 46 kg a.i./ha) through drip irrigation tapes laid out at 2-m intervals was unsuccessful at controlling the reniform nematode. Drip irrigation fields are also more difficult to fumigate using more traditional methods. Nematode damage in drip irrigation fields can be much higher than with other irrigation systems if adequate control cannot be achieved.

LITERATURE CITED

Allen, R. G., Walter, I. A., Elliott, R., Howell, T., Itenfisu, D., and Jensen, M. 2005. The ASCE Standardized Reference Evapotranspiration Equation. *in* American Society of Civil Engineers, Reston, VA.

Allen, V. G., Brown, C. P., Segarra, E., Green, C. J., Wheeler, T. A., Acosta-Martinez, V., and Zobeck, T. M. 2008. In search of sustainable agricultural systems for the Llano Estacado of the U.S. southern High Plains. Agriculture, Ecosystems. Environment 124:3–12.

Apt, W. J., and Caswell, E. P. 1988. Application of nematicides via drip irrigation. Supplemental Journal of Nematology 20 (4S), 1–10.

Bordovsky, J. P. 2007. SDI installation for evaluating crop row direction and lateral offset distance. Paper No. 072193. *in* 2007 International Meeting of the American Society of Agricultural and Biological Engineers, Minneapolis, MN, 17–20 June, 2007.

Bordovsky, J. P., and Porter, D. O. 2003. Comparison of spray, LEPA and subsurface drip irrigated cotton. Paper No. 032008. *in* Proceedings of the American Society of Agricultural Engineers 2003 Annual Int. Meeting, 1–11. St. Joseph, MI. ASAE.

Chase, C. A., Stall, W. M., Simonne, E. H., Hochmuth, R. C., Dukes, M. D., and Weiss, A. 2006. Nutsedge control with drip-applied 1,3-dichloropropene plus chloropicrin in a sandy soil. HortTechnology 16:641–648.

Colaizzi, P. D., Evett, S. R., and T. A. Howell. 2006a. Crop emergence with alternative SDI designs in a Pullman clay loam soil. Pp. 16–24 *in* Proceedings of the 28th Annual Southern Conservation Systems Conference, 26–28 June, 2006. Amarillo, TX, http://www.cprl.ars.usda.gov/wmru/pdfs/Colaizzi%202006%20SCSC%20Proceedings.pdf

Colaizzi, P. D., Gowda, P. H., Marek, T. H., and Porter, D. O. 2006b. Reducing Ogallala withdrawals by changing cropping and irrigation practices in the Texas High Plains. Pp. 113–126 *in* Proceedings of the USCID Water Management Conference: Ground Water and Surface Water Under Stress: Competition, Interaction, Solutions, 25–28 October, 2006, Boise, ID U.S Committee on Irrigation and Drainage, Denver CO.

Colaizzi, P. D., Lamm, F. R., Howell, T. A., and Evett, S. R. 2006c. Crop production comparison under various irrigation systems. Pp. 189–207 *in* Proceedings of the Central Plains Irrigation Conference, 21–22 Feb., 2006. Colby, KS, http://www.oznet.k-state.edu/irrigate/OOW/P06/Colaizzi06.pdf

Desaeger, J. A. J., Eger, J. E., Jr., Csinos, A. S., Gilreath, J. P., Olson, S. M., and Webster, T. M. 2004. Movement and biological activity of drip-applied 1,3-dichloropropene and chloropicrin in raised mulched beds in the southeastern U.S.A. Pest Management Science 60:1220–1230.

Lamm, F. R., Ayars, J. E., and Nakayama, F. S. 2007. Microirrigation for Crop Production: Design, Operation, and Management. Burlington, MA: Elsevier.

Ou, L. T., Thomas, J. E., Allen, L. H., Jr., McCormack, L. A., Vu, J. C., and Dickson, D. W. 2005. Effects of application methods and plastic covers on distribution of cis- and trans-1,3-dichloropropene and chloropicrin in root zone. Journal of Nematology 37:483–488.

Porter, D., Marek, T., Howell, T., and New, L.The Texas High Plains Evapotranspiration Network (TXHPET) User Manual Publication AREC 05-37 Amarillo, TX; Texas A&M University Agricultural Research and Extension Center.

Roberts, P. A., Magyarosy, A. C., Matthews, W. C., and May, D. M. 1988. Effects of metam-sodium applied by drip irrigation on root-knot nematodes, *Pythium ultimum*, and *Fusarium* sp. in soil and on carrot and tomato roots. Plant Disease 72:213–217.

Robinson, A. F., Akridge, R., Bradford, J. M., Cook, C. G., Gazaway, W. S., Kirkpatrick, T. L., Lawrence, G. W., Lee, G., McGawley, E. C., Overstreet, C., Padgett, B., Rodríguez-Kabana, R., Westphal, A., and Young, L. D. 2005. Vertical distribution of *Rotylenchulus reniformis* in cotton fields. Journal of Nematology 37:265–271.

Robinson, A. F., Heald, C. M., Flanagan, S. L., Thames, W. H., and Amador, J. 1987. Geographical distributions of *Rotylenchulus reniformis*, *Meloidogyne incognita*, and *Tylenchulus semipenetrans* in the lower Rio Grande Valley as related to soil texture and land use. Annals of Applied Nematology 1:20–25.

Segarra, E., Almas, L., and Bordovsky, J. P. 1999. Adoption of advanced irrigation technology: LEPA versus drip in the Texas High Plains. Pp. 324–328 *in* Proceedings of the Beltwide Cotton Conference, National Cotton Council, Memphis, TN.

Thistlethwayte, B. 1970. Reproduction of *Pratylenchus penetrans* (Nematoda: Tylenchida). Journal of Nematology 2:101–105.

Tinm, N. H., and Mieczkowski, T. A. 1997. Univariate & Multivariate General Linear Models: Theory and Application using SAS Software, Cary, NC: SAS Institute.

Wang, D., He, J. M., and Knuteson, J. A. 2004. Concentration-time exposure index for modeling soil fumigation under various management scenarios. Journal of Environmental Quality 33:685–694.

Wang, D., and Yates, S. R. 1999. Spatial and temporal distributions of 1,3-dichloropropene in soil under drip and shank application and implications for pest control efficacy using concentration-time index. Pesticide Science 55:154–160.