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Management Options for *Pratylenchus penetrans* in Easter Lily[1]

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Abstract: Alternatives to reduce or modify nematicide use for minimizing groundwater contamination in Easter lily were explored in two field trials. Alternatives to standard 1,3-dichloropropene (1,3-D) plus phorate injection in the first trial were: (i) delaying applications until after winter rains, (ii) removing roots from planting stock, (iii) 1,3-D via drip irrigation, (iv) a chitin-urea soil amendment, (v) the registered insecticide disulfoton, and (vi) several nonregistered nematicides. None of the treatments equaled the standard treatment. In the second trial, potential benefits of adding a systemic nematicide, oxamyl (OX), or a fungicide, metalaxyl (MX), to the standard treatment were explored. Preplant drip irrigation applications of metam-sodium (MS), sodium tetrathiocarbonate (ST), and emulsifiable 1,3-D were evaluated alone and in combination with postplant applications of OX and MX. Several drip-applied treatments performed comparably to the standard treatment with respect to the most important criteria of crop quality, bulb circumference. Metam-sodium in combination with either or both OX and MX, 1,3-D plus OX and MX, and ST plus OX and MX provided the best results.

Key words: Easter lily, lesion nematode, *Lilium longiflorum,* nematicide, nematode, *Pratylenchus penetrans.*

Easter lily (*Lilium longiflorum* Thunb.) has been the most important crop in Humboldt and Del Norte counties, California, and Curry County, Oregon, since the early 1940s (Jensen, 1966). These counties are within the only area of the United States in which Easter lilies are grown commercially. Approximately 250 ha of lilies are grown each year in a 3- to 6-year rotation with pastures for cattle and sheep; thus ca. 2,400 ha are part of the cropping system. Yearly farm gate value of the crop is approximately $5 million. Bulbs are sold to greenhouse operations to produce flowering plants (Hawkins, 1991).

Bulbs are grown for 2 to 4 years before they are large enough for sale. Quality is judged visually, with only white bulbs with plentiful roots being saleable. Land is prepared in May, fumigated in July, and planted from August through October; bulbs are harvested the following August through October. In the first year, bulblets (small, thumbnail-size bulbs that arise from stems of the previous crop) are planted at the rate of 256,000 to 385,000/ha. After one growing season, yearlings are replanted at the rate of 160,000/ha. At the end of the second season, if yearlings have reached 20 cm in circumference, they are sold. If smaller, bulbs are replanted for a third or even a fourth season (Hawkins, 1991; Riddle, pers. comm.).

The lesion nematode, *Pratylenchus penetrans* (Cobb) Sher and Allen, is a serious detriment to Easter lily production (Koepsell and Pscheidt, 1991). A dual nematicide application, usually consisting of a preplant fumigant followed by an organophosphate or carbamate applied at planting, is used because of the severe pest pressure caused by both infested soil and infected planting stock. The finding in 1982 that groundwater had been polluted by 1,2-dichloropropane (1,2-D) and aldicarb had significant adverse impacts on both the residents of these counties and the bulb industry (Hawkins, 1991; Warner et al., 1989). In 1983, the industry began using fenamiphos instead of aldicarb and 1,3-dichloropropene (1,3-D, Telone II) rather than a mixture of 1,2-D and 1,3-D. In 1986, the California Department of Food and Agriculture (CDFA) reported that, in Del Norte County, fenamiphos had moved below 2.4 m, which was possibly in violation of the state's Pesticide Contamination Act of 1985, and its use on lilies was withdrawn by the manufacturer (Hawkins, 1991). The use of 1,3-D in California was suspended from April 1990 until early in 1996, and growers turned to metam-sodium or methyl bromide plus an at-plant application of phorate, an organophosphate.

The climate of the region is characterized by cool summers with coastal fog, mild winters, and an average annual rainfall of 190 cm (primarily from November to March). Cool soil temperatures, high water tables (ca. 12 m), and acidic soils contribute to the potential for groundwater contamination by pesticides in the area (Warner, 1985).

In field trials conducted during the 1988–89 and 1989–90 growing seasons, we explored several objectives we thought could reduce nematicide use or modify usage patterns to minimize the potential for groundwater contamination. In 1988–89, our objectives were to determine if: (i) nematicide applications could be delayed until after heavy winter rains had subsided, (ii) removing nematode-infected roots from planting stock would improve control over standard nematicide applications, (iii) drip irrigation applications of nematicides could provide control similar to traditional injection applications of 1,3-D, (iv) a chitin-urea soil amendment could provide nematode control, (v) a registered organophosphate insecticide could also provide nematode control, and (vi) several nonregistered products could provide nematode control.

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During the subsequent growing season (1989–90) our objectives were to repeat the most successful treatments and to determine if adding a systemic nematicide or a fungicide application to the standard fumigant plus organophosphate treatment could improve crop quality.

We strongly emphasize that our trials were planted with bulblets of a size that were not expected to grow to a marketable size at the end of a single growing season, but would typically be replanted by a grower for at least 1 more year prior to reaching a marketable size. Therefore, relative size rather than marketable size of yearling bulbs is one of several criteria by which to judge the success of the treatments.

Materials and Methods

Field trials were conducted at the Easter Lily Research Foundation Station in Brookings, Oregon, during the 1988–89 and 1989–90 cropping seasons in a site known to be infested with *P. penetrans*. The area had been cropped alternately to a mixture of pasture grasses and clover for 3 to 4 years and Easter lilies since the 1970s. The soil type was a Knappa heavy clay loam with a pH of 5.3, a stable organic matter content of 7%, and a cation exchange capacity of 23 (L. J. Riddle, pers. comm.). The experimental areas were managed following standard commercial practices. Land preparation in April and May consisted of mowing, disking, plowing, and disking again following the application of 5,000 kg/ha of agricultural lime and 1,000 kg/ha of gypsum. In early July, the soil was deep-ripped and subsoiled. At planting, 1,000 kg/ha of 6-20-20 fertilizer was applied. An additional 240 kg/ha of calcium nitrate was top-dressed in February and April. Herbicides used were glyphosate (Monsanto, St. Louis, MO) prior to bulb emergence, napropamide (ICI Americas, Richmond, CA) plus diuron (Griffin, Valdosta, GA) at emergence, and diuron following bulb emergence. From January through May, a foliar fungicide (copper hydroxide, Griffin, Valdosta, GA) was applied every 10 days, weather permitting, and the fungicides iprodione (Rhone-Poulenc, Research Triangle Park, NC) and chlorothalonil (ISK Biotech, Mentor, OH) were applied every 30 days. From June through October, copper hydroxide was applied every 30 days.

In each experiment, plots were 1 row (1.02 m) wide by 6 m long, arranged in four randomized complete blocks. Planting stock was Nellie White bublets handpicked from stems of the previous year's crop weighing ca. 7 g each. Each plot was planted with 160 bublets placed in two lines spaced 3.75 cm between bublets in a line and 8 cm between the two lines. Bublets were planted 10 cm deep in October and harvested in September. Prior to planting and following standard grower practice, bublets were dipped for 1 hour at 12 °C in a freshly made solution of 0.72 kg a.i. pentachloronitrobenzene (Terraclor 400, PCNB, 40% pentachloronitrobenzene, Uniroyal Chemical Company, Middlebury, CT), 0.95 kg a.i. tetramethylthiuram disulfide (42-S Thiram, 42% tetramethylthiuram disulfide, Gustafson, Plano, TX), and 0.81 kg a.i. carboxin (Vitavax-34, Gustafson, Plano, TX) per 379 liters of water and planted within 24 hours of treatment.

Both trials were sprinkler-irrigated as needed. Plots receiving drip-applied nematicide applications received additional water during the application. Drip irrigation emitters were spaced 30 cm apart with application rates of 2 liters/hour per emitter (Classic, CL 1653-12, Drip in Irrigation Company, Fresno, CA). Drip irrigation treatments were injected into the drip irrigation tubing with a piston pump (Model 1-70, Inject-O-Meter, Clovis, NM). For preplant nematicide applications in 1988, tubing was arranged lengthwise over the soil from which beds would be formed with three lengths of tubing per bed at 20-cm intervals. In 1989, tubing for preplant treatments was laid on top of preformed beds with two lengths per bed, with 20 cm between tubes. For postplant treatments in 1988, a single length of tubing was laid on top of the beds, and in 1989 a single length was buried 8 cm deep in the bed.

Treatment effects were evaluated through estimations of nematode population densities in soil and root samples and assessment of crop quality. Soil samples consisted of eight 2.5-cm-diam cores per plot, taken to a depth of 30 cm. Nematodes were extracted from a 400-cm^3 soil subsample with a modified semiautomatic elutriator and sucrose centrifugation technique (Byrd et al., 1976). Nematodes also were extracted from roots removed from the base of the bulbs (5 bulbs/plot). Roots were weighed and placed in an intermittent mist chamber for 72 hours (Ayoub, 1977). Extracted nematodes were identified and counted at ×45 magnification.

In 1989, the circumference of each harvested bulb was measured and the measurements were averaged to determine the mean bulb circumference per plot. In 1990, a regression equation was developed to equate bulb weight with bulb circumference. To develop the equation, 154 bulbs were selected randomly from all plots and individually measured and weighed. The total number of bulbs and total weight of bulbs for each plot were determined and the mean circumference for each plot was determined (Crisosto et al., 1999; Ryugo, 1988; Westwood, 1978). In both experiments, visual ratings of average foliage growth per plot and root health for each plot were made by the same observer based on a scale from 1 (poor) to 10 (healthy).

The description of the nematicide treatments and abbreviations used in data tables are listed in Table 1. In the 1988–89 experiment, there were 12 treatments (Tables 2 and 3). Treatments were applied prior to planting on 12 September, at planting on 3 October, or postplant on 20 June. The standard treatment consisted

TABLE 1. Descriptions of nematicide treatments and abbreviations used in text and tables.

	Treatment					
	Preplant			At planting (ap) or postplant (pp)		
Abbreviation		Rate kg a.i./ha[a]	Drip irrigation[b]		Rate kg a.i./ha	Drip irrigation
UNT	Untreated control	—	—	—	—	—
STANDARD	1,3-dichloropropene	428	—	Phorate (ap)	9.0	—
MS 407	Metam-sodium	407	1000–2	—	—	—
XRM 146	XRM 5053	146	300–2	—	—	—
1,3-D + CLIP + PH	1,3-dichloropropene plus clipped roots	428	—	Phorate (ap)	9.0	—
1,3-D + OX	1,3-dichloropropene	428	—	Oxamyl (pp)	13.7	100–2
CHITIN	Chitin-urea	1494	—	—	—	—
OX	—	—	—	Oxamyl (pp)	13.7	100–2
ET	—	—	—	Ethoprop (pp)	13.4	100–2
XRM 16	—	—	—	XRM 5053 (pp)	16.0	100–2
DI	—	—	—	Disulfoton (pp)	13.4	100–2
ST 200	—	—	—	Sodium tetrathiocarbonate (pp)	200.5	500–2
1,3-D	1,3-dichloropropene	428	—	—	—	—
1,3-D + PH + ME	1,3-dichloropropene	428	—	Phorate (ap) + Metalaxyl (pp)	9 + 9.6	100–1.5
1,3-D + PH + OX	1,3-dichloropropene	428	—	Phorate (ap + Oxamyl (pp)	9 + 9.6	100–1.5
MS 314	Metam-sodium	314	800–2.5	—	—	—
1,3-D + ME + OX	1,3-dichloropropene	428	—	Metalaxyl (pp) + Oxamyl (pp)	9.6 + 9.6	100–1.5
MS + OX	Metam-sodium	314	800–2.5	Oxamyl (pp)	9.6	100–1.5
MS + ME	Metam-sodium	314	800–2.5	Metalaxyl (pp)	9.6	100–1.5
MS + ME + OX	Metam-sodium	314	800–2.5	Metalaxyl (pp) + Oxamyl (pp)	9.6 + 9.6	100–1.5
ST 1004	Sodium tetrathiocarbonate	1004	1,000–2.5	—	—	—
ST + ME + OX	Sodium tetrathiocarbonate	1004	1,000–2.5	Metalaxyl (pp) + Oxamyl (pp)	9.6 + 9.6	100–1.5
XRM 122	XRM 5053	122	300–2.5	—	—	—
XRM + ME + OX	XRM 5053	122	300–2.5	Metalaxyl (pp) + Oxamyl (pp)	9.6 + 9.6	100–1.5

[a] Rates are expressed as the amount of material that would actually be applied.
[b] Rates are ppm a.i. followed by the length of time in hours over which the product was applied.

of 1,3-D (94% a.i., Dow AgroSciences, Indianapolis, IN) injected 30 cm deep with a hand applicator (Maclean's Fumigun, Neil A. Maclean Co. Inc., San Francisco, CA) in 2 lines spaced 30 cm apart with 30 cm between injection points with 3.5 ml applied at each point followed by an at-plant treatment of phorate (Rampart 10 G, American Cyanamid, Wayne, NJ) placed on top of and around bublets prior to covering them with soil. In another treatment, 1,3-D and phorate were applied and

TABLE 2. Effect of nematicide treatments on growth of Easter lilies (1988–1989).

	Crop quality at harvest[a]				
	Growth Ratings				
Treatment	Foliage	Roots	Number of bulblets	Bulb survival	Bulb circumference (cm)
UNT	2.0 cde[b]	1.3 d	18 a	57 ab	8.6 a
MS 407	6.8 b	2.8 c	83 b	81 bc	11.3 d
XRM 146	2.3 cde	1.5 d	28 a	52 a	9.3 abc
STANDARD	8.5 a	7.0 a	132 cd	105 cd	12.2 de
1,3-D + CLIP + PH	9.0 a	6.5 a	158 d	116 d	12.7 e
1,3-D + OX	7.8 ab	5.5 b	103 bc	91 cd	12.4 e
CHITIN	3.0 cde	2.0 cd	42 a	42 a	10.0 c
OX	3.5 c	1.5 d	44 a	47 a	9.3 abc
ET	3.0 cd	1.8 d	23 a	47 a	8.8 ab
XRM 16	1.5 de	1.5 d	24 a	48 a	9.6 bc
DI	2.0 cde	1.8 d	15 a	35 a	8.8 ab
ST 200	1.3 e	1.3 d	13 a	47 a	8.4 a

[a] Growth ratings were subjective on a scale from 1 = poor to 10 = healthy looking. Bulb survival out of 160 planted per replicate.
[b] Means followed by the same letter within columns are not significantly different according to LSD test ($P \leq 0.05$). Data are means of four replicates.

TABLE 3 Effect of nematicide treatments on densities of *Pratylenchus penetrans* in soil and roots (1988–1989).

	Pratylenchus penetrans				
	Soil (number/1,000 cm^3)			Roots (number/gram)	
Treatment	4 Nov	23 June	18 Sept	23 June	18 Sept
UNT	1.44 b[a]	2.43 cd	2.68 bc	3.01 cd	1.83 cd
MS 407	0.43 ab	2.44 cd	3.67 d	2.93 cd	2.63 e
XRM 146	1.46 b	1.87 bc	2.91 cd	3.11 cd	2.23 de
STANDARD	0.44 ab	0.43 a	1.91 ab	1.89 b	1.06 ab
1,3-D + CLIP + PH	0.00 a	1.36 b	2.48 bc	1.13 a	0.76 a
1,3-D + OX	0.00 a	2.16 bcd	3.11 cd	2.63 c	2.18 de
CHITIN	1.44 b	2.62 cd	3.14 cd	3.13 cd	1.92 cde
OX		2.25 cd	1.20 a	3.21 d	1.44 bc
ET		2.58 cd	2.67 bc	2.95 cd	1.84 cd
XRM 16		2.72 d	2.54 bc	3.30 d	2.02 cde
DI		2.72 d	2.72 bc	3.18 d	2.07 cde
ST 200		2.78 d	2.54 bc	3.28 d	2.13 de

Data are means of four replicates. Initial population density in soil in September = 96 ± 24 SE/1,000 cm^3, in planting stock in October = 0.1/gram bulblet tissue, and in roots = 26/gram based on a composite sample of 10 bulblets.
[a] Means followed by the same letter within columns are not significantly different according to LSD test ($P \leq 0.05$). Nematode counts were transformed by log 10 $(x + 1)$ prior to analysis.

TABLE 4. Effect of nematicide treatments on growth of Easter lilies (1989–1990).

	Crop quality[a]					
	Growth ratings				Bulbs	
	Foliage			Roots		
Treatment	19 Feb	5 June	12 Sept	12 Sept	Number surviving	Circumference (cm)
UNT	2.3	2.0 ab[b]	1.3 a	1.5 a	28 ab	10.0 a
1,3-D	1.3	2.3 ab	2.0 abc	2.3 abc	33 abc	11.1 abc
STANDARD	2.0	6.8 e	5.0 fg	6.8 f	91 f	13.5 e
1,3-D + PH + ME	2.3	5.8 de	4.3 efg	6.3 f	93 f	13.3 de
1,3-D + PH + OX	1.5	5.5 cde	5.3 g	6.5 f	73 def	13.5 e
MS 314	1.8	3.5 abcd	2.5 abcd	3.3 bcd	53 bcd	12.2 cde
1,3-D + ME + OX	2.0	3.5 abcd	2.0 abc	2.0 ab	50 bcd	11.5 bc
MS + OX	2.0	5.3 cde	3.8 def	4.8 e	83 ef	13.5 e
MS + ME	2.3	3.8 abcd	2.8 bcd	3.5 cde	52 bcd	12.4 cde
MS + ME + OX	2.3	5.0 cde	3.8 def	4.3 de	75 def	13.5 e
ST 1004	1.8	3.3 abc	1.8 ab	1.8 a	32 abc	11.2 abc
ST + ME + OX	3.0	5.8 de	3.3 cde	3.3 bcd	64 de	12.4 cde
XRM 122	2.5	4.3 bcd	2.5 abcd	2.5 abc	57 cd	12.0 cd
XRM + ME + OX	2.5	5.8 de	3.3 cde	3.5 cde	62 de	13.1 de

Data are means of four replicates.

[c] Growth ratings were subjective, made by the same observer on each date on a scale from 1 = poor to 10 = healthy looking. Bulb survival out of 160 planted per replicate.

[d] Means followed by the same letter within columns are not significantly different according to LSD test ($P \leq 0.05$).

the plot planted with bulblets from which the roots had been removed by hand prior to planting. Injected 1,3-D was also combined with a postplant application of oxamyl (Vydate L, 24% a.i., Dupont, Wilmington, DE) via drip irrigation tubing. XRM 5053 (1,3-D plus emulsifier, 65% a.i.) and metam-sodium (Vapam, 33% a.i., Amvac, Newport Beach, CA) were applied preplant via drip irrigation tubing. A chitin-urea soil amendment (ClandoSan 618, Igene Biotechnology, Inc., Columbia, MD) was spread in a 1.02-m band down the center of the plot and incorporated with a power tiller to a depth of 20 cm prior to bed formation. Oxamyl, ethoprop (Mocap EC, 69.6% a.i., Rhone-Poulenc, Research Triangle Park, NC), disulfoton (Di-Syston 8, 85% a.i., Bayer, Kansas City, MO), XRM 5053, and sodium tetrathiocarbonate (GY-81, Enzone, 32% a.i., Entek, Elkridge, MD) were applied postplant as separate treatments via drip irrigation tubing. Rates for the drip applications were determined from those found successful in previous trials on other crops (J. D. Radewald, pers. comm.).

The 1989–90 experiment had 14 treatments (Tables 4 and 5). Treatments were applied prior to planting on 14 September, at planting on 16 October, or postplant on 3 November. 1,3-Dichloropropene was applied preplant as in 1988. Injected 1,3-D also was applied (i) in combination with an at-plant application of phorate applied as in 1988 (standard treatment), (ii) with an at-plant application of phorate plus a postplant application of metalaxyl (Subdue, 25.1% a.i., Novartis, Greensboro, NC) via drip irrigation tubing, (iii) with an at-plant application of phorate plus a postplant application of oxamyl via drip irrigation tubing, and (iv) with a combined postplant application of metalaxyl and oxamyl applied as previously described. Metam-sodium was applied preplant via drip irrigation tubing. This treatment was also applied in combination with a postplant application of (i) metalaxyl, (ii) oxamyl, and (iii) a combination of metalaxyl and oxamyl as described previously. Sodium tetrathiocarbonate was applied preplant via drip irrigation tubing. This treatment was also

TABLE 5. Effect of nematicide treatments on densities of *Pratylenchus penetrans* in soil and roots (1989–1990).

	Pratylenchus penetrans				
	Soil (number/1,000 cm^3)			Roots (number/gram)	
Treatment	3 Nov	19 Feb	12 Sept	19 Feb	12 Sept
UNT	1.82	2.27 c[a]	2.24	1.48 d	1.92 fgh
1,3-D	2.09	2.17 c	2.33	1.38 cd	2.06 gh
STANDARD	1.65	2.12 c	2.83	0.22 a	0.70 ab
1,3-D + PH + ME	1.25	1.60 bc	2.75	0.63 ab	0.67 ab
1,3-D + PH + OX	1.00	1.90 c	1.57	0.24 a	0.41 a
MS 314	0.85	2.03 c	2.04	0.55 ab	1.56 def
1,3-D + ME + OX	1.97	0.97 b	2.38	1.17 bcd	1.85 efgh
MS + OX	0.55	0.00 a	2.63	1.13 bcd	0.97 bc
MS + ME	0.58	1.78 c	1.68	0.67 abc	1.29 cd
MS + ME + OX	0.85	0.93 b	2.46	0.27 a	1.37 cde
ST 1004	2.10	2.09 c	2.29	1.21 bcd	1.87 efgh
ST + ME + OX	1.05	2.12 c	2.53	1.09 bcd	1.50 def
XRM 122	1.65	2.20 c	2.57	0.71 abc	1.73 defg
XRM + ME + OX	1.59	2.22 c	2.68	0.78 abcd	1.40 cde

Data are means of four replicates. Initial population density in soil in September = 638 ± 147 SE/1,000 cm^3, and in planting stock in October = 15/gram of root based on a composite sample of 10 bulblets.

[a] Means followed by the same letter within columns are not significantly different according to LSD test ($P \leq 0.05$). Nematode counts were transformed by log 10 $(x + 1)$ prior to analysis.

applied in combination with a postplant application of metalaxyl and oxamyl as described previously. XRM 5053 was applied preplant via drip irrigation tubing. This same treatment was also applied in combination with a postplant application of metalaxyl and oxamyl as described above.

In the 1988–89 experiment, samples were taken 4 November for treatments to which nematicides had been applied (nematodes in soil), 23 June (nematodes in soil and in roots), and at harvest on 18 September (nematodes in soil and in roots, visual ratings of foliage and roots, number of bulblets per stem, number of surviving bulbs, and bulb circumference). In the 1989–90 experiment, samples were taken on 7 November (nematodes in soil), on 19 February (nematodes in soil and roots, visual rating of foliage), on 5 June (visual rating of foliage), and at harvest on 12 September (nematodes in soil and roots, visual rating of foliage and roots, number of surviving bulbs, and bulb circumference).

Results were subjected to analysis of variance followed by LSD comparison testing at $P = 0.05$ and by linear regression analysis (Abacus Concepts, Berkeley, CA). Nematode counts were transformed with log 10(x + 1) to normalize variance prior to analysis of variance.

Results

In the 1988–89 experiment (Table 2), STANDARD outperformed UNT in all crop quality measurements ($P \leq 0.05$). The 1,3-D + CLIP + PH treatment performed better than UNT ($P \leq 0.05$) but did not improve crop quality over STANDARD. The 1,3-D + OX application also outperformed ($P \leq 0.05$) UNT and was comparable to STANDARD with respect to all crop quality measurements except the root-rating score. The MS 407 treatment outperformed UNT in all crop quality measurements except bulb survival and was comparable to STANDARD with respect to bulb circumference and survival. None of the remaining treatments exceeded UNT with the exception of bulb circumference for CHITIN and XRM 16.

In 1988, the initial *P penetrans* population density was 96 ± 24 SE/1,000 cm^3 soil, 0.1/gram of bulblet tissue, and 26/gram root (Table 3). On 4 November, *P penetrans* populations were lower ($P \leq 0.05$) than UNT for the 1,3-D + CLIP + PH and the 1,3-D treatments that would later receive an application of OX, but not for STANDARD. On 23 June, just prior to the post plant treatments, soil nematode populations that were lower ($P \leq 0.05$) than UNT were found in STANDARD and 1,3-D + CLIP + PH. At harvest on 18 September, only OX had soil nematode populations lower ($P \leq 0.05$) than UNT. Populations in MS 407 were higher ($P \leq 0.05$) than UNT.

Within roots, populations on 23 June were lower than UNT ($P \leq 0.05$) in STANDARD and 1,3-D + CLIP + PH applications. Fewer nematodes were recovered from 1,3-D + CLIP + PH treatments than STANDARD ($P \leq 0.05$). At harvest, STANDARD and 1,3-D + CLIP + PH had fewer nematodes within the roots than UNT ($P \leq 0.05$). In September, the MS 407 treatment had more nematodes within roots than UNT ($P \leq 0.05$).

In the 1989–90 experiment, all treatments appeared to be similar ($P \leq 0.05$) when rated visually soon after crop emergence on 19 February (Table 4). The mean bulb circumference for each plot was determined by $y = 3.43 + 0.047x$, $r^2 = 0.895$, $P = 0.0001$, where y = circumference and x = weight. From 5 June on, seven treatments consistently outperformed ($P \leq 0.05$) UNT in crop quality criteria. These were STANDARD, 1,3-D + PH + ME, 1,3-D + PH + OX, MS + OX, MS + ME + OX, ST + ME + OX, and XRM + ME + OX. However, only two treatments were equivalent to STANDARD ($P \leq 0.05$). These were 1,3-D + PH + ME and 1,3-D + PH + OX. Two treatments, MS + OX and MS + ME + OX, were similar ($P \leq 0.05$) to STANDARD with respect to all crop quality ratings except root rating. On 5 June, ST + ME + OX and XRM + ME + OX were similar ($P \leq 0.05$) to STANDARD with respect to the visual rating and circumference. MS 314 applied by itself outperformed ($P \leq 0.05$) UNT with respect to root rating and produced bulbs with a circumference similar ($P \leq 0.05$) to STANDARD. MS + ME application was similar to MS alone but also had a foliage rating at harvest better than UNT. 1,3-Dichloropropene + ME + OX together outperformed UNT with respect to circumference. The XRM 122 treatment could be distinguished from UNT in bulb survival and circumference.

At planting in 1989 (Table 5), bulblet roots contained 15 *P. penetrans*/g root and the soil 638 ± 147 SE/1,000 cm^3 soil. On 3 November prior to the postplant applications and at harvest on 12 September, no differences were evident in the number of nematodes in soil samples ($P \leq 0.05$). On 19 February, three treatments (1,3-D + ME + OX, MS + OX, and MS + ME + OX) had lower soil nematode populations ($P \leq 0.05$) than UNT and than STANDARD. Nematode levels in roots on 19 February were lower ($P \leq 0.05$) than UNT in STANDARD, 1,3-D + PH + ME, 1,3-D + PH + OX, MS 314, MS + ME, MS + ME + OX, and XRM 122. At harvest on 12 September, STANDARD, 1,3-D + PH + ME, 1,3-D + PH + OX, MS + OX, MS + ME, MS + ME + OX, and XRM + ME + OX had lower nematode populations within roots than UNT.

Regressions with negative slopes different from zero were obtained for foliage rating, root rating, and bulb weight vs. nematodes in roots at harvest, confirming the importance of nematodes in this cropping system: $y = -0.02x + 4.20$, $r^2 = 0.72$, $P = 0.0001$ where y = foliage rating and x = nematodes per gram of root at harvest; $y = -0.03x + 5.32$, $r^2 = 0.70$, $P = 0.0002$ where y = root rating and x = nematodes per gram of root at harvest; and $y = -0.18x + 39.49$, $r^2 = 0.78$, $P = 0.0001$ where y =

bulb weight in grams and x = nematodes per gram of root at harvest.

Discussion

Pratylenchus penetrans biology and control have been extensively studied because *P. penetrans* is the most economically important plant-pathogenic nematode in the northeastern states (Mai et al., 1977). It is a migratory endoparasite living either within roots or in soil. The length of the life cycle in alfalfa at 30 °C was 30 days, 37 days at 25 °C, and 92 days at 15 °C. Nematode populations increased at temperatures as low as 9 °C and thus may be active most of the year in Easter lily fields (Hawkins, 1991; Mai et al., 1977; McWhorter and Anderson, 1951; Steiner, 1945).

Pratylenchus penetrans was found in Easter lily fields as early as 1946 (Butterfield, 1947). Disease symptoms on Easter lilies are general devitalization of the plant, retarded top growth, chlorotic foliage, and restricted root growth (Overman, 1961). Bulbs may not even be able to emerge. In less serious cases, the symptoms are not evident until late in the growing season.

Pratylenchus penetrans has a broad range of 400 host plants (Jensen, 1953; Mai et al., 1977). Because of its wide host range, nonchemical control measures such as crop rotation and use of resistant varieties generally have not been feasible. The nematode has been found statewide in California (Siddiqui et al., 1973) and is of economic concern on ornamentals, apples, cherries, and strawberries (McKenry and Roberts, 1985).

Effective management of *P. penetrans* requires control in both planting stock and soil. Soil nematicides or chemical treatments of bulbs prior to planting have improved bulb growth (Gill and Good, 1964; Hart et al., 1967; Jensen, 1966; Maggenti et al., 1967; Maggenti et al., 1970; L. J. Riddle, pers. comm.). Several of the chemicals we tested (e.g., metam-sodium; 1,3-D, ethoprop; and sodium tetrathiocarbonate, which releases carbon disulfide) were expected to control only nematodes present in soil while oxamyl was expected to control nematodes within roots as well. The current registration status of all chemicals should be determined prior to use.

It was hypothesized that minimizing nematicide applications prior to or during the rainiest months of the year (November through March with approximately 25 cm precipitation/month during this period) would improve efficacy by reducing potential leaching from the root zone. We tested this hypothesis by applying five different products via a drip irrigation system in June 1989 after rains had subsided. None of these treatments performed as consistently as the standard treatment with respect to crop quality. At harvest, out of all treatments including the standard, only the postplant oxamyl treatment had soil nematode populations lower than the control. By examining bulbs 2 weeks after planting in 1989, we observed that root growth had already begun at this time. It is likely that nematode invasion and reproduction were occurring at this time, several months before foliage emerged above ground. Without a preplant treatment, most bulbs did not emerge in the spring. Even with subsequent nematicide treatments, bulbs never recovered and were often smaller at harvest than when planted.

Other researchers have studied the effect of root removal from bulbs on nematode control (Bald et al., 1958; D'Herde et al., 1960). Root removal in combination with the standard treatment could not be statistically separated from the standard treatment. Although approximately 80% of the nematode inoculum can be eliminated by root removal, the remaining nematodes combined with those naturally present in soil are apparently sufficient to cause significant problems. Hot water treatments could reduce nematode numbers in roots prior to planting (Jensen and Caveness, 1954) but could present potential for exacerbation of fungal diseases owing to circulation of fungal propagules, which might not be killed by the treatments, in the treatment tank.

Although we have seen benefits from the use of a chitin-urea soil amendment in trials conducted on other California crops (Westerdahl et al., 1992), such benefits were not evident in this study. Disulfoton (an organophosphate insecticide registered on Easter lilies) did not prove useful as a nematicide in this study.

Drip irrigation application of nematicides is an effective method of applying chemicals to soil on other crops (Apt and Caswell, 1988; Nakayama and Bucks, 1986; Radewald et al., 1986; Westerdahl et al., 1993). However, none of the treatments applied via drip irrigation in 1988–1989 equaled the standard injection method. Metam-sodium applied preplant and oxamyl applied postplant in combination with injected 1,3-D showed the most promise for future evaluation. In 1989–1990, several drip-applied treatments performed comparably to the standard treatment with respect to the most important criteria of crop quality, which is bulb circumference. Those showing the most promise included metam-sodium in combination with either or both oxamyl and metalaxyl, 1,3-D plus oxamyl and metalaxyl, and sodium tetrathiocarbonate plus oxamyl and metalaxyl. The rate of 1,3-D applied as XRM 5053 via drip irrigation was less than half that applied in the standard injection treatment. Given that use of 1,3-D in California is volumetrically restricted on a township basis, development of this method of application could permit larger areas to be treated prior to reaching the township cap. Adding the fungicide metalaxyl to the nematicide treatments or an additional nematicide treatment (oxamyl) to the standard combination treatment did not appear to provide any benefits.

For drip irrigation application of nematicides, the choice of application equipment, emitter spacing, nematicide, length of application, soil type, timing and amount of irrigation before and after treatments, depth of groundwater, nematode pest, crop and its rooting depth must all be considered for a given treatment situation (Westerdahl et al., 1993). For *P. penetrans* on a shallow rooted crop, in a shallow groundwater situation, and with a relatively fine-textured, constantly wet, high-organic-matter soil, we chose relatively short, constant rate treatments designed to treat only the root zone of the crop. Our experiments demonstrated that drip irrigation applications of several nematicides could provide benefits to Easter lilies without phytotoxicity. Although drip application is more complex than traditional preplant shank injection combined with sprays or granules at planting, it may allow growers to use a broader spectrum of materials, combine two or more chemicals if necessary, and reduce the potential for various forms of environmental contamination.

The cost of a drip irrigation system is more than the cost of conventional application equipment. Part of the differential could be recovered by the use of smaller amounts of chemicals as was demonstrated in this study with the use of XRM 5053, an emulsifiable formulation of 1,3-D. Methods of accounting that use only the costs of chemicals, equipment, and application to evaluate a given control method may underestimate the costs of nematode management because they do not take into account the potential to result in groundwater contamination and the subsequent cleanup cost.

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