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Effects of Soil Solarization on *Rotylenchulus reniformis* in the Lower Rio Grande Valley of Texas

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Abstract: Soil solarization was evaluated for control of *Rotylenchulus reniformis* in the lower Rio Grande Valley of Texas. In field experiments, solarization significantly reduced soil nematode population densities 0–15 cm deep and increased yields of lettuce and cowpea. The length of time required for 90% mortality of nematodes in soil heated under controlled conditions in the laboratory varied from 25 hours to less than 1 hour between 41 and 47 C. Daily exposures of nematode-infested soil to lethal temperatures for sublethal time periods had a cumulative lethal effect. In water, vermiform stages required up to 10 days to recover from sublethal thermal stress. Eggs were similar to juveniles in their sensitivity to high temperatures. Lethal time–temperatures under controlled conditions were in general agreement with field results.

Key words: reniform nematode, *Rotylenchulus reniformis*, solarization, temperature, thermal death.

Rotylenchulus reniformis Linford and Oliveira is an important agronomic pest of numerous crops grown in tropical and subtropical regions of the world. In the subtropical lower Rio Grande Valley (LRGV) of Texas, it affects several major crops including cotton (*Gossypium hirsutum*), cantaloupe (*Cucumis melo* var. *cantalupensis*), onion (*Allium cepa*), and lettuce (*Lactuca sativa*). Among several options for controlling *R. reniformis* is soil solarization, the solar heating of soil by tarping with polyethylene film. Solarization has not been used commercially for nematode control in the LRGV; however, it can have pronounced effects on plant-parasitic nematodes (2,4,5), and for several months each year climatic conditions in the LRGV are similar to those where solarization has proven economically practicable (1). Our objective was to conduct a preliminary evaluation of soil solarization for controlling *R. reniformis* populations in the LRGV.

Materials and Methods

Effects of soil solarization in the lower Rio Grande Valley: Four parallel field experiments were conducted in 1983–85 on a sandy clay loam soil (52% sand, 17% silt, 31% clay) naturally infested with *R. reniformis*. Two experiments were conducted in 1984 and are distinguished as 1984-A and 1984-B. Each of the four experiments included six blocks of five randomized treatments: 1) summer fallow, 2) fumigated summer fallow, and 3–5) summer fallow tarped with 102-μm-thick polyethylene film (PF) for 4, 6, or 8 weeks. Fumigation consisted of injecting a 1,3-dichloropropene + 1,2-dichloropropane mixture (94 liters/ha, 1983) or 1,3-dichloropropene alone (75 liters/ha, 1984 and 1985) 25–30 cm deep, 15 cm from each side of the seed furrow, 56 days preplant. Each plot consisted of two beds, 6.1 m long and 1 m wide with a border row on each side. Beds were irrigated and allowed to equilibrate to field capacity before tarping. During solarization, soil temperatures of tarped and untarped beds were monitored continuously with thermistors planted 7.5, 15, 22.5, and 30 cm below the soil surface. Upon completion of the 8-week solarization, beds were seeded. Rainfall provided field capacity soil moisture at planting in all plots. In 1983, 1984-A, and 1984-B, beds were planted to cowpea (*Vigna unguiculata* subsp. *unguiculata*). The 1985 experiment included lettuce. Late season plant heights were measured in each cowpea experiment. Yield was taken in all experiments except 1984-A, where pea set failed. Two or three graduated soil samples at depths of 0–7.5, 7.5–15, 15–22.5, and 22.5–30 cm were taken from each plot with a hydraulic core sampler (5-cm-d) before treatment, upon plastic removal, preplant, and at harvest.

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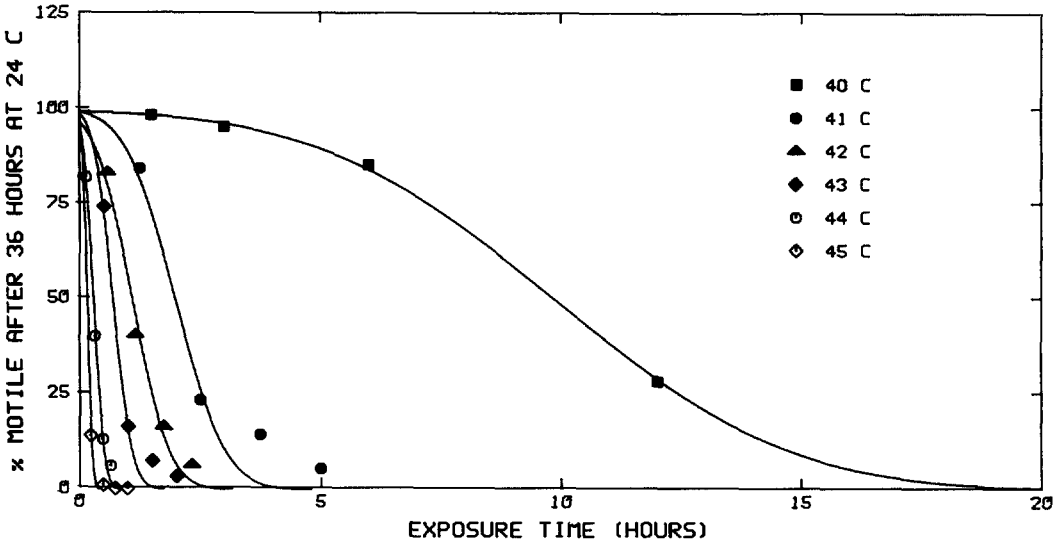

FIG. 1. Motility of vermiform *Rotylenchulus reniformis* after 36 hours recovery (24 C) following exposure to temperatures of 40–45 C for various time intervals. Each datum represents the percentage of 300 nematodes observed to move within 5 seconds. Binomial confidence limits of each datum are within ± 5%. Sigmoid curves represent cumulative inverse normal distributions that were fitted to data by least squares with a reiterative computer algorithm.

Ungraduated samples (ca. 7.5–22.5 cm) were collected mid-season.

Preliminary examinations of lethal temperatures and exposure times under laboratory conditions: Results of several preliminary experiments dictated the rationale for subsequent, more definitive investigations and are presented here. Initially, two experimental populations of vermiform *R. reniformis* (juveniles, adult males, and pre-parasitic adult females) were extracted from soil by Baermann funnel and exposed in water to various temperatures (35–45 C) for various time intervals (1–120 hours). Twenty-four to thirty-six hours after nematodes were returned to ambient temperature (24 C), the percentage of 300 nematodes that moved spontaneously within 5 seconds was determined for each treatment. For each temperature, a cumulative inverse normal distribution (CIND) was fitted to motility data, based on the assumption that life expectancy was normally distributed within the population. From these functions (Fig. 1) were derived tentative Lt50 values which were used to define exposure times to be examined in the following experiment.

Soil, naturally infested with an exceptionally high population density of *R. reniformis* (300 nematodes/cm^3 determined by Baermann funnel extraction), was subjected in water baths to five temperatures (37–44 C) each for two unique time intervals for which previous motility data predicted 50 and 100% mortality. All soil was placed

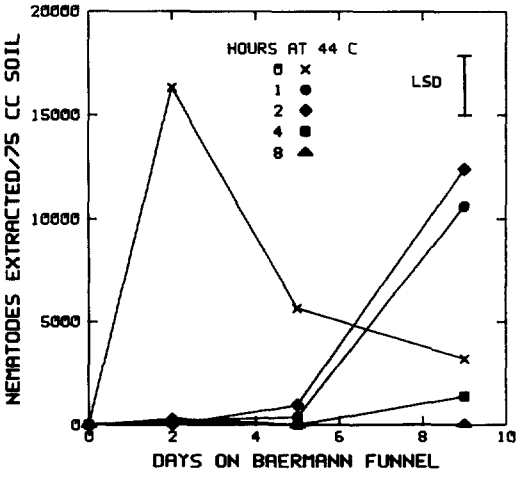

FIG. 2. Numbers of *Rotylenchulus reniformis* collected from Baermann funnels (75 cm^3 soil/funnel) 2, 5, and 9 days after exposure to 44 C for various time intervals.

TABLE 1. Influence of time of exposure to temperatures between 41 and 47 C on the viability of *Rotylenchulus reniformis* eggs and vermiform stages in water and in soil.

	41 C	42 C	43 C	44 C	45 C	46 C	47 C	CK
Exposure time	2	1	0.75	0.33	0.167	0.083	0.033	30
(hours)	6	3	2.25	1	0.5	0.25	0.100	30
	10	5	3.75	1.67	0.83	0.417	0.167	
	30	15	11.25	5	2.5	1.25	0.5	
Eggs hatched/egg	15.8	31.0	34.4	7.2	12.2	30.4	13.6	17.9
mass at 408 hours	7.3	11.9	12.6	7.0	14.7	13.1	14.9	13.9
(50–100 egg masses	5.9	8.1	0.8	7.1	4.9	6.6	13.1	
per treatment)	0	0.2	0	0	0	0	0	
Cumulative movement	89	93	99	96	70	105	104	98
(% of control,	49	77	77	71	85	58	100	102
300 nematodes	40	51	31	58	64	57	83	
per treatment)	0	0	0	0	0	0	0	
Nematodes extracted	148	173	187	223	310	217	192	219
per cm^3 soil	259	155	244	173	201	200	186	308
(Baermann funnel)	284	244	133	239	233	141	125	
(LSD = 101)	68	80	32	36	41	31	21	

in baths simultaneously. Soil at higher temperatures received relatively short exposures (0–48 hours) and, after removal from baths, was maintained at 24 C until the end of all temperature treatments (5 days). All soil was then placed on Baermann funnels for 48 hours. Large numbers of nematodes (ca. 300/cm^3) were recovered from all soil aliquants, indicating little or no population reduction for any treatment. Four hypotheses concerning failure to kill nematodes within soil were considered: 1) slower temperature equilibration within soil than in water, 2) egg hatch in soil during the 7-day interval at 24 C, 3) slow recovery of nematodes from thermal stress, and 4) lower sensitivity of nematodes to high temperature in soil than in water. To test these hypotheses, naturally infested soil was exposed to 44 C for 1 hour; this was the exposure time, based on initial motility data, necessary to achieve 100% mortality. Other aliquants of soil were exposed to 44 C for 2, 3, 4, 5, 6, and 8 hours. Immediately after temperature exposure, soil was placed on Baermann funnels; these funnels were sampled after 2, 5, and 9 days. Funnel harvests at 48 hours suggested high mortality for all exposure times; however, a big increase in extractable nematodes occurring between 5 and 9 days indicated that very slow recovery or egg hatch was responsible for the discrepancy previously observed between lethal conditions in water and soil (Fig. 2).

Comparison of thermal death among nematodes in soil, eggs in water, and vermiform nematodes in water: Rotylenchulus reniformis were propagated on cantaloupe in greenhouse pots containing sandy loam soil (72% sand, 13% silt, 15% clay). When a second crop of plants was ca. 6 weeks old, pots were emptied. Egg masses (EM) were removed from roots and resuspended in deionized water (10 EM/ml). Moist soil (2 kg) was placed on Baermann funnels (100 g/funnel) to obtain a suspension of vermiform developmental stages (100 nematodes/ml). The remaining soil (15 kg) was thoroughly mixed, then poured into 100-ml test tubes (80 cm^3 soil/tube), which were gently tamped and individually covered with aluminum foil to retard drying. Soil moisture determinations (w/w) before and after temperature treatment indicated no measurable moisture loss. Tubes were then placed in a water bath at 30 C. Substantial amounts of small roots within soil ensured the inclusion of many egg masses of *R. reniformis*. After 24 hours, tubes were transferred to water baths at temperatures of 41–47 C (± 0.1 C) for four time intervals per temperature (Table 1). Exposures were

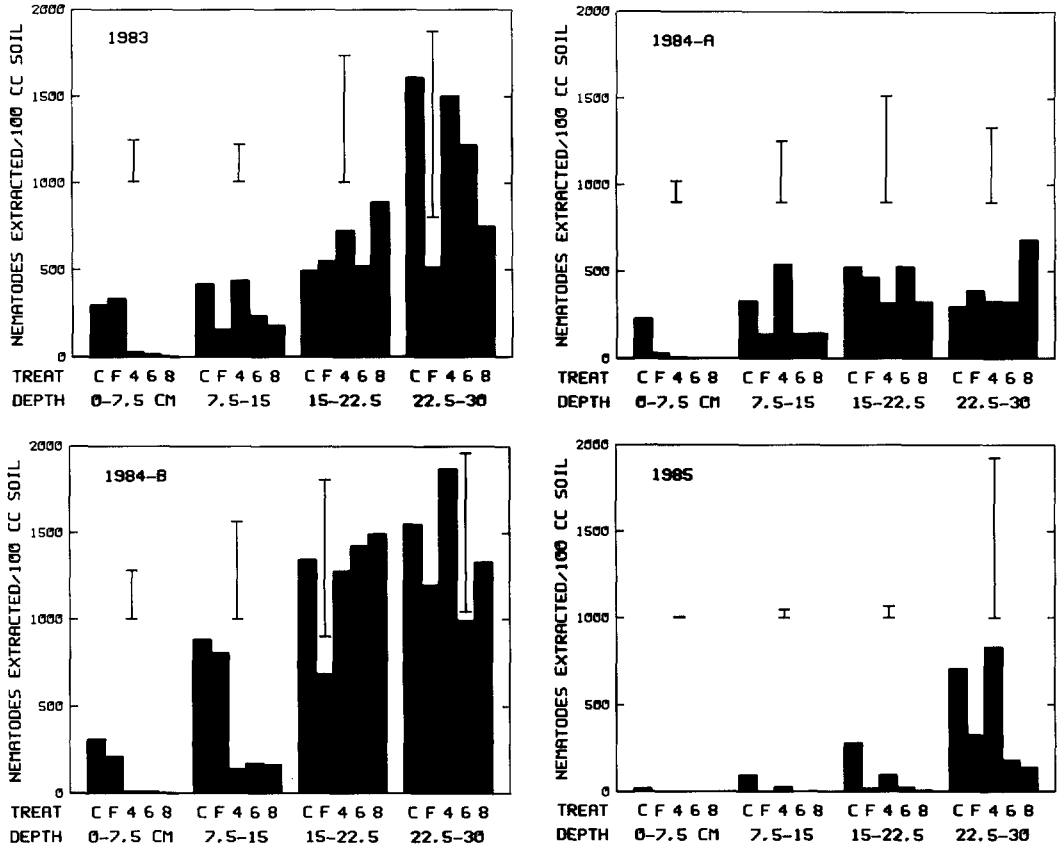

FIG. 3. Numbers of *Rotylenchulus reniformis* extracted by Baermann funnel from soil samples taken at four depths after 8 weeks of summer fallow that also included no additional treatments (C), fumigation (F), and solarization for 4 weeks (4), 6 weeks (6), and 8 weeks (8). Brackets indicate least significant differences at $P = 0.05$.

time sequenced so that all tubes were removed within a 3-hour interval. Simultaneously, capped vials (25 ml) containing suspensions of eggs or vermiform nematodes in water (10 ml) were submerged in the same baths as soil. To improve aeration, vials were gently but continuously rocked with a mechanical apparatus. Also included were experimental controls exposed only to 30 C, consisting of 12 soil tubes, two EM vials, and two vials of vermiform *R. reniformis.* Temperature readings from thermistors in representative soil tubes verified the achievement of experimental temperatures (± 0.1 C) within 2 minutes. Immediately after temperature exposures, the contents of three soil tubes per time–temperature combination were placed on three Baermann funnels and the contents of three additional tubes were set aside at ambient temperature (24 C). Funnels of the first set of tubes were harvested after 2 and 9 days. On day 10, soil from the second set of tubes were placed on three funnels which were harvested after 2 and 9 additional days. The contents of vials containing aqueous suspensions of eggs or vermiform nematodes were transferred directly from temperature baths to culture dishes at 24 C. Motility and the numbers of eggs hatched were measured six times during the next 3 weeks.

Effects of daily exposure of nematodes within soil to marginally lethal conditions: Soil was obtained and placed in tubes as described for comparisons between deaths of eggs and vermiform nematodes in soil and water. After 24 hours of equilibration at 30 C,

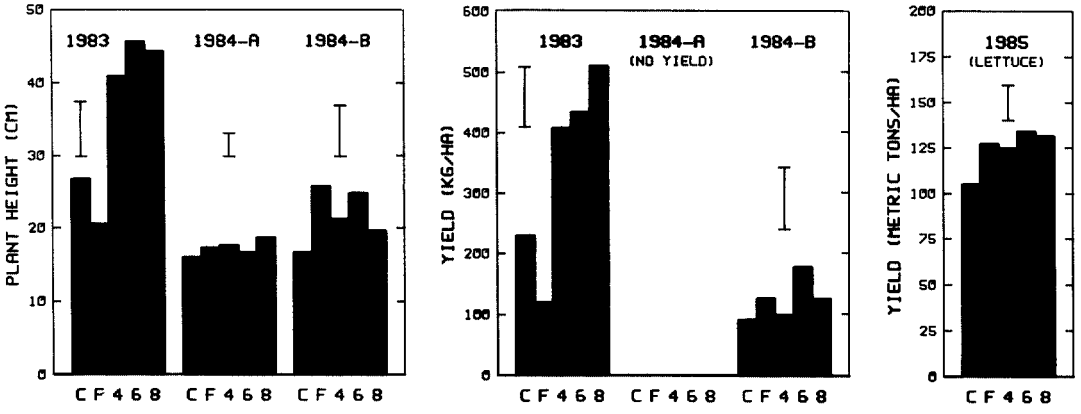

FIG. 4. Mid-season plant heights and crop yields obtained in field experiments on the effect of soil solarization on *Rotylenchulus reniformis*. All data except yield in 1985 indicate responses of *Vigna unguiculata* subsp. *unguiculata* (cowpea). Yield in 1985 is for *Lactuca sativa* (lettuce). Preplant treatments included 8 weeks summer fallow with no additional treatment (C), with fumigation as described in text (F), and with solarization for 4 weeks (4), 6 weeks (6), and 8 weeks (8). Brackets indicate least significant differences at $P = 0.05$.

four sets of tubes (six tubes per set) were held for 100 minutes at 44 C, then returned to 30 C. One hundred minutes exposure to 44 C was repeated for 1, 2, 4, or 8 consecutive days. Immediately after each final exposure, soil from each set was processed for nematode extraction as described for comparisons between death in soil and water. A control set of six tubes held continuously at 30 C was processed simultaneously with each treated set.

RESULTS AND DISCUSSION

In all four field experiments, soil solarization substantially reduced nematode population density 0–15 cm deep (Fig. 3). Several weeks after planting a susceptible crop, soil samples indicated relatively small differences in nematode population densities among treatments; these were usually undetectable at harvest. In 1985 only, population reduction was detected also at 15–

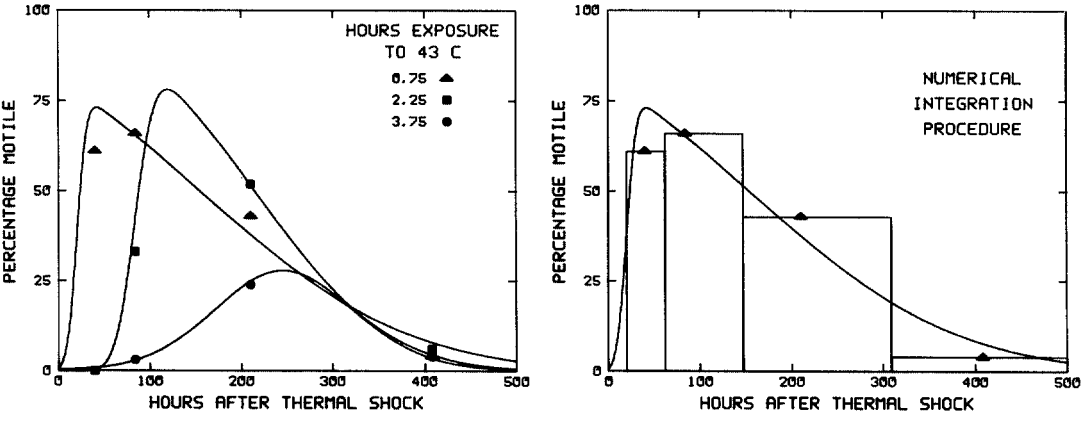

FIG. 5. Recovery of motility by *Rotylenchulus reniformis* after exposure to 43 C for various time intervals (left) and a diagram (right) illustrating the method of integration used to estimate cumulative motility 0–3 weeks after exposure of nematodes to each temperature, 41–47 C. Each datum (left and right) represents the percentage of 300 nematodes observed to move within 5 seconds; binomial confidence limits for all data are within ± 5%. Areas within the bars (right) were added for each time–temperature treatment; the total area was divided by the total area obtained for the control to yield a percentage of cumulative motility.

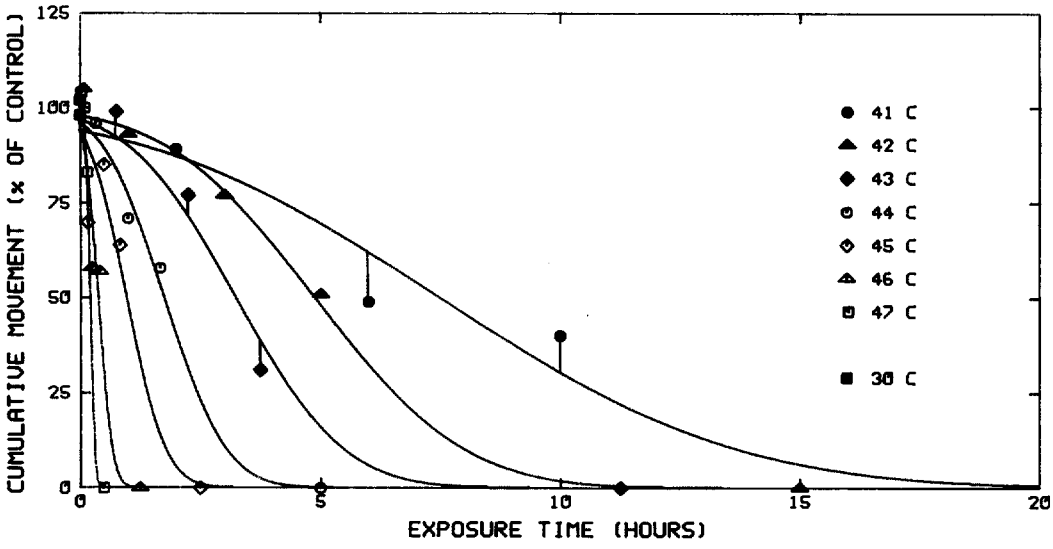

FIG. 6. Cumulative motility of *Rotylenchulus reniformis*, expressed as a percentage of cumulative motility of control nematodes, 0–3 weeks after exposures to temperatures of 41–47 C for various time intervals. Original motility measurements were based on percentages of 300 nematodes observed to move within 5 seconds. Sigmoid curves represent cumulative inverse normal distributions fitted to data by least squares with a reiterative computer algorithm.

22.5 cm. Solarization consistently surpassed fumigation in reducing nematode population density only within the top 7.5 cm of soil. In two of the three experiments for which yield data were available, solarization increased yields of cowpea and lettuce (Fig. 4). Because much greater nematode population densities occurred below than above 15 cm (Fig. 3), yield increases appear to have resulted from the death of a small proportion of the total nematode population within the soil profile. We speculate that early season effects on plant development were the biggest contributor to eventual yield differences.

Upon sublethal exposures to high temperatures in water, vermiform *R. reniformis* became inactive. Recovery required 1–10 days, depending upon exposure time and temperature. After ca. 20 days, control nematodes also became inactive. Thus, recovery was slow compared with normal longevity in water. A simple numerical integration procedure was used to estimate the total movement occurring 0–508 hours after thermal shock for each treatment (Fig. 5). These values were divided by that of the control and, by fitting CIND functions to the resulting percentages as described for preliminary experiments, Lt50 values were obtained (Fig. 6).

Egg hatch terminated ca. 3 weeks after thermal shock for all treatments. Lt50 values for eggs were obtained by dividing eggs hatched per EM for each treatment by eggs hatched per EM for the control at 3 weeks

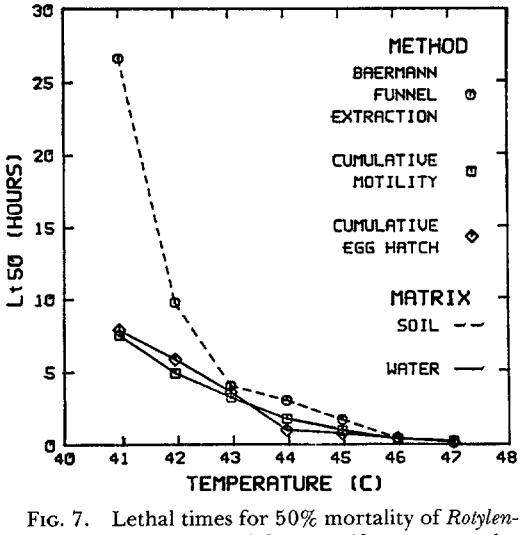

FIG. 7. Lethal times for 50% mortality of *Rotylenchulus reniformis* obtained for vermiform nematodes in water, eggs in water, and nematodes in soil.

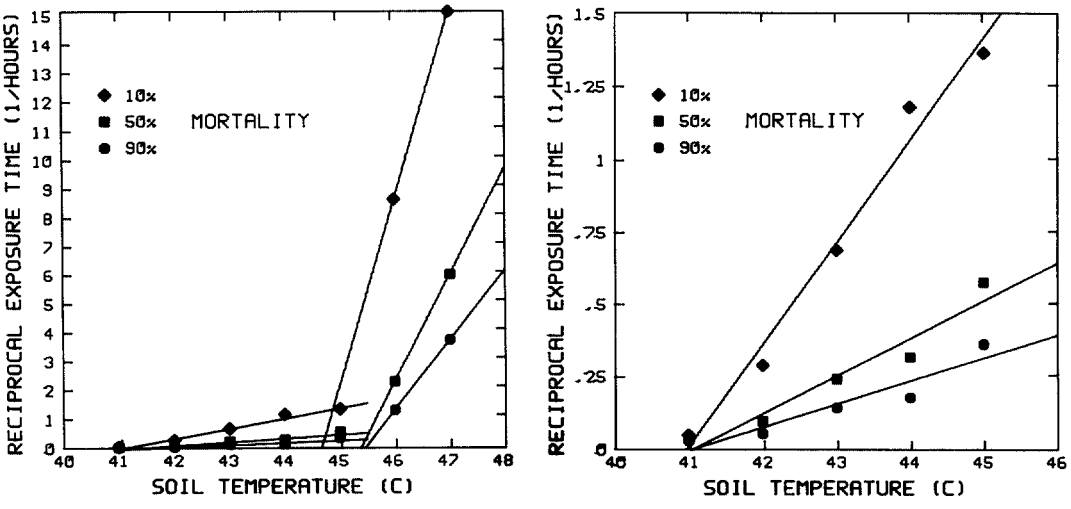

FIG. 8. Reciprocal-time thermal death predicted for *Rotylenchulus reniformis* in soil at mortality levels of 10, 50, 90%. Predictions were obtained through definite integration, via numerical approximation methods, of inverse normal distributions, integrals of which had been fitted to original Baermann funnel data by least squares, using a reiterative computer algorithm. Linear functions depicted also were fitted by least squares and were used to generate deathmaps.

and fitting CIND functions to the resulting percentages (Table 1).

Baermann funnel extractability of nematodes within soil increased many fold during 10 days post-treatment incubation at 24 C. Second harvests of funnels with soil incubated for 10 days yielded very few additional nematodes. The nematodes extracted from this soil were considered the best available measure of survival and were used to generate Lt50 values (Table 1).

Lt50 values for nematodes in soil and water were similar between 43 and 47 C (Fig. 7). At 41–42 C, data indicated nematodes to be more sensitive to temperature stress in water than in soil. Eggs appeared similar to vermiform stages in temperature sensitivity. Reciprocal time plots of Lt10, 50, and 90 for nematodes in soil indicated a lethal threshold at ca. 41 C. Linear functions fitted to these data provided a summary of theoretical knowledge of time temperature conditions affecting thermal death (Fig. 8).

Comparisons of reciprocal time functions with 58 days of digital hourly temperature data (0.1 C resolution) at four soil depths in 1985 permitted predictions concerning the occurrence of lethal exposure times for all temperatures 40–48 C for each day. Such predictions were generated at five mortality levels (10, 20, 50, 80, and 90%) of *R. reniformis* at each depth; their graphical representations are referred to here as deathmaps (Fig. 9). We emphasize that these predictions are based only on the effects of a single exposure to high temperature; they do not consider cumulative lethal effects that might result from repeated exposures.

Deathmaps for 1985 (Fig. 9) indicated a close relationship between maximum daily temperature (MAXDT) and the achievement of lethal conditions for *R. reniformis*. This is not a trivial result, in view of diurnal temperature fluctuations within soil (Fig. 10) far below and above the 41 C threshold. Maximum daily temperatures of ca. 42 C predicted only 10–20% mortality, whereas MAXDT of ca. 43 C predicted 90% mortality (Fig. 9). Based on this observation, 42.5 C was selected as a critical temperature to be used in the interpretation of MAXDT for the remaining three experiments for which digital hourly data were not available. The 42.5 C MAXDT criterion predicted high nematode mortality 0–15 cm deep in all four experiments

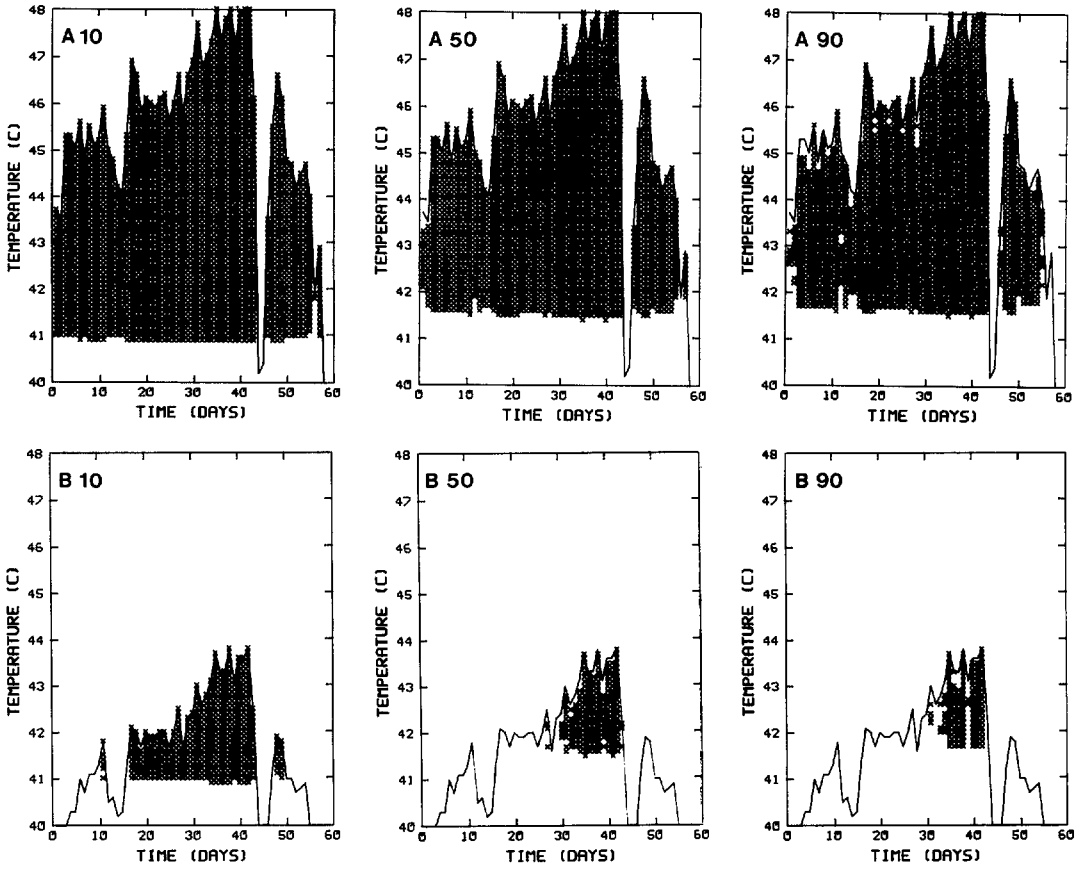

FIG. 9. Deathmaps of *Rotylenchulus reniformis* for the 1985 solarization field experiment. Shaded areas indicate achievement of lethal time–temperatures, based on comparisons between laboratory results and digital hourly soil temperatures in the field, at mortality levels, left to right, of 10, 50, and 90%. A) Data for the 0–7.5 cm deep soil layer. B) Data for 7.5–15 cm. Solid lines above shaded areas indicate maximum daily soil temperatures at depths of 7.5 and 15 cm for A and B, respectively.

(Fig. 11); this agrees well with field observations. It did not predict the population density reduction achieved at 15–22.5 cm in 1985 (Fig. 3).

Repeated daily exposure of soil for 100 minutes to 44 C in the laboratory resulted in a cumulative lethal effect which, according to Baermann funnel results, killed more than 95% of all nematodes within 8 days (Fig. 12). A single 100-minute exposure to 44 C, however, was sublethal for most members of the population. This result may explain the population density reduction achieved 15–22.5 cm deep in 1985. In comparing MAXDT data for the four field experiments, it can be seen that only in 1985 were MAXDT above the 41 C threshold sustained at the 22.5-cm depth for several days (Fig. 11). Rebois (3) detected reduction of *R. reniformis* population densities within artificially infested soil after 27 days at constant 36 C. Minimum daily temperatures at 22.5 cm were almost always below 36 C in our 1983 and 1984 experiments. More information is needed concerning the importance of repeated exposures of *R. reniformis* to marginally sublethal conditions within soil.

Soil solarization by tarping seed beds with 102-μm PF during a summer fallow was a reproducibly effective method for reducing population densities of *R. reniformis* 0–

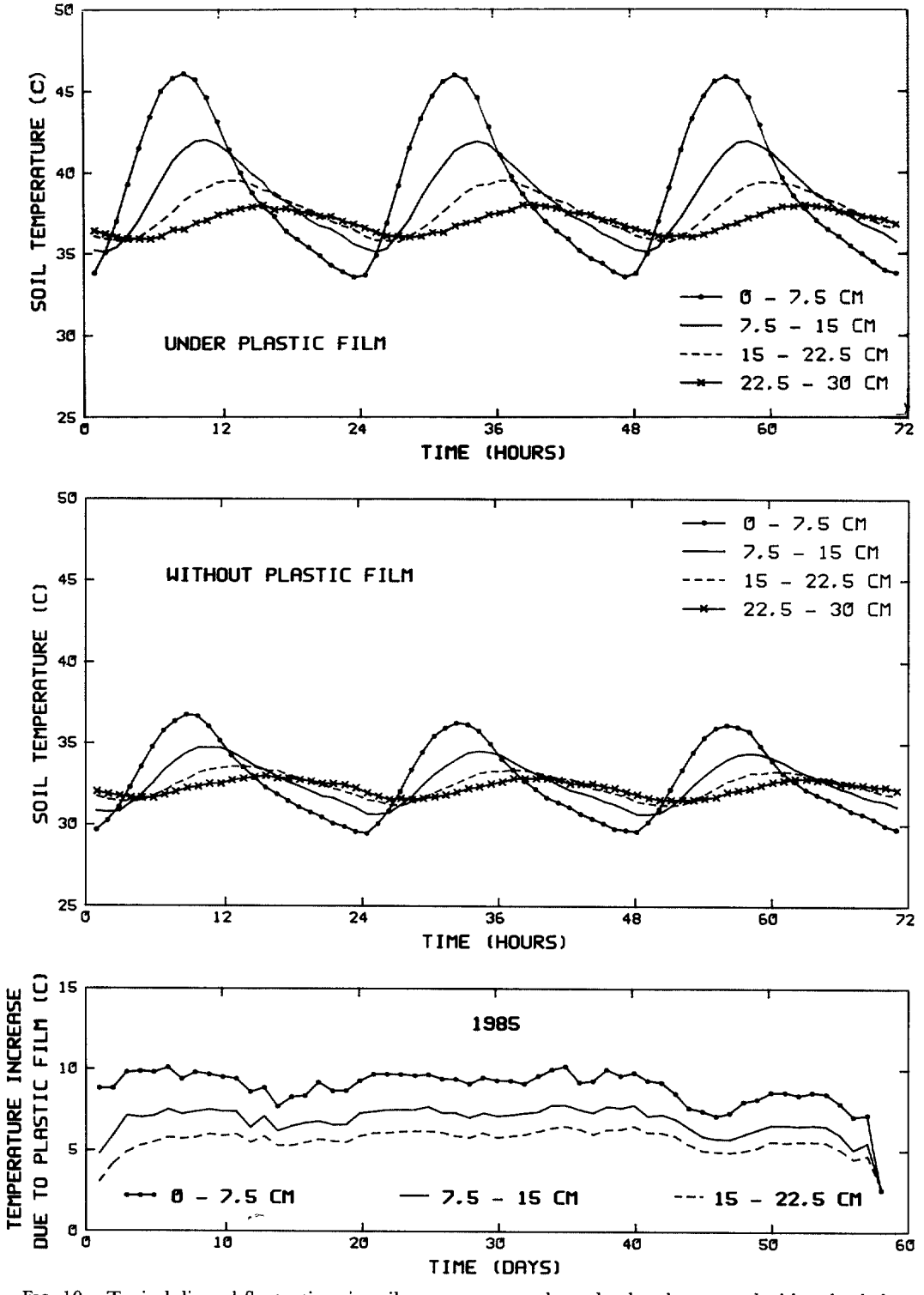

FIG. 10. Typical diurnal fluctuations in soil temperature at three depths when tarped with polyethylene film (top) and when not tarped (center). Data are from 1985 solarization experiment. Elevations in maximum daily soil temperature that resulted from tarping in 1985 (bottom).

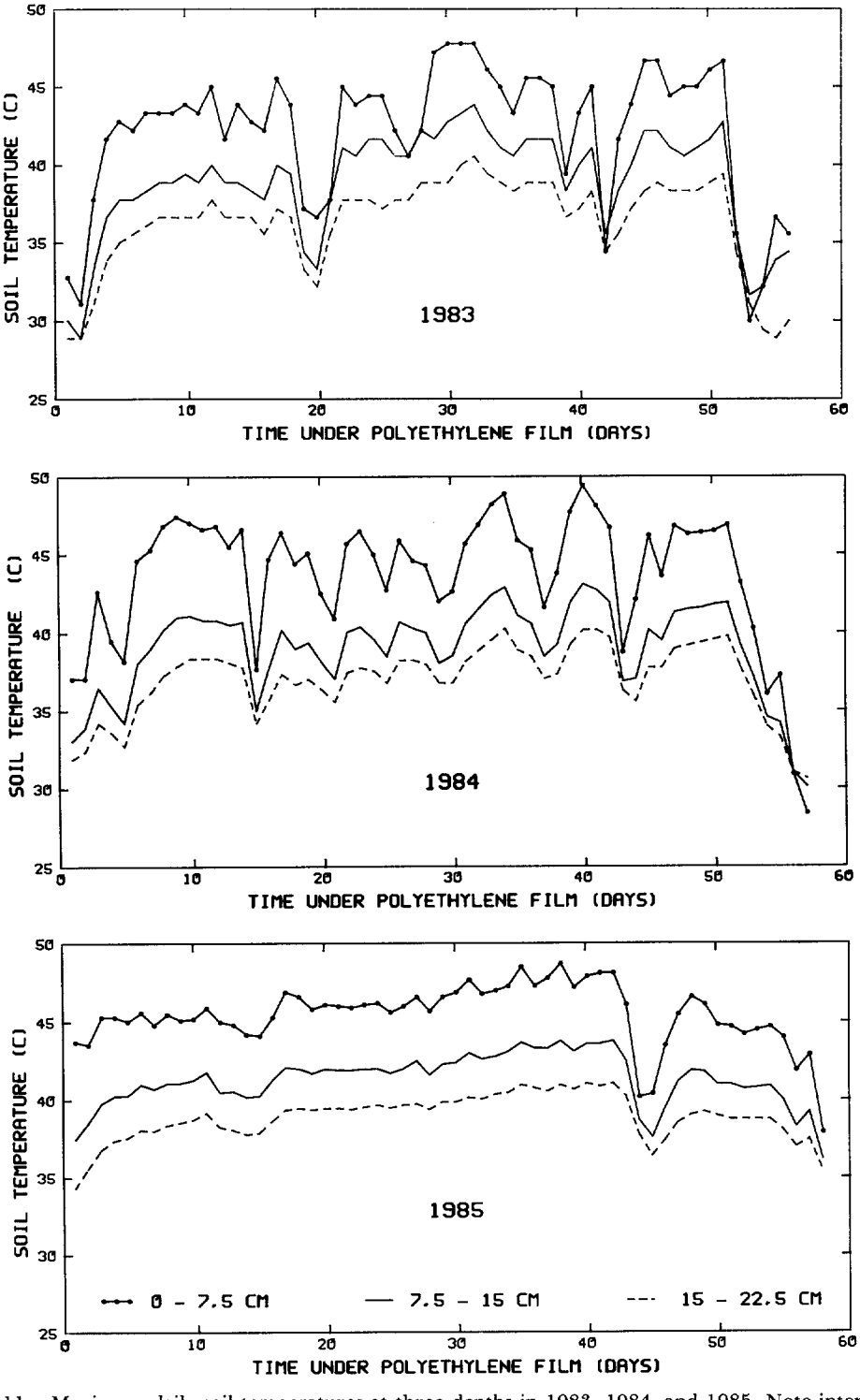

FIG. 11. Maximum daily soil temperatures at three depths in 1983, 1984, and 1985. Note intermittent temperature depressions that occurred on cloudy and rainy days, particularly in 1983 and 1984.

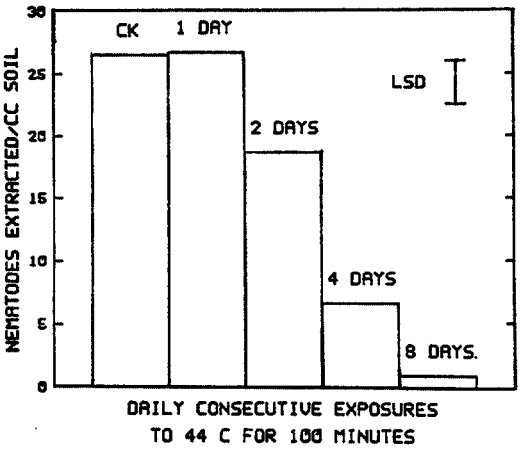

FIG. 12. Effect of repeated daily exposures of *Rotylenchulus reniformis* in soil to 44 C for 100 minutes.

15 cm deep. The greatest densities of *R. reniformis*, however, occurred below 15 cm, and in 2 of 3 years, frequent periods of cool, rainy weather prevented the achievement of lethal time–temperature conditions deeper than 15 cm (Fig. 11). Clearly, there is potential for improvement. For control of many plant pathogens, much emphasis has been placed on the duration of solarization (usually 4–8 weeks) (1); our data do not indicate comparable importance to control of *R. reniformis* in the lower Rio Grande Valley. Marginally sublethal MAXDT at the 15-cm depth were achieved reproducibly in our experiments several days after 102-μm PF application. Soil temperature elevation 0–30 cm deep equilibrated within 10 days (Fig. 10); thereafter, temperature fluctuations of solarized soil tracked fluctuations in ambient conditions. Differences between nematode population density reductions at 4 and 8 weeks were relatable to the achievement of lethal MAXDT in response to favorable weather. In 1985, cumulative lethal effects at 22.5 cm also appeared to result from fortuitous climatic conditions rather than from prolonged soil heating. Higher temperatures than we achieved can be obtained for short time intervals through use of thinner films. These films have greater radiation transmissivity than 102-μm PF but substantially less resistance to degradation from ultraviolet light and mechanical fatigue. Our results indicate a need to explore such alternatives.

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