MAINTAINING BARRIERS TO THE SPREAD OF *RADOPHOLUS CITROPHILUS* IN FLORIDA CITRUS ORCHARDS[†]

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ABSTRACT

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Studies were conducted to determine methods to restrict inter-orchard spread of *Radopholus citrophilus*. Experiments focused on the ability of a nematode to migrate in root-free soil and on methods to restrict the growth of citrus roots across root-free buffer zones. In migration trials, the nematode moved > 1.4 m in 1 year from infected to noninfected seedlings when host roots were permitted to grow toward one another. However, when citrus root growth was restricted by pruning, the nematode did not infect roots on seedlings growing 1.5 m distant from infected seedlings. In orchards, roots grew at an annual rate of > 0.90 m but < 1.5 m following pruning with a trenching machine. Sampling following cutting of roots and root system excavation indicated that long pioneer roots did not grow at depths > 1.5 m until they grew beyond the undercanopy area of the tree. Therefore, vertical hedging of trees to permit trenching near the trunk will significantly increase the number of major roots which are cut. Methyl bromide injected 60 cm deep in sandy soil at rates of 224 and 448 kg/ha penetrated at least 4.5 m in sufficient concentration to kill buried citrus seedlings.

Key words: burrowing nematode, migration, nematode buffers, nematode management, quarantine, *Radopholus citrophilus*.

RESUMEN

Duncan, L. W., D. T. Kaplan y J. W. Noling. 1990. La utilización de barreras para evitar la diseminación de *Radopholus citrophilus* en huertos de cítricos en Florida. Nematrópica 20: 71–88.

Se llevaron a cabo estudios para determinar métodos que restringen la diseminación de *Radopholus citrophilus* entre huertos. Los experimentos estuvieron enfocados hacia la habilidad del nematodo para migrar en suelo sin raíces y en los métodos capaces de restringir el crecimiento de las raíces de cítricos a través de zonas tope (buffer zones) libres de crecimiento radicular. En evaluaciones de migración, el desplazamiento del nematodo fue > 1.4 m en un año desde plantulas infectadas a otras no infectadas cuando las raíces

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del hospedador se les permitió crecer libremente. Sin embargo, cuando el crecimiento radicular fue restringido por una poda, el nematodo no infectó las raíces de plantulas sanas localizadas a 1.5 m de distancia de otras infectadas. En los huertos, las raíces crecieron a una tasa $>$ 0.90 m pero $<$ de 1.5 m después de una poda con una máquina excavadora de zanjas. El muestro realizado después del corte de las raíces con la máquina excavadora indicaron que raíces largas de desarrollo activo, no crecieron en profundidades mayores a 1.5 m hasta que alcanzaron un área superior equivalente a la copa del arbol. Consecuentemente, una configuración vertical del seto de los arboles que permita excavar zanjas cerca del tronco, incrementará significativamente el número de raíces cortadas de gran tamaño. La inyección de bromuro de metilo a 60 cm de profundidad en suelo arenoso en dosis de 224 y 448 kg/ha penetró por lo menos 4.5 m en suficiente concentración para matar plantulas de cítricos enterradas.

Palabras claves: cuarentena, manejo de nematodos, nematodo barrenador, *Radopholus citrophilus*.

INTRODUCTION

Spreading decline is a disease of citrus caused by the burrowing nematode, *Radopholus citrophilus* Huettel, Dickson and Kaplan. The disease occurs only in orchards on the deep, sandy soils characteristic of the central ridge region of Florida. Following the discovery of the causal agent of the disease, it was estimated that spreading decline reduced fruit yields to 40–70% of normal (15). Currently, losses may be mitigated somewhat due to widespread use of irrigation and use of herbicides rather than disking for weed control which has been adopted by some growers and is recommended for management of burrowing nematode infested orchards (17).

Burrowing nematode buffers were used extensively for 30 years beginning in 1954 as a means of restricting the spread of *R. citrophilus*. Buffers were established following intensive sampling to delimit nematode spatial distribution in an orchard. Rows of trees surrounding an infested area were removed and the resulting wide, bare zone of soil between infested and noninfested orchard was treated twice annually with ethylene dibromide (EDB) (15). Chemical soil treatment not only killed *R. citrophilus* but also citrus roots and weeds which could serve as sources of food for nematodes migrating across buffers. The Division of Plant Industry of the Florida Department of Agriculture and Consumer Services assisted growers in all aspects of sampling and buffer establishment and maintenance.

The original buffer program was discontinued in 1984 when EDB was deregistered as a soil sterilant due, in part, to widespread contamination by the chemical of groundwater adjacent to nematode buffers (9). Alternative chemicals to kill citrus roots deep in the soil are unavailable and no new buffers have been established since 1984. Some growers have attempted to maintain existing buffers by mechanically pruning citrus roots along the edges of buffers with trenching machines and by using herbicides for weed control.

Research aimed at the continuation of the buffer program has focused on methods to prevent citrus root growth into buffers and on the ability of *R. citrophilus* to migrate in root-free soil. Either mechanical or chemical methods of preventing citrus root growth into buffers could be effective if the nematode moves only short distances in the absence of host roots. A major consideration in excluding citrus roots from buffers concerns the spatial distribution of the root system. The distribution of the shallow portion of the root system has been characterized (3,5,7,8,13) and citrus roots near the soil surface have been recovered up to 21 m from the tree trunk. The spatial distribution of the deeper root system is less well understood. Trees growing in deep sands, characteristic of the Florida ridge, have roots deeper than 5 m at the dripline (7); however, the potential boundary of the deeper root system is undefined. Ford (7) measured feeder roots 6.7 m from rough lemon (*Citrus jambhiri* Lush.) trunks at depths to 2.7 m. Since roots grow at significant depths and long distances from the tree trunk, options for excluding roots from buffers are limited. Suitable chemicals must penetrate deeply in the soil without persisting in groundwater that is encountered in some ridge locations at less than 3 m deep. The use of mechanical devices to prune roots could succeed only if portions of deeply growing roots lie near the soil surface at the point where pruning occurs.

The experiments reported herein provide information regarding 1) the lateral movement of *R. citrophilus* in root-free soil and in soil containing citrus roots, 2) growth rates of citrus roots into burrowing nematode buffers and the spatial distribution of roots in buffers and on the edges of orchards, and 3) the efficacy of mechanical root pruning and of methyl bromide (MBr) for excluding citrus roots from buffers.

MATERIALS AND METHODS

Nematode movement: Four concrete aboveground tanks (1.4 m wide × 2.0 m long) were each divided in half lengthwise using corrugated fiberglass dividers. A layer of plastic (0.15 cm thick) with drainage holes and a second layer of shade cloth were used to continuously cover the sides and the wire mesh tank bottoms. The tanks then were filled with MBr-treated Astatula fine sand (hyperthermic, uncoated typic quartzipsamments; 92% sand, 2% silt, 6% clay) to a depth of 0.45 m. A single 60-day-old rough lemon seedling was planted 18 cm from each end of six tanks and at just one end of two tanks on 17 September 1987. On 27 October, one end of six of the tanks was infested with 2 500 *R. citrophilus* biotype 1 (10) by pouring the nematodes either into soil depressions at the base of a seedling or into fallow soil. Inoculation was repeated on 9 December using 1 200 *R. citrophilus*/inoculation site. Nematodes were from monoxenic burrowing nematode cultures maintained on carrot disks.

Four treatments were established. In the first (pruned-inoculated), a seedling at one end of a tank was inoculated with nematodes and the root systems of the plants at both ends of the tank were pruned at 45-day intervals by digging up the seedlings and pruning the root system. The second treatment (nonpruned-inoculated) was identical except that roots were allowed to grow undisturbed. In the third treatment (nonpruned-noninoculated), roots of plants at both ends of the tanks grew unpruned and free of nematodes. In the fourth treatment (pruned-fallow-inoculated), a seedling was planted at just one end of the tank. Nemadotes were inoculated into bare soil 18 cm from the opposite end of the tank. Treatments were replicated twice and assigned randomly to the tanks which were located in a screenhouse. Clear plastic canopies were constructed 1.5 m above the tanks to avoid flooding from rainfall. Seedlings were watered as needed and routinely sprayed for foliar pest control. Plants were fertilized biweekly with 20-20-20 (N-P-K) at a rate of 0.5 g/L.

Soil samples were collected bimonthly beginning 6 months after planting. Eight soil cores (5-cm diam × 30 cm deep) were taken from the midregion of five equally spaced (40 cm) zones across each tank and composited as samples. Soil was mixed and 100-cm^3 subsamples were processed for 24 hours on Baermann funnels. Nematodes were extracted (18) from roots washed from the remaining soil after which roots were dried in an oven at 70 C and weighed. At the final sampling, all plants were removed from the soil in order to process the entire root systems for recovery of nematodes.

Mechanical root pruning: A burrowing nematode buffer was selected near Babson Park, Florida. The buffer was 18 m wide and separated two orchards of 'Valencia' oranges (*Citrus sinensis* (L.) Osbeck) on rough lemon rootstock. Trees were 18 years old and were spaced 8 m apart within rows and 8 m between rows. The soil was Astatula fine sand and groundwater levels at the times of sampling were below 4.5 m. The experiment was conducted on the noninfested side of the buffer.

On 16 October 1985 a trenching machine was used to dig trenches along the buffer, parallel to the tree row, 4.5 m from the tree trunks and approximately 1.5 m outside of the canopy driplines. The trench was 0.6 m wide × 1.5 m deep. Three treatments were evaluted: 1) control trees in front of which no trench was dug for a distance of 8 m centered on the trunk, 2) trees whose roots were cut by trenching, and 3) trees whose roots were cut and in front of which the trench was lined with a polypropylene fabric designed to impede root growth. In the fabric treatment, a 4-m length of landscaping fabric (Duon, Phillips Fibers Corp. Seneca, South Carolina 29602) made of needle punched, nonwoven polypropylene (2.5 mm thick) was placed vertically to a depth of 1.2 m along the face of the trench nearest to the tree. Soil was bulldozed and shoveled back into the trenches following establishment of all treatments. Individual trees for treatment were selected randomly from a row of 31 trees and each treatment was replicated four times.

Regrowth of roots into the buffer was evaluated on 6 November 1986, 385 days after treatment. A second trench of the same dimensions was dug parallel to the first. The trench was 0.45 m further from the trees than the original trench so that the walls proximal and distal to the original trench were 0.45 m and 1.05 m, respectively, from the point at which roots were originally severed. A 3-m length of trench, centered on treated trees, was evaluated for root growth on a 0–2 scale. Trees were assigned scores of 0.0 if no roots were present or scores of 0.5–2.0 based on the visible root density. A score of 0.5 represented a single mass of feeder roots and a score of 2.0 represented a nearly continuous presence of roots along the 3-m distance. Due to frequent collapsing of trench walls shortly after excavation, the depth to which roots could be observed effectively was sometimes no more than 1.0 m. Treatment means were evaluated using Dunnett's procedure to compare all treatments against a control.

Treatments were evaluated again on 28–29 January 1988, 834 days after treatment. Soil samples from each treated tree were obtained with bucket augers (8-cm diam) in 0.3-m increments to a depth of 3.6 m. Samples were obtained at distances of 3.6, 4.2, 4.8, 5.4, 6.0, and 7.2 m in a line from the tree trunk toward the buffer middle. Two trees on the edge of the same buffer but outside of the treatment zone were sampled in the same manner in order to obtain information on root distribution of untreated trees since an evaluation trench had been dug previously in front of all treated and control trees. Samples were washed and roots collected on sieves (2-mm opening) and weighed.

Depth of MBr penetration in soil: Two experiments were conducted on 23 February and 20 April 1989 to determine whether MBr penetration in sandy soils is sufficient to kill roots at depths to 4.5 m. In both experiments, pairs of 4-month-old 'Milam' lemon seedlings with intact, bare root systems were folded carefully and tied in bundles 15 cm long. Ropes were used to suspend the pairs of seedlings in holes (8-cm diam) at depths in 0.9-m increments to 4.5 m after which the holes were refilled. Soil was tamped with a cushion on the end of a pole during the refilling process. In the first experiment, MBr was injected with a single chisel 0.45 m deep in a line passing directly above the buried seedlings. Three treatments were replicated twice: nontreated control plots and plots treated with 224 kg/ha and 448 kg/ha MBr (98%) and chloropicrin (2%). In the second experiment, MBr was injected 0.6 m deep. The same treatments and number of replicates were used in the second experiment with the addition of two treatments in which a plastic cover (1.25 mm thick × 3 m wide) was installed immediately over MBr-treated soil at each rate. The experiments were conducted at different locations in Astatula fine sand.

Fourteen days after treatment, holes were dug parallel to the original holes and seedlings at the ends of the ropes were recovered. The stems were pruned to 15 cm long and seedlings were planted in moist potting mixture and placed in a greenhouse where temperatures ranged from 25 to 28 C. At 34 and 56 days posttreatment, the number of seedlings that retained green leaves or that had grown new leaves was determined. Seedlings were considered dead if, 56 days posttreatment, they possessed no green tissue nor new leaf growth.

Root system excavation: Portions of mature citrus root systems were excavated at two Florida ridge locations. The primary purpose of the excavations was to determine the general growth pattern of the deeper portion of the root system. Trees were 'Valencia' orange on rough lemon rootstock and were > 20 years old. Orchard spacing at the two sites was 9.1 m × 9.1 m and 7.6 m × 7.6 m and soil depth to groundwater was > 3.6 m at both locations. On 24 March and 15 June 1989, a backhoe was used to excavate a rectangular quadrant, beneath and beyond tree canopies, 2.4 m deep. In each case, trees were located on the edges of orchards. The holes were dug such that two perpendicular walls exposed the root system 0.5 m from the trunk to the midpoint between trees within the row and 0.5 m from the trunk outward from the orchard to at least 2 m beyond the dripline. After a hole was excavated, large pioneer roots (> 2.5-cm diam near their origin) that were uncovered on the walls of the hole were mapped during further hand excavation. Roots were followed either until they reached the end of the excavated wall or until they progressed so far away from the plane of the wall that hand excavation was impractical. A portion of the root system of one tree was examined on 24 March and of two trees on 15 June. The average canopy radius of the tree in the first orchard was 3.34 m and of the two trees in the second orchard was 2.1 m.

RESULTS

Nematode movement: A paired *t*-test of root weight per tank zone averaged across all sample dates indicated that the seedlings in the nonpruned-noninoculated control treatment grew more root tissue than those in the nonpruned-inoculated treatment ($P < 0.05$). Nevertheless, in the nonpruned-inoculated treatment, roots were detected in all zones of one tank on 8 March and in all zones of all tanks by 19 July (Table 1). The temporal progression of root growth through successive zones preceded detection of nematode movement across the tanks. On 19 July, nematodes were detected beyond the zone of infestation for the first time in the nonpruned-inoculated treatment and by 22 September all zones of both tanks were infested with *R. citrophilus*. When the root systems of inoculated seedlings were pruned, no nematodes were detected more than one zone (40 cm) from the point of inoculation nor were nematodes detected in zones where roots were absent. No nematodes were recovered from soil or roots in the pruned-fallow inoculation treatment.

Mechanical root pruning: Roots had grown at least 0.45 m into buffers in all treatments by 385 days following treatment (Table 2). Roots were visible on the distal trench wall of one-half of the control trees. However, no roots were visible on the distal walls of trenches, 1.05 m from where root systems had been severed. Installation of the cloth barriers resulted in fewer observed roots ($P < 0.05$) along the trench wall than in the nonpruned controls.

The distribution of roots measured in the buffer zone 834 days posttreatment indicates the pruning-polypropylene treatment was effective in reducing root extension (Fig. 1). The major apparent difference between undisturbed root systems and those which were pruned mechanically was a greater lateral extension of the root systems of nondisturbed trees, particularly in the first 1.5-m soil depth. Roots were recovered from soil samples at all distances up to 7.2 m from the trunks of nontreated control trees (Fig. 1A). The farthest distance from the trunks of root-pruned trees at which roots were found was 6.0 m (Fig. 1B). At distances beyond 4.8 m from trunks of root-pruned trees, roots were detected only in samples > 1.5-m soil depth. In the pruning-polypropylene treatment, no roots were detected at any depth when samples were obtained more than 4.2 m from the trunk (Fig. 1C).

Chemical root pruning: No seedlings buried at 4.5 m in control treatments were alive at 56 days following treatment in the first experiment, probably because this depth bordered the groundwater table (Table 3). One-half of the control seedlings placed at 0.9 m also died. All control seedlings at depths from 0.9–3.6 m survived in contrast to 92 and 42% of seedlings treated with 224 and 448 kg/ha, respectively, of MBr. Methyl bromide treatments were not sufficiently effective to kill 100% of seedlings when injected at 0.45 m. However, the compound appeared to have moved to depths of at least 3.6 m, since no plant treated with 448 kg/ha exhibited new shoot growth 34 days posttreatment compared with 88% of the control seedlings.

Methyl bromide injected at 0.6 m affected seedlings to depths of 4.5 m in the second experiment. Seedling survival at the 0.9-m depth was low in the control treatment as it was in the first experiment. However, 88% of control plants below a depth of 0.9 m grew new leaves by 34 days posttreatment compared with 19% of plants treated with 224 kg/ha of MBr and none of the plants treated with 448 kg/ha. By 56 days

Table 1. Growth of citrus roots and migration of *Radopholus citrophilus* through soil in tanks when root systems were either pruned periodically or left undisturbed following inoculation with *R. citrophilus* on 27 October and 9 December, 1987.

Soil zone[v]	8 March 1988			10 May 1988			19 July 1988			22 September 1988		
	No. nematodes		Root weight[y]	No. nematodes		Root weight	No. nematodes		Root weight	No. nematodes		Root weight
	Soil[w]	Root[x]		Soil	Root		Soil	Root		Soil	Root	
						Pruned-inoculated						
1[z]	0	0	0.09	2	0	>0.22	0	47	0.25	0	348	0.44
2	0	0	0.00	0	0	0.11	0	0	0.01	0	1 875	0.01
3	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00
4	0	0	0.00	0	0	0.02	0	0	0.00	0	0	0.01
5	0	0	0.10	0	0	0.39	0	0	0.19	0	0	0.29
						Nonpruned-inoculated						
1	0	19	0.24	0	16	>0.21	0	4 257	0.14	12	3 278	0.32
2	0	0	0.03	0	0	0.01	0	1 774	0.07	2	7 072	0.04
3	0	0	0.01	0	0	0.00	0	2 965	0.10	0	13 454	0.11
4	0	0	0.01	0	0	0.04	0	0	0.13	0	6 338	0.23
5	0	0	0.17	0	0	0.26	0	0	0.31	4	173	0.61
						Nonpruned-noninoculated						
1	0	0	0.10	0	0	0.22	0	0	0.33	0	0	0.53
2	0	0	0.01	0	0	0.07	0	0	0.16	0	0	0.27
3	0	0	0.01	0	0	0.01	0	0	0.15	0	0	0.26
4	0	0	0.01	0	0	0.04	0	0	0.15	0	0	0.28
5	0	0	0.06	0	0	0.19	0	0	0.38	0	0	0.64

Pruned-fallow inoculated												
1	0	0	0.05	0	0	0.29	0	0	0.27	0	0	0.51
2	0	0	0.00	0	0	0.00	0	0	0.01	0	0	0.01
3	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00
4	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00
5	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00

[v] Zones 1–5 represent 0.4, 0.8, 1.2, 1.6, and 2.0 m, respectively.

[w] Number of nematodes in 100 cm^3 of soil.

[x] Number of nematodes in 1 g of oven-dried roots.

[y] Weight (g) of oven-dried roots per sample.

[z] Zone 1 was inoculated in treatments containing *R. citrophilus*.

Table 2. Mean root density visible on the walls of a trench dug parallel to the line of previous buffer treatments. The proximal wall of the trench was 0.45 m from the centerline of the previous trench and the distal wall was 1.05 m from the previous centerline.

	Distance from plane of pruning treatment	
	0.45 m	1.05 m
Control nonpruned	1.13[z]	0.50
Pruned	0.45 a	0.00
Pruned + cloth	0.13 b	0.00

Values in same column followed by different letters differ significantly (*P* = 0.05) from control treatment according to Dunnett's procedure (one tail).

[z] Scores range from 0.0 (no roots visible) to 0.5 (a single root or bundle of fibrous roots) to 2.0 (roots continuously visible) along 3-m section of trench.

posttreatment, 38% of the control seedlings buried below 0.9 m were dead. By that time, only one MBr-treated plant remained alive.

Root excavation: During the first excavation, three large (> 2.5-cm diam) primary roots were exposed on the trench wall which was perpendicular to the tree rows (Fig. 2A). Each of these roots grew progressively deeper with increasing distance from the tree trunk. Beneath the canopy of the tree, no major primary root was observed deeper than 1.2 m. Lateral roots < 0.5-cm diam grew straight downward from primary roots beneath the canopy and supported abundant masses of fibrous roots. All of the large primary roots which were found below 1.2 m in the buffer zone beyond the tree canopy were less than 1.2 m deep in the zone from the trunk to the canopy perimeter. In the second excavation, some primary roots beneath the canopy occurred at greater depths than roots observed in the first survey (Fig. 2A). Two primary roots on each tree were sufficiently long to map. On each tree, one of the roots remained above 1 m until it was beyond the dripline whereas the other root grew to depths up to 1.5 m while still beneath the canopy. The deepest pioneer root found beneath canopies in either orchard at a point midway between the dripline and the trunk was 0.80 m (Fig. 2B).

Roots mapped during the excavations were growing at approximately 90° angles from the direction of the tree rows. Most other roots in the trench zone were cut during the excavation. However, one large root remained uncut during the final excavation and grew at a 30° angle from the in-row wall across a corner of the trench space and into the distal perpendicular wall. The farthest that it proved practical to measure this root was to a point on the trench wall 1.2 m from the trunk. However, the horizontal space actually traversed by the root from the emergent wall to that point (since it was growing at an angle across the trench) was 2.33 m. The root was growing at a downward angle and was 1.5 m deep, 1.2 m from the trunk.

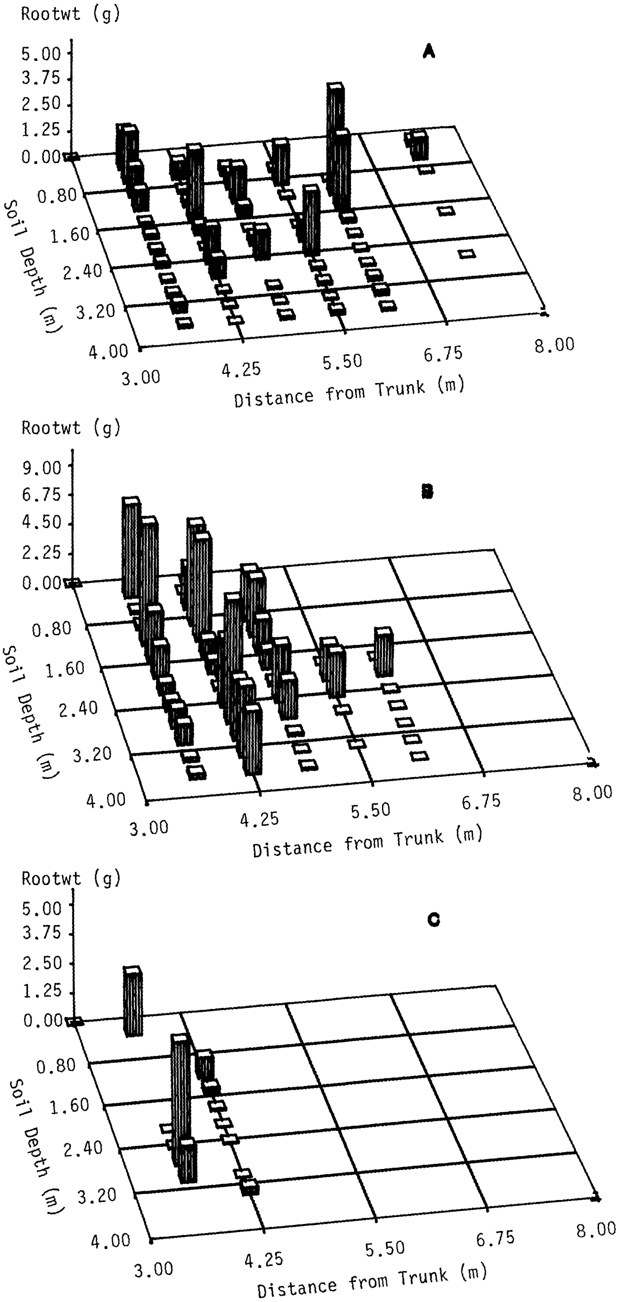

Fig. 1. Feeder root weights (per volume of soil) recovered in a *Radopholus citrophilus* buffer at various soil depths and distances from 'Valencia' orange trees on rough lemon rootstock. Samples were obtained 834 days after treatment from in front of A) nontreated control trees; B) trees whose root systems were pruned near the drip-line with a trenching machine; and C) trees whose roots were pruned and the trench lined with a polypropylene barrier.

Table 3. Percentage of 'Milam' lemon seedlings exhibiting new shoot growth following burial for 14 days at different soil depths and treatment with different doses of methyl bromide-chloropicrin. Following treatment, the soil either was covered immediately with plastic tarpaulins (T) or was not tarped (NT).

	Experiment 1						Experiment 2									
	34 days post-treat			56 days post-treat			34 days post-treat					56 days post-treat				
Depth (m)	0	224[z]	448[z]	0	224	448	0	224 T	224 NT	448 T	448 NT	0	224 T	224 NT	448 T	448 NT
0.9	50	25	0	50	50	0	25	0	0	0	0	0	0	0	0	0
1.8	100	25	0	100	100	50	75	0	0	0	0	25	0	0	0	0
2.7	100	50	0	100	75	75	100	0	0	0	0	50	0	0	0	0
3.6	100	50	0	100	100	50	100	50	0	0	0	100	0	0	0	0
4.5	0	25	0	0	75	25	75	25	0	0	0	75	25	0	0	0

[z] Dose in kg/ha.

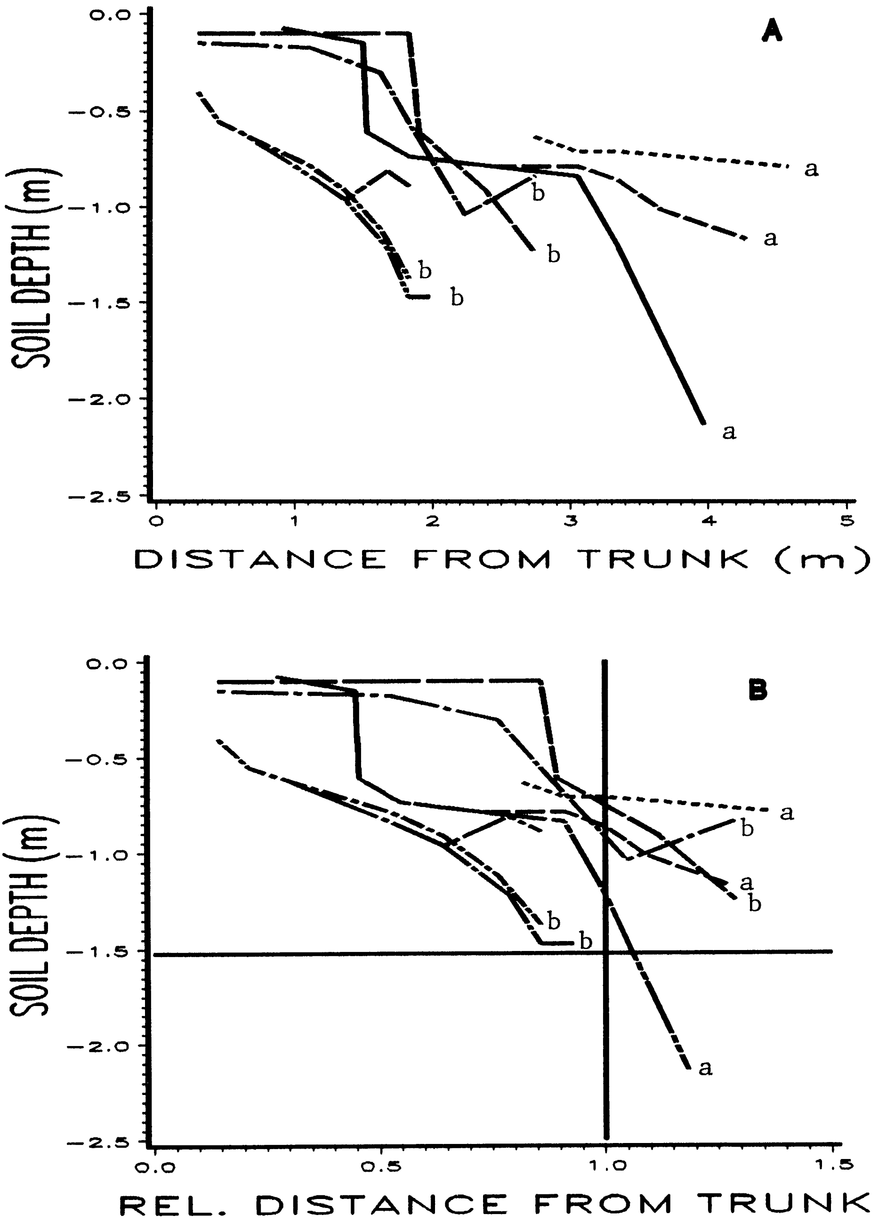

Fig. 2. Growth patterns of rough lemon pioneer roots (> 2.5-cm diam near their origin) into soil on the edge of orchards. A) Actual distances measured in a line 90° from the direction of the tree row outward from the orchard from a tree with a canopy radius of 3.4 m (a) and from two trees with canopy radii of 2.1 m (b). B) Data normalized by dividing distance by canopy radius to illustrate the relative growth patterns of roots beneath and beyond the under canopy area.

DISCUSSION

Despite the ability of *R. citrophilus* to migrate at nearly the same rate as roots growing through bare soil (6,14) and more rapidly when roots are in situ (15,16), the nematode was unable to migrate through root-free soil in the present study. *Radopholus citrophilus* traversed a distance of 1.5 m in 280 days but only following root colonization of bare soil zones (Table 1). Further evidence that the nematode moved behind the growing root front is the fact that while roots in both tanks of the pruned-inoculated treatment colonized all zones of the tanks between May and September, nematodes did not migrate across those tanks by the end of the experiment. We conclude from these results that treatments which prevent root contact across buffers can effectively prevent the spread of *R. citrophilus* without use of nematicides.

Since 1984, root pruning via trenching machines has been the only method available to restrict citrus root growth into buffers. However, the actual requirements to achieve complete root pruning are unknown because the innate distribution of the citrus root system in a deep sandy soil is not well-defined. Ford (7) sampled rough lemon root systems of mature trees growing for "several" years adjacent to bare soil from which a row of trees had been removed. He detected roots 6.7 m and 7.9 m from the trunk and as deep as 2.7 m and 1.5 m, respectively. The root distribution of trees growing adjacent to buffers untreated for 4 years in this study (Fig. 1A) was similar to those measured previously. Roots were recovered in the middle of buffers, 7.3 m from tree trunks and at depths to 2.7 m. Roots recovered at all depths 7.3 m from the trunk were 17% as abundant as roots recovered 3.6 m from the trunk. In the study by Ford, root abundance 7.9 m from the trunk was 13% of that measured 3.6 m from the trunk.

Efficacy of the polypropylene barriers compared to simple root pruning suggests that roots grow downward and outward from the point of pruning relatively quickly (Fig. 1B). By 2.3 years after pruning, when no polypropylene was installed, roots were recovered 6 m from the trunk at depths between 1.8 and 4.5 m. Roots were found at all depths below 0.6 m on these trees at distances up to 4.8 m from the trunk. The trenches did not cut roots below 1.5 m and cloth barriers were installed to a 1.2-m depth. Thus, comparison of the root distributions of all treatments 2 years following root pruning suggests that roots occurring at some depth and distance from the tree trunk are much closer to the soil surface in the region between the trench and the trunk (Fig. 1). Otherwise, it is likely that trees with polypropylene barriers should have exhibited a more extensive deep root system. These data were supported by the root system excavations that revealed a majority of larger pioneer roots reaching depths below 1.2 m only as they approached distances from the trunk in the zone of the canopy dripline (Fig. 2B).

This study suggests that efficacy of root system pruning for barrier maintenance will increase significantly if distance between the trunk and the trench is minimized. Hedging of the canopy on the buffer side of the tree row to permit trenching to occur close to the trunk may be the only method by which mechanical pruning can effectively limit root growth across buffers. For the excavated trees in this study, a 1.5-m deep trench would have severed all pioneer roots if dug beneath the tree canopy but would have cut only about 60% of the large roots if constructed at any point beyond the dripline (Fig. 2B). The probability of cutting all major roots increases inversely with the distance between the trench and the tree trunk. If buffer zones are deemed to be economically worthwhile, the high costs of buffer construction and maintenance suggest that the additional cost of tree hedging to increase the probability of successful nematode containment may be sound economically.

The frequency with which root pruning is necessary to maintain buffer integrity requires additional research on how quickly roots regrow under different conditions. The average rate of regrowth into buffers in the present study was at least 0.75 m but less than 1.35 m per year. Roots were recovered 1.8 m in advance of where root pruning occurred 2.3 years following treatment but not at a distance of 3.0 m in advance (Fig. 1B). It appears that root regrowth was greater in the deeper soil profiles; shallow soil sampling would not have accurately reflected the general pattern of root extension following pruning.

Assuming an annual regrowth rate of cut roots of 1.5 m (somewhat greater than that measured herein) suggests that buffers constructed by removing a single row of trees would not require annual root pruning. Tree rows are typically 7–9 m apart. Removing a row of trees results in buffers of 14–18 m from trunk to trunk. If roots were pruned within 2 m of the trunks on each side of the buffer, the resulting root-free zone would be 10–14 m. Left unpruned, roots from adjacent sides of the buffer would not meet in the middle for more than 3–4 years following pruning. Therefore, in wide buffers, biennial root pruning is likely to provide an adequate safety margin to maintain buffer integrity.

Almost certainly, some practices can be employed to reduce the rate of root ingress into buffers. Rows of trees bordering the buffer should be irrigated or fertilized only on the side interior to the buffer. Research should be conducted on use of deep rooted, non-host plants in the buffers to compete with citrus for soil moisture and nutrients.

Use of barrier materials such as polypropylene cloth in combination with trenching requires further evaluation. Whereas sampling data indicate that the rate of root ingress into barriers was reduced by the polypropylene fabric, citrus roots are able to penetrate this fabric. Therefore, higher density materials will be required to block extension of roots permanently. Machinery exists to place these fabrics along roadways to depths greater than 2.5 m, but the cost of installation is high. If such physical barriers become economically feasible, the breakeven point will occur first on larger orchards because the ratio of the circumference which is treated to the area which is protected will decline. For example, a barrier surrounding and protecting an orchard with square dimensions of 100 m on a side would require 400 m of protective treatment to safeguard 10 000 m^2, a ratio of 0.04. The same ratio for a square orchard 1 000 m on a side is 10 times smaller.

In order to use MBr for buffer maintenance, movement of root-lethal concentrations is required as deep as roots grow at the point of soil injection. Whether depth limitations similar to those for trenching would be encountered with MBr is not clear however, since MBr was detected by gas chromatography in significant concentrations to depths of 3.0 m in disturbed soil profiles (12). With deep placement (0.6–1.5 m) in undisturbed soil, adequate doses to kill citrus roots (> 3.5–cm diam) harboring *Armillaria mellea* (Vahl.) Quel. were obtained at soil depths of 2.4–3.7 m (11). Although empirical data are lacking, deep placement of MBr into dry, sandy soil is likely to result in greater downward movement than would occur in finer textured soils (2,12).

These studies support the propensity of MBr to move downward in deep sands. Although placement efficacy was not tested directly, deeper placement corresponded to greater penetration and seedling mortality. With deep placement, covering of soil was unnecessary to achieve nearly complete mortality of the seedlings to depths up to 4.5 m. The response of large, healthy pioneer roots subjected to these conditions is unknown, however, since even control seedlings were affected adversely by the experimental method. Nevertheless, the results indicate clearly the potential for an undetermined dose of MBr to penetrate adequately soils typical of the central ridge to kill the deeper portions of the citrus root system. This is fortunate since injection could occur near the dripline of the tree without the necessity of hedging and far enough from the trunk to preclude major phototoxicity to the tree.

The present limitation to developing procedures to use MBr in burrowing nematode buffers is a lack of understanding of the potential for groundwater contamination. The depth of penetration in these studies exceeded 4.5 m which is beyond the depth to groundwater in many orchards in central Florida. Thus, the behavior of MBr at the soil-water interface will determine whether the compound can be safely used for buffer maintenance.

The data presented herein suggest the feasibility of maintaining a burrowing nematode buffer program with either mechanical or chemical control methods. The cost of establishing and maintaining buffers has always been high and will increase if mechanical methods are used. Estimates of damage to citrus by the burrowing nematode previously convinced many growers that buffers were economically sound management tools. However, some of the practices more recently adopted in Florida citrus, such as irrigation and changes in cultivation practices, also are recommended to manage *R. citrophilus*-infested orchards. Consequently, it is unknown whether crop losses due to the nematode have been mitigated in recent years. There is clearly a strong need for such information in order to evaluate the current benefit likely to accrue from practices that slow the spread of the pest.

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