Worldwide Dissemination of Radopholus similis and Its Importance in Crop Production[1]

J. H. O'BANNON[2]

Abstract: The burrowing nematode, *Radopholus similis*, attacks agronomic and horticultural crops and many weeds, and is reported to reproduce on more than 250 plant species. Two races of *R. similis* are recognized. Although one race attacks citrus and the other race does not, they are morphologically similar. At present, the citrus race is found attacking citrus only in Florida, U.S.A., but it is known to infect more than 250 species and varieties of noncitrus plants. Although it has many hosts, *R. similis* is probably most widely distributed on banana and is found worldwide. Although best known as a pest of *Piper nigrum, Musa* spp., and *Citrus* spp., it also attacks many crops that are important in world commerce and in subsistence-type agriculture, a factor which makes it a significant agricultural pest. Worldwide dissemination occurs primarily when parasitized plants are moved into areas where the pest could adapt. Yield losses of 12.5 tons/ha in bananas have been reported from *R. similis* infection. Infections suppress orange and grapefruit yields as much as 70-80%. Because of the severity of *R. similis* damage (particularly to banana and citrus), extensive control programs have been developed. Prevention, cultural practices, resistant varieties, and chemical pesticides interact to reduce losses. *Key Words:* citrus, control, banana.

A disease capable of destroying an agricultural industry deserves careful attention in the agricultural, scientific, and sociological communities. The burrowing nematode, *Radopholus similis* (Cobb) Thorne, is associated with pepper yellows. This disease destroyed much of the pepper industry upon which the economy of the Island of Banka in Indonesia was based. A similar situation threatened Central America in the late '60s and early '70s when the Fusarium wilt-susceptible Gros Michel banana was replaced with the wilt-resistant Cavendish varieties which were more susceptible to *R. similis* (28). Production declined with consequent profit losses in areas favorable for the nematode. Fortunately, in this case, managers became aware of the impending crisis and heeded the warnings of nematologists who recognized this potential disaster. It is now important to recognize that the citrus industry, in areas that are favorable for this nematode, could also be threatened.

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[2]Research Nematologist, United States Department of Agriculture, Agricultural Research Service, USDA Horticultural Research Laboratory, Orlando, Florida 32803. I would like to express my thanks to the many persons contacted concerning *Radopholus similis* in their countries and the many others who provided me with useful data on *R. similis*, especially that portion relating to bananas. They were: W. H. Bear, R. A. Dunn, J. E. Edmunds, R. P. Esser, J. P. Flavin, S. R. Gowan, Y. P. Hung, S. R. Johnson, G. C. Martin, R. W. Metz, R. W. McLeod, D. L. Milne, L. G. L. Reis, J. Román, S. E. Simpson, C. Sosa-Moss, P. L. Taylor, A. Vilardebo, E. J. Wehunt, and A. Wybou.

The nematode was first described by Cobb from diseased banana plants from Fiji in 1893 (5). Spreading decline of citrus was recognized in Florida in the late 1920s, but *R. similis* was not determined to be the cause until 1953 (21). Banana and plantain diseases caused by *R. similis* are known by various names, such as black head (cabeza negra) and toppling disease (caida de la planta). The nematode has been known by various names, including *Tylenchus similis* Cobb, *T. actocaudatus* Zimmerman, *T. biformis* Cobb, *Anguillulina similis* Goodey, and *Rotylenchus similis* (Filipjev) Filipj., and Schuurm.-Stekh. Although best known as a pathogen of *Piper nigrum, Musa* spp., and *Citrus* spp., *R. similis* also attacks many crop plants that are important in world commerce and in subsistence-type agriculture, a factor that makes it one of the most significant nematode species of agriculture.

Most information about the effects of the burrowing nematode on its host has been obtained from investigations on economic crops (such as coffee, pepper, sugarcane, tea, and especially banana and citrus). The effects of the burrowing nematode on two dissimilar hosts, monocotyledon (banana) and a dicotyledon (citrus), provide us with useful information on nematode variability.

Banana (*Musa* spp.) plants are herbaceous perennials with branched underground stems which bear many roots, several lateral buds, and erect, leafy pseudo-stems. The adventitious root system consists primarily of secondary or cord roots that may extend laterally in the soil for 5-8 m from the corm (rhizome) and about 2 m deep.

Citrus is a multifarious evergreen and has a taproot and many branch roots. Roots of a commonly grown Florida rootstock, rough lemon [*Citrus limon* (L.) Burm. f.], have been traced laterally as far as 21.3 m and to a depth of 4 m.

HOST PATHOLOGY AND SYMPTOMS

Nematodes may enter banana roots through the epidermis anywhere along the root and cause reddish brown cortical lesions, a diagnostic characteristic of this disease. According to Blake (4), nematodes occupy an intercellular position within the cortex 1-4 cells beneath the epidermis and feed on the cytoplasm of nearby cells. When most of the cytoplasm has been ingested, the nucleus disintegrates and the cell wall ruptures. Lesions and cavities formed in the cortex extend to the endodermis, which acts as a barrier to stelar invasion.

Migration of nematodes in the cortex and colonization of the lesions by other parasites and saprophytes enlarge the lesion. The surface of the invaded tissue is black, with the advancing margin being typically reddish brown. Invaded cortical root tissue atrophies, and the stele is invaded by secondary organisms which weaken it and cause it to break easily. The root system is sometimes reduced to a few short root stubs at the base of the corm. Nematode entry into the corm is through roots and leaf scars or around emerging buds, or it may occur directly from the soil and result in diffuse black lesions (13).

Nematodes enter citrus root tips from the root cap to the region where epidermal cells have started to suberize. If the apical meristem is destroyed, terminal growth ceases. If terminal growth continues, the lesion eventually will be located several centimeters from the root tip; the root would then appear to have been invaded at a site other than at the root tip (6).

An infected tree has approximately one-half as many functional feeder roots as a healthy tree, and the remaining roots are in the upper 75 cm of the soil. At depths between 25 and 75 cm, 25-30% of the feeder roots are destroyed; at depths below 75 cm, 90% of the feeder roots are destroyed (10).

DISTRIBUTION

The genus *Radopholus* occurs in most tropical and semitropical areas of the world. According to Sher (20), *Radopholus* may be indigenous to Australia and New Zealand. Although it has many hosts, *R. similis* is probably most widely distributed on banana, and is found worldwide on banana except in Israel (16) and Taiwan [Y. P. Hung, Personal Communication] (Table 1). Some of the reported geographical localities are too cold to support field infestations of burrowing nematode and are represented by greenhouse infestations.

The most important means by which *R. similis* is introduced into new geographical areas is on infected plants. Man has efficiently distributed this nematode throughout the world by moving parasitized plants into areas to which the nematode could adapt. The burrowing nematode has adapted well and has been reported to reproduce on more than 250 plant species. Development of physiological races expands the host range and is another means of adaptation and dissemination. Once such natural obstacles as oceans and land masses

TABLE 1. Geographic localities where *Radopholus similis* has been detected.

Australia	Granada	Peru
Brazil	Guadeloupe	Philippines
British Honduras	Guatemala	Puerto Rico
Cameroon	Guinea	Quebec, Canada[a]
Ceylon	Honduras	Republic of
Columbia	India	South Africa
Congo	Indonesia	Rhodesia
Costa Rica	Ivory Coast	Somali Republic
Cuba	Jamaica	St. Lucia
Dominica	Japan[a]	St. Vincent
Ecuador	Kenya	Surinam
Egypt	Madagascar	Thailand
El Salvador	Martinique	Trinidad-Tobago
England[a]	Mexico	United States
Ethiopia	Mozambique	Arizona[a]
Fiji	Netherlands[a]	California[a]
Formosa	New Zealand	Florida
France[a]	Nicaragua	Louisiana[a]
Gabon	Nigeria	Texas[a]
Germany[a]	Pakistan	
Ghana	Panama	

[a]Greenhouse detection: area probably too cold or otherwise not suitable for field infestations, or intercepted before getting to the field.

are overcome, the nematode can be disseminated locally through plants, soil, water, or other organisms. Suit and DuCharme (21) reported that *R. similis* has spread at a rate of 6-60 m/year in citrus groves, but averages 15 m/year. Studies conducted in Honduras on rate of spread of *R. similis* on 'Valery' banana indicated movement of approximately 2.5 m in 1 year (27).

Intercontinental movement of infested plant material will continue to provide a real hazard to world agriculture. Continual vigilance is necessary to prevent the introduction of these parasites, both on a local and an international level. Introduction of just one gravid *R. similis* female may result in the establishment of a new infestation. *Radopholus similis* has been transported around the world and introduced into new areas in infected planting stock, an occurrence verified recently in Mozambique (L. G. L. Reis, Personal Communication) with banana corms and with intercepted infected, ornamental plants shipped from the tropics to the U.S.A. (22). Regulatory measures minimize indiscriminate introduction; however, the rapidity and ease of movement of large quantities of plant material favor the chance introduction of nematodes and other pests. It is therefore imperative to adopt and enforce an effective inspection program.

SIGNIFICANCE TO AGRICULTURE ECONOMICS OF DEVELOPED AND DEVELOPING NATIONS

Because of its wide host range and geographical distribution, *R. similis* poses a threat in tropical and subtropical countries where national economies are dependent on export of agricultural products. The severity of crop losses is dependent on host susceptibility and environmental conditions. Losses vary with the different conditions under which the host is grown and, therefore, must be evaluated on a local basis. Estimates of potential losses may be obtained by measuring yield increases after nematode control or by comparing yields between infected and noninfected hosts. Because most of the information regarding this nematode species comes from research on bananas and citrus, and because data on economic damage caused by *R. similis* on other crops are limited, only the economics of citrus and banana production will be discussed herein.

The banana is one of the most important exportable commodities of tropical areas, and it is of great economic potential in the subtropical zones. In 1973, 6,395,100 metric tons of bananas were exported (Table 2), with world demand expected to increase to more than 7,000,000 in 1974.

The demand for citrus is increasing annually. Florida produces 75.3% of the citrus in the U.S.A. Exports of fresh fruit continue to increase at a rapid rate. In 1972, 6,165,300 metric tons of citrus were exported worldwide (Table 2).

Radopholus similis probably causes greater worldwide losses in banana yields than any other banana pathogen, with the exception of Sigatoka disease. Depending on plant density and bunch weight, yield/ha will range from 40-80 tons for the Cavendish varieties and 10-40 tons for Gros Michel. Yield losses of 12.5 tons/ha have been reported as the result of *Radopholus* infection alone. Other reports indicate that fruit yields on infected plants may be suppressed by as much as 50% within 3-4 years after planting, and the number of uprooted or blown-down plants may be increased by 60% (1).

TABLE 2. Banana and citrus world production and export.

Producing area	Percent exported	
Banana-producing areas and percent exported 1973		
Central America	50.8	
South America	28.2	
Far East	7.9	
Africa	6.6	
Canary Island and Madeira	5.8	
Mediterranean Area	0.2	
Oceania	0.5	
Export production (metric tons)		6,395,100
Citrus-producing areas and percent exported 1972		
North America	13.0	
South America	1.7	
Far East	0.4	
Australia	—	
Africa	22.3	
Mediterranean area	62.6	
Export production (metric tons)		6,165,300

In a comparison of two 4-ha citrus groves, one planted with healthy seedlings and one with burrowing nematode-infected seedlings, the healthy grove was producing 1,322 boxes of citrus/ha ($2,644.00/ha) and the infested grove 62 boxes ($123.00/ha) at the end of 9 years.

A healthy grapefruit tree can produce 14-17 boxes/tree; a similarly aged, infected tree, produces only 4-6 boxes. Infestations of grapefruit suppress yields by 50-80% and orange yields by 40-70%. At an average fruit value of $2.00/box, a healthy tree would have a yield value of $28.00-$34.00. On the basis of an average of 173 trees/ha, 1 ha of healthy trees would have a yield return of $4,843-$5,880, whereas returns from 1 ha of infected trees would range from only $1,383-$2,075. Examples of *R. similis* infections of bananas and citrus (by country) are presented in Table 3 to illustrate the dangers of this pest in world food production.

PHYSIOLOGICAL RACES AND HOST RANGE

Two races of *R. similis* are recognized on the basis of host specificity. One race attacks banana only, and the other race attacks both citrus and banana (3, 7, 23). The existence of a possible third race that attacks citrus only was reported but has not been studied (7). *Radopholus similis* on banana is morphologically similar to that on citrus (24). At present, the race of *R. similis* pathogenic to citrus occurs only in Florida.

The host list of burrowing nematode includes plants belonging to widely separated genera. More than 1,200 clones of *Citrus* spp. were tested with the citrus race of *R. similis* and all were found susceptible. More than 250 species and varieties of noncitrus plants, cultivated and wild, are hosts of the citrus race of *R. similis*. Unlike the citrus race, the banana race seems to

TABLE 3. Selected production areas and prevalence of *Radopholus similis*.

Production area	Hectares (in 1,000s)	Percentage of area infested with *R. similis*	Source (Personal communications)
Musa spp.			
Australia	12.4	100	McLeod, R. W.
Dominica	4.0	100	Edmunds, J. E., Gowan, S. R.
Granada	2.0	100	Edmunds, J. E., Gowan, S. R.
St. Lucia	4.9	100	Edmunds, J. E., Gowan, S. R.
St. Vincent	2.0	100	Edmunds, J. E., Gowan, S. R.
Brazil	100.0	—	Johnson, S. R., Taylor, P. L.
Columbia	27.0	90	Johnson, S. R., Taylor, P. L.
Costa Rica	25.5	90	Johnson, S. R., Taylor, P. L.
Guatamala	4.9	100	Johnson, S. R., Taylor, P. L.
Honduras	16.2	100	Johnson, S. R., Taylor, P. L.
Nicaragua	2.0	90	Johnson, S. R., Taylor, P. L.
Panama	11.6	100	Johnson, S. R., Taylor, P. L.
Ecuador	85.0	80	Villacis, J.
Cameroon	2.5	100	Vilardebo, A.
Ivory Coast	7.0	100	Vilardebo, A.
Madagascar	1.5	100	Vilardebo, A.
Guadeloupe	7.5	100	Vilardebo, A.
Martinique	9.0	100	Vilardebo, A.
Mozambique	4.0	7	Reis, L. G. L.
Jamaica	32.4	100	Hutton, D.
Puerto Rico	39.5[a]	90	Román, J.
Republic of South Africa	9.0	11	Milne, D. L.
Rhodesia	0.2	31	Martin, G. C.
Philippines	27.0	90	Dolar, S. G.
Citrus			
Florida	365.0	1	

[a]Plantain.

have a more restricted host range. Host-range studies (9), however, indicate that more than one banana race may occur in Central America. Since the citrus race is so destructive to citrus in Florida and has such an extensive host range, investigations should be conducted in other geographical areas where *R. similis* is present to determine experimentally if this race could survive on citrus. An important environmental factor apparently is necessary for development of the disease on citrus. Spreading decline occurs most often in the central ridge area of Florida. The nematode can be found on citrus in other soil types, but symptoms will vary from slight to severe. Host response can be used to identify possible races (Table 4), but some hosts are susceptible to both races (Table 5).

The existence of physiological races should be considered when clonal material is selected for *R. similis* resistance. Physiological races could account for differences in host range and variation encountered when ecological and other biological studies are made.

CONTROL

Prevention and Cultural Control: Preventive measures are the most effective and economic means of control. Clean "seeds" are utilized universally to prevent the introduction of burrowing nematodes with banana-planting material. Since bananas produce few true seeds and are normally propagated vegetatively from lateral buds or corms, a pathogen infecting the mother plant is thus transferred to the daughter seedpiece.

Seedpieces (corms) should be selected for size and uniformity and trimmed (pared) to remove all roots and discolored tissue (14, 26). The pared corms should then be dipped into a slurry made by mixing 20 kg hydrated lime, 20 kg copper sulphate, 1,288 ml 70% DBCP (1,2-dibromo-3-chloropropane), and 455 liters water. After being dried, seed-pieces are ready to plant.

Heat therapy has also been generally adopted for treating seed-pieces. Trimmed or pared corms are immersed in hot water (53-55 C) for 20-25 min. Seedpieces prepared in this way can be planted in the field or in quarantine areas for further selection and certification as disease-free material.

Site certification has proven to be the most effective method for production of *R. similis*-free citrus nursery stock. Certain minimal requirements must be met for certification: planting sites must be 122 m from any known burrowing nematode infestation, or a 15-m chemically treated buffer must be maintained between infested area and clean area. Infected nursery stock or nursery stock growing within 45 m of infested environs can only be certified if treated in hot water for 10 min at 50 C.

In Florida, the ornamental and foliage industries are valued at nearly 128 million dollars. Nematodes are estimated to be responsible for about a 5% loss in these crops. Losses would be higher, but stringent control measures, accompanied by sanitation practices, have minimized nematode problems. Accordingly, the ornamental and foliage plant industries in Florida have instituted strict quarantine measures to prevent the dissemination of *R. similis* through plant movement. If *R. similis* is intercepted, the shipment is refused.

Sanitation programs in nurseries have been most successful in limiting the hazards of *R. similis* infestations in ornamental plants. A strict program is recommended by the Florida Division of Plant Industry nematologists and supervised by plant specialists to aid growers in obtaining pest-free nursery stock.

In Australia (R. W. McLeod, Personal Communication), planting is recommended only in land which has not grown bananas, sugarcane, or cow cane for at least 3 years. In Natal (11), neither weed control nor the destruction or removal of infested banana plants eliminated *R. similis* during a 13-month test period. In Central America, it was recently found that clean fallow for at least 14 months did not eliminate *R. similis.*

Crop rotation with grasses, such as pangola, was effective in Puerto Rico (J. Román, Personal Communication). *Crotalaria spectabilis* and *C. striata* have been suggested as cover crops. Sugarcane grown for 5 months has been reported to eliminate *R. similis* in Jamaica (12). Most agronomic and edible horticultural crops that are susceptible to *R. similis* are shown in Table 5.

TABLE 4. Host adaptation and possible races of *Radopholus similis* based on host response.

Race	Plant	Host status[a]	Location[b]
Host-Nonhost Banana Race			
	Beta vulgaris L.	H	Honduras
	Beta vulgaris L.	NH	Natal
	Crotalaria juncea L.	H	Natal
	Crotalaria juncea L.	NH	Honduras, Panama
	Cucumis sativus L.	H	Natal
	Cucumis sativus L.	NH	Honduras
	Cucurbita pepo L.	H	Natal
	Cucurbita pepo L.	NH	Honduras
	Cyperus rotundus L.	H	Hawaii
	Cyperus rotundus L.	NH	Honduras, Panama
	Gossypium hirsutum L.	H	Rhodesia, Puerto Rico
	Gossypium hirsutum L.	NH	Honduras, Panama
	Ipomoea batatas (L.) Lam.	H	Hawaii
	Ipomoea batatas (L.) Lam.	NH	Honduras
	Saccharum officinarum L.	H	Australia, Natal, Rhodesia
	Saccharum officinarum L.	NH	Honduras, Puerto Rico, Jamaica
	Tephrosia vogelii Hook. f.	H	Panama
	Tephrosia vogelii Hook. f.	NH	Honduras
	Vigna unguiculata (L.) Walp.	H	Honduras
	Vigna unguiculata (L.) Walp.	NH	Panama
	Zea mays L.	H	Honduras, Rhodesia, Natal
	Zea mays L.	NH	Panama
Host-Nonhost Citrus and Banana Race			
Citrus	*Ananas comosus* Merr.	H	Florida
Banana	*Ananas comosus* Merr.	NH	Natal
Citrus	*Musa paradisiaca* var. *sapientum*	H	Florida
Citrus	*Citrus* spp.	H	Florida
Banana	*Citrus* spp.	NH	Australia, Natal, Rhodesia, Panama, Honduras, Florida, Puerto Rico, Fiji
Citrus	*Hibuscus esculentus* L.	H	Florida
Banana	*Hibuscus esculentus* L.	NH	Hondurus
Citrus	*Indigofera hirsuta* L.	H	Florida
Banana	*Indigofera hirsuta* L.	NH	Honduras, Panama
Citrus	*Ipomoea batatas* Lam.	H	Florida
Banana	*Ipomoea batatas* Lam.	NH	Natal
Citrus	*Litchi chinensis* Sonn.	H	Florida
Banana	*Litchi chinensis* Sonn.	NH	Natal
Banana	*Mangifera indica* L.	H	Natal
Citrus	*Mangifera indica* L.	NH	Florida
Citrus	*Momordica charantia* L.	H	Florida
Banana	*Momordica charantia* L.	NH	Panama
Citrus	*Pinus elliottii* Englm.	H	Florida
Banana	*Pinus elliottii* Englm.	NH	Natal
Citrus	*Pinus toeda* L.	H	Florida
Banana	*Pinus toeda* L.	NH	Natal
Citrus	*Poncirus trifoliata* Raf.	H	Florida
Banana	*Poncirus trifoliata* Raf.	NH	Natal, Fiji
Citrus	*Raphanus sativus* L.	H	Florida
Banana	*Raphanus sativus* L.	NH	Natal

[a]H = Host, NH = Nonhost.
[b]Several of the plants shown are known to be susceptible to *R. similis* in countries other than reported here, but it is not known if the *R. similis* reported is the banana race.

TABLE 5. Horticultural and agronomic crops on which *Radopholus similis* was able to reproduce.

Scientific name	Common name
Allium porrum L.	Leek
Ananas comosus Merr.	Pineapple
Arachis hypogaea L.	Peanut[a]
Beta vulgaris L.	Beet[a]
Brassica napobrassica Mill.	Rutabaga
Brassica oleracea L.	Broccoli
Brassica oleracea L.	Cabbage
Brassica oleracea L.	Cauliflower
Camellia sinensis (L.) Kuntze	Tea
Capsicum annum L.	Pepper[a]
Capsicum annum L.	Sweet pepper
Citrullus vulgaris Schrad.	Watermelon[a]
Citrus spp.	1,200 susceptible varieties
Coffea arabica L.	Coffee
Coffea robusta L.	Coffee
Carya illinoensis Koch.	Pecan
Cucumis melo L.	Cantaloupe[a]
Cucurbita pepo L.	Pumpkin[a]
Cucurbita pepo L.	Squash
Daucus carota L.	Carrot
Dioscorea alata L.	Yam
Diospyros virginiana L.	Persimmon
Eragrostis tef (Zucc.) Trotter	Teff
Ficus racemosa L.	Fig
Fragaria chiloensis DuC.	Strawberry
Glycine max Merr.	Soybean[a]
Hibiscus esculentus L.	Okra
Ipomoea batatas Lam.	Sweet potato
Lactuca sativa L.	Lettuce
Litchi chinensis Sonn.	Lychee
Lycopersicon esculentum Mill.	Tomato[a]
Medicago sativa L.	Alfalfa[a]
Musa paradisiaca L.	Plantain
Musa paradisiaca var. *sapientum* Kuntz	Banana[a]
Musa spp.	Banana
Persea americana Mill.	Avocado[a]
Petroselinum crispum L.	Parsley
Phaseolus vulgaris L.	Red bean[a]
Piper nigrum L.	Pepper[a]
Prunus persica Batsch	Peach
Psidium guahava L.	Guava
Raphanus sativus L.	Radish
Sacchanum officinanum L.	Sugarcane[a]
Solanum tuberosum L.	Potato
Theobroma cacao L.	Cacao
Triticum aestivum L.	Wheat
Vigna basei (Craib.) Backer	Cowpea
Vigna sinensis Savi	Pea
Zea mays L.	Corn[a]
Zingiber officinale L.	Ginger

[a]Crop plants known to be susceptible to the banana and citrus races of *R. similis*.

Some citrus growers have been able to live with spreading decline by the judicious use of irrigation. Spreading decline symptoms are found principally in well-drained sands with a 5-7% moisture-holding capacity and a permanent wilting point of approximately 2.5%. In Florida, minimal rainfall from February to May puts additional stress on trees already weakened by *R. similis*. The optimum feeding site for *R. similis* is below 75 cm, but roots in the top 30-45 cm of soil are still functional. If roots in this upper zone are kept moist with adequate irrigation, tree stress is lessened, fruit drop is minimized, and trees remain economically productive.

Resistant Varieties: Clonal material from plants that seem to be resistant to *R. similis* should be tested under field conditions with nematode collections representing different biotypes. A clone might be resistant to one *R. similis* race and susceptible to another. Variability of virulence among nematode biotypes must also be considered when breeding is done for resistance.

Little is known of the genetic basis of resistance to *R. similis* in bananas, but several varieties of the Bluggoe type (ABB) are quite resistant. Subspecies of *M. acuminata* differ in susceptibility, and Gros Michel (AAA) cultivar is more resistant than Cavendish (AAA) cultivars. Because of susceptibility to Panama disease, Gros Michel has been replaced with the more nematode-susceptible Cavendish cultivars in the Caribbean area and Central America. Attempts are being made to incorporate the *R. similis* resistance of the Gros Michel banana into new hybrids (19).

Virtually no immunity to *R. similis* has been found in citrus. In the search for citrus, citrus relatives, and hybrid rootstocks resistant to *R. similis*, only 15 were found worthy of field testing. Three of these rootstocks were formally released to the citrus industry in 1964: 'Estes' rough lemon, 'Ridge Pineapple' sweet orange, and 'Milam' lemon. Estes rough lemon subsequently was found to be sufficiently damaged by *R. similis* to be considered susceptible. 'Carrizo' citrange and 'Algerian' navel sweet orange are also resistant to *R. similis*. The use of *R. similis*-resistant rootstocks, Milam lemon, or Ridge Pineapple for biological barriers against the spread of *R. similis* has been advocated (17).

Chemical Control: Although considerable efforts have been expended (particularly with bananas and citrus), chemical control of *R. similis* has been difficult to achieve. Of the methods developed and the many chemicals used, few have been widely accepted. Most control efforts have been directed toward reducing nematode numbers and toward creating conditions for a favorable plant response. This approach is necessary, because control for more than one season is the goal. With bananas and citrus, continuous production must be maintained for several years for maximum economic returns. Eradication of *R. similis* from citrus has been the goal. Chemical control of *R. similis* in other crops has been difficult because of the diversity of the environmental and cultural conditions and the broad spectrum of host plant types cultivated throughout the world.

Nematicides, both as pre- and postplant treatments in infested areas, still offer the best short-term method of coping with the nematode, particularly with bananas (8, 25). Many nematicides have been evaluated under varied environmental conditions because of the wide geographical range of the host plants.

The 1,3-dichloropropene-1,2-dichloropropane (D-D) mixtures and ethylene dibromide (EDB), applied at rates of 300 liters/ha or 150 kg/ha at planting (15), resulted in increased production of banana for 1 year with further nematicidal treatment needed the following year. Tests with 1,2-dibromo-3-chloropropane (DBCP) showed that applications of 40 liters (a.i.)/ha at planting time followed by 25 liters (a.i.)/ha 3 or 4 months later and by 15 liters (a.i.)/ha annually thereafter gave satisfactory results in the Ivory Coast (15).

In Florida, control of *R. similis* infestation in citrus has been the "push and treat" method. Infected trees are bulldozed out of the soil and burned, D-D is applied at a rate of 672 kg/ha, and the ground is left fallow for 2 years following treatment. Herbicides are used to maintain an area free of weeds.

With the development of carbamate and organophosphate nematicides (such as carbofuran, phenamiphos, ethoprop, fensulfothion, oxamyl, and misal), new emphasis has been placed on nematode control in both banana and citrus. These materials have been or are being tested in citrus spreading decline areas in Florida [at experimental rates of 8-11 kg (a.i.)/ha] as postplant applications of granular materials broadcast on the soil or as foliar sprays.

Economics of Control: The major goal of the nematode control program is prevention, which is more effective and economical than a curative approach. Since prevention is not always possible, more costly control programs are often initiated. To assess the economic feasibility of a chemical control measure, the effect of the control on the cost of production must be determined. Cost of chemical-control measures will vary widely because of the different economic conditions under which crops are grown.

When *R. similis* is controlled on banana, high plant density is maintained, bunch weight is increased, the number of production cycles is increased, frequency of replanting is reduced, and yield increases are often 30-60%.

A cost-benefit analysis of nematode control was obtained from tests in Puerto Rico (18). Use of nematode-control measures on *R. similis* infected plantain resulted in a net increase in profits of 1,600%, a net gain of $1,692/ha. In studies using DBCP for nematode control of bananas in Central America, costs of chemical and application range from $60.00-$120.00/ha, with application costs alone ranging from $20.00-$27.00/ha.

In bananas, nematode control from planting time onward is recommended to insure high yields. Economic production can only be achieved where control is maintained. Financing is available only to those willing to invest in rehabilitative practices.

Radopholus similis "control" in Florida citrus is an infinitely more complex problem. Once the nematode becomes established in a grove, the present recommended way to control the disease is by the push and treat method. Removing a diseased tree results in total loss of income from fruit that would have been produced by the infected trees and the cost of buying and establishing new trees. Reliable estimates (2) place the average cost of growing a single tree to 4 years of age at approximately $33.00, and the average loss of return from fruit not produced during the 4 years at $80.00 or a total loss in income of

$113.00/tree. On the basis of an average of 173 trees/hectare, the grower incurs a $19,549 loss/ha.

In Florida, from 1954 to 1974, the high costs of the burrowing nematode-control programs consisting of certification, push and treat, and buffers represented more than the total loss of fruit production. But, if these drastic actions had not been taken, it is estimated that instead of the less than 2,000 ha infested in 1975, more than 21,500 ha would have become infested.

REGULATION AND RESEARCH

Because of the economic importance of the effect of *R. similis* on citrus in Florida and the dangers of exporting the pest to other areas, inter- and intrastate and international quarantines have been established for all plant material being imported or exported from Florida. These quarantine measures result in economic loss to the ornamental plant industry of Florida and demonstrate how far reaching a nematode problem can be.

The limited occurrence of *R. similis* on citrus in Florida, compared to the world-wide distribution on banana, has made it possible to devise uniform regulatory measures applicable to a specific area. When *R. similis* was found to cause spreading decline of citrus in Florida in 1953, regulatory programs were initiated to prevent the nematodes from becoming established in new areas and to eliminate or slow down its natural spread.

Federal and state regulatory agencies worked together to combat the disease. Surveys initiated in 1954 indicated that more than 6,070 hectares of citrus had become infested with *R. similis* over a period of years.

Costs of regulation in Florida were generally on a matching basis. In 20 years, the total cost of regulatory procedures was approximately $20,000,000, a yearly average of $1,000,000. During this same period, federal and state research agencies expended some $8,300,000, or an average of $415,000 a year, with a total cost of $28,300,000.

In 1955, there were an estimated 2,430 hectares of citrus infested with *R. similis* with an average yield loss of $3,632/hectare, or yield losses of $8,825,760 annually. Regulatory cost for that year was 11% of the yield loss. If the disease had been allowed to progress unchecked by regulatory action, it was projected that more than 18,130 hectares would be infested by 1965 (R. P. Esser, Personal Communication). Yield losses in 1965 would have then amounted to nearly $66,000,000 annually. Projected estimates of the total loss of income from spreading decline were $196,738,444.

In January 1973, 2,205 infested hectares remained, a reduction from the original infestation of 63.7% and 87.7% of the projected infestation if the nematode were not controlled. The steady reduction of infested properties has resulted from the many regulating programs designed to prevent movement of this pest from infested areas and to insure that newly established plant nurseries and citrus properties are free of the pest. The principles evolved from the Florida nursery site approval program have provided a model for regulatory systems. The cost of regulatory programs in this case seems well within the bounds of the section of "Necessity" in the Quarantine Definition stated by the National Plant Board July 25, 1931, "The economic gains expected must outweigh the cost of administration and the interference with normal activities."

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