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Management of the Citrus Nematode, *Tylenchulus semipenetrans*

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Abstract: Of the many nematode species that parasitize citrus, *Tylenchulus semipenetrans* is the most important on a worldwide basis. Management of the citrus nematode remains problematic as no one tactic gives adequate control of the nematode. An overall management strategy must include such components as site selection, use of non-infected nursery stock, use of at lease one post-plant nematode control tactic, and careful management of other elements of the environment that may stress the trees. Nematicides continue to play a key role in management of this pest. Optimum results require careful attention to application techniques.

Key words: biological control, citrus, citrus nematode, *Citrus paradise,* nematicides, nematode management, host resistance, *Poncirus trifoliate,* soil solarization, Swingle citrumelo, *Tylenchulus semipenetrans*

Citrus is grown on grafted trees worldwide in Mediterranean and subtropical climates. Numerous species of plant-parasitic nematodes have been associated with the citrus rhizosphere but few reproduce on citrus and cause damage to the trees. *Tylenchulus semipenetrans, Radopholus similis, Pratylenchus coffee,* and *Meloidogyne* spp. are considered major nematode pests because they cause significant economic losses in multiple regions of the world. *Belonolaimus longicaudatus* causes serious damage to citrus, but only in Florida. Other nematodes are considered minor pests because they rarely cause significant economic losses or are restricted to relatively small geographic areas. These include *Hemicycliophora arenaria* and *H. nudata, Paratrichodorus lobatus* and *P. minor, Pratylenchus brachyurus* and *P. vulnus,* and *Xiphinema brevicolle* and *X. index* (Duncan, 1999). Because *T. semipenetrans* is the dominant pathogenic species in most citrus regions and among diverse soil textures, information on control measures is most extensive for this nematode. For management of other nematodes attacking citrus, see Duncan and Cohn (1990) and Duncan (1999).

Economic Importance, Symptoms, and Damage

Most studies estimate yield losses due to *T. semipenetrans* to be in the range of 10% to 30% depending on the level of infection. Mature trees can tolerate large numbers of these nematodes before exhibiting lack of vigor or decline symptoms; however, young trees grow poorly if replanted into nematode-infested soils (Duncan and Cohn, 1990). Symptom development depends on overall orchard conditions. As with other root diseases and nutrient deficiencies, aboveground symptoms include stunting, slow growth, yellowing, reduced foliage, reduced fruit size, and yield. Such symptoms are not readily distinguishable from other production problems without sampling and extraction of nematodes from root and soil samples. Nematode damage to the root system impairs the ability of the tree to absorb water and nutrients necessary for normal growth. Damage is greatest when other root-limiting factors such as fungal infections, water stress, or poor growth during early development also impact nematode-infected trees. As for belowground symptoms, feeder roots heavily infected by the citrus nematode are slightly thicker than healthy ones and have a dirty appearance because of the adhesion of soil particles to the gelatinous matrix deposited by the female nematode on the root surface. Because symptoms may not be apparent on lightly infected roots, infected nursery stocks may easily go undetected (Duncan and Cohn, 1990).

Damage thresholds—nematode population densities that suppress tree growth and yield—are influenced by several factors including aggressiveness of the nematode population, soil characteristics, susceptibility of the rootstock, presence of other pathogens, and grove management practices (Duncan and Cohn, 1990). Therefore, establishing damage thresholds is not a simple task, and it is mainly based on experience gained in a given region. For example, nematicide treatments are recommended in California if more than 400 nematode females/g root are found in samples collected in February to April or 700 females/g root in May and June (Westerdahl, 2000). In South Africa such treatments are recommended when 100 females/g root are found (Le Roux et al., 2000). Control measures in Cyprus are recommended when nematode densities reach 5,000 juveniles/250 cm^3 soil (Philis, 1989), whereas 4,000 juveniles/g root are the critical level for decline symptoms in Israel (Cohn, 1969). All of these values should be taken as benchmarks, but they do reveal regional differences and many factors may affect the nematode-plant host interaction. For example, higher population densities of *T. semipenetrans* are found in alkaline than in acid soils (Van Gundy and Martin, 1961). A further complication is that degradation of most post-plant applied nematicides is enhanced at pH >7.0.

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Sampling and monitoring: Estimates of nematode population densities should be the basis for every nematode management decision, including those taken before planting an orchard. The objective is to relate numbers and kinds of nematodes to an expected crop performance level. Resulting data also can provide evidence for the worth of various control tactics. Due to the aggregated spatial distribution of nematode populations, collection of composite samples from appropriate numbers of soil cores is necessary. Sample size should be optimized in relation to a predetermined level of sampling error, infestation level, and orchard size (Abd-Elgawad, 1992; Davis, 1984; Duncan et al., 1994a; McSorley and Parrado, 1982). Samples may be collected with a sampling tube, auger, or shovel. Each soil sample should reach 30 to 45 cm deep and should include feeder roots and soil from each soil texture or rootstock choice across the field. For comparison purposes, it is important to standardize a sample season, preferably when peak populations are attained (Duncan and Cohn, 1990). Nematodes should be extracted and identified in properly equipped laboratories by trained personnel. For extraction procedures and identification of major nematode genera, see Hooper and Evans (1993). There are numerous procedures for extraction of nematodes from soil or roots, and each has a different efficiency.

Nematode Management

Management of nematodes implies the use of various tactics in concert over an extended period of time. Control implies a specific act or several acts within a limited time frame leading to a marked reduction in either the pest population or the damage cause by the pest (Thomason and Caswell, 1987). When analyzing a nematode problem, one should be aware that although a known pathogenic nematode is present, it might not be the "limiting factor." A limiting factor is that biotic or abiotic component of the system that restricts utilization of inputs by the crop. If trees do not respond with improved yield despite nematode control, then the nematode is not the limiting factor (Thomason and Caswell, 1987). Therefore, the existence of other possible limiting factors (root-rot fungi, viruses, poor water management, salinity, initial replant problems, etc.) should be investigated and corrected before considering nematode control. Contemporary management systems must take into consideration the forthcoming ban on the use of methyl bromide (MBr).

Exclusion and preventive measures: Most plant-parasitic nematodes attacking citrus have a limited geographical distribution, except for *T. semipenetrans.* This nematode has become widely distributed although it has a narrow host range. Its occurrence is restricted to citrus, grape, olive, and a few additional plant species of minor importance. Thus, presence of *T. semipenetrans* is usually the result of introductions via contaminated nursery stock. Exclusion methods require that all participants work together for a common benefit, but the impetus for such efforts generally occurs sometime after the pest has become well established in a particular region. Exclusion includes regulatory activities; use of certified nematode-free trees, nematode-free soil, or growth media; and sanitation. Quarantine measures use tactics that restrict movement of plants and soil from infested areas, and are usually implemented at regional or national levels by regulatory agencies. Occasionally, eradication procedures are used where and when the pest presence can be delimited. The goal is to avoid the need for subsequent and continuous use of expensive control tactics because it is nearly impossible to eradicate nematodes once they are introduced into orchards.

Use of certified nematode-free planting stocks is the best way to avoid the introduction of nematodes in an orchard. Nurseries should be established in areas far from citrus orchards to avoid contamination of nurseries and subsequent spread of the nematode with vehicle-transported material, movement of soil, farm implements, animals, wind, and irrigation or runoff water. In most citrus regions, there are regulatory programs administered by different government agencies to limit the spread of pest and diseases through nursery stocks. For example, in California since 1960 there has been a nematode-free certification program for glasshouse or field-grown nursery stock to limit spread of the nematode. Soil fumigation with MBr or 1,3 dichloropropene (1,3-D) following a 2-year fallow period is the foundation for certification of field-grown nursery stock. In Florida, however, regulations require virgin, nematode-free sites to be used for nursery production. For container-grown stocks, the planting soil may be treated with steam, solarization (Stapleton et al., 1999), or MBr. Field comparisons of various soil treatments as alternatives to MBr have long been under way for tree and vine nurseries (McKenry et al., 1997). In regions where production of nematode-free planting stock is not compulsory or feasible, physical (solarization, steam, thermotherapy) or chemical (chemotherapy, fumigation, nematicides) methods can be used for nematode population reduction or eradication. Irrigation water from wells is preferred. However, if it is not possible, nematode-contaminated water can be decontaminated through use of settling ponds and filtration systems, but such procedures require careful maintenance (Cohn, 1976). Citrus nurseries in South Africa have adopted containerized production systems and use sterile growing media, a clean water supply, and less susceptible rootstocks (Le Roux et al., 2000).

Efforts should be made to prevent nematode citrus pests currently confined to some regions from being introduced in other citrus production regions. This would be the case for *Meloidogyne* spp. that occur in China and India (Vovlas and Inserra, 2000) and *B. lon-*

gicaudatus in Florida (Duncan, 1999). The risk of accidental introductions of these nematodes in other regions is high because both can be disseminated with non-citrus propagative plant material.

Pre-plant Management Methods

Once nematodes are detected within a production region, the most effective management strategy is to reduce initial population densities prior to establishing an orchard. A long-term perspective should be taken when planting an orchard. Thus, high expenditures for pre-plant management will be justified because of long-term increases in yield and a reduced need for repeated post-plant treatments.

Site preparation: Physical disturbance and soil manipulation can accelerate the mortality rate of nematodes due to desiccation or direct exposure to sunlight. However, the citrus nematode and other nematodes attacking citrus are hardy and can survive a long time after removal of infected trees (Hannon, 1964). They may survive within remnant citrus roots or deeper in the subsoil, where soil moisture and temperature fluctuate least. Citrus nematode populations can be gradually reduced in the surface 15 cm, where soil drying and higher soil temperatures occur. When replanting an orchard, roots from the previous crop should be removed to the maximum extent possible because infected roots will act as reservoirs for the nematode. Deep sub-soiling may be necessary to remove shallow hard pans or fracture deep subsurface soil layers that may restrict root penetration of deeper soil layers. Unlike most soilborne fungal pathogens, nematodes can occur in large numbers as deep as the old roots had penetrated the soil.

Soil fumigant choices: Soil disinfestation by fumigation is the most effective approach to control of soilborne pests, weed propagules, and pathogens, including nematodes. Pre-plant fumigation must be considered when replanting citrus orchards because substantial damage to young trees can occur if nematodes or other soilborne pathogens are present (McKenry, 1987, 1999).

Two main groups of chemicals, halogenated hydrocarbons (MBr, 1,3-D and chloropicrin) and methyl isothiocyanate liberators (metam sodium, metam potassium), are currently available. Other products, including iodomethane and sodium azide (only effective at acidic pH), are under study. Pre-plant soil fumigation with halogenated hydrocarbons can effectively control *T. semipenetrans* for several years (Le Roux et al., 1998; O'Bannon and Tarjan, 1973; Reynolds and O'Bannon, 1963; Sorribas et al., 2003) although none of the fumigants will eradicate nematodes.

From the list above, MBr is by far the most volatile and effective soil fumigant. It possesses greatest flexibility relative to use conditions. Iodomethane provides a close second choice, but it has its own unique limitations, including phytotoxicity to certain crops such as plum. Its impact on citrus is unknown. Delivery shanks pulled through soil a distance of 1.6 m apart can deliver MBr throughout the surface 1.6 m of soil profile. However, this fumigant is so volatile and persistent that as much as one half of the applied amount can escape prematurely from the treated soil surface. In 1992 the Montreal Protocol listed MBr as an ozone-depleting material, and a procedure for banning its use was initiated. Under the protocol, MBr will be prohibited in developed countries after 2004, except for quarantine and pre-shipment uses, and for temporary "Critical Use Exemptions" granted for approved uses. For developing countries complete phaseout is scheduled for 2015. After the phaseout, MBr might be used but only for approved emergency uses.

Fumigants based on 1,3-D are relatively less persistent and less volatile than MBr. Delivery shanks spaced 45 cm apart can adequately treat 1.6 m of soil profile, including remnant roots, if the soil is adequately dried and coarse-to-medium textured.

Metam sodium (MS) properly applied as a soil drench also can control nematodes deep within certain soil profiles and has utility in citrus soils. Unlike true fumigants, this product does not move more than 5 cm from each shank outlet when chiseled into soil. The greatest limitation to acceptable delivery of MS is the uniform delivery of large volumes of water across the field. This can be achieved using drip irrigation systems. Treatment rates of 370 kg MS/ha can provide excellent control of nematodes to 1.6-m depth and kill remnant roots to 1.3-m depth, but only if the soil can be quickly infiltrated with large volumes of water needed to make the delivery. Highly porous soils are good candidates for MS drenches, particularly if the previous crop was shallow rooted.

Citrus can be grown on coarse-to-very fine-textured soils varying in depth from 30 to more than 150 cm. The pre-plant products listed above can perform very well when properly applied to coarse-textured sandy and loamy sand soils having a uniform soil profile. With greater soil preparation effort and higher application rates, these products also can perform as well as MBr in well-prepared medium-textured silt loam soils. In deep finer-textured clay loams and clay soils, it is the self-dispersing nature of MBr that renders it unique. Products such as chloropicrin (CP) and 1,3-D have one-third and one-fifth the volatility of MBr, respectively. They are self-dispersing and offer breadth of activity, but as greater soil moisture contents are encountered in finer-textured and deeper soils, their application rates must be raised above that suggested for MBr. In addition, more attention must be paid to soil preparation, including soil profile drying.

Equivalent performance by fumigants other than MBr requires their application at higher rates, whereas regulatory actions in Florida and particularly California have reduced the permissible application rates of 1,3-D. The maximum application rate in California is currently 370 kg/ha for 1,3-D and 390 kg/ha for CP. These reduced rates do not reach as deep into the soil or remnant root pieces as does 370 kg/ha MBr. During the transition away from MBr, it will also be apparent that 1,3-D, CP, and MS possess unique characteristics of their own when it comes to the "increased growth responses," weed control capability, longevity in soil, depth of penetration, and spectrum of pest control. Their spectra of control, and hence impact on growth of replants, should not be expected to be similar to that of MBr.

One response to the shortcoming of MBr alternatives has been the popularity of mixes of soil fumigants that are commercialized in a single product (i.e., 1,3-D plus CP). There are advantages to this approach when the purpose of the mix is to broaden the spectrum of disease control. However, if the problem is achieving adequate dispersal for deep-rooted perennial crops, then these mixes do not solve the shortcoming of MBr because each fumigant moves at its own rate and distance once released into the soil. If the maximum application rate of 370 kg 1,3-D/ha allowed in California is inadequate, adding 170 kg/ha of CP or MS will not improve disease control. The greatest difficulty in achieving nematode control is that of the active ingredient reaching the target pest. For example, MBr, CP, 1,3-D, and MS applied simultaneously at a rate of 224 kg/ha each in the same treatment at 45 cm beneath the soil surface will not provide any better nematode control than 224 kg/ha MBr alone. Regardless of the application rate, MS will move only 5 cm from the line of delivery and therefore degrade to the toxic methyl isothiocyanate, which is also relatively immobile, along that line. The 1,3-D and CP will each move as far as 30 cm from the point of release through soil but will contact nematodes already dead from MBr. There are effective ways of combining fumigants when treating replant soils. Injection of 1,3 D at a 45-cm depth can be coupled with an application of MS or metam potassium within the surface 15 cm as a replacement for MBr. In well-dried, finer-textured soils, CP could be applied by shank at a 75-cm depth coupled with 1,3-D applied at a 45-cm depth. Another alternative would be MBr applied at a reduced dose of 224 kg/ha at a 75-cm depth with 370 kg 1,3-D/ha applied at a 45-cm depth. This approach would greatly diminish MBr escape to the atmosphere. Unfortunately, the goal of the Montreal Protocol is to halt MBr manufacture rather than its escape from soil.

Important considerations for soil fumigants are their cost and economics, phytotoxicity, residue problems, movement and persistence, dissipation, human toxicity, effect on non-target organisms, lack of specificity, and amount and technology or equipment for application. Factors that affect their efficacy include soil porosity, moisture content, temperature, and dose (McKenry, 1987). Information on fumigants other than MBr for use in citrus is limited because pre-plant fumigation in citrus is not as common as for other crops. Moreover, citrus is not a high-priority crop for chemical companies. Nevertheless, the experience gained in other perennial crops will probably be useful for citrus.

Soil solarization: Covering moistened soil with a clear plastic sheet is an attractive way to disinfest shallow soil layers in regions with hot and dry summer months. Its major advantages are the simultaneous control of insects, soilborne pathogens, weeds, and nematodes, and an increased growth response through modification of the physical, chemical, and biological properties of the soil. The main limitations are its dependence on climate, the long duration of the treatment (40 to 60 days), and the fact that the passive solar heat transfer does not penetrate more than 20 cm into the soil profile even after long solarization periods. Manufacture and disposal of plastic material used for solarization poses environmental problems. There is little published information on the effect of solarization in citrus soils, perhaps because most citrus is grown in subtropical areas where abundant rainfall and high soil moisture are common—conditions that do not favor the temperature increase needed for effective solarization. In South Africa, solarization has provided inconsistent suppression of the citrus nematode and tree growth response (Cronje et al., 2002), probably because nematodes associated with perennial crops dwell deep within the soil profile and are not affected by solarization that is most effective close to the soil surface (Stapleton et al., 2000).

Steam: Steam treatment of soil is widely used in the Netherlands, where MBr has been banned for several years, typically in facilities that have heating systems used mainly for heating the greenhouse during the cold season. Heating the soil or growth media to 70 °C, mainly by means of aerated steam, can be useful and economical for disinfestation of shallow layers of growth media for nursery beds and containerized transplant production. This is especially true when a steam-generating system is already in place to provide heat during winter months. A permanent manifold for delivering steam can be installed in nursery beds in greenhouses. Careful soil or substrate preparation is required for effective disinfestations. Steam treatment of vermiculite or tuff stones is usually effective but is more difficult for peat soils due to their high water content (Tjamos et al., 1999). The use of steam in open fields requires expensive infrastructures and careful soil preparation to allow steam penetration into the soil, in addition to the high cost of fuel and water.

Thermotherapy and chemotherapy: The use of hot water dips to eliminate nematodes from plant material is effective only when the thermal tolerance of the nematode is less than that of the plant material. Bare root dips of citrus seedling at 45 °C for 25 minutes (Baines et al., 1949) or 50 °C for 10 to 20 minutes (Silva et al., 1987a) is effective against the citrus nematode without adverse effect on the plant. Chemotherapy by dipping bare roots in chemical solutions reduces nematode densities but does not eliminate them (O'Bannon and Taylor, 1967; Silva et al., 1987b) and is generally less effective and poses more health risks for workers than thermotherapy. Removing soil adhered to roots before heat or chemical treatment can limit the utility of this tactic, particularly for transplants grown in the ground due to increased labor costs.

Resistant rootstocks: Resistance is generally the most useful, environmentally sound solution to increasing yields by suppression of nematode population densities. A rootstock is classified resistant when it greatly inhibits nematode reproduction relative to a known susceptible standard. The only source of genetic resistance identified against *T. semipenetrans* is derived from *Poncirus trifoliata.* Some selections of *P. trifoliata* are highly resistant (Pf/Pi < 1) to *T. semipenetrans,* whereas others are only moderately resistant (Pf/Pi > 1) relative to the reference rootstock (Verdejo-Lucas and Kaplan, 2002). The hybrid rootstock Swingle citrumelo (*Citrus paradisi* × *P. trifoliata*) is highly resistant to the citrus nematode (Kaplan and O'Bannon, 1981; Lo Giudice and Inserra, 1980). However, both *P. trifoliata* and Swingle citrumelo grow poorly in alkaline soils. Troyer and Carrizo citranges (*Citrus sinensis* × *P. trifoliata*) are considered moderately resistant in some regions. Continuous cultivation of resistant rootstocks may lead to the development of new biotypes or select virulent populations of the nematode. Baines et al. (1974) reported that citrus nematode biotypes could develop on all the resistant rootstocks available at that time. Populations of *T. semipenetrans* capable of reproducing well on Swingle citrumelo have been reported in Florida (Duncan et al., 1994b) and South Africa (Le Roux et al., 2000), but these populations appeared to be confined to the sites where they were detected. Also, a progressive adaptation of the nematode to reproduce on rootstocks previously described as moderately resistant (i.e., Troyer and Carrizo citranges) can occur as a result of their continuous cultivation (Verdejo-Lucas et al., 1997). The presence of high nematode levels at the time of replanting or when interplanting moderately resistant and susceptible rootstocks can reduce their relative resistance level to *T. semipenetrans* (Verdejo-Lucas et al., 2003). Soil salinity increased nematode egg production on several resistant genotypoes but did not markedly reduce nematode resistance (Mashela et al., 1992).

Although many citrus rootstocks are available, the number of candidates adapted to any one area, and resistant or tolerant to locally important diseases or pests, is limited. As a result, extensive areas are planted on a single rootstock in the majority of the citrus regions. This near monoculture system within a region represents a high risk for disease or pest outbreaks. For example, citrus tristeza virus caused an epidemic that killed more than 17 million trees on sour orange rootstock in Spain (Cambra, 1994). This experience has been repeated in Brazil, Florida, and California.

The existence of physiological races or biotypes of *T. semipenetrans* that differ in their host preference poses a limitation to rootstock selection. Three biotypes are recognized to date: citrus, mediterranean, and poncirus (Gottlieb et al., 1987; Inserra et al., 1994; Verdejo-Lucas et al., 1997). The citrus biotype infects many genera in the Rutaceae, including *Citrus* spp. Troyer and Carrizo citrange, as well as olive, grape, and persimmon, reproduces poorly on *P. trifoliata* and some hybrids of this genus. The host range of the mediterranean biotype is similar to the citrus biotype, with the exception of olive, which is not a host for this biotype. The poncirus biotype reproduces on *Citrus* spp., *P. trifoliata,* and hybrids of *P. trifoliata* as well as grape, but not olive. Based on literature reports, it appears that the citrus biotype occurs in California and Italy, the mediterranean biotype in countries of the Mediterranean basin and South Africa, and the poncirus biotype in California, Israel, and Japan (Inserra et al., 1994). New rootstocks continue to be developed through classical sexual hybridization, somatic hybridization, and genetic transformation to meet regional demands, and they are being screened to identify their resistance to nematodes (Verdejo-Lucas et al., 2000).

Post-Plant Management

Once trees are infected, no curative methods of nematode control are available. The life cycle of the citrus nematode is regulated by host phenology in addition to seasonal changes in the soil environment (Duncan and Cohn, 1990). This fact must be considered for the use of post-plant control tactics. There may be one, two, or even three peaks of nematode population density per year depending on nematode life stage measured, year, and orchard. The number of females infecting roots is the best indicator of seasonal activity of *T. semipenetrans* (Sorribas et al., 2000) and also for evaluating the efficacy of nematicides (Hamid et al., 1988). The application of control tactics will be more effective during periods of active root development because conditions that favor root growth also may enhance the increase of nematode densities (Duncan and Noling, 1987).

Nematicides: Various nematicides have successfully been used to decrease densities of *T. semipenetrans* on citrus in many regions. However, repeated applications are needed to maintain reduced densities and consistent yield increases. Little effect of treatment on yield and fruit quality may be obtained the first year after their application, but efficacy can be demonstrated in the second year (Davis et al., 1982; Van Gundy et al., 1982; Wheaton et al., 1985). Two main groups of nematicides, oxime-carbamates (aldicarb, oxamyl, carbofuran) and organophosphates (fenamiphos, ethoprophos, and cadusaphos), are available. Of these, granular Cadusafos has shown superior efficacy against the citrus nematode (Le Roux et al., 1996; McClure and Schmitt, 1996; Philis, 1997; Walker and Morey, 1999). Additionally, the broad-spectrum product Enzone, which liberates low concentrations of carbon bisulfide within soil, can reduce citrus nematode populations if properly applied. All of these products are directly lethal to the nematodes and have activity against insects. Their primary action is a result of direct contact. Once these nematicides reach more than 8 cm into soil, their action is mostly due to sublethal effects including modification of nematode behavior. For example, stimulation of egg hatch, inability of males to find females, or inability of females to find roots are known effects of aldicarb (Hough and Thomason, 1975).

Most of the early formulations of the nematicides developed in the 1960s were as granules that were spread on the soil surface and incorporated mechanically into the top 10 cm of soil. Currently, emulsifiable concentrates are available for application through drip irrigation systems. Nematicides break down in the soil or plants by hydrolysis and oxidation, and their properties relative to movement in soil and persistence should be considered. They include the solubility of the nematicides in water. For example, oxamyl is highly soluble (280,000 ppm at 25 °C), followed by aldicarb (6,000 ppm at 25 °C), ethoprophos (750 ppm), fenamiphos (700 ppm at 20 °C), carbofuran (700 ppm at 25 °C), and cadusafos, which has very low solubility (248 ppm) (Hague and Gowen, 1987). Generally, the higher the solubility, the greater the potential movement of the active ingredient to the target. The amount of soil moisture is another important factor influencing distribution of the nematicide in soil. Products of low solubility also can be highly adsorptive to dry soil particles, rendering them unavailable for deeper movement. The type of irrigation, which influences root and nematode distributions, also influences the efficacy of the nematicides. Whereas flood and furrow irrigation are still the most common forms of irrigation in some regions, low-volume irrigation through micro-sprinklers or drippers is more common in other regions; citrus is not irrigated in other regions because of adequate rainfall. In drip irrigation systems, roots are largely confined to areas moistened by the drippers, and drip-applied treatments provide control only to the wetted zone (McKenry et al., 1997). Hence, irrigation is often recommended before nematicide application. In these systems, application technology becomes a critical issue for effective control.

In addition, soil texture can influence product dispersal because finer-textured soils with small pore spaces and greater cation exchange capacity are more difficult to treat than sandy soils with larger pore sizes and minimal cation exchange capacity. Nematicides have to persist long enough for nematodes to be exposed to an effective dose (= concentration × exposure time). However, extended persistence is not a desirable characteristic because of the risk of contaminating groundwater and(or) accumulation of toxic residues on fruits. The amount of organic matter also affects nematicide effectiveness because most products are highly adsorbed to organic matter, which can impair their overall dispersal (Bromilow, 1980). Another problem with non-fumigant nematicides is the accelerated microbial degradation (AMD) that can occur in soils when populations of microorganisms capable of metabolizing nematicides increase with repeated use of a nematicide. Aldicarb and fenamiphos exhibited AMD in certain citrus soils in South Africa (Le Roux and Ware, 1996). In California, AMD has been observed to develop more rapidly with microsprinkler applications than with drip delivery systems (McKenry, pers. comm.).

Biological control: Microbial antagonists can regulate nematode populations through direct parasitism or predation in a density-dependent manner or via release of toxic metabolites. Therefore, low nematode densities are needed to maintain adequate densities of the antagonist (Jaffee, 1993). The endemic antagonists are often poor competitors. Additionally, plant-parasitic nematodes associated with perennial crops live deep in the soil, whereas microbial antagonists tend to inhabit the shallowest 15 cm where biological activity is greatest.

A diversity of antagonists of the citrus nematode, including trapping and parasitic fungi, bacteria, and predacious nematodes and mites, occur naturally in citrus orchards (Roccuzzo et al., 1992; Stirling and Mankau, 1977; Walter and Kaplan, 1990), although little is known of their role in regulating densities of *T. semipenetrans*. *Pasteuria* spp. affected seasonal fluctuations of the citrus nematode but only in one of four study orchards (Sorribas et al., 2000). The egg-parasitic fungus, *Paecilomyces lilacinus,* reduced *T. semipenetrans* densities in pot experiments (Parvatha Reddy et al., 1991), and the results were best when combined with organic amendments (i.e., oil-cakes). Similar results were observed in an 8-year-old Valencia orchard on rough lemon rootstock (Le Roux et al., 2000). This fungus is now produced commercially in several countries including Australia, Colombia, Germany, and South Africa. A product of biological origin from the hyphomycete *Myrothecium,* DiTera, has been developed as an environmentally compatible biological alternative to chemical control. It is noteworthy that metabolites, rather than live organisms, are added to soil, killing nematodes in the soil on contact. At present, DiTera has registrations in the United States, Chile, and Panama. As with nematicides, soil moisture and temperature affect the persistence of biological control agents (BCA) once applied into the soil.

Biological control may be helpful in regions where chemical control is not available or affordable, and in orchards under organic farming. Biological control may be more successful at moderate rather than at high pest pressure due to the inverse relationship between nematode densities and level of control of the BCA (Bourne and Kerry, 1999). Biological control remains primarily an experimental system, and additional field data are needed to increase the knowledge on the BCAs in relation to the nematode once applied in the field. The limited reports on field results have not been sufficiently promising to attract attention for industrial development. Difficulties in mass production, formulation, and stability of the formulated product also hinder their development.

Agronomic and cultural practices: Many properly established orchards generate high yields in the presence of nematodes, but often conditions exerting stress on the plant result in suboptimal production, which in turn may eventually produce losses. Rotations with annual crops for 1 to 3 years before replanting citrus helps to reduce citrus nematode populations, but the economics of such rotations limits their use. Controlling weeds will reduce competition for water and nutrients but will have little impact on citrus nematode populations because of high host specificity. If other nematodes with wider host ranges were present in the field, then the control of weeds may impact the densities of such nematodes. Fallowing for 4 months to 1 year before replanting an orchard is a common practice but may not be sufficient due to nematode survival within old roots. Other constraints of fallowing include soil erosion, soil structure impairment, economics, and reduction of densities of beneficial organism. Fallowing combined with careful soil preparation in addition to chemical alternatives may be needed for nematode control in replant situations. For instance, a 4-month fallow, site preparation, and treatment with 1,3-D retarded citrus nematode reinfestation for 3 years in a replanted orchard (Sorribas et al., 2003).

Mulching is a cultural practice that can help reduce water loss from the soil as it reduces evaporation, moderates extreme daily soil temperatures, and helps suppress weed competition. As a consequence, the crop's environment is modified, promoting tree vigor and increased yield. Black plastic films are suitable for regions with low rainfall or poorly distributed rain but not for humid conditions because of accumulation of excessive humidity under the plastic film. Organic mulches should be 10 cm thick and placed on the soil surface in an area of 1- to 3-m diam. around the tree. Nematode densities may increase on mulched trees due to more favorable conditions for root growth and nematode reproduction, but those trees may be more tolerant to nematode damage because of reduced temperature and moisture stresses. Mulched trees, particularly in new plantings, need reduced irrigation to prevent problems caused by root rot fungi, snails, and bacteria.

Interactions with other soilborne pathogens: The most common interaction that occurs in citrus nematode worldwide is that with the root-rot fungus *Phytophtora nicotianae.* Both the fungus and nematode parasitize the cortex of the fibrous root system, reducing the mass of fibrous roots, and are capable of reducing citrus yield (Duncan et al., 1993). El-Borai et al. (2002a) reported that the nature of that interaction was antagonistic and resulted in less root infection by the fungus, reduced fungal development in roots, and mitigated growth reduction of citrus seedlings. Eggs of *T. semipenetrans* inhibited mycelial growth of *P. nicotianae* and *Fusarium solani* (El-Borai et al., 2002b). The antagonistic interaction between these pathogens could explain significant increases in *P. nicotianae* propagule densities in soil following reduction of nematode population in Florida citrus orchards (Graham and Duncan, 1997). The interaction of *T. semipenetrans* with *Fusarium solani* reduced citrus growth (Labuschagne et al., 1989) although soil temperature greatly influenced the individual and combined effects of *F. solani* and *T. semipenetrans* (O'Bannon et al., 1967). Because the nematode and fungus are ubiquitous in the roots of healthy and declining trees, their interactions are probably significant factors in citrus decline, and determining which one is the most limiting factor is important when selecting control tactics.

Summary

Nematode management requires a thorough understanding of the growth of the host plant; the biology, ecology, and epidemiology of the nematode; and the influence of the environment on the nematode-plant interaction in a given region. When selecting tactics, one should consider that combining certain tactics may produce unwanted effects.

Additional research is needed to find means for interrupting the nematode's life cycle, enhancing microbial activity in the rhizosphere to promote plant growth or increase its tolerance to the nematode, and identifying compounds that interfere with host finding mechanisms of the nematode. Any chemical, microbial, cultural, or management approach that is developed must be within the capability of the grower and should meet the necessary environmental and economic requirements. The grower will benefit if these treatments are reliable, practicable, and economically justified, and the consumer will benefit if the product has the desirable quality, is free of toxic residues, and is reasonably priced.

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