

Nematode Management In Commercial Vegetable Production¹

J. W. Noling²

Nematode Pests of Vegetable Crops in Florida

Plant parasitic nematodes (Figure 1), are small microscopic roundworms which live in the soil and attack the roots of plants. Crop production problems induced by nematodes therefore generally occur as a result of root dysfunction, reducing rooting volume and foraging and utilization efficiency of water and nutrients. Many different genera and species of nematodes can be important to crop production in Florida. In many cases a mixed community of plant parasitic nematodes is present in a field, rather than having a single species occurring alone (Table 1). In general, the most widespread and economically important nematode species include the root-knot nematode, *Meloidogyne* spp., and sting nematode, *Belonolaimus longicaudatus*. The host range of these nematodes, as with others, include most if not all of the commercially grown vegetables within the state. Yield reductions can be extensive but vary significantly between plant and nematode species. In addition to the direct crop damage caused by

nematodes, many of these species have also been shown to predispose plants to infection by fungal or bacterial pathogens or to transmit virus diseases, which contributes to additional yield reductions.

Table 1 lists nematodes which may affect vegetable crops in Florida; many may cause significant yield reductions.

Biology & Life History

Most species of plant parasitic nematodes have a relatively simple life cycle consisting of the egg, four larval stages and the adult male and female (Figure 2). Development of the first stage larvae occurs within the egg where the first molt occurs. Second stage larvae hatch from eggs to find and infect plant roots or in some cases foliar tissues. Host finding or movement in soil occurs within surface films of water surrounding soil particles and root surfaces. Depending on species, feeding will occur along the root surface or in other species like root-knot, young larval stages will invade root tissue, establishing permanent feeding sites within the root. Second stage

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2. J. W. Noling, professor, Entomology and Nematology Department, Citrus Research and Education Center, Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Lake Alfred, FL 33850.

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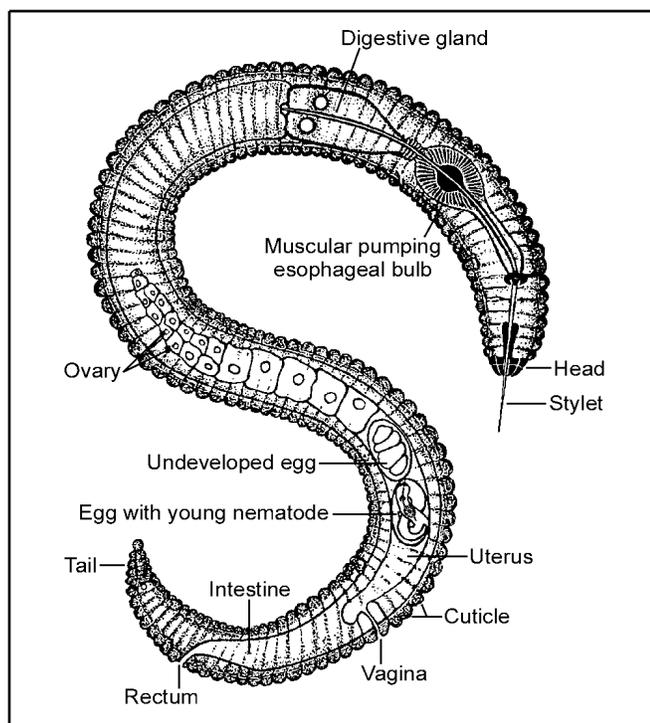


Figure 1. Nematodes: microscopic roundworms which parasitize and feed on the roots and tissues of plants.

Table 1. Nematodes which affect vegetable crops in Florida.

Common Names	Scientific Names
Root-knot nematodes	<i>Meloidogyne</i> spp.
Sting nematodes	<i>Belonolaimus</i> spp.
Stubby-root nematodes	<i>Trichodorus</i> spp.
Root-lesion nematodes	<i>Pratylenchus</i> spp.
Cyst nematodes	<i>Heterodera</i> spp.
Awl nematodes	<i>Dolichodorus</i> spp.
Stunt nematodes	<i>Tylenchorhynchus</i> spp.
Lance nematodes	<i>Hoplolaimus</i> spp.
Spiral nematodes	<i>Helicotylenchus</i> spp. <i>Scutellonema</i> spp.
Ring nematodes	<i>Criconemoides</i> spp.
Dagger nematodes	<i>Xiphinema</i> spp.
Bud and leaf nematodes	<i>Aphelenchoides</i> spp.
Reniform nematodes	<i>Rotylenchulus</i> spp.

larvae will then molt 3 times, to become adult male or female. For most species of nematodes, as many as 50-100 eggs are produced per female, while in others

such as root-knot, upwards of 2000 may be produced. Under suitable environmental conditions, the eggs hatch and new larvae emerge to complete the life cycle within 4 to 8 weeks depending on temperature. Nematode development is generally most rapid within an optimal soil temperature range of 70 to 80°F.

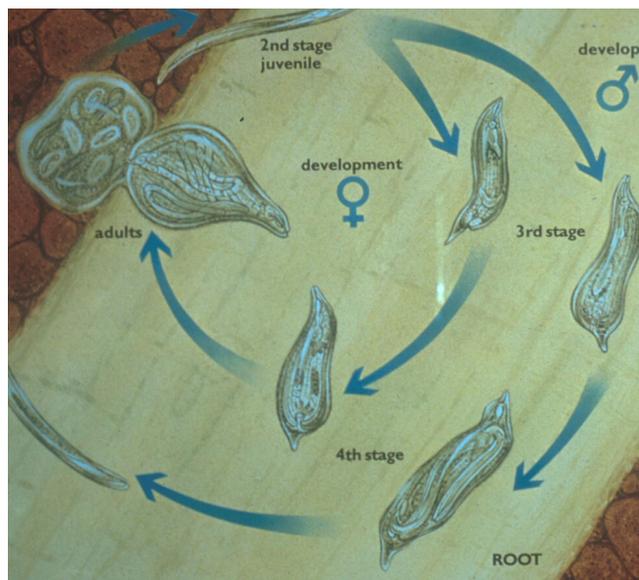


Figure 2. The life cycle of the root-knot nematode, proceeding from eggs, through juvenile stages to adult males and females.

Symptoms

Typical symptoms of nematode injury can involve both above ground and below ground plant parts. Foliar symptoms of nematode infestation of roots generally involve stunting and general unthriftiness (Figure 3 and Figure 4), premature wilting and slow recovery to improved soil moisture conditions, leaf chlorosis (yellowing) and other symptoms characteristic of nutrient deficiency. An increased rate of ethylene production, thought to be largely responsible for symptom expression in tomato, has been shown to be closely associated with root-knot nematode root infection and gall formation. Plants exhibiting stunted or decline symptoms usually occur in patches of nonuniform growth rather than as a overall decline of plants within an entire field.

The time in which symptoms of plant injury occur is related to nematode population density, crop susceptibility, and prevailing environmental



Figure 3. Plant stunting of strawberry caused by the sting nematode, *Belonolaimus longicaudatus*. Note irregular field distribution of stunted plants.



Figure 4. Stunting of citrus seedlings caused by the sting nematode, *Belonolaimus longicaudatus*. Note irregular field distribution of stunted plants.

conditions. For example, under heavy nematode infestation, crop seedlings or transplants may fail to develop, maintaining a stunted condition, or die, causing poor or patchy stand development. Under less severe infestation levels, symptom expression may be delayed until later in the crop season after a number of nematode reproductive cycles have been completed on the crop. In this case above ground symptoms will not always be readily apparent early within crop development, but with time and reduction in root system size and function, symptoms become more pronounced and diagnostic.

Root symptoms induced by sting or root-knot nematodes can oftentimes be as specific as aboveground symptoms. Sting nematode can be very injurious, causing infected plants to form a tight mat of short roots, oftentimes assuming a swollen appearance (Figure 5). New root initials generally are

killed by heavy infestations of the sting nematode, a symptom reminiscent of fertilizer salt burn. Root symptoms induced by root-knot cause swollen areas (galls) on the roots of infected plants (Figure 6). Gall size may range from a few spherical swellings to extensive areas of elongated, convoluted, tumorous swellings which result from exposure to multiple and repeated infections. Symptoms of root galling can in most cases provide positive diagnostic confirmation of nematode presence, infection severity, and potential for crop damage.



Figure 5. Swollen and abbreviated citrus fibrous root symptoms caused by the sting nematode, *Belonolaimus longicaudatus*.

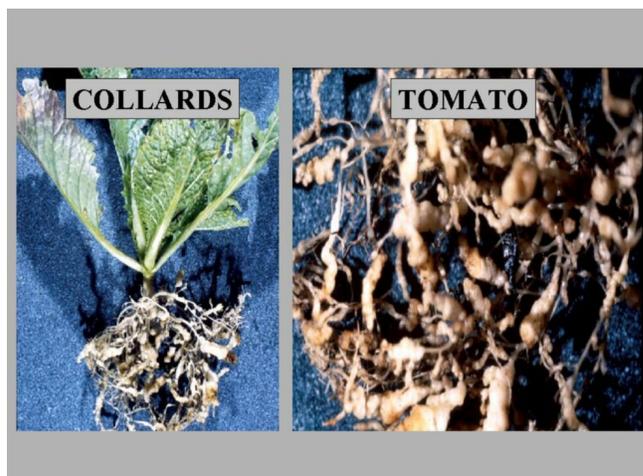


Figure 6. Root-knot nematode (*Meloidogyne* spp.) induced galling of collard and tomato roots. Note the enlarged, tumorous type expansions (galls) of the plant roots.

Damage

For most crop and nematode combinations the damage caused by nematodes has not been accurately determined. Most vegetable crops produced in Florida are susceptible to nematode injury, particular

by root-knot and sting nematodes. Plant symptoms and yield reductions are often directly related to preplant infestation levels in soil and to other environmental stresses imposed upon the plant during crop growth (Figure 7). As infestation levels increase so then does the amount of damage and yield loss. In general, the mere presence of root-knot or sting nematodes suggests a potentially serious problem, particularly on sandy ground during the fall when soil temperatures favor high levels of nematode activity. At very high levels, typical of those which might occur under doubling cropping, plants may be killed, particularly in the presence of other disease pathogens. Older transplants, unlike direct seed, may tolerate higher initial population levels without incurring as significant a yield loss.

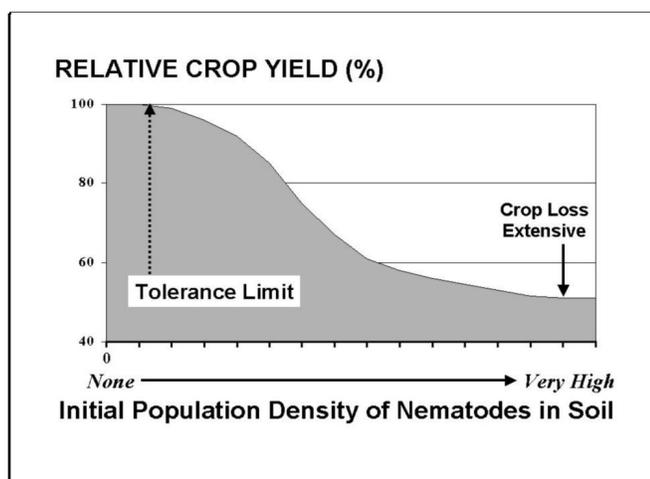


Figure 7. Typical nematode induced crop damage relationship in which crop yields, expressed as a percentage of yields that would be obtained in the absence of nematodes, decline with increased population density of nematodes in soil. The tolerance level is identified as the initial or minimal soil population density at which crop damages is first observed.

Multiple-Pest Interactions: A Basis for Crop Loss Assessment and Nematode Management

It is frequently not possible to confidently predict crop losses due to nematodes based solely on soil and root sample information of nematode population density, because of the uncertainty of the interactions between plant parasitic nematodes and their environment, and with other pest species. Much is known about the impact of specific pests, agronomic inputs, and environmental factors on plant growth

when they are manipulated and studied separately. Less is known about the combined action of various pests and the effects interacting plant stresses have on pest populations or the rates at which these populations develop. In particular, prediction of crop loss for advisory purposes must be able to partition and account for the interaction of multiple pests under varying agronomic practices and conditions. Crop loss information from the total pest complex forms the basis for rational or optimal farm, crop and pest management decisions. In this way pesticide use can be most efficiently and prudently prescribed.

During development, plants are exposed to different levels and complexes of competing pests. For example, many kinds of nematodes and fungi are generally present in the soil and their populations may be assessed prior to planting. Other pests, including insects, weeds and certain fungi and bacteria arrive and are assessed much later in the growth of the crop. The timing of pest attacks, whether they occur simultaneously, sequentially, or any combination of the two during the development of the plant can profoundly alter final crop yield.

Individual species of nematodes (root-knot, sting, lesion, etc.) seldom occur alone but rather in a community with many other species of plant parasitic nematodes. The presence of one species may enhance, retard or have no obvious effect on the population dynamics of another competing nematode species when present on a particular host plant. For other host plants, soil types, cultural, edaphic, and environmental conditions, the effects of such competitive interactions between nematode species may be very different. Therefore one cannot extrapolate interaction predictions from one host plant to another. The interactions between nematodes or with other pests may be physical, such as simple competition for food or space, or may be functionally mediated through the plant and represented by a change in food quantity or quality, or in production of antibiotic chemicals.

Types of Interactions

Changes caused in the plant by one stress factor may indirectly influence the subsequent impact of a second stress factor. Alteration of host plant

physiology in response to nematode parasitism may increase, decrease, or have no apparent effect on the susceptibility of the plant to additional pests. When two or more pests attack a plant, the interaction may be synergistic where the combined effects of the pests are greater than the sum of the effects of each pest acting alone. Multiple-pest associations that cause synergistic increases in yield losses are particularly well documented for nematodes and fungi. The best documented example is the root-knot nematode, *Meloidogyne* spp., and Fusarium wilt disease on old tomato production land (Figure 8). The root-knot nematode, by causing the development of root galls, provides a nutrient-rich food source which the fungi colonize rapidly. Root-knot nematodes can thus significantly enhance disease development and yield loss, elevating primary or secondary pathogens to major pest status even though population levels or pathogenic potential of the fungi were initially very low and yield losses would have been minimal in the absence of the nematode.



Figure 8. The simultaneous occurrence of both root-knot (*Meloidogyne* spp.) and Fusarium wilt disease (*Fusarium oxysporum*) causing enhanced disease development and tomato yield loss.

In other multiple pest associations different pests may interact negatively, so that the combined effects are less than the sum of the effects of each pest acting alone. Direct competition for feeding sites or substrates or effects on host physiology may serve to lessen the full expression of each pest's damage potential. In other cases, the presence of the two or more pests do not appear to increase or decrease yield in relation to the sum of the individual pest effects. The effects are simply the pathogenic potential of each

species and the levels to which they are suppressed or enhanced. Ultimately, multiple-pest effects are dependent on a myriad of complex factors, many of which are not well understood or studied.

Periodic measurement of pest population density may also be needed to detect seasonal population changes, since affected tissues and prediction of yield as a function of pest population varies seasonally when different pests and disease-causing organisms are present. For example, highest nutsedge populations frequently occur in the field when moderate to high *Meloidogyne* populations have reduced crop growth and allowed weed development. This further reduces crop yields and increases pest control expenses. The interaction in this case is sequential and illustrates the importance of nematode management programs. Failure to account for covariation of weed and nematode populations misrepresents the true impact of the nematode on crop productivity even though the weeds, through competition for water, light, and nutrients, caused the additional loss in yield.

Quantifying Nematode Stress

Many factors serve to isolate and maintain certain nematodes within particular locations of the field. As the environment of a particular field changes, so does the relative involvement and pathogenicity of the nematode and pest complex present. For example, as the coarse-particle size content of soils increase, the synergistic interaction between root-knot nematode and certain fungi generally increases. Increasing soil particle size also increases damage from the nematode and fungus alone. Preliminary sampling, which is accomplished prior to harvest or after destruction of the previous crop, is necessary to identify infested areas and ranges in nematode population levels within the field. Sampling procedures are described in nematode assay kits available from the Nematode Assay laboratory or local County Extension Offices. See *Nematode Assay Laboratory*.

Typically many different species of nematodes are recovered from a soil sample submitted for nematode diagnostic and advisory purposes. To formulate a control recommendation, the damage

anticipated from the most pathogenic species is first considered. Other less pathogenic species of nematodes present are then ranked and their expected effects related to the damage expected from the most pathogenic species. Their relative pathogenic ratings in terms of the most pathogenic species are then summed across species and population densities to provide a cumulative total of pathogenic equivalents. Since anticipated damage from the most pathogenic species is the benchmark, plant damage is assessed in terms of standardized units of pathogenicity for all nematode species involved.

Distributional Aspects

The ability to predict crop losses attributable to nematodes and other pests at a field level is based on accurate description of pest density, distribution, and areas where different nematode or pest species occur together. The areas of overlap are important since they form the critical areas for pest interaction. Development of nematode crop loss predictions uniquely determined for individual fields and pest species will undoubtedly await further refinements in many different areas of nematology, including sampling methods, and descriptions of nematode field distribution patterns.

If nematode field distribution were known, field estimates of crop loss including the relative involvement of the species present and recommendations for 'spot' treatment could be estimated. For example, in all areas of the field where no species overlap occurs, it would be possible to apply a single damage relationship accounting for each pest by summing over the frequency and density of each pest occurring within each unit area of the field. For areas in which pests overlap, the resultant damage relationship would have to include the individual affects of each pest as well as the interaction term summed over the number of overlapping areas to arrive at an estimate of crop loss. The total loss would then be the simple addition of expected loss for each area of the field with respect to pest density and distribution. For many pest-crop systems, incorporation of the interaction term could significantly improve crop loss prediction by considering synergistic or antagonistic relationships among nematodes and with other pathogenic organisms.

Nematode control strategies may influence other pest species, which in turn can alter the incidence and severity of the disease complex or alter the susceptibility of the plant to other stress factors. In fact, much of the evidence for the involvement of nematodes in disease complexes is based on lower disease severity when nematode were controlled. Most soil fumigant nematicides, applied at specific rates and formulations, can differentially affect nematode and other soil borne pests as well as soil nutrient relations through their effects on non-target soil microorganisms. Justification for use of specific formulations and dosage levels of fumigant nematicides could well be based on the diversity and levels of pests within the field, since many fumigants differentially effect the soil borne pest complex. Similarly, selection of non-fumigant insecticide/nematicides could be based on consideration of their expected effects or levels of injury for all pests that are present.

Field Diagnosis & Sampling

Because of their microscopic size and irregular field distribution, soil and root tissue samples are usually required to determine whether nematodes are causing poor crop growth or to determine the need for nematode management. For nematodes, sampling and management is a preplant or postharvest consideration because if a problem develops in a newly planted crop there are currently no postplant corrective measures available to rectify the problem completely once established. Nematode density and distribution within a field must therefore be accurately determined before planting, guaranteeing that a representative sample is collected from the field. Nematode species identification is currently only of practical value when rotation schemes or resistant varieties are available for nematode management. This information must then be coupled with some estimate of the expected damage to formulate an appropriate nematode control strategy.

Advisory or Predictive Sample

Samples taken to predict the risk of nematode injury to a newly planted crop must be taken well in advance of planting to allow for sample analysis and treatment periods if so required. For best results,

sample for nematodes at the end of the growing season, before crop destruction, when nematodes are most numerous and easiest to detect. Collect soil and root samples from 10 to 20 field locations using a cylindrical sampling tube (Figure 9), or if unavailable, a trowel or shovel. Since most species of nematodes are concentrated in the crop rooting zone, samples should be collected to a soil depth of 6 to 10 inches. Sample in a regular pattern over the area, emphasizing removal of samples across rows rather than along rows (Figure 10). One sample should represent no more than 10 acres for relatively low-value crops and no more than 5 acres for high value crops. Fields which have different crops (or varieties) during the past season or which have obvious differences either in soil type or previous history of cropping problems should be sampled separately. Sample only when soil moisture is appropriate for working the field, avoiding extremely dry or wet soil conditions.



Figure 9. The collection of soil samples for nematode analysis can be acquired from the field using a cylindrical sampling tubes, trowels, or shovels.

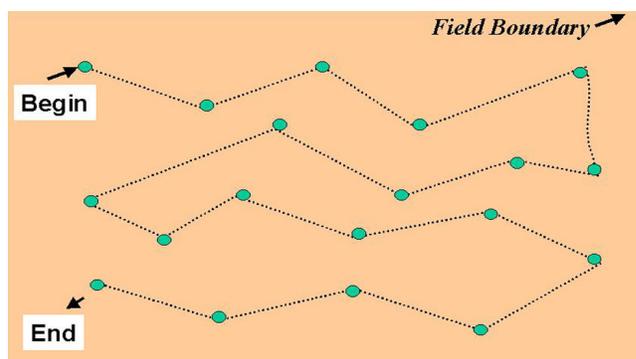


Figure 10. Sampling pattern.

Diagnostics on Established Plants

Roots and soil cores should be removed to a depth of 6 to 10 inches from 10 to 20 suspect plants. Avoid dead or dying plants, since dead or decomposing roots will often harbor few nematodes. For seedlings or young transplants, excavation of individual plants maybe required to insure sufficient quantities of infested roots and soil. Submission of additional samples from adjacent areas of good growth should also be considered for comparative purposes.

For either type of sample, once all soil cores or samples are collected, the entire sample should then be mixed thoroughly but carefully, and a 1 to 2 pint subsample removed to an appropriately labeled plastic bag. Remember to include sufficient feeder roots. The plastic bag will prevent drying of the sample and guarantee an intact sample upon arrival at the laboratory. Never subject the sample(s) to overheating, freezing, drying, or to prolonged periods of direct sunlight. Samples should always be submitted immediately to a commercial laboratory or to the University of Florida Nematode Assay Laboratory for analysis. If sample submission is delayed, then temporary refrigerated storage at temperatures of 40 to 60°F is recommended.

Recognizing that the root-knot nematode causes the formation of large swollen areas or galls on the root systems of susceptible crops, relative population levels and field distribution of this nematode can be largely determined by simple examination of the crop root system for root gall severity (Figure 11). Root gall severity is a simple measure of the proportion of the root system which is galled. Immediately after final harvest, a sufficient number of plants should be

carefully removed from soil and examined to characterize the nature and extent of the problem within the field. In general, soil population levels increase with root gall severity. This form of sampling can in many cases provide immediate confirmation of a nematode problem and allows mapping of current field infestation. As inferred previously, the detection of any level of root galling usually suggests a nematode problem for planting a susceptible crop, particularly within the immediate areas from which the galled plant(s) were recovered.



Figure 11. Field diagnosis for the presence and severity of root-knot nematodes via visual examination of uprooted plant root systems for root galls.

Nematode Management for Vegetables in Florida

More than 40 types of vegetables are grown commercially in Florida. Most, probably all, are subject to nematodes and soilborne pathogens which can seriously reduce quantity, quality, or uniformity of yields. Most vegetables grown in Florida are for fresh market sales, often intended for marketing "windows" of a few weeks or days when alternative supplies are few and prices are best. Any factor such as nematode damage to roots which delays maturity can make the crop unprofitable, even if a respectable yield is obtained later. The high unit value of fresh-market vegetables and their generally high susceptibility to nematode damage make it very important to minimize populations of potentially harmful nematodes before planting.

It is sometimes possible to grow one or two crops on "new" land without serious losses to nematodes. However, continued cropping to favorable host plants will almost always result in progressively greater populations of nematode pests (and other soil-borne pests and pathogens) which cause increasingly serious damage to successive crops. Unless one has an endless supply of new land, it is advisable to manage the land in such a way as to minimize the build-up of nematodes, and to provide optimum conditions for effective use of nematicidal chemicals when they are needed.

Currently nematode management considerations include crop rotation of less susceptible crops or resistant varieties, cultural and tillage practices, use of transplants, and preplant nematicide treatments. Where practical, these practices are generally integrated into the summer or winter 'off-season' cropping sequence. It should be recognized that not all land management and cultural control practices are equally effective in controlling plant parasitic nematodes and varying degrees of nematode control should be expected. These methods, unlike other chemical methods, tend to reduce nematode populations gradually through time. Farm specific conditions, such as soil type, temperature, moisture, can be very important in determining whether different cultural practices can be effectively utilized for nematode management.

Cultural Practices

Crop Rotation

For crop rotation to be effective, crops unsuitable for nematode infection, growth, or reproduction must be introduced into the rotation sequence. In most of Florida it is not uncommon to observe a multispecies community of nematodes all occurring within the same field. Under these circumstances it may not be possible to find a rotation or cover crop which will effectively reduce populations of all nematode pests, particularly if root-knot and sting nematodes occur in combination. In this case, crop rotations detrimental to root-knot, which is generally the most difficult to control, should be selected. In some cases, resistant crop varieties are available which can be used within the rotation sequence to minimize problems to some species of root-knot but not sting nematodes.

Use of poor or nonhost cover crops within the rotation sequence, may in some cases offer an effective approach to nematode control. Two leguminous cover crops adaptable for managing soil populations of sting or root-knot nematode include hairy indigo (*Indigofera hirsuta*) and american jointvetch (*Aeschynomene americana*). Sorghum is also a popular cover crop restoring large amounts of soil organic matter, but is a good host for sting nematode but not root-knot.

Most of the small grains commonly used as winter cover crops in central and north Florida, such as rye, barley, wheat or oats, can support limited reproduction of root-knot nematode. To avoid an increase in root-knot populations, these crops should only be planted when soil temperatures are below 65°F, a threshold temperature for nematode activity. Cover crop rotations with some pastureland grasses (particularly pangola digitgrass, and to some extent bahiagrass, and bermuda grass) have significantly reduced, but not eliminated, root-knot nematodes.

In north Florida, long term (6- to -9 year) pastureland rotations have allowed economic melon production within root-knot infested fields. It should be recognized that as the crop rotation period is shortened or eliminated, nematode problems will intensify accordingly. Other perennial legumes currently under evaluation may play an important role in future nematode management programs.

For cover crops to be most effective, stands must be established quickly and undesirable weeds which can serve as alternative hosts must be controlled (Figure 12). Given that many different weeds serve as alternative plant hosts to nematodes (ie. nutsedges), it may not be possible to manage root-knot nematode with crop rotation unless an integrated program to manage weeds is also considered and implemented within the field. With many cover crops, rapid stand establishment has been a significant problem. Similarly, economic crop rotation sequences are often further complicated by lack of crop management skills, specialized equipment to grow and harvest the crop, or by the lack of closely located processing facilities or markets. In some cases other measures should be considered such as fallowing which is usually as

efficient as crop rotation for reducing field infestations of nematodes.



Figure 12. Effective use of cover crops for nematode management require exclusion of undesirable weeds which can serve as excellent hosts for nematode reproduction.

Fallowing

Clean fallow during the off-season is probably the single most important and effective cultural control measure available for nematodes. When food sources are no longer readily available, soil population densities of nematodes gradually decline with death occurring as a result of starvation. Due to the wide host range of many nematode species, weeds and crop volunteers must be controlled during the fallow period to prevent nematode reproduction and further population increase. At least two discing operations is generally required to maintain clean fallow soil conditions during the interim period between crops.

Fallowing by use of herbicides to deplete nematode populations is a much slower process because the soil is not disturbed, thereby subjecting nematodes from deeper soil layers to the drying action of sun and wind. The unfavorable effects of fallowing on soil organic matter and soil structure is usually more than compensated for by the level of nematode control achieved and the resulting increase in crop productivity. When soil erosion is a

potentially serious problem other measures should be considered.

Biological Control

At present there are no effective, commercially available, biological control agents which can be successfully used to control nematodes.

Plant Resistance

Use of nematode-resistant crop varieties have not been extensively evaluated in Florida, but is often viewed as the foundation of a successful integrated nematode management program, particularly on all high value crops in which methyl bromide is currently used. Commercially available nematode-resistant varieties are currently available only for tomato, pepper, southernpea, and sweet potato. In a resistant variety, nematodes fail to develop and reproduce normally within root tissues, allowing plants to grow and produce fruit even though nematode infection of roots occurs. Some crop yield loss can still occur however, even though the plants are damaged less and are significantly more tolerant of root-knot infection than that of a susceptible variety.

In tomato, a single dominant gene (subsequently referred to as the Mi gene) has been widely used in plant breeding efforts and varietal development which confers resistance to all of the economically importance species of root-knot nematode found in Florida, including *Meloidogyne incognita*, *arenaria*, and *javanica*. Commercially resistant fresh market varieties, climatically and horticulturally adapted for Florida, have only become recently become available utilizing the gene. Unfortunately, in previous research with resistance tomato varieties, the resistance has often failed as a result of the heat instability or apparent temperature sensitivity of the resistant Mi gene. For example, previous research has demonstrated threshold soil temperatures and incremental reductions in nematode resistance with each degree above 82° F, such that at 89°F, tomato plants are fully susceptible (Figure 13). This would suggest that in Florida, use of these varieties may have to be restricted to spring plantings when cooler soil temperatures prevail.

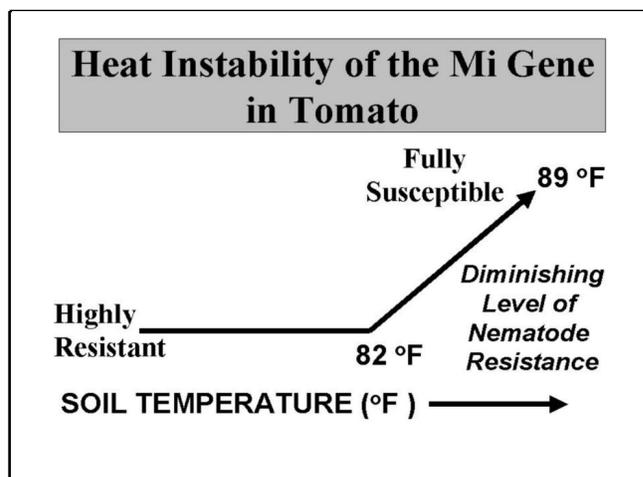


Figure 13. Diagrammatic representation showing the complete loss of root-knot nematode resistance conferred by the Mi gene in tomato with increasing soil temperature.

In pepper, two newly developed root-knot nematode resistant varieties (Carolina Belle and Carolina Wonder) were released from the USDA Vegetable Research Laboratory for commercial seed increase in April 1997. Both varieties are open pollinated, and homozygous for the N root-knot nematode resistant gene. Preliminary research has demonstrated that these varieties confer a high degree of resistance to the root-knot nematode, however expression of resistance is heat sensitive. Further research is necessary to characterize the usefulness of these varieties under the high soil temperature conditions of Florida. Like tomato, use of these varieties may have to be restricted to spring plantings when cooler soil temperatures prevail.

In addition to problems of heat instability, the continuous or repeated planting of resistant plant varieties will almost certainly select for virulent races of *Meloidogyne* capable of overcoming the resistance. Therefore the duration and/or utility of the resistance may be time-limited. In previous field studies evaluating sequential plantings of resistant tomatoes, resistance breaking nematode races were shown to develop within 1 to 3 years. Since new races of the nematode can develop so rapidly, a system of integrated control usually mandates the rotation of resistant and non-resistant (susceptible) varieties to slow the selection process for new virulent races.

Recent trials in Florida have already demonstrated the capacity of some species or races of root-knot to reproduce and inflict damage upon a

resistant tomato variety. The results of these experiments have also demonstrated that even with a resistant variety, which were damaged less than that of a susceptible variety, some consideration of initial soil population levels of the root-knot nematode must be observed to minimize tomato yield losses. Given that significant yield losses can still occur, combined efforts to manage soil populations to low levels prior to planting must still be considered, particularly if tomatoes are planted as a fall crop. If this situation develops, the combination of a nematicide and resistant variety may also comprise an option to reduce nematode populations to nondamaging levels.

Soil Amendments

Many different types of amendments and composted materials have been applied to soil to suppress populations of plant parasitic nematode and improve crop yield and plant health. Animal manures, poultry litter, and disk-incorporated cover crop residues are typical examples of soil amendments used in agriculture to improve soil quality and as a means for enhancing biocontrol potential of soil. Some amendments which contain chitin and inorganic fertilizers that release ammoniacal nitrogen into soil suppress nematode populations directly and enhance the selective growth of microbial antagonists of nematodes. More recently, composted municipal wastes and sludges have been used to amend soil to improve soil fertility, organic matter content, water holding capacity, nutrient retention, and cation exchange capacity.

Suppression of soilborne pathogens via the incorporation or simple mulching of composted amendments is reputedly based on enhanced microbial activity and increased numbers of antagonists generated by decomposition of the amendment in soil. Soils with a diversity of beneficial microorganisms are more suppressive to pathogens than soils with little or no biological diversity. Other possible mechanisms for pathogen suppression by composts include direct inhibition of the pathogen or reduced infectivity of the organisms into the plant host. Population increases of beneficial organisms in soil appears to be the direct result of environmental changes brought about by the amendments after addition to soil. This suggests that to sustain soil

suppressiveness, amendments must be periodically reapplied to maintain the soil environment conducive to antagonists.

The level to which soilborne pest and disease control can be achieved is not only related to the type of material but to the age of the compost. Nematode and disease suppression has been repeatedly demonstrated with composted municipal yard wastes containing significant quantities of tree bark. If the compost is immature, the product may not only be difficult to handle and have an offensive odor, but may contain salts and metabolites toxic to plants. For example, weed suppression has been demonstrated with some types of immature composted materials which contain and or produce organic acids with phytotoxic properties.

Other studies have shown that soils amended with different sources of composted municipal wastes were disease suppressive as long as they were relatively fresh (< 6 months), but as the composted municipal waste was aged, disease suppressiveness was lost. In other Florida studies, application of composted municipal wastes at rates up to 120 tons per acre have not been shown to be pesticidal in activity, but actually dramatically increased populations of nematodes and other disease organisms such as *Fusarium* and *Phytophthora* spp. Nematode population increases were directly related to increases in plant growth and root system size with amendment application rate.

Recent studies in Florida have also been conducted to determine the extent to which increasing application rates of a municipal solid composted waste effect the ability of tomato plants to tolerate root infection by species of root-knot nematode (*Meloidogyne* spp.) These studies showed that in a sandy soil, poor in organic matter content (less than 2%), tomato yields could be increased significantly with soil amendments in both nematode free or nematode infested soil. The impact of the root-knot nematode on tomato yield was effectively constant however, suggesting that application of the soil amendment did not enhance the ability of tomato plants to tolerate infection by the root-knot nematode. Much of the previous and ongoing research in Florida also seems to indicate that the major effects of soil

amendments to crop yields appear to be less related to nematode or soil pathogen control than to enhanced plant nutrition and nutrient and water availability.

It is not clear at this time and preliminary stage of university field research whether benefits to crop growth after the initial crop following soil amendment application can be expected. Recent studies showed no response in second crop tomato yields (double crop) following amendment application rates from 15 to 120 tons per acre. Disappearance of nutrients and soil organic matter content appears to be very rapid in the hot, moist soils of Florida. Preliminary research suggests that reapplication of the amendments may have to be made on a near annual basis to sustain crop growth and yield benefits.

In summary, the high rates of application (tons / acre) and attendant costs required for crop response and nematode control for many different types of organic amendments, and the apparently rapid losses of the materials in soil appears to preclude use of these materials primarily to homeowner or small farm operations at this time. However, with additional research and advances in application technology and use efficiency, use of soil amendments may become an integral component of Florida crop production systems.

Flooding

Flooding has been shown to suppress nematode populations (Figure 14). Alternating 2 to 3 week cycles of flooding and drying have proven to be more effective than long, continuous flooding cycles. At present, only limited areas within the state are situated to take advantage of flooding as a viable means of nematode control. Given the growing concern about aquifer depletion, salt water intrusion, and water use inefficiencies, it seems unlikely that Florida water management officials will continue to permit flooding within these areas in the future.

Soil Solarization

Soil solarization is a nonchemical technique in which transparent polyethylene tarps are laid over moist soil for a 6 to 12 week period to heat noncropped soils to temperatures lethal to nematodes



Figure 14. Extended periods of off-season field flooding can promote the decline of soil population density of nematodes in production fields.

and other soil-borne pathogens (Figure 15). Soil temperatures are magnified due to the trapping of incoming solar radiation under the clear, polyethylene panels.



Figure 15. Soil solarization, the use of clear plastic panels as bed coverings to heat non-cropped soils to temperatures lethal to nematodes and other soilborne pathogens.

To be effective, soils must be wetted and maintained at high soil moisture content to increase the susceptibility (thermal sensitivity) of soil borne pests and thermal conductivity of soil. Wet mulched soils increase soil temperatures due primarily to the elimination of heat loss by evaporation and upward heat convection, in addition to a greenhouse effect by prohibiting dissipation of radiation from the soil. At the end of the solarization period the clear plastic is painted with a white latex paint to allow continued use of the plastic as a mulch cover for the production of vegetables on raised beds.

The most successful use of soil solarization appears to occur in heavier (loamy to clay soils) rather than sandy soils. Soils with poor water holding capacity and rapid drainage can significantly inhibit heat transfer to deeper soil horizons. Loss of pest control is directly correlated with soil depth. The depth to which lethal temperature can be achieved (6 to 8 inches) is also dependent on the intensity and duration of sunlight and ambient temperature.

At present, the only time to consider soil solarization for pest control is during our hot, summer and early fall months, which fortunately are 'off-season' in most peninsular Florida vegetable row crops. Unfortunately our summers are also our wettest period of the year with frequent afternoon rain showers which have a cooling effect on the soil.

Many different pests have been suppressed and or controlled by soil solarization, particularly within arid environments with intense sunshine, and limited cloud cover and rainfall. Recent studies in Florida have demonstrated that soil solarization can also be effective in a subtropical environment.

Plant parasitic nematodes have generally proved to be more difficult to control with soil solarization, as has some weed pests such as crabgrass in a central Florida study. The results of preliminary experiments are also suggesting the potential for selection pressures towards a buildup of heat tolerant individuals which may serve to reduce soil solarization efficacy after repeated use as a nematode control tactic.

In some studies, effective use of solarization for nematode control has required an integrated systems

approach, coupling solarization with other chemical or nonchemical approaches. For example, the combined use of soil solarization with a nematicide has improved nematode control and crop yield. In addition, use of virtually impermeable, photo-selective plastic mulches may also complement low dose fumigant treatments to reduce weed seed germination and growth in the event of extended periods of cloud cover occurring during the solarization regime. At this time, further research is needed demonstrating soil solarization pest control activity and consistency in the various geographical regions of Florida where vegetable crops are grown.

Other Cultural Practices

One of the foundation principals of an integrated nematode management strategy is to ensure early destruction of the crop immediately after final harvest (Figure 16). The major objective is to remove the plant food source (roots) which maintains nematode reproduction and soil population growth. Any delay in crop termination can significantly increase soil populations of nematodes, particularly in the span of a few weeks after final harvest if the plant and its roots are not killed immediately. In general, the more nematodes left in the soil after a crop, the more which will survive to infect roots of the following crop, and the more difficult it will be to achieve satisfactory nematode control with any chemical nematicide. Clearly, the opportunity to enhance nematode control with soil fumigation and minimize losses in crop yield due to nematodes is dependent upon the adoption of early crop destruction after final harvest.



Figure 16. Early crop destruction of select rows within a strawberry production field, utilizing a water soluble fumigant applied via the drip irrigation system.

Currently, tomato fields are sprayed with paraquat in a 'top - down' approach to kill the foliage after harvesting is completed in the spring or fall (Figure 17). While foliage is killed, roots are initially unaffected by the paraquat treatment, and nematode reproduction continues until nutrient reserves within roots are exhausted and roots die. New field research efforts are evaluating a 'bottom - up' approach in which water soluble fumigants are chemigationally applied via drip irrigation to simultaneously and immediately: 1) kill the roots; 2) stop nematode reproduction; 3) reduce soil population levels of nematodes; and 4) kill the foliage, as in the paraquat treatment. Previous research has demonstrated the feasibility of the approach with drip applied metham sodium (Vapam), and more recently with metham sodium or Telone EC. Results of recent field research trials have clearly demonstrated the ability to kill foliage via destruction of roots. Soil populations of nematodes also were substantially reduced in the 'bottom - up' approach. However, the efficiency in reducing nematode populations in soil was directly related to the volume of water supplied and the resultant distribution of the water soluble fumigant within the bed. To maximize the efficiency of the 'bottom - up' approach will require additional on-farm chemigation research to determine the most appropriate drip emitter spacing and injection period to maximize bed coverage within the plant row.

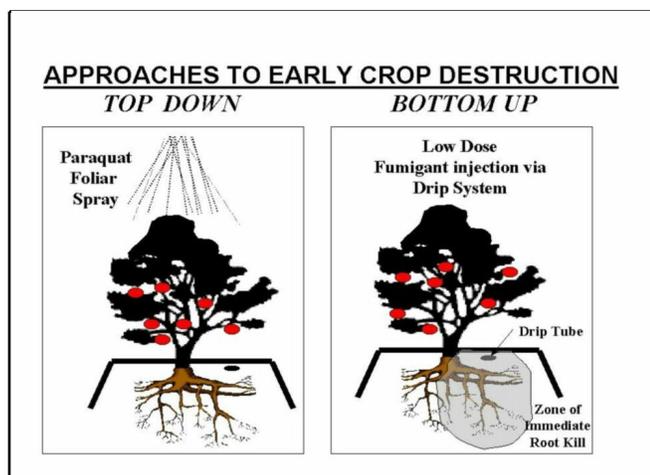


Figure 17. Comparison of top down crop destruction approach utilizing a foliar applied herbicide and a bottoms up approach to kill plant roots using a drip injected fumigant.

Use of nematode free transplants is also a recommended cultural practice since direct seeded

plants are particularly susceptible since they are vulnerable to injury for a longer duration, during an early, but critical period of crop development.

Since nematodes can be carried in irrigation water that has drained from an infested field, growers should avoid use of ditch or pond waters for irrigation or spray mixtures. In most cases, a combination of these management practices will substantially reduce nematode population levels, but will rarely bring them below economically damaging levels. This is especially true of lands which are continuously planted to susceptible crop varieties. In these cases some form of pesticide assistance will still usually be necessary to improve economic crop production.

Chemical Control

Nonfumigant Nematicides

All of the nonfumigant nematicides (Table 2) currently registered for use are soil applied, with the exception of Vydate, which can also be applied foliarly. They must be incorporated with soil or carried by water into soil to be effective. These compounds must be uniformly applied to soil, targeting the application toward the future rooting zone of the plant, where they will contact nematodes or, in the case of systemics, in areas where they can be readily absorbed. Placement within the top 2 to 4 inches of soil should provide a zone of protection for seed germination, transplant establishment, and protect initial growth of plant roots from seeds or transplants.

Most studies which have been performed in Florida and elsewhere to evaluate non-fumigant nematicides have not always been consistent, either for controlling intended pests or for obtaining consistent economic returns to the grower, particularly when compared with conventional preplant mulched fumigation with methyl bromide or other broadspectrum fumigants. As the name implies, they are specific to nematodes, requiring integrated use of other cultural or chemical pest control measures. Many are reasonably mobile and are readily leached in our sandy, low organic soils, thus requiring special consideration to irrigation practices and management.

Nematode management must be viewed as a preplant consideration because once root infection occurs and plant damage becomes visible there are very few nematode management options available to help resolve the nematode problem and avoid potentially significant crop losses. In this regard, pest and crop monitoring activities are very important considerations for early detection of pending problems. Once the discovery is made that nematodes have colonized plant roots and stunted crop growth, the question is whether it is possible to effectively reduce nematode population levels and restore crop yield potential.

At present the only post plant nematicide which can be used in some crops to help resolve an established nematode problem is Vydate (Oxamyl). Vydate is not considered a true nematicide, but rather a nematostat. Nematostats, rather than kill nematodes, induce a narcotic effect which paralyzes the nematode and prevents it from feeding, movement, mating, and other normal activities. The narcotic effect is only as persistent as adequate Vydate concentrations are maintained within soil and roots. Following nematicide application, irrigation and rainfall can dilute and leach toxic concentration from the nematode environment, thereby restoring the nematodes ability to conduct normal bodily functions. As a result, repeated and sequential Vydate applications to soil are required to maintain toxic (narcotic) concentrations. Field observations of crop rescue attempts with Vydate injections via the irrigation system have usually demonstrated some improvement to plant growth and vigor, but not necessarily yield. Many factors simultaneously interact to influence the extent to which plants respond to Vydate treatment. Not all factors are well understood at this time.

In general, use of Vydate as a postplant, crop rescue treatment for nematodes should considering the following:

1. Foliar applications of an upward and downwardly mobile systemic, such as Vydate, have not proven to be consistently effective for nematode control or for improved plant growth response. Vydate treatment should not be considered unless made via the drip irrigation system.

2. Fields with previous history of nematode problems should be closely monitored after transplanting. The sooner a nematode problem is identified in the field and the sooner Vydate treatments are initiated, the greater the response in plant growth and yield will be. Clearly the nematode problem and impact to crop yield will intensify over time if nothing is done, particularly if the plant undergoes periods of moisture stress.
3. Regardless of the time of discovery in the field, plant with roots which are heavily galled are not likely to respond satisfactorily (stage a dramatic comeback) to Vydate treatment.
4. The inability to uniformly distribute Vydate along the entire plant row via the irrigation system in itself sets a limit to the degree of possible plant improvement.
5. After Vydate application, the effect of daily irrigation (ie., two or more times per day) on Vydate soil and root concentrations and crop yield response is not well understood. However, given the possible dilution and leaching effect of daily irrigation cycles, repeated weekly applications throughout the remainder of the growing season were demonstrated to be superior to 1 or 2 early season applications made immediately after discovery of the nematode problem in the field.

Fumigant Nematicides

In Florida, use of broadspectrum fumigants effectively reduces nematode populations and increased vegetable crop yields, particularly when compared with nonfumigant nematicides. Since these products must diffuse through soil as gases to be effective, the most effective fumigations occur when the soil is well drained, in seedbed condition, and at temperatures above 60°F. Fumigant treatments are most effective in controlling root-knot nematode when residues of the previous crop are either removed or allowed to decay. When plant materials have not been allowed to decay, fumigation treatments may decrease but not eliminate populations of root-knot nematodes in soil. Crop residues infested with root-knot nematode may also

increase soil populations to the extent that significantly higher rates of application may be required to achieve nematode control. To avoid these problems, growers are advised to plan crop destruction and soil cultivation practices well in advance of fumigation to insure decomposition of plant materials before attempting to fumigate.

The proposed ban on methyl bromide in the U.S.A. in 2005 will no doubt create a void for Florida farmers in the chemical arsenal currently used for soilborne pest and disease control. This fact is made quite clear from a review of recent field research trials conducted in Florida which shows that no single, equivalent replacement (chemical or nonchemical) currently exists which exactly matches the broadspectrum efficacy of methyl bromide. In preparation for the phase-out and loss of methyl bromide, university research programs within Florida have been intensified to identify and evaluate more robust strategies which minimize cropping system impacts, accounting for a diverse range of pest pressures and environmental conditions.

Based on summary and comparison of methyl bromide alternative chemical trial results in Florida since 1994, Telone C-17 or Telone C-35 (1,3-Dichloropropene plus 17% or 35% Chloropicrin), in combination with a separately applied herbicide for weed control, has been identified as the best chemical alternative replacement for methyl bromide for some vegetable row crops such as tomato, pepper, and strawberry. This has also been demonstrated in large scale, commercial field trials around the state. In these studies, use of any of the other alternative fumigants, except Telone C-17 or C-35 and chloropicrin in combination with a herbicide treatment, resulted in lower yields than that of methyl bromide with increasing pest pressure. Under conditions of high pest pressures (nematodes, disease), other IPM practices might also be required and combined to achieve adequate control and economic crop productivity. (See other Methyl Bromide Documents: ENY-034, ENY-046, ENY-048, ENY-049.)

All of the fumigants are phytotoxic to plants and as a precautionary measure should be applied at least 3 weeks before crops are planted. When applications

are made in the spring during periods of low soil temperature, these products can remain in the soil for an extended period, thus delaying planting or possibly causing phytotoxicity to a newly planted crop. Field observations also suggest rainfall or irrigation which saturates the soil after treatment tends to retain phytotoxic residues for longer periods, particularly in deeper soil layers.

Summary

In summary, nematode control measures can be conveniently divided into 2 major categories including cultural and chemical control measures. None of these measures should be relied upon exclusively for nematode management. Rather, when practical and economics permit, each management procedure should be considered for use in conjunction with all other available measures for nematode control and used in an integrated program of nematode management.

In addition to nematodes, many other pests can cause crop damage and yield losses which further enforces the development of an overall, Integrated Pest Management (IPM) program, utilizing all available chemical and nonchemical means of reducing pest populations to subeconomic levels. An IPM approach further requires that growers attempt to monitor or scout fields for pest densities at critical periods of crop growth.

Prescriptive Approaches to Soil Pest Control with Methyl Bromide and Chloropicrin

During development, plants are frequently exposed to different levels and complexes of competing pests. A combination of pest stressors on plant growth may interact such that the combined effects of the pest complex are greater than the added effects of each pest. Nematode parasitism frequently increases plant susceptibility to plant pathogenic fungi and bacteria. The interaction among pests is well documented in tomatoes on old production land when *Fusarium* wilt disease and Root-knot nematode (*Meloidogyne* spp.) are both present (Figure 18). Young plants are very susceptible to the combination of pests, collapsing prior to harvest. The nematode,

by impairing water and nutrient availability, disrupts root function and plant growth processes. These effects combined with the vascular blocking due to the wilt fungi can be particularly severe, and if widespread, result in total crop failure.



Figure 18. The simultaneous occurrence of both root-knot nematode (*Meloidognyne* spp.) and Fusarium wilt disease (*Fusarium oxysporum*) causing enhanced disease development and tomato yield loss.

This interaction between pests seriously limits the use of economic thresholds developed for individual pests and justification for specific, individual pest-oriented control strategies. The severity and reoccurring nature of multiple-pest problems, as in tomato production on old land, underscores the need for control strategies which consider population density of all members of the pest complex and their combined impact on crop yield.

Methyl bromide (MB) and chloropicrin (CP) are marketed as broad spectrum soil fumigants to control such soil-borne pests as insects, weeds, nematodes, and fungi. They are currently registered within Florida under various labels and formulations as preplant treatments for tomatoes, peppers, eggplant, broccoli, cauliflower, melons, strawberry, and seedbeds for transplants (see Methyl Bromide/Chloropicrin Formulations Registered for Vegetable Crop Use). MB is commonly mixed in various proportions with CP. In low concentrations, CP is used primarily as a field marker for detection of escaping MB fumes.

Since the discovery of CP in 1848 and MB in 1932, considerable research has been done to evaluate their dispersion and dissipation characteristics and efficacy of each against a myriad

of urban, storage, and soil-borne pests. Even with this extensive research base, some uncertainty exists concerning the broad spectrum activities of MB, CP, and their mixtures.

Lethal levels required to control individual pests are determined from study of dose-response relationships of individual pests with each pesticide product. Pest control practices are then generally based on pesticide levels required to kill the most tolerant or resistant economically important pest species. In general, the degree of nematode or general soil pest control increases non-linearly as fumigation rate increases. In the case of MB-CP mixtures, product selection becomes more complex since each compound is known to possess greater toxicity than the other to specific pests. This differential toxicity of the two components of MB-CP mixtures should allow a more prescriptive approach to pest control for fields with differing pest complexes.

Weeds

In the case of different weeds, the relative susceptibility of different weeds to MB and CP formulations and dosage levels have not been adequately assessed. MB is the primary herbicidal agent for the MB-CP mixture and the weed control properties decrease as the rate per acre of the MB decreases. This is especially pertinent to weed species with hard seed coats or large corms or tubers. Many weeds, including mallow, morning glory, vetch, dodder and some species of clover are difficult to control at recommended rates and methods of application and marked growth stimulation, especially of grasses and hard seeded legumes can also occur in response to inadequate rates of fumigation. At a broadcast rate of 400 lbs/a, nutsedge control can be marginal with formulations of 67-33% (268 lb MB/a); this has therefore promoted the use of 98-2% methyl bromide-chloropicrin formulation (392 lb MB/a) for more effective nutsedge control.

Failure to control tolerant weeds such as nutsedge and pigweed with MB is most frequently related to inadequate soil preparation and dry soil conditions prior to fumigation. Pretreatment irrigation 1 to 2 weeks prior to fumigation is recommended to encourage seed/tuber germination

and susceptibility to diffusing gases. Weed control at the bed surface may also be incomplete midpoint between injection points and permit weeds to compete with transplants set off-center of the injection path.

Nematodes

In general, nematodes are much more sensitive to the multipurpose fumigants than are fungi, bacteria, weeds, or most forms of soil dwelling insects. Although sensitive, many nematodes still survive the fumigant treatment even at application rates sufficient to affect other more tolerant pests. The survival of nematodes is influenced by many factors. The presence of large, undecayed roots prior to treatment can shelter endoparasitic nematodes from lethal gases. It has been shown that undecayed roots can be 8 to 16 times more resistant to fumigants than the pests or pathogens living in them and this resistance increases markedly with root size. Inconsistent control of root-knot nematodes has occurred with CP when complete decay of infested roots was not achieved prior to fumigation. Conversely, excellent control of root-knot nematode-infested roots has been obtained with MB, which penetrates intact root tissues more readily.

The vertical migration of nematodes within the soil, especially prior to cool and/or dry fallow periods is now being considered as another important factor which maintains populations below treated zones following fumigation. In very dry soils, many nematodes which can survive in a dehydrated state can tolerate 10 times the dose lethal to active forms in moist soils. The rapid escape of volatilizing gases near the soil surface only compounds the problem. Another commonly overlooked factor is dosage level, the quantity of chemical per unit area of soil required to achieve control. Dosage levels required for effective control vary not only with soil type, soil moisture, and temperature but also nematode infestation level. Higher dosages are generally required to reduce higher populations to desired subeconomic levels.

Other Plant Pathogens

MB and CP are also used to reduce the incidence of soil borne fungal pathogens such as *Fusarium* and *Verticillium*. In field and laboratory studies, MB has generally failed to control *Verticillium*, even at rates in excess of 200 lbs/a. In other tests, MB was ineffective for control of *Fusarium* and *Corynebacterium*. Microslerotia of *Verticillium* are difficult to kill and control of the microslerotial forming fungi decreases rapidly with MB dosage, especially in soils with high organic content. In contrast to MB, CP is an excellent fungicide, active against many plant pathogenic fungi of economic importance. Toxicological studies relating the level of control of soil borne plant pathogens to increasing levels of CP in MB mixtures have not been performed or are not readily available. In some cases it has been shown that percent control of *Verticillium*, *Fusarium*, *Rhizoctonia*, *Phythium*, and *Thielaviopsis*, all economically important fungal pathogens, increased when chloropicrin was added to MB. This increased level of control in relation to MB or CP alone is apparently due to the additive toxicity of the two compounds together.

Formulation Assessment

Based solely on the above toxicological information, some general guidelines for MB-CP formulation decisions can be inferred. In fields where the primary objective is weed control, formulations emphasizing MB should be used as in formulations with 98% MB and 2% CP. Formulations with 67% MB and 33% are generally regarded as borderline for nutsedge control. In fields where plant pathogenic fungi are the primary problem, formulations emphasizing CP should be used, as in 67% MB and 33% CP. For nematode control, MB has certain advantages over CP. MB is cheaper, easier to handle, less corrosive to equipment and permits field replanting sooner than CP. If chloropicrin is used at high levels in the formulation, then treatment and consequently replanting should be sufficiently delayed to allow for root decay and to prevent any undesirable phytotoxic effects to the following crop.

The higher price of chloropicrin relative to methyl bromide is, in addition to differential toxicity,

an important economic factor influencing fumigant use, rate, and formulation decisions. The difference in price allows the use of greater field dosage rates of MB than other formulations when equivalent material costs are considered.

The real cost to the grower is not solely determined by comparison of the difference in product price. The comparative efficacies of the different rates and formulations of methyl bromide and chloropicrin are important considerations, especially pertinent when equivalent costs are evaluated. Formulation decisions based entirely on material costs can result in production losses due to marginal or incomplete control of MB tolerant or resistant pests. In this case the philosophy that 'more is always better' can have serious economic consequences and should be avoided. At the same time it underscores the need for further study and economic analysis comparing returns over costs for different rates and formulations of fumigant nematicides.

The environmental and nutritional consequences of pesticide use is becoming of primary concern to many public and governmental agencies. Agricultural chemical are more closely scrutinized, especially as they relates to environmental fate, toxicity, worker safety, and pesticide misuse. Development of more prudent and efficient pest management strategies is therefore essential.

Chemigation

Chemigation refers to the injection and delivery of agrichemicals through an irrigation system which are now increasingly used in Florida agriculture to deliver nematicides, as well as other broad spectrum fumigant materials to control soil insects, nematodes, fungi, and weeds. Both federal (EPA) and state regulatory agencies (DACS) currently permit application of these compounds through drip irrigation systems provided: 1) necessary backflow, antisiphon irrigation equipment is installed; 2) the treated crop is contained on the pesticide label; and 3) the pesticide label specifically details instructions for irrigation injection. In general, chemigation of nematicides has been shown to be both feasible and effective when the drip irrigation and chemical

injection systems are properly installed, calibrated and operated, and when the proper chemicals are utilized and applied uniformly. In this regard chemigation is no different from conventional pesticide application systems in that effective nematode control will always be contingent upon the care and precautions taken to insure proper soil conditions and accurate calibration and uniform delivery of nematicides.

In general, the delivery of nematicides through drip systems appears to be a promising approach for precision application to the principal root zone of plants and for controlling nematodes prior to planting, for postplant applications to infested crops to salvage yield, or for post harvest, crop destruction and nematode management (Figure 19). For many high value vegetable crops, the future of chemigation appears to lie in its use for multiple cropping systems, enhancing yields of the 2nd crop, in conjunction with soil fumigation and film mulch with the primary crop. However, various problems continue to plague us in Florida with regard to crop and pest control response variability for soil chemicals applied via a drip irrigation delivery system.



Figure 19. Early crop destruction of select strawberry rows within a production field, utilizing a water soluble fumigant applied via the drip irrigation system.

Most Florida vegetable soils are classified as fine sands with low water holding capacity and high hydraulic conductivity, which allows water to easily, and in some cases the chemicals in them, to rapidly percolate through soil. Recent field research evaluating various irrigation practices and total irrigation water volumes have been conducted to increase our understanding of the dynamic of water movement in soil. The objective of this research is to

achieve a broader based, environmentally sound, use recommendation for chemigated compounds. Although this work is ongoing, significant advancements have been made in the commercial development of drip application technologies by conducting field evaluations of how drip irrigation water, colored with a blue tracer dye, moves in soil within a raised, mulch covered, plant bed (Figure 20).



Figure 20. Illustration of the incremental radial expansion of the wetted zone in a raised plant bed after pulsing the injection of a blue, water soluble, dye applied through a drip irrigation system. Each ring represents 2 hours irrigation run and injection time.

Water Movement in Soil

During the injection process, chemigated pesticides are delivered to the plants rooting zone within a limited wetted area directly below each drip emitter. From a single drip emitter, a small, circular wetted area may only be visible at the soil surface in many of the coarse sands characteristic of crop production in Florida. For short irrigation cycles and limited water volume, the shape of the wetted zone tends to be circular, with a dry zone midway between emitters (Figure 21). However, the width, depth, and cross-sectional area of the wetted zone generally increases with irrigation water volume, typically forming a hemispherical shape until water fronts from adjacent emitters along the drip tape collide (Figure 20). As water fronts from adjacent emitters collide, a wetted strip usually develops parallel to the drip line (Figure 22). In general, the convergence of the wetting fronts midway between emitters is a much slower process as the distance increases between individual emitters on the drip tube. For chemigational purposes therefore, where maximum bed coverage along the entire bed is important,

emitters which are to widely spaced along the row (18 to 24 inches) are likely to compromise overall treatment efficacy with most chemigated, nematicidal compounds.



Figure 21. Top, side, and cross sectional view of a raised plant bed illustrating the small, circular wetted areas beneath individual drip irrigation emitters using a blue tracer dye injected into the irrigation water. Drip injection time of 2 hours.



Figure 22. Top, side, and cross sectional view of a raised plant bed illustrating the development of a wetted strip after water fronts from adjacent emitters collide. A blue, water soluble, tracer dye is injected into the irrigation water to characterize drip water movement over time.

Bed Coverage

As indicated previously, the size and volume of wetted soil, defined as bed coverage, increases with irrigation volume. In the overall analysis of the relationship between total irrigation water volume and bed wetted zone (coverage), it appears that most bed wetting occurs in the time to deliver the first 300

gallons of water expressed per 100 linear feet of bedded row. Use of greater volumes of irrigation water will not insure expanded bed coverage but drive water fronts deeper into soil. If a maximum water penetration depth of 16-20 inches from the top of the bed is assumed adequate for nematode control, then irrigation run times required to deliver water volumes of 100 to 200 gallons per 100 linear feet of row should not be exceeded so as to contain the wetting front within the future rooting zone of the plant in the bed.

Bed coverage can be easily determined if the dimensions of the plant bed are known. For a typical 9 inch tall raised bed, drip emitter spacings of 12 inches, and a bed width of 36 inches, the entire plant bed is usually not wetted during a single, short irrigation cycle. Since bed coverage is so strongly related to volume of water applied, relatively high volumes of water are needed to cover a large percentage of the soil volume in the bed. However, even long irrigation cycles of 10 to 12 hours may not effectively disperse water all the way to the shoulders of the raised bed (Figure 23). In the sands of Florida, a maximum radial movement of 8 to 10 inches from the drip source, or 50 to 60 percent of total bed volume, could be achieved with irrigation run times upwards of 12 hours. For a given water volume, the use of two drip tapes per bed always increased spatial distribution of irrigation water (treated volume) such that bed coverages upwards of 85 to 95 percent was achieved. Greater bed coverage occurs simply because of the spacing between drip tubes on the bed and the increased number of emission points along the bed. In dry seasons with little or no rainfall and declining water tables, limited movement of water into the shoulder of the plant bed has also been observed, even when two drip lines per bed have been used to supply irrigation water.

The vertical and horizontal movement of water in the plant bed following irrigation is dependent on many factors other than water volume, the most important of which is soil type (hydraulic conductivity and water holding capacity), initial soil moisture conditions, soil compaction, and presence of a shallow subsurface impermeable soil horizon, compacted traffic layer, or perched water table. On sandy soils, nematode control maybe limited by the



Figure 23. Cross sectional view of a raised plant bed illustrating how irrigation water may not move radially outwards to the sidewalls or shoulders of the bed, even after long irrigation cycles. A blue, water soluble, tracer dye is injected into the irrigation water to characterize drip water movement over time.

width and depth of the wetting pattern and the distribution of pesticide within the wetted zone. Factors which affect water infiltration and radial movement will also affect the location of the chemical in the soil. For example, the presence of a shallow compacted traffic layer at a 6 to 8 inch soil depth has been observed to severely restrict downward penetration of drip water, and in some instances has resulted in the flooding of row middles once saturation of soil above the restrictive layer occurs. In the presence of a traffic compacted layer, the use of two drip tubes per bed only expedites the time in which flooding occurs within the field.

Chemical Movement

Nematicides applied with irrigation water are carried by water into the soil but are generally not moved throughout the entire wetted zone but only a proportion of the distance moved by the water itself. Limited horizontal movement of irrigation water in many coarse textured Florida sands have inhibited the efficacious use of nematicides. In general, nematode control has increased as the broadcast application rate increased and when the drip tube was shallowly buried (< 4 inches) in the soil. Drip irrigation systems have also been successfully used to deliver soil fumigants nematicides such as methyl bromide and chloropicrin into mulched beds through bi-wall tubing prior to planting using a hot gas method. Excellent

weed and nematode control have been obtained and crop yields significantly increased. Application of fumigant nematicides through micropore tape has been ineffective for controlling nematodes or improving yields due to a rapid loss and poor linear distribution of the fumigant along the tape. Many other factors also affect nematicide transport through soil including chemical solubility, organic matter adsorption, and microbial degradation.

Calibration and Injection

For proper calibration growers must have field specific information regarding the size and shape of the wetted area, particularly as they relate to the quantity and duration of a single application of irrigation water. For some nematicides, the amount of chemical injected into the drip irrigation system would then be calculated according to the surface area of each acre actually wetted by emitters. Calculation of pesticide rates are frequently based entirely on bed width and assumptions of uniform movement and distribution of the pesticide throughout the wetted zone which, in fact, seldom occurs. When pesticide rates are calibrated based solely on bed width and not wetted zone, then pesticides may be applied at phytotoxic levels in the volume of the plant bed in which the pesticide is distributed. Poor root growth may occur in areas where nematodes are controlled due to phytotoxic effects as well as in areas where nematodes are not exposed to the chemical.

If the entire bed is wetted during an irrigation cycle, the amount of chemical injected per acre is a simple proportion (bed width/row spacing) of the maximum broadcast rate of application. When the entire bed is not wetted, then the calculation becomes more complex since the maximum cross sectional area of the wetted zone or the average width of the wetted band must be determined. The average width of the wetted band is then related to row spacing to determine what proportion of the broadcast rate to apply.

Once the overall pesticide rate has been calculated, the next step is determining when and for what duration the chemical will be injected into the irrigation cycle. Chemicals injected too early in the

irrigation cycle may be effectively pushed out of the rooting zone with continued application of water (Figure 25). If injected over a short period, the chemical may form only a small hemispherical zone of effective control around each emitter. The injection time must also reflect the time required to flush the chemical from the irrigation lines. Ideally, the chemigation operation will disperse and maintain the chemical throughout the entire rooting zone of the plant, at toxic concentrations, for sufficient time to be effective.

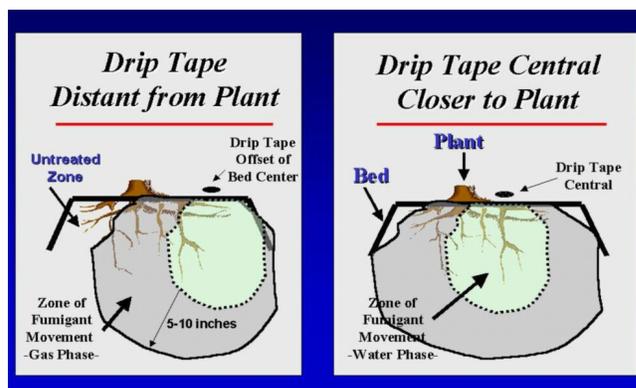


Figure 25. Diagrammatic representation of the potential for significant radial expansion of fumigant treated soil zone as a result of gas phase movement. Importance of central drip tube placement towards maximizing bed coverage with a chemigated fumigant.

Injection Scheduling

Different injection schedules have also been evaluated to determine whether better results would be obtained by applying chemicals in higher concentrations in a single application at the beginning of the crop or by spreading the application of lower concentrations over more of the crop growing season in repeated applications. In general, nematicides applied over an extended cropping season have been found to be more effective than a single, early season application towards improving crop yields. However, it is unlikely that the introduction of nematicides into the root zone for the entire cropping season will prove to be necessary to achieve maximum yield increase. Preplant nematode control practices have repeatedly been shown to be more effective than postplant applications for nematode control and increasing yield, since nematodes that become established within root tissues, may be shielded from the pesticide in the soil and survive the treatment.

Waiting Periods

Following chemical injection, a waiting period for subsequent irrigations is another important factor which is frequently overlooked which could strongly influence nematode control. An irrigation delay is required because the effects of many nematicides are cumulative such that nematode mortality increases as exposure time to the chemical increases. And more importantly, the effects with some nematicidal compounds can be reversible once the pesticide has been flushed from the environment which surrounds the nematode. In this case, the objective may be to maintain lower concentrations over an extended time through repeated applications. However, in Florida soils with low organic matter and water holding capacity, water availability and stress to the plant may be compromised to retain chemicals within the plant rooting zone. An irrigation delay may be particularly severe to plants when weather conditions are hot and dry and plant water demand is high.

The level of pest control that is achieved is related primarily to pesticide concentration, outward radial movement which determines total treated soil volume, and residence time of the chemical in the soil. Research information is accumulating regarding optimal strategies for injection of pesticides to maximize nematode control and crop yield. Considerably more information is needed regarding pesticide movement, outward gaseous phase movement, and longevity in the soil in order to determine optimal irrigation frequency and number of pesticide applications.

It should also be recognized that once in the soil, nematicides may be transported by water through the various soil strata down to groundwater. The risks associated with chemigation, such as the downward transport of nematicides to groundwater, should therefore be of primary concern. Highly permeable sandy soils with low organic matter, and shallow groundwater are typical of Florida crop production and those usually associated with high risk of groundwater contamination. In this regard irrigation scheduling programs using moisture depletion as a basis for determining the timing and quantity of water application may become critical for maintaining pesticides within the rooting zone of crops and

avoidance of groundwater contamination problems. Managing pesticides within the soil profile may go along ways in providing more effective nematode control, providing consistent economic returns to the grower, and resolution of environmental and human health concerns.

Response Variability

The relation between drip irrigation run time and depth, width, and cross sectional bed area wetted by drip irrigation water can be very different between farms due to differences in irrigation practices, drip system operating pressure, drip tube flow rate, and differences in tube numbers per bed and emitter spacing. Differences in soil type, depth to soil layers restrictive to water movement and bed width also impact drip water distribution. Prior to the application of soil fumigants through drip irrigation systems, growers should determine optimum run times and water volumes particular to their situation. The use of a water soluble tracer dye to determine wetting patterns is a simple and quick solution and should be considered as a means of developing an on-farm chemigation strategy.

In not all instances are growers capable of injecting agrichemicals into the irrigation system over a long period of time, using relatively high water volumes. In the case of drip applied fumigant compounds, some reductions in irrigation run times or water volumes could be achieved if significant radial movement of fumigant gases occurs after drip application when new soil air passages redevelop (Figure 26). Some recent field trials have demonstrated that the 'fumigant' effect may be as much as 5 to 10 inches further than movement of the compound in its liquid phase. The range of gas movement is dependent upon fumigant concentration in irrigation water, the higher the concentration the greater the radial movement. This suggests even less irrigation water, and quite possible a single drip tube per bed, may be all that is required to achieve soil pest control efficacy due to the evolution and movement of fumigant gases from the wetted zone after fumigant application.

Even though our knowledge and understanding of the dynamics of drip water movement in soil increases, this does not mean that growers, armed

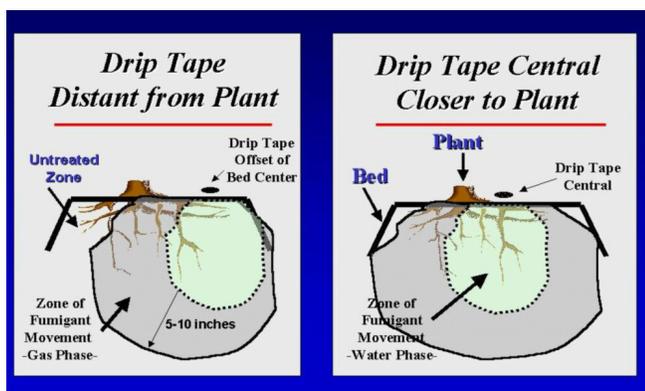


Figure 26. Importance of plant proximity and of central drip tube placement towards maximizing bed coverage with a chemigated fumigant.

with this information, will achieve immediate success without cost or change. For example, recent grower field demonstration trials have shown that flaws in irrigation system design could significantly compromise treatment efficacy of any water soluble, nematicidal compound. The principal problem involves delivery uniformity throughout the entire field. In some grower field trials, significant drops in drip line water pressure from one end of the field to the other, established a gradient of diminishing volume of water output and hence of treated soil volume, particularly down the row. If soil samples for comparisons of nematicidal efficacy along the row had been taken, they surely would have shown a decline in efficacy down the row which corresponded to reduce drip flow rate. These recent experiments clearly show that use of pressure regulators across the entire field with adequate water flow sizing requirements are a must for delivery uniformity of a chemigated compound.

Drip Tube Placement

The proximity of the plant to the drip tube has also been demonstrated to be very important in terms of defining pest control efficacy and plant growth response with a chemigated fumigant (Figure 26). In two separate experiments conducted a number of years ago, it was observed that metham sodium application rates as low as 10-15 gallons per treated acre could be effectively used for crop destruction purposes if established plants were within two inches of individual drip emitters. Identical studies with plants positioned 6 to 8 inches from the drip line required 20-30 gallons per treated acre to achieve the

same level of plant mortality. Presumably, a two-fold increase in application rate was needed to compensate for the additional distance and irrigation volume required to contact the primary root zone of the plant. The problem is even further amplified when one considers typical production practice of laying the drip tape on one side of the bed and planting the crop offset of center on the opposite side of a 32 to 36 inch wide raised bed (Figure 26). Ideally the tape would be placed in the center of the bed and the crop planted offset of the tape. Bed widths may also need to be evaluated since narrower beds (24 inches) could be more easily and uniformly covered with a water soluble fumigant than wider 34-36 inch wide beds. Given the sandy nature of Florida soils, narrower bed widths, drip tubes with closer drip emitter spacing (likely in the range of 8-12 inches), and planting practices which place plants closer to the drip tube may need to be adopted to more effectively utilize the drip tape for chemigational purposes.

General Conclusions for Nematicide Chemigation

- Regardless of drip tube manufacture, irrigation run time, tube flow rate, emitter spacing, or total volume water applied, it was virtually impossible to wet more than 50-60% of the bed with a single drip tube per bed when beds are 32-36 inches wide.
- In the sandy soils of Florida, two drip tubes will likely be required to treat upwards of 85-95% of the entire mulch covered bed with any chemigational nematicidal compound.
- For the sandy soils of Florida, most bed wetting seems to occur in the time to deliver the first 300 gallons of water expressed per 100 linear row feet, and that lesser volumes (100-200 gallons / 100 linear feet of row) should be considered if depth of penetration (<16 inches) of the wetting front is an important consideration.
- Soils and grower production practices markedly differ, and differences in soil type, compaction, and depth to restrictive layers can all effect water movement and the final distribution of chemicals within, which enforces the need by growers to

conduct their own field studies to optimize the utility of the drip irrigation system for chemigational purposes.

- It would appear that irrigation injection schedules previously utilized to evaluate drip applied fumigants (such as Vapam®) in Florida field research efforts have significantly underestimated irrigation run times or water volume requirements for maximizing bed coverage, and therefore in all likelihood, soil pest control efficacy.
- Finally, the effect of applying large volumes of water to the raised bed on plant nutrition and fertility programs needs to be furthered researched. Surely some readjustment in the fertility program must be developed to minimize leaching impacts from use of the drip system for preplant soil fumigation.

Explanation of Rates Listed in the Nematicide Tables for Vegetable Crops

Chemicals used to control nematodes include non-fumigant nematicides, fumigant nematicides, and multipurpose fumigants. Refer to Characteristics of Principal Nematicides for discussion of the characteristics of each of these groups.

"Overall" soil fumigation is done by injecting fumigant from outlets equally spaced across the entire field. Outlets (behind chisels or coulters) are spaced:

1) All fumigants except Vapam (metham sodium): 12 inches; if less than 12 inches, the rate per outlet should be reduced proportionally. The rate of fumigant within the area actually treated should never exceed the maximum overall rate (broadcast rate).

2) Vapam (metham sodium): 5 inches.

"Row" application of fumigants refers to treatment of a relatively narrow band of soil with one or more outlets centered on the planting row. This generally provides adequate protection for annual crops with much less fumigant per acre of field. If two or more outlets are used per row, they should be spaced and the rate per outlet should be the same as

for overall treatment. Row fumigant rates in the tables assume use of one outlet per row, with rows 36 inches apart, unless otherwise noted. Wider spacing of rows will require less total fumigant per acre, and closer spacing will require more, than the "Gal/Acre" estimate based on 36-inch row spacing.

The dosage listed for some fumigants should be increased for organic soils (peat and muck); others should not be applied to such soils; see labels.

Rates of non-fumigant materials are given in weight or volume units of formulation (See Non-Fumigant Nematicides Registered for Vegetable Crop Use). The maximum rate per 1000 ft of row should not be exceeded; wider row spacing will use less total chemical per acre, but closer row spacing must not result in more total material used per acre than the maximum permitted on a broadcast basis.

Table 2. Non-Fumigant Nematicides Registered for Vegetable Use.

Vegetable	Non-fumigant nematicides				
	MOCAP	TEMIK	COUNTER	NEMACUR*	VYDATE
Beans	*				
Peas	*				
Carrots					*
Celery					*
Corn, sweet	*		*		
Cabbage	*			*	
Brussel sprouts				*	
Cucumbers	*				*
Melons					*
Squash					*
Okra				*	
Potatoes		*			*
Potatoes, sweet	*	*			*
Eggplant	*			*	*
Tomatoes					*
Peppers					*

* Do not apply Nematicur 3 or Nematicur 15G to hydrologic soil group A soils that are excessively drained and predominately sand or loamy sand with shallow water tables (less than 50 feet deep). Bayer CropScience will discontinue sales of all Nematicur products May 31, 2006.

This information was compiled as a quick reference for the commercial Florida vegetable grower. The mentioning of a chemical or proprietary product in this publication does not constitute a written recommendation or an endorsement for its use by the University of Florida, Institute of Food and Agricultural Sciences, and does not imply its approval to the exclusion of other products or practices that may be suitable. Products mentioned in this publication are subject to changing State and Federal rules, regulations and restrictions. Additional products may become available or approved for use. Growers have the final responsibility to guarantee that each product is used in a manner consistent with its label.