Movement and Toxicity of Nematicides in the Plant Root Zone[1]

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Toxicity and Mode of Action

Many of the nematicides currently used in Florida are restricted-use fumigant, organophosphate, or carbamate pesticides. Considerable work has been done to study the behavior of these pesticides in soil and to predict their movement and efficacy. The results from this research show that an understanding of the movement and distribution of a nematicide in soil is probably as important to control as is its toxicity to the nematode. If toxic concentrations of the nematicide do not come in contact with the nematode for sufficient time, acceptable levels of control will not occur.

The Target Organism

Plant parasitic nematodes are small, aquatic, microscopic roundworms that live in films of water surrounding soil particles and plant roots. The presence of a water film is essential to the nematode for locomotion and maintenance of body fluids. The body of the nematode, when inflated with fluids, acts like a skeleton, preventing internal collapse. In dry soils, body fluids are lost, the body wall collapses, and many nematodes die as a result of dehydration. However, some can survive desiccation in a suspended state for long periods and come back to life when soil water conditions are restored. In the dried state, nematodes are more resistant to high soil temperature and nematicides.

Nematodes feed on the roots or foliar tissues of plants. In many parts of the world, nematodes are a major limiting factor for agricultural production, causing serious reduction in crop quantity, quality, or harvest uniformity. All fruit and vegetable crops are susceptible to nematodes. Total crop failures frequently occur when crops are planted into areas with high nematode population levels. Plant symptoms that develop in response to nematode parasitism are generally those associated with root dysfunction. Development of small, stunted, and chlorotic plants generally reflects reduced water and nutrient uptake caused by injury to the root system. Correspondingly, root damage generally increases with nematode infestation level, particularly where plants are grown on fine- to coarse-textured, sandy soils with low water-holding capacity. The subtropical soil environment, which favors a rapid increase in nematode population levels and plant damage, has contributed significantly to the extensive use of different chemical nematicides to allow economic crop production in Florida.

Nematicides

Chemicals that kill nematodes are called nematicides. Two broad categories of nematicides are currently registered and available for use in Florida. The classification system is based upon the way these chemicals move in soil. Fumigant nematicides, including chloropicrin, 1,3 dichloropene, allyl isothiocyanate, dimethyl dibromide, metam sodium, and potassium, are formulated as liquids that vaporize and move through open air spaces in soil as a gas. Nonfumigant nematicides, including Mocap, Vydate, Nimitz, and Counter are generally formulated as either granules or liquids and move by downward percolation in soil water.

1. This document is ENY-041 (formerly RF-NG002), one of a series of the Department of Entomology and Nematology, UF/IFAS Extension. Original publication date March 1997. Revised December 2014 and December 2016. Visit the EDIS website at http://edis.ifas.ufl.edu.

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The nonfumigant nematicides are often further classified as contact or systemic nematicides depending on whether they kill nematodes in soil by contact or are taken up by the plant first and affect nematodes when they feed from cellular fluids within the plant.

Mode of Action

Nematicide mode of action refers to the lethal action of a nematicide on specific and vital life processes within tissues of the nematode. For example, broad spectrum fumigant nematicides penetrate the body wall of the nematode directly and do not have to be eaten to be effective. Once inside the body cavity of the nematode, they affect different internal organs when these organs are bathed by body fluids containing the nematicide. Metam sodium (Vapam) is a very soluble compound that becomes activated in water. Decomposition is rapid in water. A secondary byproduct (MITC) that forms in the presence of water directly penetrates the nematode body wall and simultaneously interferes with many different vital processes, including enzymatic, nervous, and respiratory systems. Death of the nematode is rapid under these conditions. In general, fumigant concentrations in internal body fluid frequently reach equilibrium with soil concentrations within about 30 minutes to 4 hours. In some cases nematicide concentration may accumulate to much greater levels within the nematode than in soil.

Nonfumigants also penetrate the body wall of nematodes directly. Unlike the fumigants, these chemicals give little or no control of fungal or bacterial diseases but can be insecticidal depending upon the nematicide used. As insecticides, the organophosphates (Mocap) and carbamates (Vydate) act as acetyl cholinesterase inhibitors, interfering with normal nerve impulse transmission within the central nervous system of insects. This is known to cause abnormal behavior, paralysis, and death. Available information for nonfumigant nematicides suggests that the more primitive nervous system of nematodes is also affected. However, these compounds are not as toxic to nematodes as they are to insects and are not generally considered to be true nematicides. Nematode mortality is often due to a "narcotic" effect and behavioral modification rather than killing. Disruption of nerve impulses, which ultimately may be lethal at high concentrations over an extended time period, affects primarily nematode behavior and development in soil. For example, body movement, mating behavior, and mobility in soil are reduced, as well as root penetration and feeding. Delayed egg hatch and molting and reduced development within plant tissues may also occur. Reduced nematode infection, development, and reproduction in the plant are primarily responsible for observed reductions in nematode population growth following nonfumigant nematicide treatment.

A common misconception regarding nonfumigant nematicide use is that contact with the nematicide in soil imposes irreversible effects upon the nematode. This is, however, not the case. If exposure is short and at low concentration, the effects maybe reversible once the pesticide is removed or flushed from the environment of the nematode. For some nematicides such as Vydate, nematode recovery is often possible after short exposure (24 hours) to concentrations as high as 1000 ppm. After 24-hour exposure to 10 ppm of Vydate, other species of nematodes were capable of complete recovery and normal reproduction. Similar reversible effects have been observed with carbamate nematicides such as Temik aldicarb.

Systemic nematicides may be rapidly absorbed and distributed within plant root tissues once they are introduced into the soil or onto plant foliage. Many different factors affect plant absorption, translocation, and final nematicide concentration in roots. Pesticides that are very soluble and mobile in soil may reduce the opportunity for plants to concentrate systemic nematicides in roots if leaching losses are significant. Total plant or root-system size also appears to be important. In citrus, for example, dilution effects have been suggested for reduced effectiveness of both fungicides and nematicides in diseased trees of larger size. If pesticides are applied in bands, then a higher proportion of the total root system of the smaller tree will be bathed in the pesticide. Pesticide may therefore become proportionally more concentrated in the smaller, weakened trees than in larger more vigorous trees.

The toxic properties of systemic nematicides (Vydate) appear to be primarily protective rather than directly toxic to the nematode. Systemic nematicides that are absorbed and translocated into roots appear to only inhibit feeding, temporarily inactivate nematodes, or repel them from roots and surrounding areas, rather than kill them, as the term "nematicide" would indicate. In these cases, death occurs as a result of disorientation and starvation.

Dosage: The Product of Concentration and Time

The lethal effect of nematicides is determined by two components. The first is concentration (C) of the nematicide in soil solution, usually expressed as parts per million (PPM). The second is the length of time (T) the nematode is exposed, expressed in minutes, hours, or days. The level of nematode control is then related to dosage, the amount of pesticide placed in the environment of the nematode for a known length of exposure time (concentration × time). Total exposure is the sum of CT products. For most organisms, nematodes included, there is a nematicide concentration level below which kill is not obtained regardless of the length of exposure. If exposure to 10 ppm for 20 days (200 CT) is the minimum dosage required to kill a nematode, then exposure to 4 ppm for 50 days (200 CT) will be totally ineffective, even though the nematode has received the same cumulative dosage. In this example, a minimum concentration of 10 ppm was required to effectively contribute to the lethal or disorientating activity of the nematicide. For most nematodes, long exposures to low concentrations of fumigant nematicides above the minimum concentration appears to be more effective than short exposures to higher concentrations.

All nematode species are not equally susceptible to a given nematicide, nor are all life stages of a given species equally sensitive given the same exposure time. For example, after a 24-hour exposure to the fumigant nematicide EDB, only 75% of a population of free-living nematodes in soil were killed while the citrus nematode did not survive a 0.5 hour exposure to EDB at the same concentration. In dry soils, many nematodes that can survive in a dehydrated state can tolerate 10 times the lethal dose of methyl bromide compared to active forms in moist soil.

In practice, fumigant nematicides are commonly injected through a series of uniformly spaced shanks into soil. As the liquid volatilizes, gases begin moving in mass flow, diffusing radially outward in all directions from the point of injection. Since diffusion is greater in air above the soil surface, upward mass flow and diffusion is usually greater than downward movement, and much of the gas may escape the soil and enter the atmosphere. As the nematicide front moves through soil, gaseous molecules are adsorbed to particle surfaces, redissolve into soil solution, and fill empty air spaces between soil particles. Maximum nematicide concentration decreases as do the sums of CT products with distance from the point of injection. Eventually, with time and distance, concentrations fall below an immediate killing level. The number of nematodes killed by fumigant treatment within these areas depends on the number of CT units that develop within the nematicide-treated zone. The relationship between nematicide application rate and nematode control is therefore not only a measure of pesticide toxicity but one of chemical dispersion as well. If dispersal is good, increases in chemical application rates will result in higher CT values and provide control to a greater soil volume. If dispersal is poor, increases in application rates will not provide control to a larger soil volume.

Unlike fumigant nematicides where water may effectively block efficient dispersion in soil, nonfumigant nematicides must be carried by rainfall or irrigation water into soil to be effective. Nematicide concentration and its persistence above a certain effective concentration is also important for nematode control with nonfumigant nematicides. The apparent failure to control nematodes with nonfumigant nematicides in many instances is very likely the result of excessive rainfall or irrigation and poor chemical retention within the primary rooting zone of the crop.

Factors Affecting Nematicide Movement and Retention in Soil

It is becoming increasingly apparent that the inconsistencies in nematode control with soil-applied nematicides and finds of agricultural chemicals in surface and groundwater are related to the movement and persistence of these chemicals in soil. Considerable work has been done to study the behavior of pesticides in soil and to predict their movement. These studies have emphasized the complex processes at work and the difficulties in generalizing soil and production factors influencing pesticide fate and movement in soil. The purpose of this summary is to describe some of the important soil and environmental factors that affect nematicide distribution and movement in soil and to relate this information to nematode control.

Types of Nematicides

As indicated previously, nematicides are broadly classified into two categories based upon their movement in soil. Fumigant nematicides are formulated as liquids that rapidly vaporize to a gas and move through open air spaces in soil. Nonfumigant nematicides are generally formulated as granules or liquids and are moved by downward flow of soil water. The nonfumigant nematicides can then be further subdivided as contact or systemic nematicides depending on whether they are absorbed by the plant.

Nonfumigant nematicides are all 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. If the nematicide does not come in contact with nematodes in soil, little nematode control will occur. Information concerning the position of the nematode in soil combined with the dispersal characteristics of the nematicide is therefore critical to the level of nematode control achieved, given soil and other environmental conditions. Tillage and irrigation practices are also of paramount importance.

Effect of Tillage

NEMATODE DISTRIBUTION

In preparation for planting, fields are generally disked to ensure seedbed tilth and uniform soil moisture conditions. During tillage, nematodes are moved in the direction and depth of tillage. Some nematodes die as a result of abrasive collisions with soil during mixing while those brought near the surface die as a result of the drying action of wind and sun. Prior to disking, the vertical distribution of nematodes in soil is generally related to rooting distribution of the previous crop or weed host. The number of nematodes at any depth is then related to the amount of roots that were available to the nematodes at that depth. After tillage and bedding, the greatest number of nematodes is still retained in the surface 12 inches of soil, but now they may be more uniformly distributed throughout the field, particularly below the surface desiccation layer. The challenge for nematode control is then to disperse and maintain nematicides within the 12-inch zone of greatest nematode abundance (also the rooting zone for the plant), at toxic concentration for sufficient time to be effective.

PESTICIDE DISTRIBUTION

Nematicides are applied and incorporated into soil to increase their effectiveness and to avoid animal and human contact. The method of application and incorporation can have a major impact on the spatial distribution (both vertical and horizontal) of pesticide in the field. The variability of the distribution of the nematicide in soil depends upon the degree of incorporation and the extent to which the chemical is redistributed in soil by diffusion and leaching in soil water. Failure to effectively control nematodes may often be explained by poor nematicide application and/or incorporation with field equipment. Older, gandy-type applicators are particularly troublesome because they are difficult to calibrate to uniformly apply pesticides. Growers should recognize that variability in pesticide distribution introduced at the soil surface during application and incorporation may persist and be reflected in terms of erratic plant growth and yield reduction due to poor nematode control.

Contact or systemic nematicides must be uniformly applied to soil, targeting the application toward the 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 and transplant establishment and protect initial growth of plant roots from seeds or transplants. As the roots extend downward, nematicides are then leached in soil solution with additional irrigation or rainfall to protect the new roots. Protecting outward, lateral growth of roots depends on the bandwidth in which nematicides are applied. In general, bandwidths of 8 to 15 inches are recommended for vegetable crops. If bandwidths are too narrow, vagrant root growth into untreated soil renders crops vulnerable to nematode and disease infection. For crops such as tomatoes, early nematode invasion followed by fusarium disease infection within untreated soil may be all that is required to kill the plant.

To control nematodes, nematicides are applied in bands or broadcast on the soil surface and incorporated into the soil, sprayed onto the plant foliage, or applied in the furrow with the seed. Applications made to the seed furrow, as in the case of potatoes, generally produce large concentrations of nematicides around the seed tubers, which may damage them (as is the case with Mocap) and only suppress nematodes populations close to the tubers. More reliable yield increases and better nematode control are generally obtained with deeper, uniform mixing of nematicide granules in soil. This implies that the movement of chemicals distributed only within shallow soil layers cannot be relied upon to compensate for poor initial distribution. For nematicides such as Vydate, which are systemic and can be very mobile in sandy or sandy loam soils with low organic matter content, the method of incorporation is not as critical for nematode control. For these very soluble nematicides, vertical distribution in soil may not limit nematode control, and little improvement in nematode control may occur by more thorough mixing. Conversely, more uniform soil distributions of Mocap may be required for optimum nematode control because these chemicals are less soluble and are highly bound to soil organic matter. In these cases, poor distribution in the field may limit efficacy, especially in soils containing high organic matter.

Studies conducted to evaluate pesticide incorporation with farm equipment have indicated that power rotovators (L-bladed or spiked) will generally mix nematicide granules more uniformly to the working depth of the implement and therefore provide better nematode control, whereas harrows (spring-tined, reciprocating, and rotary) will give a more shallow, uneven soil distribution. The most uniform applications probably occur with liquid formulations sprayed onto the soil surface and immediately incorporated with a power rotovator.

Plant Uptake of Systemic Nematodes

When systemic nematicides are applied to moist soil, the active ingredients are rapidly released (even from granules) and absorbed by plant roots. For Temik, movement in plants is bidirectional, both up and down. When they are applied to soil, the toxicant is moved upward to the foliar parts of the plant. For Vydate, the toxicants are moved downward or towards the ends of roots. The amount of toxicant that is absorbed is related to the abundance of roots that come in contact with the toxicant in soil solution. For tree crops, little absorption and concentration of the systemic nematicide in the plant root system may occur if treatments are directed to areas where there are few roots (i.e., outside the tree canopy). For annual crops, little root absorption may occur if the nematicide is mobile in soil and leached with excessive irrigation or rainfall to deeper soil depths before sufficient root growth has occurred. For some crops, this problem is overcome by applying the nematicide during hilling or other cultural practices, or to foliage after plant establishment.

Systemic nematicides, when absorbed by roots, have been shown to be more protective in nature, to reduce nematode invasion, and in some cases to slow nematode development. In most cases, however, the main effect of systemic nematicides appears to be in soil rather than by systemic action in the plant. Vydate, although readily taken up by plants, is believed to act as a nematicide mainly in the soil solution by interfering with the locomotion and feeding of newly hatched nematode larvae and causing their death by starvation or poisoning. Thus, a good distribution of nematicide in the rooting zone is essential when hatched larvae are moving towards the roots. This may be achieved, as previously indicated, by mixing the chemical thoroughly with the soil, or, if the chemical is sufficiently mobile, by subsequent lateral diffusion and downward leaching.

Soil Type and Organic Matter Content

The soil is composed of sand, silt, and clay particles mixed in various proportions with other inorganic and organic matter constituents. Soils have an interconnecting maze of air passages lined with water film and filled (when not at field capacity) with varying gaseous mixtures. Nematodes live in the water film surrounding soil particles and plant roots, and therefore, to be effective, nematicides must enter the water film.

The air passages between soil particles vary in size, shape, and continuity depending upon the distribution of soil particle sizes, degree of aggregation (clumping or clodding), presence of textural layers, and, lastly, soil moisture content. Sandy soils usually contain larger pores and less aggregated soil structure and drain very quickly. Water and nematicide movement is often vertical in sandy soils with little lateral capillary spreading unless impermeable subsurface soil layers are present. In contrast, heavier clay soils have much smaller particle sizes and more aggregated, compacted structure, and generally drain poorly. Water-holding capacity in heavy soils is higher than in sandy soils, which serves to dilute the concentration of nematicide faster with depth. Although the lateral spreading of water and nematicide is generally greater for heavier soils, the zone of nematode control is usually smaller due to smaller but more numerous pore spaces and restricted movement.

Nematicide dispersion (spreading) in soil following application occurs with water movement. Nematicide dispersal in sandy soils is generally very poor (usually less than 6 inches). In these sandy soils, increases in chemical application rates will generally not provide control to a greater soil volume, although nematicide may be leached to layers below the root zone. If dispersal is good (as in some of the heavier, sandy loam soils), increases in application rates may provide control to a larger soil volume within the crop root zone. The risk for surface runoff and erosion is, however, much greater for these soils.

The organic matter content for most soils in Florida is generally low, and it declines rapidly with soil depth. The highest levels occur within the surface 12 inches of soil. Soil organic matter content has a major influence on soil water-holding capacity as well as nematicide dispersal. Nematicide dispersal may be severely restricted due to the reversible and irreversible binding (adsorption) of nematicide molecules onto organic matter surfaces. As the nematicide moves through soil, many toxicant molecules disappear through sorption on soil particles and by chemical and biological degradation. Soil-water content and temperature are the two major soil environmental factors that control pesticide degradation rates. As binding of nematicide molecules to organic matter increases, toxicant concentrations present in soil water become lower.

As indicated, the mobility of a nematicide depends primarily upon its affinity for soil organic matter and the physical characteristics of the soil to which it is applied. In sandy soils, for example, both Temik and Vydate are weakly adsorbed to organic matter and therefore potentially very mobile in soil, whereas Mocap is more strongly sorbed and less mobile. It should be recognized at this point that many nematicides are degraded into byproducts that are toxic to nematodes and that bind and leach in soil differently than the parent nematicide. For example, most nonfumigant nematicides are degraded into two or more toxically active components in plants and soil, and these metabolites may be more mobile than the parent compound itself. This is not true of Vydate, which is readily mobile through soil. Mocap has no toxic degradation byproducts.

Nematicide application rates required for effective nematode control may be determined by the extent to which nematicide adsorption to soil organic matter occurs; the volume of treated soil, which is determined by soil type; and soil moisture content. For example, nematicide treatments have been observed to be generally more effective when decomposition of crop debris has occurred, since adsorption of the nematicide is reduced considerably. For fumigant nematicides, and possibly nonfumigant nematicides, higher application rates may be required for effective nematode control due to the "sink" effects of organic matter in soil.

Irrigation

Many different types of irrigation systems are used in Florida crop production, the majority of which include overhead, seep, and drip systems. Regardless of type, the primary objective of irrigation is to promote plant growth by avoiding shortages in plant water supply due to inadequate rainfall. University recommendations for irrigation in Florida generally suggest that the amount and timing of irrigation be based on crop evapotranspiration and soil water depletion. To determine the amount of water to be applied, a moisture characteristic curve specific to the irrigated field should be used. Based on the water-holding capacity of the soil, the amount of irrigation water applied should be adequate to restore only the root zone to field capacity. In fact, less than field capacity of root zone may be desirable so as to provide for additional storage space available for rainfall, should it occur. The methodology for determining the quantity of water required to irrigate a crop is well documented in other Extension publications.

Maximizing retention of soil-applied nematicides within the crop rooting zone should also be a primary consideration within grower irrigation practices. The apparent failure to control nematodes in the field is often the likely result of excessive irrigation or rainfall soon after application and poor chemical retention in the rooting zone of the crop. On sandy soils, nematicide efficacy is related to depth of water movement and distribution of pesticide within the wetted zone. Factors that affect water infiltration will also affect the location of the chemical in the soil.

For overhead systems, water is uniformly delivered to the soil surface or a major part thereof via guns or sprinklers, while for drip systems, a wetted strip develops along the drip line. Nematicide movement in soil out of the rooting zone of the plant and potential for groundwater contamination is directly related to total precipitation and soil organic matter content. Greatest downward movement of most nematicides occurs in low-organic soils (<1%) following heavy irrigation and rainfall, both of which can be typical characteristics of many producing areas in Florida. Under these circumstances, greatest leaching potential would occur for nematicides like Vydate or Temik, which are very soluble, move readily in soil, and have low affinity for organic matter. None of the nematicides currently available for use in Florida are immune from the problems of root-zone leaching. Regardless of the nematicide or irrigation system, maximum depth of nematicide penetration in soil increases with amounts of irrigation. More importantly, the duration of the period in which total nematicide residues are contained entirely within the crop rooting zone generally decreases with the amount and frequency of irrigation.

For seep-irrigated crops, irrigation water is introduced into the field through a series of ditches and then allowed to laterally seep into the bedded land areas between ditches. When crops are also grown under plastic mulch, leaching losses can be significantly reduced. Pesticides are shielded from rainfall and the confining layer (a prerequisite for seep irrigation) forms a barrier against vertical loss while the water moves into the field. Within this irrigation system, pesticide movement is primarily by upward water diffusion. As the artificial water table is raised and lowered within the field, pesticides move with the advancing or receding water front. Fertilizers applied during bed formation have been shown to concentrate on or near the highest point of the bed surface due to the upward, capillary movement of subsurface water. On heavier soils, similar results have been obtained with furrow irrigation when pesticides are applied to the bed shoulders. In recent studies with the nematicide Mocap, downward mobility was considerably reduced when the nematicide was placed under the plastic mulch. However, after the mulch was removed and crop (tomato) residues tilled into the soil, Mocap concentrations were detected at depths well below those previously recorded, illustrating the influence of heavy rainfall on pesticide movement after tarp removal.

Most nonfumigant nematicides applied at label rates are not true nematicides in that they kill all nematodes immediately on contact. In fact, as nematicide concentrations decrease in soil or roots (due to dilution, leaching, and chemical and microbial degradation) the ability of many nematodes to hatch normally from eggs, move through soil, search for mates, find and penetrate plant roots, and continue growth and development can be restored once the nematicide is flushed from the environment surrounding the nematode. If concentrations are maintained at high levels in soil or roots, death usually occurs as a result of starvation. Waiting periods for subsequent irrigations following nematicide application may therefore be critical for adequate nematode control if maximum contact activity is expected.

Conclusions

All nematicides currently available for use in Florida need to be uniformly applied and incorporated and can be leached from the root zone (and some to groundwater) unless attempts are made to manage their retention in the plant root zone. The vertical and horizontal movement of water and nematicides in soil following application is dependent on many factors, the most important of which is soil type (hydraulic conductivity and water-holding capacity), initial soil moisture conditions, soil compaction, presence of shallow subsurface impermeable layers and water table, and rate and volume of water delivery. Rainfall can also heavily influence the movement of nematicides from the rooting zone, particularly when irrigation precedes heavy rainfall. In all cases, therefore, nematicide use must be coupled with sound principals of water management.