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Chapter 4. Integrated Pest Management[1]

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Disease Management

The health of vegetable crops is best maintained through management practices that integrate different techniques. When making management decisions, it is important to consider the economics of the crop; the cost of the management practice; the history of the production area; weather and climatic conditions; and potential risk for a disease to develop. Integrated management strategies are more likely to successfully control diseases than nonintegrated ones because they reduce disease risk through multiple techniques, often before infection begins. Nonintegrated strategies can also adequately manage a disease; however, producers must limit expectations about the probability that they will see significant economic return from a crop. Ultimately, integrated management strategies provide a means for producers to reduce the risk that they will have significant economic losses from a disease.

Economics

Often the top priority of any producer is the economic benefit they will see from the application of a specific management strategy (e.g., fungicide application). These benefits will depend upon the market price of the crop as well as the cost of the specific management strategy. Typical costs include the price of a cultivar, labor, machinery, fuel, and various consumables used in an integrated disease management strategy. All these costs are variable, and it is up to the producer to assess the inputs required for managing specific diseases so they can calculate the economic returns from their decisions, if any.

Disease Identification

Proper management of any plant disease starts with an accurate identification of the pathogen or pest causing the problem. Many different types of pathogens (i.e., fungi, bacteria, viruses, and nematodes) are involved in diseases of vegetable crops, which can require very different management strategies. In order to assess which management

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strategy is most appropriate, there needs to be information about the pathogen present in a field. This information can be gained by assessing the crop either yourself or with the aid of a professional. Many guides and applications are available for disease identification; however, proper identification often requires the use of a microscope to identify key structures or use of a more complex test (e.g., DNA/RNA-based and serological). Many printed and electronic (e.g., EDIS, UF/IFAS Extension) resources are available for disease identification, but if a producer is unsure about how to identify a disease, they should contact their county UF/IFAS Extension office or nearest UF/IFAS Plant Diagnostic Clinic for help.

Disease Risk

Once a pathogen has been identified, monitoring of the disease is critical to collecting the information needed to make a beneficial management decision. The distribution of a disease within a field can inform a producer about where and when the disease may be a problem. Monitoring is also critical to determining the risk of a producer's crop experiencing significant economic impacts from a disease. For example, if a disease is affecting only 5% of a production area, it is likely that a combination of multiple low-cost strategies will effectively manage the disease. However, if a disease is causing a problem in 50% or more of the field, then different management strategies likely will be needed to adequately reduce its impact.

Many integrated management methods are available for disease control, and many of these methods are often chosen even before the crop is planted. Three important preplant tools are site determination and preparation, crop rotation, and cultivar selection. Site determination and crop rotation are two excellent methods for reducing a pathogen population within a specific site. For example, fields with a history of a disease are more likely to have that disease again, especially if it has been continually planted with susceptible host plants. Removal of debris through tillage or the planting of a nonhost plant can limit the pathogens present and thus reduce a disease's overall impact. Cultivar selection is also critical to determining how likely a disease is to continue developing and spread within a field. Resistant cultivars will most likely require less inputs than susceptible cultivars after disease establishment.

Multiple postplant management options are also available to producers. These include, but are not limited to, weed control, irrigation management, nutrient management, soil amendments, sanitation practices, and canopy regulations (e.g., staked tomatoes). These management options are aimed at reducing plant stresses and limiting mechanical movement of the pathogen within a field site. For instance, weeds can serve as alternate hosts for a pathogen and can stress plants by competing for essential nutrients such as calcium. Stressed plants are more prone to pathogen infections, and alternate weed hosts create local inoculum sources that can cause problems under the right environmental conditions. These management strategies provide better results when used as prevention methods, and they are even more useful when combined with preplant methods.

Inoculum is the pathogen propagule that can cause infection in vegetable crops. The amount of inoculum present is critical to the development and spread of disease. Monitoring provides producers with an initial assessment of the pathogen's inoculum; however, the production of further inoculum is highly dependent on the environment. Environmental conditions that are conducive for pathogen development vary, but with proper identification, one can assess the risk of continued inoculum production. Many disease models and decision support systems (e.g., for strawberry) are available to evaluate disease risk based on environmental conditions. When determining the risk of further disease development, it is important to consider the environment and the likelihood that disease will continue to develop. Biological and chemical products are an important component of many disease management programs. These products provide postinfection management options; however, they should be integrated with all other techniques mentioned in this chapter. The efficacy of these products will vary depending on timing of the application and the physical mode of action of the product. Often these products will be more efficacious when applied early in a disease epidemic, before the pathogen has produced significant amounts of inoculum. All of these products should be used following recommended rates and application frequencies, and within all labeled requirements. It is important to consider the cost of these products and what average yield savings will equal the cost of a product application. In general, product application is costliest when there is no disease present or when a product does not affect the disease afflicting the crop. However, preventative applications can be beneficial, particularly when the disease risk is high. Thus, proper disease assessment is critical for any management strategy.

Three key factors for successful integrated pest management:

- **Economics:** successful programs are not only effective but also cost-effective.

- **Diagnosis:** proper disease identification is a critical first step to determining proper management.
- **Disease risk:** management strategies will be more effective in high-risk situations.

Summary

Successful disease management starts with assessing the economics of the cropping system and understanding the disease risk. Diagnosis of the disease is the first step in any management plan because it can affect the techniques that can be used in the current growing season as well as in the future. Many pre- and postplanting management techniques that can be used to reduce disease risk are available to producers. Ultimately, integrated plant disease management strategies provide producers with the tools to obtain acceptable yields with adequate economic returns that are more sustainable than the results achievable with a single management method.

Detailed Source: "Integrated Disease Management for Vegetable Crops in Florida" (https://edis.ifas.ufl.edu/pp111)

Pest Management

The management and control of insect and mite pests can be challenging even under optimum conditions. Integrated pest management (IPM) is a useful approach for protecting vegetables from multiple pests. It involves integration of cultural, physical, biological, and chemical methods to maximize productivity in a way that is ecologically sound and safe. Often, but not always, it means limiting the use of broad-spectrum insecticides and miticides. IPM implies management of all crop pests, including insects, mites, diseases, nematodes, and weeds; however, only insects and mites will be considered here. Where possible, the effects of measures to control diseases and weeds should enhance or, at least, not interfere with the management of insects and mites.

Many of the general IPM principles and tactics that apply to the control of plant diseases apply to the management of insects and mites. These include regular scouting or monitoring for problems, identifying pests and their life stages, keeping good records of pest management practices, using exclusion techniques, practicing good sanitation, testing soil or plants for nutrients, using biological control agents when possible, and timely application of selective pesticides when needed.

Crop Scouting and Monitoring

To detect pests and the damage they cause before a problem becomes serious, growers must visually inspect plants once or twice a week. As a first step, growers should observe the overall plant, looking for speckling or bronzing on leaves, holes and other damage caused by chewing insects, distorted growth, and fruit damage. The next step is to carefully inspect all plant parts from ground- or stem-level up to the growing tip. Some insects will feed on roots, others on stems, leaves, flower blossoms, and fruit. The grower must become proficient at quickly examining these plant parts and recognizing the presence of pests and the damage they cause. Workers engaged in cultural practices should be trained to recognize insects and the damage they cause.

Both the upper and lower leaf surfaces must be thoroughly inspected. Many insects, as well as some diseases, begin their infestation or infection from the lower side of the leaf. Many insects and mites only feed on the underside of the leaf and may never move to the upper leaf surface or other plant parts until populations become so great that overcrowding forces movement. Attention should be given to the midrib area under the leaf and along large, lateral, lower-leaf veins. The leaf axils, growing tips, and terminal buds should be carefully inspected. Often weeds serve as hosts for insects, mites, and diseases that can move to vegetable crops, and they should be removed (see section on sanitation).

Some insects, particularly thrips, will be found within the blossoms, so these should be included in the inspection. You can gently tap the blossoms over a white pan or card to see these tiny insects. The area under the calyx or stem end of tomatoes and cucumbers can also be an attractive hiding place for insects. Generally, insects inhabit secluded areas of the plant that provide protection.

Yellow sticky traps are useful for monitoring the adult (flying) stages of many insects. Blue is more attractive to thrips, but yellow works well also. Traps are usually placed vertically at or just above the plant canopy. Some insects, such as thrips and leafminers, can be caught just above the surface of the growing medium. One recommendation is to use one to three cards per 1000 sq ft. Traps should be inspected weekly and replaced regularly. A system of numbered traps can facilitate sampling and simplify recordkeeping. Yellow sticky tape can be used on a larger scale to reduce insect populations by trapping. Yellow sticky traps and tape are available from many online distributors.

Many of the arthropod pests that infest vegetable crops are very small. Mites are $\frac{1}{50}$–$\frac{1}{60}$ of an inch long. Thrips, aphids, whitefly crawlers, and the eggs of other harmful insects are not much larger. Growers should have at least a 10x hand lens (jeweler's hand lens) to examine, but a 16x–20x is preferred. With a hand lens, a grower can quickly identify many of the arthropod pests that are otherwise difficult to see. If possible, growers should buy and learn to use a common dissecting microscope. These microscopes can be purchased either as a monocular (one-barrel) or binocular (two-barrel) type. They have approximately 10x–200x magnification. With a microscope, a grower can see small mites, such as broad mites, and disease lesions clearly. This tool can be very helpful in detecting and diagnosing problems early.

Identification of Insects and Mites

Proper identification of insects and mites and the damage they cause is critical. If the grower knows exactly which pests are present, proper chemical or biological controls can be selected and steps can be taken to exclude or limit further introductions and spread. In Florida, UF/IFAS Extension offices in each county can help with pest identification (to find an office near you, visit https://sfyl.ifas.ufl.edu/find-your-local-office/). Workshops may be offered on pest scouting and identification, and many publications and online resources are available (see https://ipm.ifas.ufl.edu).

Recordkeeping

Good records can help growers see trends in pest infestations, keep track of the success or failure of control efforts, and determine how the environment affected the crop. Of course, pesticide application records are essential and should include the product name, EPA registration number, active ingredient, amount used, target pest, effectiveness, and the time and date of application. Some variables that general records should include are daily minimum and maximum temperatures, measurements of plant growth and development, the pH of the growing medium, soluble salts, general root health, and other specific crop observations. Insect counts from monitored plants and sticky cards are also useful for identifying trends over time and for determining the effectiveness of control efforts. Over several seasons, it may be possible to see that certain problems occur at the same time each year. Details of releases of beneficial insects and mites should be recorded.

Management Strategies and Tactics

Exclusion

Growers need to make every effort from the beginning of a crop until the final harvest to prevent the introduction of insect and mite pests into the vegetable crop. Highly reflective or metalized plastic mulches have been used in agriculture for many purposes, but the primary use has been to repel certain insects such as thrips, psyllids, or whiteflies. Metalized mulches are effectively used in crop production by covering the narrow raised beds in a full-bed polyethylene mulch production system.

Sanitation

Sanitation should be practiced for managing insects and mites as well as diseases that can use weeds and plant debris as temporary hosts. The following practices are strongly recommended:

- Burning, burying, or hauling away all leftover roots and other plant parts so that there is no chance that insects in the egg, larval, nymphal, pupal, or adult stages could remain in the greenhouse. Crop residues must be removed immediately after the final harvest.
- Sanitation must be practiced not only during preplant times but also throughout the growing period. Workers should immediately dispose of plant parts generated by pruning, such as leaves and stems. Culls (undesirable) or overripe fruit should be removed from the greenhouse and surrounding areas. Insects are often attracted to and can live for long periods on these plant materials.
- Weeds should not be allowed to grow around or within the greenhouse. A 10-to-30-foot vegetation-free zone around the greenhouse can be created with a heavy-duty geotextile weed barrier material typically used in the container nursery industry as a groundcover.
- A clean transplant program will aid in keeping pests out. Plants coming from other locations should be carefully inspected for insects, mites, and diseases and temporarily quarantined until ensured that the plants are free of pests. Workers should avoid wearing yellow clothing because it is highly attractive to insects which may hitch rides into the greenhouse or from one greenhouse to another.

Biological Control

Biological control means providing or releasing insect or mite predators, parasitoids (specialized parasites that ultimately kill their hosts), nematodes, or disease-causing organisms (fungi, bacteria, and viruses) that attack insect pests. Some biological control agents are incompatible with insecticides. Therefore, it is important to check for the toxicity of the applied insecticides to the main predators and parasitoids associated with the pests. Elimination of natural enemies through insecticide application can result in secondary pest infestation (e.g., elimination of predatory mites with a pyrethroid application can lead to a spider mite outbreak). Reducing or eliminating chemical pesticides leads to a safer working environment, can reduce production costs, and, in the case of organic production, can result in premium prices for the crop. Biological control, however, is much more management-intensive than conventional insecticides and miticides; it requires a greater knowledge of pest biology and pest numbers. Many factors contribute to the success or failure of biological control: type and quality of the natural enemy selected, release rates, timing, placement, temperature and humidity, and the previous use of insecticides and miticides.

Suppliers can provide technical advice on the optimum use of their products. Some have detailed websites. In general, releases must be made when or before the pest population is first detected. High pest populations will be difficult to control biologically. Some predators and parasitoids are better adapted to particular temperature and humidity conditions than others, and some do better on some crops than others. The life span of the parasitoid or predator will determine how often it has to be reintroduced. It is important to note that if all the pests are eliminated, the natural enemies will also be eliminated. Providing nectar sources (flowering plants) may prolong the life of parasitoid wasps. Yellow sticky cards may have to be temporarily removed to avoid trapping predators and parasitoids.

Insecticides and Miticides

Even when a good biological control program has been established, there may be times when a conventional insecticide or miticide is needed. Biorational insecticides, such as insecticidal soaps, oils, neem products, and *Bacillus thuringiensis* (Bt) can be much less harmful to beneficial insects, although active against pest species. Systemic insecticides, insect growth regulators (IGRs), repellents (essential oils or nano clays), and pheromones used for mating disruption also fall into this category. Some products are harmful to some stages of some beneficial insects and not others. Oils, for example, are toxic to lacewing eggs and adult parasitoid wasps, but they have relatively little effect on adult lady beetles and lacewings. Soaps are toxic to young lady beetle larvae. Neem and Bt products are generally safe for use with natural enemies. Other advantages of biorational insecticides are shorter reentry intervals and safety for workers.

Conventional insecticides and miticides also have a place in IPM if biological controls and biorational insecticides do not offer sufficient control. However, these options are limited to only a few registered pesticides. The development of resistance to insecticides is more likely if a product is used repeatedly. Therefore, pesticides with different modes of action should be used in a sequence that will help prevent resistance.

The following steps are suggested when using any pesticide:

Step 1: Choose the right insecticide or miticide.

Only after the grower has properly identified the pest can the best insecticide or miticide be selected. Insecticides and miticides are sometimes effective against one pest but useless against other closely related pests. Also, one pesticide may be effective against a specific developmental stage, while others may be effective against a different stage, or even against all developmental stages. For instance, growth regulators such as Pyriproxyfen are only active against immature stages, not adults. Properly identifying the pest and understanding its biology and life cycle allow the grower to make wiser decisions when choosing an insecticide or miticide. Growers should consult UF/IFAS Extension resources, pesticide companies and dealers, published literature, and, ultimately, the pesticide label for helpful information.

Step 2: Use the correct amount of pesticide.

After choosing the pesticide, the grower must carefully read the label to determine the correct amount to use. Sometimes this decision will be based on the size or stage of the pest and whether the population is high or low. For example, small caterpillars may require the lowest recommended label rate, while large ones may require the highest.

It is critical that the quantity of pesticide be accurate; growers should buy a set of graduated cylinders that are marked in ounces (oz) and milliliters (cc or mL), as well as a set of good-quality measuring cups. Plastic syringes (minus the needles) are very useful for measuring thick liquids, such as suspension concentrate (SC) formulations. These are available in several sizes from suppliers of animal feed. A scale is essential for weighing dry flowables, wettable granules, and other dry formulations. Measuring devices, such as graduated cylinders, should have pouring lips and graduated markings that enable accurate measurements.

Plastic is generally safer than glass. Accurate measurement is essential for efficacy against the target pest, a safe range of pesticide residues on the crop, efficient use of chemicals and money, and the reduction or elimination of phytotoxicity (burning).

Proper measuring devices also play an important role in the overall safety and handling of pesticides. They aid in preventing spills of concentrated materials. Pesticide concentrates are usually handled when the sprayer is loaded and diluted sprays are being prepared. Special handling precautions are necessary at this time. The applicator must be particularly careful in handling finished sprays but even more so in dealing with the more dangerous concentrated material. Workers must be mindful and cautious and use all pesticides according to the label.

If applicators use too much pesticide, the following problems can result:

- The crop can have more residue than the law allows, which can pose health hazards to consumers and could prevent the crop from entering the market until it has undergone special cleaning.
- The crop can be confiscated by authorities for excessive residues and destroyed without any compensation to the grower. Resulting negative publicity can harm the future markets for that commodity.
- Reentry by workers into overdosed areas could be dangerous and lead to illnesses, medical costs, and liability to the grower.
- Production costs could increase without the benefit of added profits.
- Phytotoxicity is more likely to occur.

It is important not to exceed the label rates. If the maximum labeled rate is not achieving the desired results, look for other reasons for failure, such as poor coverage or resistance to the insecticide in the target insect population.

Step 3: Apply pesticides at the right time.

The chosen pesticide should be applied at the correct time. This is one of the most difficult tasks any grower faces. Determining the best time to apply chemical control is a very dynamic undertaking. Failure to treat at or near the correct time is one of the major reasons for unsuccessful pest management.

- Growers should regularly and thoroughly inspect the crop so that they are aware of the presence of insects and mites as well as any increase in numbers.
- Growers should know the pest, its behavior, and its ability to damage the crop.
- Growers should be aware of the number of insects or mites that constitute an economic or action threshold. Thresholds for each pest where information is available are discussed later in this chapter.
- Growers should know the biology of the pest so that insecticide or miticide application can be aimed at the weakest, most vulnerable stage or size. Some stages of insects and mites, such as the egg stage, can seldom be controlled. Young larval or nymphal stages are more easily controlled and require less insecticide or miticide than older stages. Pesticides generally do not affect pupae (large larvae nearing this stage are also difficult to control).

It is generally best to apply pesticides in the late afternoon or evening hours when temperatures start to decrease. (As a rule, insecticide or miticide applications should be made while temperatures are low.) This also allows for maximum exposure before "airing" out the sprayed area for employees. Also, many insects are most active at night. The risk of phytotoxicity is greater when applications are made during the middle of the day when temperatures are high. However, it has been reported that better mite control can be achieved by spraying early in the morning hours. Pesticides should not be applied when plants are water-stressed.

Step 4: Apply pesticides correctly.

There are many factors and components that add up to proper application of pesticides.

Timing is one of the most important steps in pest control efforts. It does little good to complete the first three steps properly and then fail to deliver the material to the target area at proper time. Spray equipment must be properly calibrated. A calibration mistake can result in applying too little pesticide and not achieving control, or applying too much, which is wasteful and illegal.

Growers should purchase the proper type of equipment to meet the needs of the operation and use equipment designed for the target pest. Each pest differs in habits and behavior, and a single piece of equipment may not meet all needs.

High-volume sprayers are popular and have been used for years. They can accommodate a wide range of pesticide types and offer flexibility in their operation. However, high-volume sprayers require a lot of labor, are time-consuming to use, and are considered low in application efficiency. It has been estimated that less than 10% of the active ingredient reaches the actual target when using high-volume systems. However, most insecticides and miticides are labeled for high-volume application.

For best results, knowledge about the pest and its biology should be coupled with the capabilities of the equipment. To reach the bottom sides of the leaves in thick canopy crops, a driving, directed spray may be required. If the crop canopy is thin, a rolling fog, atomizer, or electrostatic applicator may be very effective. Many insecticides can produce vapors that aid in controlling insects even when the coverage is less than desired. However, proper coverage can further enhance their fumigating properties.

Another consideration when correctly applying insecticides and miticides is the proper maintenance of spray equipment. Many spray operations are hampered, and their effectiveness drastically reduced because the spray cannot be delivered at the proper pressure, droplet size, or pattern due to excessive wear, improper adjustment, or broken or improperly working parts. Growers should regularly check nozzles and discs for wear and tear and replace them when they do not meet specifications. Discs and nozzles wear fast when flowables, suspensions, and wettable powder formulations are used. Workers should be aware of spray pressure and have accurate gauges. Inaccurate pressure—even small errors—can result in improper droplet size and failure to deliver the desired coverage. Equipment upkeep also factors heavily in the overall success of spray operations. Most insecticides are highly corrosive and will react with hoses, lines, nozzles, tanks, and other components. The resulting corrosion affects the spray patterns and leads to the formation of foreign particles that clog the equipment. Applicators should use the spray as soon as it is mixed and thoroughly clean and rinse the equipment as soon as they are finished spraying.

Workers must mix only the spray that is needed for the job. Leftover spray allowed to sit in the sprayer can quickly destroy it and other sprayer parts, lines, and components. Leftover spray also must be carefully and legally disposed of by application to a labeled site. Disposal of pesticides is a growing concern, with liability becoming more of a problem. Therefore, growers need to plan carefully for the amount of pesticide they need, use what is mixed, and clean up properly afterward.

Spray equipment must be properly stored after cleaning to keep it free of dust, dirt, and other foreign materials. Rust particles, pieces of rubber lines, and other unwanted particles can quickly stop up a system or cause poor spray patterns, particularly when pressure is applied.

Clean water should be used for spraying. Water is the most commonly used diluent (carrier) for pesticide sprays. Water frequently contains dirt, sand, or corrosion from the pipes or lines that may enter the spray tank. Loading hoses or pipes can be dirty. These contaminants can cause severe operational problems. Growers should filter water as many times as possible to ensure freedom from contamination. Filters should be used between the source of water, the spray tank, and where the water enters the tank. Filters are also needed between the tank and the final nozzle. This allows the spray to flow and be delivered in the pattern needed to meet the capabilities of the equipment.

Pesticides should be used as soon as they are mixed. Once mixed with water, the pesticide begins to change. The effective life of certain pesticides can be only hours once they are mixed with water. Water with a pH over 7.0, which is neutral, can be particularly detrimental to many pesticides. Generally, the higher the pH, the faster the pesticide is broken down and rendered useless. Under Florida conditions, where underground water is frequently high in calcium carbonate with resulting water pH of 8.0–8.5, it is even more important not to allow finished spray to sit any longer than necessary.

Weed Management

Weeds compete with vegetable crops for light, water, and nutrients. This competition decreases plant vigor, yield, and crop quality. It also interferes with hand harvest and can complicate or prevent machine harvest. Weeds also serve as alternative hosts for diseases, viruses, and nematodes. EDIS documents with lists of weed hosts for viruses and plant pathogens include ENY863, "Common Weed Hosts of Insect-Transmitted Viruses of Florida Vegetable Crops" (https://edis.ifas.ufl.edu/in931), and HS1335, "Weeds as Reservoirs of Plant Pathogens Affecting Economically Important Crops" (https://edis.ifas.ufl.edu/hs1335). There are also a range of books and EDIS documents that can help identify weeds in Florida, such as *Weeds of the South* and *Weeds of the Northeast*.

The first step in weed management is frequent and proper scouting. Fields should be scouted frequently early in the production year when the crop is more susceptible to competition. Keep in mind that weed populations tend to be patchy, are greater along the edges of fields, and will vary within and between fields due to minor changes in site characteristics, such as increased soil moisture or changes in soil type. Scouting should be completed in a zigzag pattern that covers the entire field area. Be sure to include locations with known differences that might lead to increased weed incidence, such as low-lying areas and areas with a history of weeds. All observations should be recorded in a field manual for future reference.

Proper identification and an understanding of the life cycle is important for selecting the correct method and timing of weed control. Weeds may be annuals, biennials, or perennials. Annual weeds emerge from seeds, grow, and flower within a single year. Summer annuals emerge in the spring and grow through the heat of the summer months. Summer annuals include pigweed, morning glory, crabgrass, pusley, and goosegrass. Winter annuals emerge during the fall and grow during the winter months. Biennial weeds emerge from seed and typically form rosettes but do not flower and produce seeds until after a dormancy period. Biennial weeds include wild carrot, cutleaf evening primrose, and common mullen. Perennial weeds can grow and produce flowers for multiple years. Perennial weeds produce vegetative structures, such as stolons, rhizomes, tubers, or large roots, that generate new plants. Perennial weeds include nutsedge, Bermuda grass, Brazil pusley, and creeping beggarweed.

Weed management practices can be separated into five categories: preventative, cultural, mechanical, biological, and chemical. The most successful weed management programs will incorporate more than one type of weed control.

Preventative Control

The first step is site selection. Select a field with low weed populations and treat problem areas, such as poor drainage, prior to crop establishment. Control or mow the weeds at the edges of fields or irrigation furrows to prevent seed formation. Seeds can move on equipment, on wind, on animals, and in water, and they may spread throughout the field. Weed seed can also move between fields on tractors, blades of cultivators, heads of harvest equipment, and other items. All equipment should be cleaned after completing a task in a field with a high weed population. When possible, limit travel in the field to periods when weed seeds are not mature, and when possible, work your cleanest fields first and move toward the ones with the greatest weed populations. Purchase crop and cover-crop seed from reputable sources to limit the amount of weed-seed contamination. When possible, prevention of weed seed production will help reduce weed seedbanks over time and reduce future problems. Keep in mind that seeds can mature on a weed in some situations after it has been hand-pulled.

Cultural Control

A healthy crop is a better competitor with weeds. Use healthy transplants or seeds with excellent germination to ensure quick canopy closure when possible. Plants stressed by diseases/nematodes or improper watering (too wet or too dry) are less competitive. Proper nutrition is important; minimize fertilizer in the row middles, where crops will not benefit but weeds will. Select the proper row spacing that will allow for quicker canopy closure.

Crop and variety selection has an impact on weed growth. Crops that are tall or have large leaves shade the soil surface and prevent weed seed germination. Crops such as cabbage, beans, and corn are very competitive crops. Onions and carrots allow more light to the soil surface and are less competitive. The same principle of light penetration to the soil surface can be applied to crop varieties—a variety that is compact or smaller in growth will be less competitive compared to other varieties.

Multiple vegetable crops are grown with polyethylene mulch. The horticultural benefits of plasticulture are reduced water loss, improved nutrient management, and increased fumigant retention. Plastic mulches also prevent light penetration to the soil surface and inhibit weed seed germination. Weeds can germinate under clear or white plastic mulches that allow light to reach the soil surface. If white mulch is desired, select one that has a black underside to prevent light penetration. When plastic mulches are used, grass and broadleaf weed emergence is limited to the crop hole and row middle. Minimizing the size of the planting hole can reduce the number of weeds that emerge. Yellow and purple nutsedge are the only species that pierce the plastic mulch and can rapidly spread within a mulched bed.

Crop rotation is an effective weed management tool. Growing the same crop repeatedly with the same weed management practices can select for difficult-to-control weed species as well as other pests and diseases. Properly designed rotations typically include a range of (1) crop types, preferably with a mix of row and agronomic crops; (2) planting dates; (3) agrochemical inputs; and (4) weed management tools. Choose a rotation based on crop competitiveness, use of mulch or cultivation, and different herbicide modes of action. The inclusion of cover crops can be an effective weed management tool. Care must be taken to observe plant-back restrictions for herbicides, or injury may occur in subsequent crops.

Cover crops should be included in any crop rotation. Cover crops shade the soil surface and prevent weed germination. Some cover crops such as rye have allelopathic compounds, which are plant chemicals that prevent seed germination. Additional information can be found under the Ask IFAS "Cover Crops" topic (https://edis.ifas.ufl.edu/topics/cover_crops).

Mechanical Control

Mechanical weed control includes plows, cultivators, mowers, hoes, and hand-weeding. Chisel and moldboard plows are used at the beginning of the season and cultivate deep into the soil profile. This process buries weed seeds below the germination zone. Light cultivation with a field cultivator controls small weeds by cutting them and is shallow to prevent weed seeds from being brought to the soil surface. A single cultivation provides excellent control of annual weeds; however, cultivation may break apart pieces of perennial weeds and cause the weed to spread. Repeated cultivation is important for perennial weed control because it encourages repeated growth and can reduce the carbohydrates in the storage structure of the weed, which can reduce the population over time.

Basket, tine, or finger cultivators lightly disturb the soil surface and control small weeds by breaking roots or foliage. Basket cultivators will provide control in the row middles; however, weed control in the crop row will be minimal. Tine or finger cultivators may provide better weed control in the crop row.

Use mechanical weed control only when it will be most effective because mechanical weed control degrades soil structure, dries the soil surface, and prunes crop roots.

Biological Control

Biological control relies on the use of one or more biological agents to damage a weed species. This method uses plant pathogens, insects, or other animals. Several control agents are host-specific, controlling certain weed species (e.g., tropical soda apple leaf beetle and tropical soda apple, Pakistani hydrilla tuber weevil and hydrilla). Because these organisms have narrow feeding habits, this method is typically used in natural and aquatic areas for a single invasive species. Biological control is not used in vegetable production due to the multiple weed species in the field; however, research is being conducted and new techniques may emerge in the future.

Chemical Control

Proper herbicide selection can be an effective weed control tool. Herbicides are classified by their mode of action, which is how they affect plant growth. Herbicides are separated by application placement, selectivity, and translocation.

Application placement includes foliar-applied or soil-applied herbicides. Foliar-applied herbicides control the weeds after emergence above the soil surface (postemergence). Proper coverage of the foliage is important for foliar-applied herbicides, and a surfactant is often required for proper absorption of the herbicide. Soil-applied herbicides control the weeds before emergence above the soil surface (preemergence). Soil-applied herbicides are applied to the soil surface or require incorporation into the soil surface. Incorporation reduces vaporization of certain herbicides or places the herbicide closer to the weed seed. Incorporation tactics include irrigation, rainfall, or light cultivation. Poor incorporation will result in reduced efficacy.

Herbicide selectivity results in control of a specific type of weed, such as broadleaf or grass weeds only. Auxin herbicides (2,4-D, clopyralid) control broadleaf weeds only and thus are commonly used in grass crops or turfgrass. Carfentrazone and certain sulfonylureas have excellent control of broadleaf weeds and cause low to no injury to grass crops. Grass-only herbicides (clethodim, sethoxydim, fluazifop) control only grass weeds and can be applied over the top of broadleaf weeds.

Herbicides can be grouped as translocating or contact herbicides. Translocating herbicides (glyphosate, halosulfuron) move from the contact point to another part of the plant. This is important when controlling perennial weeds, which require root death for complete control. Contact herbicides (carfentrazone, paraquat) kill the area around the contact point; complete coverage is important for these herbicides.

Herbicide-resistant weed species have become more problematic. Paraquat-resistant American black nightshade, paraquat-resistant goosegrass, and glyphosate-resistant Palmer amaranth have been documented or observed in Florida vegetable crops. To prevent resistance, growers should incorporate nonchemical methods, rotate modes of action, use products with multiple modes of action, use correct rates, and maintain constant monitoring.

Nematode Management

Plant-parasitic nematodes are some of the most difficult pests or pathogens that growers in Florida face. They are hard to recognize, are often confused with other biotic or abiotic problems, and can cause total crop loss in many fruits and vegetables. This is especially true in Florida's warm and sandy soils, where nematodes, such as root-knot (*Meloidogyne* spp.) and sting (*Belonolaimus longicaudatus*), can build up rapidly to high and damaging levels. In Florida, much more than anywhere else, managing nematodes is not only an option but necessary.

Life Cycle

Plant-feeding nematodes go through six stages—an egg stage, four immature stages, and an adult stage. Many species can develop from egg to egg-laying adult in as little as 21–28 days during warm summer months. Immature males and females and adult males are long, slender worms. Mature adult females of some species, such as the root-knot nematode, change to a swollen, pear-like shape, whereas females of other species, such as the sting nematode, remain slender worms. Nematodes are too small to be seen without a microscope. It is believed the root-knot nematode survives from season to season primarily as eggs in the soil. After the eggs hatch, the second-stage juveniles invade roots, usually at root tips, causing some of the root cells to enlarge where the nematodes feed and develop. The male nematodes eventually leave the roots, but the females remain embedded, laying their eggs into a jellylike mass that extends through the root surface and into the soil.

Damage

Root-knot nematodes usually cause distinctive swellings, called galls, on the roots of infected plants. Infestations of these nematodes are fairly easy to identify: dig up a few plants with symptoms, wash or gently tap the soil from the roots, and examine the roots for galls. Gall size can vary significantly and depends on the crop and nematode species. On cucurbits and tomato, they can grow as large as 1 inch in diameter; on pepper, eggplant, and strawberry, they are always much smaller. On the roots of grasses and certain legumes, root-knot nematodes can reproduce without causing galling. The formation of these root galls reduces uptake of water and nutrients. Also, galls can crack and facilitate the entry of soilborne pathogens. Root-knot nematode galls are true swellings and can't be rubbed off the roots as can the beneficial, nitrogen-fixing nodules on the roots of legumes. Aboveground symptoms of a root-knot nematode infestation include stunted plants, wilting during the hottest part of the day (even when soil is moist), loss of vigor, yellowing leaves, and other symptoms similar to those associated with a lack of water or nutrients. Infested vegetable plants grow more slowly than neighboring, healthy plants, beginning in early to midseason. Plants produce fewer and smaller leaves and fruits, and ones heavily infested early in the season can die. Damage is most serious in warm, irrigated, sandy soils. Symptoms are often wrongly attributed to lack of fertilizer or water, soil insect or disease damage, or plugged drip tapes. In fumigated fields, nematode symptoms often show up at the bed ends when the fumigant rig was pulled up too early or inserted too late.

Root injury from other nematode species can produce aboveground symptoms similar to those from root-knot nematodes. However, the actual injury to the roots is more difficult to detect. Roots can be short and stubby-looking and have slightly swollen root tips, as can be the case with sting nematodes, or show dark spots or necrosis, which can be caused by lesion nematodes (as well as certain soil pathogens). In all such cases, nematode infestation should be confirmed by collecting soil and root samples and sending the material to a laboratory for positive identification.

Nematicides

Nematicides can be separated into fumigant and nonfumigant nematicides. Fumigants will be discussed in the next section in this chapter. Until recently, nonfumigant nematicides were either organophosphate or carbamate insecticides/nematicides, such as ethoprophos (Mocap), terbufos (Counter) and oxamyl (Vydate). Other similar nematicides, like fenamiphos (Nemacur) and aldicarb (Temik), are no longer registered due to their generally high toxicity and environmental risk. Recently, some new products—fluensulfone (Nimitz) and fluopyram (Velum)—have become available. These new nematicides are less toxic than the older nematicides, having a caution label instead of a danger label. They also more specifically target nematodes and should not be considered fumigant replacements. Unlike fumigants, which will control all or most soilborne pests and diseases, nonfumigant nematicides will only or mostly target nematodes, and additional measures need to be taken to manage soilborne diseases and weeds. Biological nematicide options include live organisms like *Purpureocillium lilicanum* (Melocon, Nemaclean), bacterial fermentation products from *Burkholderia rinojensis* (Majestene), and several plant extracts (see chapter 19, "Biopesticides and Alternative Disease and Pest Management Products").

Whereas fumigants need to be applied several weeks before planting, nonfumigant nematicides are typically applied shortly before or at planting of the crop. In-crop (postplant) applications are allowed for Vydate, Velum, and most of the biological nematicides (see chapter 19).

Crop destruction practices and using end-of-season nematicides or fumigants can also help to reduce nematode levels. Plant-feeding nematode populations in annual crops are always low at the start of the season because nematodes are dormant and often hiding in deeper soil layers, waiting for new roots to feed on. Populations will gradually increase during the cropping season and tend to be at their highest at the end of the crop.

Applying a nematicide at that time would likely kill nematodes at the peak of their population: while they are still active and feeding and are thus more exposed. Nematodes are much more difficult to target during the off-season, especially in the middle of summer in Florida, when they tend to move deeper into the soil waiting for the next crop to be planted. In such cases, deep injection of fumigants (about 18 inches deep) can be done to target nematodes hiding in deeper soil layers; especially in heavily infested fields, deep injection can make a big difference (see Fumigant section).

Other Nematode Management Options

Ideally, nematode management should adopt a year-round approach, from seedling production, through field preparation and while growing the crop, to off-season nematode management. Nematodes usually are introduced into new areas with infested soil or plants. The first approach is to prevent nematodes from entering the field by using only nematode-free plants. To prevent the spread of nematodes, avoid moving plants and soil from infested parts of the field. Do not allow irrigation water from around infested plants to run off because this also spreads nematodes. Nematodes can also be present in soil attached to farm equipment, tires, and boots.

Field preparation in Florida often includes soil fumigation. It can also include compost, manure, or other organic amendment applications. These may not directly kill nematodes but will stimulate soil biology and may increase nematode predators, parasites, and antagonists. Organic amendments also will increase the water- and nutrient-holding capacity of the soil, especially in sandy soils. Because nematodes will cause more damage to water-stressed plants, this can lessen the effects of nematode injury without reducing levels of damaging nematodes.

During the growing season, biostimulants, compost teas, and other organic materials can be applied as well and may help for the same reasons.

For certain crops, such as tomato, cultivars resistant to root-knot nematodes are available, and they have been shown to provide good protection against most root-knot nematode species in Florida. Although even resistant tomato varieties can still exhibit some root galling under high nematode levels, they usually maintain their yield. An additional benefit of growing a resistant variety is that the nematode levels in the soil decline rather than increase, making it more feasible to grow a susceptible crop the following season, that is, a double crop.

Growing a crop on which the nematode cannot reproduce is a good way to help manage some nematodes. Unfortunately, rotation is not as easy for managing root-knot and sting nematodes, because so many vegetable crops and weeds are hosts for these nematodes. However, if a rotation schedule can be found, rotation in combination with fallowing and other available practices can reduce root-knot nematode numbers. Annual crops that are useful in a rotation plan for reducing root-knot nematode populations include small grains and resistant tomato varieties. Fallowing is the practice of leaving the soil bare; it tends to be more effective when the soil is kept moist, which induces nematode eggs to hatch and emerging nematodes to starve because there is no food source. It is also important to control weeds on which nematodes can survive during the fallow period. During the off-season, frequent tillage can also reduce nematode populations by bringing nematodes to the surface and exposing them to the sun. Solarization, covering the soil with clear plastic for four to six weeks, is another method that can be used, although nematode control tends to be limited to the upper soil layers.

Cover crops are always a good tool to include in a nematode management plan. Cover crops can have multiple benefits, from soil improvement and weed suppression to disease and nematode control. Florida's climate allows for a wide range of cover crops to be planted. A common summer cover crop in Florida is sunn hemp (*Crotalaria juncea*), which not only fixes nitrogen in the soil but is also a poor host for many nematodes, including root-knot nematodes. (There are several EDIS publications on cover crops and nematodes.) Certain plants, such as marigolds (*Tagetes* spp.), also have direct nematicidal properties and could also be used in rotations or as intercrops.

Fumigation

Soil fumigation is a preplant chemical treatment of soil, using a pesticide product (typically a liquid) that converts to form a volatile gas once released into soil. The gas is able to diffuse through open pore space throughout the soil to provide pest and disease control. All the fumigants are phytotoxic to plants, and the fumigant gases must dissipate from soil, usually taking from a few days to well over a month (depending on environmental conditions), before seeding or transplanting can occur without risk of crop injury. They are used globally on a wide range of annual and perennial crops and can be used alone or in combination to expand control of a wide range of soil-inhabiting pest species, including various insects, nematodes, fungi, and weeds. Because of their wide range of pesticidal activity, they are often called “multipurpose” or “broad-spectrum” fumigants.

In Florida, soil fumigants are most commonly used in high-value cropping systems to protect investment in crops where pest pressure is so high that it would be economically unfeasible to grow a crop without the use of a fumigant. As such, preplant soil fumigants have had a profound influence on production agriculture in Florida and have catalyzed the development of many high-value, raised-bed, and plasticulture cropping systems. Fumigants are also used in a variety of other lower-value fruit, vegetable, and agronomic crops such as potatoes, sweet corn, brassicas, melons, and other cucurbit crops to manage nematodes and other soilborne pests and diseases. In some cases, fumigants have been adopted almost to the exclusion of all other soil pest management strategies because of their superior broad-spectrum pest control efficacy and consistent enhancement of crop growth, uniform development, fruit quality, and yield.

Methods of Application

Fumigants are formulated and applied to soil in a number of different ways. Liquid fumigants can be applied either by directly injecting them into the soil using shanks or chisels or via direct injection into the irrigation system (drip fumigation). The portion of the field that is fumigated can also vary. For example, in the production of some crops, the entire field is treated, and this represents an overall or broadcast treatment. In other situations, fumigants are only applied in the plant row or raised plant bed. In this situation, only a portion of the field is treated; this is termed a strip, band, or in-row treatment. Most liquid fumigants with high vapor pressure are shanked or knifed into the soil. As liquids with relatively high vapor pressure, they are usually stored and applied as liquids (under pressure) and begin to vaporize shortly after injection in the soil. Narrow knifelike shanks are tractor-drawn through the soil at the required depth to inject the fumigant into soil. Metal delivery tubes attached to the trailing edges of the shanks provide the conduit for injection into soil. Delivery tubes release the fumigant in the bottom of the furrow made when pulling the shank through the soil. Fumigant flow rate to the soil shanks is regulated using various combinations of pressure, metering valves, nozzle orifices, shank spacing, and speed of travel. Errors in field application are typically attributed to mistakes in calculation of treated acreage, metering, and calibrated flow rates through properly sized delivery lines.

For many of the fumigants, a special EC (emulsified concentrate) formulation is required for drip application. Metam sodium, metam potassium, allyl isothiocyanate, and emulsified concentrate formulations of 1,3-dichloropropene, chloropicrin, and dimethyl disulfide can be metered and applied through a low-volume trickle or drip irrigation system. Drip fumigation (chemigation) is the most common method of application for some fumigants like metam sodium, metam potassium, or allyl isothiocyanate. Once these fumigants are applied to soil in the presence of water, they decompose to form MITC or AITC. Because of the slow and limited diffusion of MITC or AITC gases and high affinity for the water phase, continuous delivery in irrigation water following premixing has generally resulted in more uniform soil distribution with enhanced nematode control and crop yield for these products when compared with conventional chisel injection methods. MITC distribution in soil initially follows the water distribution patterns, but unlike with other fumigants, the distribution patterns do not change over time. Moreover, MITC and AITC disappear from the soil gaseous phase at faster rates than most other fumigants.

The proximity of the plant to the drip tube has also been demonstrated to be very important in defining pest control efficacy and plant growth response with a drip-chemigated fumigant. Given the sandy nature of most Florida soils, narrower bed widths, drip tubes with closer drip emitter spacing (mostly in the range of 8–12 inches), and planting practices that place plants closer to the drip tube are needed to more effectively utilize the drip tape for chemigational purposes.

Soils and grower production practices differ markedly, and these differences in soil type, compaction, and depth to restrictive layers can all affect water movement and the final distribution of chemicals within beds and soil profile. The presence of a shallow compacted traffic layer severely restricts downward penetration of drip water and fumigants contained within it. In general, the average depth, width, and cross-sectional area wetted by drip-irrigation water increases with total water volume applied. For a given water volume, the use of two tapes per bed increases spatial distribution of irrigation water simply because of the spacing between drip tubes and the increased number of emission points along the bed. Drip fumigant users are encouraged to consult with county agricultural Extension personnel regarding specific drip fumigation recommendations on delivery system, application rates, product concentrations in irrigation water, water volumes, and optimal injection periods to maximize movement and proportions of treated bed volumes for their farm locations.

Other formulations, like those marketed for shank applications of chloropicrin, dimethyl disulfide, and 1,3-dichloropropene, are premixed and sold in compressed gas cylinders. In most cases, these fumigants are shank-injected into the soil 8–15 inches deep using a positive-pressure closed system in which the fumigant cylinders are pressurized with nitrogen. Nitrogen is an inert gas used to propel liquid flow from the cylinder through the metering systems and through armored lines to the rear shanks or chisels, exiting through a steel delivery tube welded to the back side of the shank or chisel. Deep placement is not only a requirement of the fumigant label but is essential for prolonged fumigant retention in soil. In general, the closer to the soil surface a fumigant is applied, the faster the outgassing or escape from soil, and in general the poorer the pest control response. A plastic polyethylene tarp may be laid down over the soil immediately behind the injection equipment to provide a diffusion barrier for containment of the fumigant.

Studies have also demonstrated the barrier properties of a traffic pan to shank-applied fumigants. The traffic pan is a layer of compacted soil occurring just below the level of deepest tillage implement used in the field. Fumigant gases applied above the traffic pan do not provide control of nematodes occurring below the traffic pan. Recent studies have determined that high population densities of plant-parasitic nematodes can be broadly distributed to depths 3 feet below the plant bed surface. Subsequent studies have demonstrated the importance of deep shank fumigant applications, which destroy the traffic pan and place fumigants within deeper soil horizons, where upwardly mobile nematodes reside. The physical and practical challenge that remains to be resolved is how to achieve fumigant movement in lethal concentration to the lowest soil depths where nematodes reside.

The Importance of Fumigant Placement

Proper fumigant placement is another critical element that must be considered when using any of the different soil fumigant compounds, because of the large difference in vapor pressure (Table 1). In some instances, application depth and placement varies with the formulation of the fumigant product, giving the grower the opportunity to choose between a drip or shank application. For the 3-Way system approach that utilizes 1,3-D, chloropicrin, and metam, there are essentially three different locations to consider for fumigant placement. Placement of pre-bed applications of Telone II are made on the flat to a soil depth that places the fumigant 12–15 inches from the top of the bed or nearest soil interface. If fumigants are placed at this depth and used in conjunction with a seepage irrigation system, growers should ensure that the soil is not wet at this depth. Otherwise, poor nematode control and longer aeration times and crop plant-back intervals may be observed. Chloropicrin, applied over the top of the Telone treatment, is then applied 8–10 inches deep into soil as the beds are being formed and compressed. Metam sodium (Vapam) or metam potassium (K-Pam) should be applied 4 inches from the top of the bed and 4 inches apart using multiple coulters or shanks. After application, the bed must be recompressed and mulched immediately to prevent rapid escape of volatilizing gases. The primary objective for such shallow placement is to achieve maximum control of weeds. Most other fumigants should be placed 8–12 inches deep with shanks no further than 9–12 inches apart.

While methyl bromide rapidly diffuses as a gas across a bed, many of the currently proposed alternatives lack the vapor pressure or chemical properties to move as fast and effectively throughout the bed. Their movement in the bed is clearly limited and must be accounted for in fumigant placement. For example, if the shanks are not close enough together for some fumigants, an overlap in the area between shanks may not occur, leaving streaks of pests down the length of the bed. Many products are formulated for shank or drip applications. To maximize efficacy via drip application, proper placement of the fumigant generally mandates two drip tapes per bed to improve bed coverage.

The vertical and horizontal distribution of diseases, weeds, and nematodes in correlation with spatial movement of soil fumigants from their points of injection are now being considered as some of the primary causes of fumigant treatment inconsistency and origins of bed-recolonizing populations of pests. For example, current field research is demonstrating that additional streams of fumigant placed under the tuck areas of the plastic mulch at the bed shoulders results in a significant reduction of Fusarium wilt incidence and severity within the tomato planted row compared with the standard in-the-row grower application practice. Additional streams of fumigants deeply shanked below the mulch-covered plant bed and traffic pan are also demonstrating significant reductions in plant damage by nematodes and improvements to crop yield.

In most field surveys, a compacted zone (traffic pan) occurs just below the base of the raised bed. The presence of subsurface traffic pans (a dense, highly compacted soil layer) was shown to unavoidably cause changes in the downward percolation of water, permeability and diffusion to fumigant gases, and root penetration into soil. In practical terms, the compaction zone occurs just below the depth of the deepest tillage operation or implement used in the field. Other fumigant placement studies are showing the benefits to crop production of fumigants placed under the traffic pan: this placement allows fumigant gases to make contact with deep-dwelling nematodes within the field. Because the traffic pan almost completely restricts downward diffusion in soil of a fumigant when it is applied above the restrictive layer, application below the layer reduces damaging populations of nematodes, which would have otherwise survived the fumigant bed treatment.

Physical and Chemical Properties

After application, the fumigants penetrate the soil and quickly become partitioned in liquid, gas, and adsorbed soil phases. Immediately after soil injection, fumigant movement in soil is driven by density and pressure gradients from a narrow, linear band of concentrated product deposited directly below the chisel path. As the fumigant's partial pressure falls, soil movement via mass flow becomes less important than simple gas diffusion processes. Fumigant persistence, volatility, and degradation are influenced by many factors, including chemical properties, soil properties, and environmental conditions. A partial listing of some of the physical and chemical properties of the primary soil fumigants available in Florida is provided in Table 1.

Volatilization continues as long as the fumigant remains in soil and upward movement of the fumigant occurs as long as a concentration difference exists between the soil surface and soil atmosphere. Vapor pressure is a measure of the tendency of a fumigant compound to change into the gaseous or vapor state. The temperature at which the vapor pressure at the surface of a liquid becomes equal to the pressure exerted by the surroundings is called the boiling point of the liquid. The lower the boiling point, the more volatile the fumigant compound. Note the differences between methyl bromide and all the other fumigants listed. Hot and dry soil conditions favor more rapid escape of fumigants like methyl bromide and chloropicrin, particularly within surface soil horizons. Fumigant products with high solubility and low vapor pressures are typically better suited for drip application rather than shank, which is why metam sodium, potassium, and allyl isothiocyanate are described as being better suited for drip fumigation.

Mode of Action and Lethal Dose

Fumigant mode of action refers to the lethal action of a chemical on vital life processes of an organism. For example, a broad-spectrum fumigant can penetrate the body wall of a nematode directly and does not have to be eaten to be effective. Once inside the body cavity of the nematode, different internal organs are affected, because they are bathed by body fluids containing the fumigant compound. Metam sodium and potassium are very soluble compounds that become activated in water. The fumigants and their products interfere with many different vital processes, including enzymatic, nervous, and respiratory systems. Death of the nematode is rapid under these conditions, and development of tolerant or resistant populations of nematodes to the chemical is unlikely because so many integral bodily functions are simultaneously affected. This is not to say that all organisms are equally affected, because in fields with a history of repeated applications, metam sodium can disappear rapidly and fail to provide a lethal dose following application, indicating the key role of microorganisms in accelerated degradation of the product. In general, however, the fumigant concentrations within internal body fluids of nematodes frequently reach equilibrium with soil concentrations within about 30 minutes to 4 hours. In some cases, fumigant concentration may accumulate to much greater levels within the nematode than in soil.

In general, the lethal effect of a fumigant is determined by two components. The first is concentration (C) of the fumigant in soil air or soil solution, usually expressed as parts per million (PPM). The second is the length of time (T) the pest organism is exposed, expressed in minutes, hours, or days. The level of pest control is then related to dosage, the amount of fumigant pesticide placed in the environment of the soilborne pest for a known length of exposure time (concentration × time). Total exposure is the sum of CT products. Computed in this way, the cumulative dosage, or concentration-time index (CT), is often used as a criterion with which to evaluate the effectiveness of soil fumigation. For most organisms, there is a concentration level below which kill is not obtained regardless of the length of exposure. For most nematodes, long exposures to low concentrations of fumigant nematicides above the minimum concentration seem to be more effective than short exposures to higher concentrations.

Fumigants move through soil air, dissolve in the soil water, and kill in the soil water. Fumigants are volatile substances and change into gases upon injection into the soil as liquids. The vapors can only move through continuous soil air space. Pest and disease organisms normally exist within surface films of water surrounding soil particle grains. Even as fumigants move through open air passages, fumigant molecules dissolve into these surface water films and establish a dynamic equilibrium, moving back and forth from the air to the water phase as the fumigant diffuses through the soil mass. The portion of the fumigant dissolved in the soil water establishes the concentrations responsible for the kill of most soilborne organisms.

In practice, fumigants are commonly injected through a series of uniformly spaced shanks into soil. As the liquid volatilizes, gases begin moving in mass flow, diffusing outward in all directions from the point of injection. Because 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 fumigant front moves through soil, gaseous molecules are adsorbed to soil particle surfaces, redissolve into soil solution, and fill empty air spaces between soil particles. Maximum fumigant 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 pests or disease propagules killed by fumigant treatment within these areas depend on the number of CT units that develop within the fumigant treated zone. The relationship between fumigant application rate and pest control efficacy is therefore not only a measure of fumigant toxicity but of chemical dispersion as well. If dispersal is good, increases in fumigant 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. Reducing volatilization losses from soil is an effective way to increase CT values and improve fumigant pest control efficacy. It is for this reason that water seals and impermeable plastic mulches (VIF, TIF) are used to increase fumigant diffusion resistance near the soil surface. This serves both to promote downward diffusion of the fumigant and to enhance residence time and gas phase persistence in soil.

Pest Control Efficacy

Since their introduction to Florida agriculture, many different soil fumigants have been evaluated in field research trials to characterize pest control efficacy and crop yield response. The results from many of these research trials, particularly those to evaluate methyl bromide alternatives, have provided the basis for overall generalization of pesticidal activity for the various fumigant chemicals (see Table 2). In general, this research has repeatedly demonstrated methyl bromide to be very effective against a wide range of soilborne pests, including nematodes, diseases, and weeds. Chloropicrin has proved very effective against diseases but seldom nematodes or weeds. Although fumigants provide some bacterial pathogen suppression, they have not been satisfactorily controlled by any of the soil fumigants. Historically, most of the research conducted to evaluate 1,3-dichloropropene (Telone) has repeatedly demonstrated consistently effective nematode control with little or no control provided for soilborne disease or weeds. Metam sodium, metam potassium, and Dazomet are all nonselective preplant soil fumigants that provide measures of fungicidal, herbicidal, insecticidal, and nematicidal activity. Pest control efficacy of metam sodium and metam potassium has proved inconsistent, earning good to excellent ratings in some trials, but poor in others. Field research continues to evaluate modification of rate, placement, and improved application technology to resolve problems of fumigant inconsistency with these compounds. Metam sodium and metam potassium can provide good control of weeds when placed properly in the bed; however, research to evaluate modification of rate, placement, and improved application technology have not resolved all problems of inconsistent pest control. Dimethyl disulfide (DMDS) has demonstrated good to excellent control of nematodes, disease, and weeds when coapplied with chloropicrin, but as of 2020 the product is no longer registered in the US. AITC, the newest entry to registered fumigants in Florida, has shown promise in preliminary trials but is still under field assessment in a variety of crops and plant pathogens.

Because of their target pest specificity, many of the soil fumigants are formulated together or coapplied to increase their overall level and spectrum of pest control. For example, chloropicrin is used both as a stand-alone soil fumigant, as a chemical warning agent in formulation with methyl bromide, and in formulation with 1,3-D to increase its disease control effectiveness. Examples of coformulated or sequential application include 1,3-dichloropropene plus chloropicrin formulated together as Telone C17 or Telone C35, or sequential applications involving a broadcast or pre-bed application of 1,3-dichloropropene, followed later by chloropicrin and/or metam sodium in separate soil applications. Given the general lack of herbicidal activity associated with many of the fumigants, separate application of one or more herbicides may be required to achieve effective weed control.

Much of the current field research in Florida continues to focus on evaluations of chloropicrin coapplied with additional fumigants. In this co-application approach, chloropicrin has clearly been shown to be an integral foundation component of any alternative chemical approach to providing broad-spectrum pest control activity. Of the chloropicrin combinations, Telone C-35, a combination of 1,3-dichloropropene and 35% chloropicrin, has been the most extensively evaluated in Florida field trials since 1994. DMDS in combination with chloropicrin (21%) has also been extensively studied in west central and south Florida field trials and has proven very effective for soil pest control. All DMDS formulations and applications now require that Totally Impermeable Film (TIF) be used for field application and odor abatement.

Research conducted in Florida and areas of the Southeast appear to support the general conclusion that reasonably consistent soilborne pest and disease control can be obtained with in-row or pre-bed applications of Telone C35 (35 gal/A) or Telone II, applied at 12 gallons per treated acre, followed by chloropicrin applied in the bed at 150 pounds per treated acre. In combination with Telone II, Telone C35, or chloropicrin, use of a high barrier Virtually Impenetrable Film (VIF) or totally impermeable (TIF) mulch film will generally improve fumigant performance and reduce soil gas emissions. Currently, the EPA only recognizes use of specific high-barrier VIF or TIF mulch films where the film's permeability (mass transfer coefficients) to the different fumigant gases has been measured and meets EPA-approved emission reductions to qualify for buffer-zone-reducing credits. With use of the more impermeable plastic TIF or VIF mulches, fumigant rates can be reduced 25%–40% from maximum labeled application rates. Due to use restrictions for all Telone products in Dade County, either metam sodium or metam potassium at 75 and 60 gallons per acre, respectively, in combination with shank injections of chloropicrin (150 lb per treated acre) and appropriate herbicide(s) are currently defined as the best alternatives to methyl bromide.

Given the general lack of herbicidal activity associated with the alternative fumigants, weed control is usually assigned the highest pest management priority for most methyl bromide alternative chemical systems. Regardless of crop, separate application of one or more herbicides is a requirement for effective weed control with any of the different fumigants. In general, weed control with these different fumigants (including Vapam or KPam) plus herbicides is reportedly as good as or better than with methyl bromide. There are, however, numerous examples of less-than-ideal herbicide performance in which various grasses and broadleaf weeds were not effectively controlled. The problems incurred usually demonstrate the importance of soil conditions, incorporation method, and proper rate calibration for good weed control.

Herbicide Partners

In addition to Telone II plus chloropicrin, Telone C35, or PicClor 60, additional applications of appropriate herbicides will be necessary to provide weed control for any CUE crop (Table 3). For tomato, follow the fumigant pre-bed application of Telone C35 or Telone II and chloropicrin with a tank mix of napropamide (2 lb per treated acre) and S-metolachlor (0.95 lb per treated acre); apply the tank to the top of the raised bed at plastic laying for weed control. An additional application of halosulfuron (0.024 lb) as a postemergent, directed spray for nutsedge control may be necessary. For strawberries, the fumigant application of Telone C35 is supplemented by an herbicide tank mix of oxyfluorfen (0.5 lb per treated acre) plus napropamide (4 lb per treated acre) to the raised bed surface at plastic laying. (Note: a minimum 30-day interval is required before transplanting when using oxyfluorfen.) In pepper, an herbicide tank mix of napropamide (2 lb) and S-metolachlor (0.71 lb; 3rd party label obtained through FFVA) per treated acre is applied for weed control after the Telone II pre-bed and chloropicrin injection to the raised bed at plastic laying. Recent research on soil application technologies in Florida and Georgia have demonstrated improved nutsedge control with metam sodium or potassium applied through a series of minicoulters to the established plant bed just before installation of the plastic mulch.

Avoiding Plant Phytotoxicity

All the fumigants, including the gas and water phases of these fumigants, are toxic to plants. Soil dissipation and the persistence of toxic residues is strongly influenced by environmental conditions. Any change in soil condition that promotes a cooler and/or wetter soil condition will typically delay dissipation of a fumigant compound from soil. As a result, soil applications must always be made well in advance of a seeding or planting date to ensure sufficient time for dissipation of fumigant residues from soil. The problem is usually most severe with fumigants of low vapor pressure, where longer-term planning horizons must be adopted to avoid problems of phytotoxicity or to avoid long unscheduled delays in planting after the plants have arrived from the nursery. Growers who use fumigants typically adopt planning horizons that consider beginning field preparation and soil application two to three weeks earlier than normal. This early consideration helps growers avoid problems of potential phytotoxicity that may result from use of impermeable mulches or from unexpected cold fronts or storms producing abundant rainfall. Recent studies have also demonstrated that the addition of chloropicrin in the fumigant mix can destroy microbial populations in soil that digest fumigants like DMDS, thereby contributing to longer persistence in soil and potential delays in plant-back into the bed than would have occurred with DMDS alone.

High-Barrier/Gas-Impermeable Plastic Mulch Films (VIF, TIF)

Fumigant Containment

Historically, most of the field research conducted to evaluate the use of soil fumigation has repeatedly demonstrated effective soilborne pest and disease control when applications were made under optimal soil conditions, uniformly applied at the appropriate dosage and depth, and using containment systems that prevented rapid escape of gases from soil. Any system designed to provide containment of fumigant gases must first ensure immediate closure and seal of chisel traces as they are produced behind the tractor moving across the field. Left undisturbed, the chisel traces act as chimney vents for volatilizing fumigant gases. This can be accomplished with press wheels behind the chisel or chisel injections immediately in front of bed-forming equipment. The treated field area may also be rolled to compact surface soil to increase soil density and reduce air passage size and volume. Irrigation is also often applied over the top of the treated area and/or rolled surface to form a surface water seal to further inhibit fumigant outgassing from soil. In some instances, repeated irrigations may be necessary to manage fumigant containment and off-site movement of fumigant gases.

After a fumigant is applied, the treated soil may also be tarped with a plastic polyethylene mulch to provide an additional measure of fumigant containment to soil. The plastic mulches, often a prerequisite for fumigant use, are not only a barrier in themselves but also act as a condensation surface for the formation of water droplets, which redeposit to soil as a water layer, adding another barrier to soil volatilization loss. A range of different mulches can be used to reduce fumigant emissions from soil. Low-density polyethylene (LDPE) or high-density polyethylene (HDPE) tarps have been extensively used in combination with soil fumigation as a soil covering to reduce fumigant emissions from soil. Unfortunately, the barrier properties of LDPE and HDPE to fumigant gases is quite poor, and depending on the fumigant, much of it may quickly escape the soil. In general, the permeability of a plastic mulch to a fumigant gas is directly related to its thickness, density, and chemical composition. Significant resistance to fumigant outgassing has been achieved with use of virtually impermeable mulch films (VIF) and totally impermeable mulch films (TIF). VIF mulches are typically manufactured as multilayer films that are composed of barrier polymers such as ethylene vinyl alcohol (EVOH) or polyamide (nylon) sandwiched between other polymer layers (typically LDPE), or that have metalized coatings to reduce the amount of fumigant that can move through the film and into the atmosphere. A VIF film thus is typically defined as a five-layer film where the outer two layers are LDPE. The innermost layer is nylon and is surrounded by a bridging layer on each side. TIF films are generally manufactured similarly to VIF, except the center layer that produces the barrier is made of EVOH instead of nylon.

Compared to LDPE, certain VIF and TIF films are over 20,000 times less permeable to fumigant compounds and, as a result, significantly increase the residence time of fumigants in soil. Because of their excellent barrier properties, fumigant application rates can often be reduced as much as 30%–50% without loss of pest control activity or crop yield. These mulches, although not completely impervious to fumigant gases, reduce the dissipation rate of gases into the air, thus increasing the overall efficacy of the treatment by subjecting soil pests to greater cumulative dosage levels of the fumigant. With such efficient and near-complete retention of gases to soil, these same mulch films are known for causing plant-back issues, often requiring extended periods to allow for soil water and air concentrations to fall below levels phytotoxic to seedlings and transplants. To use the high-barrier mulch technology, plantings may have to be delayed to ensure soil residues have dissipated and plant injury will not occur. A monitoring program using colorimetric detector tubes (GasTek, Kitagawa, Sensidyne) or MiniRae-type VOC meters to assess residual fumigant gases in soil should be considered before a commitment to planting is made.

Due to increased environmental and regulatory scrutiny, VIF or TIF high-barrier plastic mulch films are now mandated for use with some fumigants to receive buffer-zone-reducing credits (20%–60%) to allow fumigant applications within certain proximities of human-occupied structures. They are also extensively used to allow for reduced-rate applications of the different fumigants without compromising concentration and time dosages, thereby maintaining pest control efficacy. Today, over a hundred different manufacturers or product lines can be identified with high-barrier, VIF, or TIF status with current EPA approval for buffer-zone credit. Additional information regarding EPA-approved tarps can be found at https://www.epa.gov/soil-fumigants/tarps.

Reduced-Rate Application Technologies

Currently, soil injection equipment for many of the different fumigant compounds is designed to dispense as much as 20–40 gallons of a liquid fumigant compound through armored lines from the gas cylinder to the flow meter and rear manifold, and then through each of three chisels per bed. The system is designed and calibrated to do this while moving at 3½–5 mph, uniformly dispensing multiple liquid streams of fumigant within 7,260–10,890 linear feet of row per acre. With such high rates, the flow lines are full, with liquids moving as continuous streams without in-line voids or bubbles. At 30%–50% reduced rates of application, such as those demanded for use with high-barrier VIF or TIF films, the situation may be vastly different, particularly if metered flow rates are low and do not exceed the total capacity of the delivery tubing and manifold system. With reduced flow and presence of bubbles or even voids in flow within lines, a significant loss of back pressure occurs at the chisel orifices. The dramatic fall in back pressure with reduced rate prevents accurate and uniform flow of the fumigant between chisels. This occurs at the point where total internal volume (flow capacity) of nine chisel tubes, typically ¼ inch in diameter, exceeds the flow capacity of a ¾-inch armored delivery hose from the flow meter. When the outflow potential is greater than inflow, there is a significant loss of pressure, and without back pressure the system becomes one of gravity flow. With the existing on-farm systems, accuracy cannot be achieved at such low volumes and without significant back pressure. To resolve the back-pressure problem, it is extremely important to reduce total line volume and/or diameter of the delivery tubes from the manifold to the chisels so as to guarantee adequate back pressure at the point of fumigant release. With a high-barrier mulch, reducing the field application rate of a fumigant results in a greatly reduced rate of liquid flow. Some chisels are so reduced in flow that accuracy and uniformity of application along and between the rows was compromised along with pest control efficacy.

In all probability, use of these more gas-retentive mulches will require changes in field application and soil injection equipment to ensure accurate and uniform dispensing of such low fumigant application rates (10–15 gal/A). These required changes include smaller delivery tubing size (1/8- to 1/16-inch diameter), installation of sight gauges to monitor flow uniformity among chisel streams, and installation of a low-pressure gauge upstream of the flow divider to monitor overall back pressure (at least 15 psi) at the flow divider (Table 4).

Table 1. Physical and chemical properties of various soil fumigants.

Fumigant Compound & Physical State	Boiling Point (°C)	Vapor Pressure (mm/Hg)	Soil Degradation Half-Life (d)	Solubility (mg L^{-1})
1,3–Dichloropropene	120	28	3–5	2250
Chloropicrin	112.4	18	1–2	2270
Methyl bromide*	3.6	1420	12–20	13400
Metam sodium	112	0.4	4–5	578290
Metam potassium	114	24	4–5	complete
Allyl isothiocyanate (AITC)	112	20	4-5	89400
*Methyl bromide is only allowed for use in certain nurseries.				

Table 2. Generalized summary of maximum use rate and relative effectiveness of various soil fumigant alternatives to methyl bromide for nematode, soilborne disease, and weed control in Florida.

Fumigant Chemical[1]	Maximum Use Rate	Relative Pesticidal Activity		
		Nematode	Disease	Weed
Chloropicrin	300 lb	Some to poor	Excellent	Poor
Metam sodium (Vapam)	75 gal	Good to erratic	Erratic	Erratic
Telone II	18 gal	Good to excellent	None to poor	Poor
Telone C17	26 gal	Good to excellent	Good	Poor
Telone C35	35 gal	Good to excellent	Good to excellent	Poor to fair
Pic-Clor 60	300 lb	Good to excellent	Good to excellent	Fair to good
Potassium N methyldithiocarbamate (Kpam)	60 gal	Good to erratic	Poor to good	Poor to good
[1] All currently within EPA Fumigant Reregistration review with potential for new restrictions and applicator requirements.				

Table 3. Recommended fumigant and herbicide treatment regimens for Florida[1] fruit and vegetable growers for fields in which nematodes are considered a major pest. All rates are expressed per treated acre. Other pre- and postemergent herbicides may be required for weed control. To achieve maximum weed control, an application of metam sodium (Vapam®—75 gal/A) or metam potassium (Kpam®—60 gal/A) should be considered as a supplemental herbicide treatment using a minicoulter applicator or through a drip application using double drip tapes.

Fumigant Product, Rate, Application Sequence and Procedure		**Possible Supplemental Herbicide**	
Broadcast	**Pre-bed**		**In-Row during Bedding**
Deep Shank Telone® II (12–15 gal/A) (12–15" deep) *Applied to the flat and soil sealed with tillage and rolling.*	-	Telone® C35 (35 gal/A) **or** Pic-Clor 60 (300–350 lb/A) **or** Chloropicrin (150 lb/A) *Applied in-bed under LDPE, High-Barrier VIF or TIF Mulch Film*[3]; applied 3–5 weeks before transplanting.	Napropamide (Devrinol®) S-metolachlor (Dual Magnum®) Postemergent halosulfuron (Sandea®) Oxyfluorfen (Goal®) Vapam® HL Kpam® HL
	Deep Shank Telone® II (12–15 gal/A) (12–15" deep) *Applied pre-bed*[2] to the flat, under LDPE, High-Barrier VIF or TIF Mulch Film[3]; applied 3–*5 weeks before transplanting.*	Telone® C35 (35 gal/A) **or** Pic-Clor 60 (300–350 lb/A) **or** Chloropicrin (150 lb/A) *Applied in-bed under LDPE, High-Barrier VIF or TIF Mulch Film*[3]; applied 3–5 weeks before transplanting.	

[1] Crop recommendations for Pic-Clor 60, Telone® II, and Telone® C35 do not apply to the Homestead, Dade County production region of south Florida or where certain soil types, absence of impermeable layers, and water tables currently prohibit product use.

[2] Inject Telone® II, Telone® C35, or Pic-Clor 60 to flat soil prior to any soil mounding or bed operation (pre-bed) to a depth of at least 12 inches below the final bed top.

[3] In combination with fumigant, one must use an EPA-approved high-barrier mulch film, such as virtually impermeable (VIF) or totally impermeable (TIF) mulch films. Fumigant rates can be reduced 25%–40% from the maximum pesticide labeled application rate, depending on the selected impermeable film.

For some crop uses of S-metolachlor®, a third-party label obtained through FFVA must be in the hands of the user.

Table 4. Summary of recommended fumigant injection equipment modifications required for use of high-barrier TIF and VIF mulches and reduced-rate applications of soil fumigants.

(1) Replace tubing from manifold to chisels with smaller-diameter poly tubing to compensate for the new reduced flow capacity requirement and to increase line back pressure needed to ensure accurate, uniform flow among all chisel streams.
(2) To the manifold-flow divider, install individual sight gauges to observe uniformity of fumigant liquid flow to each chisel outlet.
(3) Install a low-pressure gauge (0–30 psi) immediately upstream of the manifold or flow divider to insure at least 15 psi of back pressure.
(4) Ensure that the flow meter registers a minimum of 10% flow.