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ENY-048

Methyl Bromide: Progress and Problems Identifying Alternatives, Volume I[1]

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Florida tomato growers have relied upon broadspectrum fumigants such as methyl bromide for over the last 35 years to resolve most of their soilborne pest and disease control problems. The use of methyl bromide as a soil fumigant is now being phased out internationally under the Montreal Protocol. Developed countries such as the U.S. are scheduled to reduce methyl bromide use from a 1991 baseline by 25% in 1999, 50% in 2001, 70% in 2003, and 100% in 2005. Florida accounts for about 30 percent of preplant methyl bromide use on a national basis. An economic analysis of the ban of methyl bromide and adoption of Telone C-17 or C-35 was conducted for Florida tomato, pepper, and strawberry production. The results of this most recent analysis indicates Mexico gaining significant market share, and losses in total shipping point revenues of $68.8 million for tomatoes and $119 million for peppers. Pepper acreage is expected to decrease an estimated 65 percent. In addition, this same University of Florida study shows that yield losses need to be reduced 50-80% from what field studies and experts currently indicate for the most likely alternatives-depending upon crop- if methyl bromide-reliant regions are to maintain market shares within 10% of current levels. It should also be recognized that if regulatory issues for a number of the currently available chemical alternatives are not resolved, economic impacts could be considerably larger than currently estimated.

After the phaseout of methyl bromide, growers will have to rely on other chemical and nonchemical pest management approaches. With this system change, growers will quickly discover that these new systems are not infallible and that primary pest problems are subject to change with different pest problems emerging over time. The change from methyl bromide to another system is expected to create changes in pest species diversity and instabilities in densities. For example, minor differences in pest control efficacy of weeds, can produce upsets in population density of other pests such as nematodes. Studies of the interrelationships between pest species (eg. weeds and nematodes) is therefore of paramount importance towards the development of more integrated pest management (IPM) programs to replace the use of methyl bromide.

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During the period 1996-1999, the USDA ARS has provided funding in the sum of $243,750 on an annual basis to conduct small plot field research at various locations and to initiate field scale demonstration / validation studies at multiple sites within the major crop producing regions of Florida. Significant funding has also been derived from other state, federal, university, and commodity groups. Florida research has encompassed evaluations of both chemical and nonchemical pest control tactics. Based on initial chemical performance studies during the period 1994-1996, Telone C-17 in combination with the herbicide Pebulate (Tillam) was identified as providing a near equivalent alternative to methyl bromide for nematode and nutsedge control in Florida fresh market tomato production. The objective of this paper is to provide an updated review of some of the research, both chemical and nonchemical, being evaluated as alternatives to methyl bromide in Florida.

Large Scale Grower Field Demonstration Trials (1996-1999)

Twenty one tomato field demonstration / validation trials have been completed since the spring of 1996. Demonstration site locations included west central (Ruskin-Palmetto-Plant City), southwest (Naples), and south central (Immokalee). Each of the trials compared Telone C-17 or Telone C-35 applied in-row or broadcast, in combination with the herbicide Tillam (pebulate) to methyl bromide for weed, disease, and nematode control and for tomato yield response. For each demonstration trial, the treated area for each fumigant treatment was a minimum of 0.5 to 7 acres. In these large scale field validation trials, attempts were made to collect crop yield information independently from two sources; 1) small research subplots; 2) grower packout from entire treated blocks. In most trials, small research subplots were established in pairs to directly compare crop yield and size grade obtained from methyl bromide and Telone / Tillam treated blocks.

A summary of the results from research subplots shows that in only 3 of 12 trials did in-row / bed applications of Telone C-17 or C-35 + Tillam produce higher yields than that of methyl bromide (Figure 1). Average tomato yield losses for the Telone-Tillam combination was 6 percent, with a range of maximum loss of 22.3% to an increase in yield of 12.6%. The results from research subplots for the broadcast Telone C35 treatment has not, in the two studies conducted, produced the same encouraging results as that of the Telone C-17 or C-35 in-row treatment. For example, two large scale field demonstration trials in southwest and west central Florida with broadcast applications of Telone C-35 (18-28 gal/a) have produced tomato yields in small research subplots which were on average 21.8% less than that of methyl bromide.

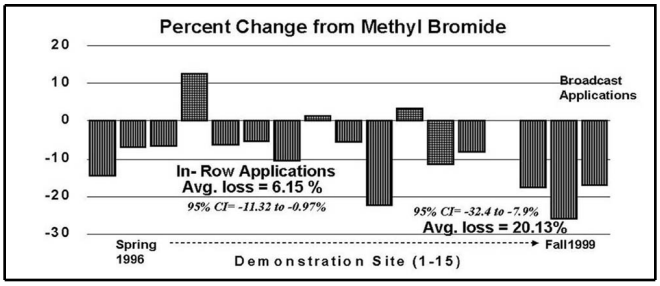

Figure 1. Summary of tomato yields of Telone C17 or C35 relative to methyl bromide from small research subplots within fifteen USDA sponsored large scale Florida tomato field demonstration / validation trials conducted Spring 1996 through Fall 1999.

The summary of grower packout data similarly shows that in only 4 of 12 demonstration trials did in-row (bed) applications of Telone C-17 or C-35 + Tillam produce higher yields than that of methyl bromide (Figure 2). Yield response ranged from losses of 22.3% to an increase in yield of 24.3 percent. Results from grower packout of the broadcast Telone C35 treatment indicated an average yield reduction of 10% compared to that of methyl bromide. Considering all sources of information, average yields of the Telone C-17 or C35 + Tillam treatment is expected to be 1 to 5 percent, with a 95% confidence interval of 9 to 13% potential yield loss (Figure 3). In addition to relatively small differences in yield, use of C-17 or C-35 has consistently resulted in plant heights which are 2 to 4 inches shorter than methyl bromide and a delay in crop maturity by about 4 days.

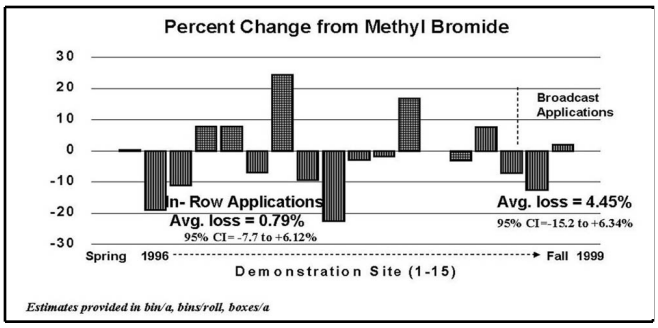

Figure 2. Summary of grower packout of Telone C17 or C35 tomato yields relative to methyl bromide from fifteen USDA sponsored large scale Florida tomato field demonstration / validation trials conducted Spring 1996 through Fall 1999.

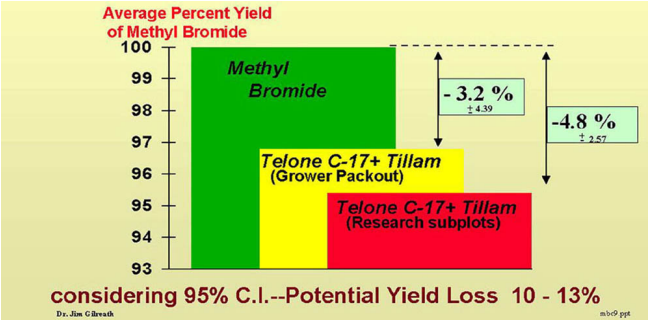

Figure 3. USDA sponsored large scale Florida tomato field demonstration / validation trials (14 trials - Spring 1996 - Spring 1998). Credits: Jim Gilreath

Pest Control Summary: Telone C-17 / C-35 + Tillam

Table 1 provides a generalized summary of the effectiveness of various fumigants which have been evaluated as alternatives to methyl bromide in Florida tomato. Previous research has demonstrated methyl bromide is very effective against a wide range of soilborne pests including nematodes, diseases, and weeds. Bacterial pathogens have not been controlled by any of the fumigants. Vapam and Basamid have generally performed very erratically and research to evaluate modification of rate, placement, and improved application technology have not resolved the problem of inconsistency. Chloropicrin has proved very effective against diseases but not nematodes or weeds. Telone C-17, a combination of two fumigants (1,3-dichloropropene + chloropicrin), was the only fumigant alternative which consistently proved to be near equivalent to that of methyl bromide in sustaining tomato yield and for nematode and disease control. None of the fumigants are as effective as methyl bromide for weed control which mandates the use of a separately applied herbicide such as Tillam.

Weed Control Summary

For acceptable weed control in tomato, Tillam (4 lb /a) has been combined and evaluated with Telone C-17 or Telone C-35 in experiments at University of Florida research centers and on commercial farms since 1994. Weed populations in plant holes within rows, emergence through the plastic mulch, as well as within row middles, was monitored in many of these trials. In a number of these trials, very few weeds were observed, or were recorded at such low densities that weed control could not be assessed reliably. In general, Tillam has provided nutsedge control comparable to that obtained with methyl bromide. Control of other weeds has oftentimes been as good as or better than that of methyl bromide. There are however, examples of less than ideal performance in which various grasses, black nightshade, ragweed, pigweed, and purslane were not effectively controlled. In addition to weed control in the bed, in three field demonstration studies, incidence and severity of weeds growing within the row middles were shown to be significantly reduced by broadcast, pre-bed applications of Tillam (4 lb/a) compared to that of methyl bromide. The results from other studies performed in North Florida (Quincy) also have showed nutsedge control was significantly improved when Tillam was used under a gas impermeable plastic mulch cover compared to the commercial standard polyethylene mulch.

Results from the completed studies have also demonstrated that incorporation method for Tillam can be quite important, not only for good weed control, but also for minimization of phytotoxicity or yield effects. Field research has demonstrated that Tillam, if not applied and incorporated properly, can be quite phytotoxic to tomato. For example, Tillam application prior to bed formation and incorporation with bedding disks (disk hillers) resulted in tomato plant stunting and reduced yield. Plant growth in some studies was severely restricted for more than half of the season and these plants never caught up with those planted in areas treated with methyl bromide. Incorporation with a grove disk (a shallow cultivating disk) or a field cultivator (S-tine harrow

with crumbler bars) appeared to provide sufficient mixing of Tillam for good weed control and no crop injury. Thorough incorporation with a light disk or a field cultivator is the preferred method and can provide results comparable to methyl bromide when combined with Telone C-17. Double disk incorporation procedures was observed to be superior in overall weed control when compared with single disk incorporation methods.

Pebulate is also not a persistent herbicide, such that various weed species germinating later in the crop season are not prevented from development which could then serve as alternative, reservoir, or carry-over hosts for various plant pathogenic nematode species. Given the narrower spectrum of herbicidal activity of the alternatives, higher end-of-season weed densities are expected. It is also not unreasonable to assume that a succession to other new, predominate weed species may occur.

Weeds are not only primary pests in themselves but also can reduce the efficacy of other alternative strategies such as crop rotation and fallow for the management of plant parasitic nematodes. Since many weeds are known to act as alternative hosts and reservoirs for nematode populations, IPM tactics must involve the coupling of weed control with nematode management strategies in both primary and rotational crops. Nematode and weed management can no longer be viewed as single actions or independent entities, but as a collective assemblage of integrated components. As such, the concept and philosophy of IPM implies that the overall strategies adopted for nematode management considers efforts to simultaneously manage weed populations (as well as other pests) within the field. Given the late season intensification of pest problems (nematode, weed), the IPM philosophy for Florida tomato growers must therefore be expanded to view nematode and weed management as a programmatic effort extending beyond the crop production season.

Telone Broadcast Soil Application Procedure

The requirement for use of a full spray suit, rubber gloves, boots, and a full face respirator by all personnel in the field at the time of Telone application has prompted a new research focus towards evaluation of broadcast, rather than in-row, treatments applied prior to bedding to minimize personnel protective equipment requirements. As with any new technology, broadcast application of Telone and Chloropicrin (C-17 or C-35) by growers will require some new field equipment and changes in application procedure and timing. Deep disking is still critical prior to fumigation to achieve deep placement and uniform diffusion of the fumigant through soil. As a broadcast treatment, the fumigant is injected through chisels spaced 10-12 inches apart and to a depth of 10 to 12 inches. The width of the tool bar and number of chisels to inject from will dictated by tractor requirements, field layout, and grower preference.

Deep placement of Telone C-17 or C-35 is not only a requirement of the pesticide 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 out gassing or escape from soil, and in general the poorer the pest control response. Years of testing have repeatedly demonstrated that open air passages between soil particles is necessary for volatilization of the liquid into a gas, and for subsequent movement of the gas in the soil. Fumigant diffusion in soil thus typically follows the path of least resistance. For example, deep diffusion of the gas will not occur if upward escape is easier, particularly if surface soil is hot, dry, recently tilled, and chisel traces remain. Upward escape is also promoted when deeper soil is cool and has higher soil moisture or is saturated (raised water table).

Unfortunately, deep injection of broadcast applications of Telone C-17 or Telone C-35 to a depth of 10 to 12 inches has not been possible in most cases because of the presence of a traffic compacted layer in the field (Figure 4). This problem is not encountered with in-row applications when 8 inches or more of soil is collected and compressed to form a raised bed. This traffic compacted layer has been observed in every grower field demonstration site surveyed. With little variation, the layer begins at a depth of 6 to 8 inches, corresponding to about half the diameter of discing blades repeatedly used for tillage operations. Straight shank or back swept chisels or gas knives typically will not cut into or

penetrate the layer, but in most instances will actually ride above, releasing a plume of fumigant on top of the layer at a depth of 6 inches. Fumigant diffusion into the compacted layer has not been measured but is believed to be minimal. Even if the knives do cut into the compacted layer, it does not appear to shatter enough of the compacted layer between chisels to be of much practical value. Recent field trials which have evaluated forward swept chisels, parachisels, and chisel plows arranged in staggered rows on the tool bars of the implement frame, have all helped to insure deep application, diffusion potential, and pesticide efficacy of Telone C-17 or C-35 applied as a broadcast treatment to the flat.

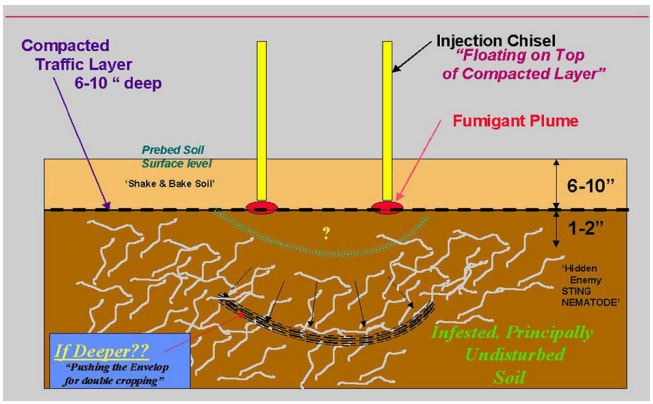

Figure 4. Importance of deep tillage land preparation for broadcast fumigant treatments. Credits: Jim Gilreath

Immediately following injection, the soil is shallow disked to a depth of 4 to 6 inches. To minimize early fumigant escape, compressing the soil with a roller immediately after application and behind the disks will decrease soil aeration and rapid escape, and with rainfall or irrigation provide for a more restrictive surface moisture seal. This is all done, preferably via a single implement and single pass through the field, to break up the channels left in the soil by the chisels and to compact the soil surface to prevent premature escape of the fumigant from soil. The field is then left undisturbed for at least 5 days prior to bedding, and at least 21 days prior to planting to avoid any phytotoxic effects from fumigant residues in soil. A separate herbicide application (ie., Tillam) is then made to soil a week after fumigant application or as late as at the time of bedding. Do not plant if the fumigant can still be detected in soil from normal plant rooting depth.

Tillam Application Procedure

Tillam is an old product in the thiocarbamate family of herbicides. Tomato is the only vegetable crop for which Tillam is labeled and label expansion is unlikely due to the age of the product and lack of patent protection. Use of Tillam on tomatoes can provide effective control of many weeds, including nutsedge, if it is applied correctly. Among the application factors which affect Tillam performance, use of the proper rate and thorough soil incorporation are the most important. Tillam is a preemergence herbicide and has no activity on weeds when sprayed post emergence. It is a very volatile compound and must be mixed into the soil as soon after application as practical to prevent loss of product and greatly diminished weed control.

Rate

Tillam must be applied at the full label rate of 2/3 gallon (86 oz.) per treated acre to be effective. Reducing the rate will reduce efficacy greatly. Rates in excess of 2/3 gallon per acre may cause crop injury and reduce tomato fruit production. Small discrepancies in rate generally are not a problem. Typical damage consists of stunting and may include malformed leaves. Foliar chlorosis is not normally observed and would suggest some other causal agent. Good agitation in the tank is important and spray pressure should be maintained below about 40 psi to minimize spray drift and assure that all product is going where you want it - on the soil.

Timing

Tillam is a very volatile herbicide and must be incorporated **immediately** after it is applied. Because of this, growers should consider placing the herbicide boom on the incorporation implement frame so Tillam is applied to the soil surface immediately in front of the tillage implement. In research and grower demonstration trials, Tillam has been sprayed to the soil surface in an application volume of 20 to 40 gallons of water per acre and incorporated immediately.

Soil Incorporation

Tillam should be applied uniformly to the entire field from ditch to ditch so there is no chance that nontreated soil can be pulled into the bed. Not only should the sprayer be checked for uniformity and accuracy of application rate, but Tillam also must be incorporated properly. Research has demonstrated that Tillam must be mixed thoroughly into the soil to the depth of the bed to provide good nutsedge control. Since bedders pull soil from about 6 to 8 inches deep, Tillam must be incorporated to at least this depth. Deeper mixing also may be advantageous for broadcast field applications. For example, nutsedge control has been achieved even in the row middles when the broadcast, pre-bed application of Tillam was deeply incorporated and all of the Tillam treated soil was not moved into the finished bed. If nutsedge is not the target weed, Tillam can be applied more shallowly, but movement of too much nontreated soil into the bed can reduce efficacy. A shallow incorporation on the bed surface would provide control of small seeded annual weeds, such as crabgrass, but would not provide good nutsedge control since nutsedge easily can emerge from deeper in the bed.

Method of incorporation for Tillam can be quite important, not only for good weed control, but also for minimizing phytotoxicity or negative plant growth and yield effects. For example, in one experiment plant stunting was observed when Tillam was incorporated with bedding disks. Bedding disks tend to fold soil and layer surface applied materials rather mixing them thoroughly. A concentrated layer of Tillam in the soil can cause delays in plant development, early season phytotoxicity, and restrict root growth until the herbicide degrades to a point where it no longer impedes root development. In the study in question, tomato fruit production was reduced to about 2/3 of what it should have been and maturity was delayed by approximately 2 weeks. Application of Tillam in the throat of a bedder, expecting the bedder to properly mix it into the soil, is a recipe for disaster similar to the use of bedding disks or disk/hillers. The mixing is not thorough enough with this equipment and poor weed control and crop injury are almost certain to follow. Thorough incorporation with a disk, rototiller, or a field cultivator is the preferred method and can provide results comparable to methyl bromide when combined with Telone C-17 or C-35. Incorporation with a disk may require two passes to thoroughly mix Tillam, whereas under good soil conditions a field cultivator (s-tine harrow) usually can achieve the desired extent of mixing in one pass. A rototiller is the best incorporation implement, but they are slower than a disk or cultivator, require more horsepower to operate and are not as readily available as a disk or cultivator.

Speed of incorporation can be important for good mixing. Generally when using a disk or a field cultivator, ground speed should be at least 6 mph in order to throw the soil more and assure complete working of the soil. At slower speeds soil mixing is not as good because of less action. With disks, the amount of set can be a factor in mixing. Maximum set is to be discouraged because it tends to bury the herbicide more than desired and disking at this stage is strictly for herbicide incorporation, not for land preparation where maximum set to the gangs is more commonly practiced. The extent of set should be enough to mix the soil to the desired depth without leaving the soil surface in a less than acceptable condition, such as deep troughs or ridges, and not so much that the ground speed can not be maintained above 6 mph.

Soil Conditions

Soil temperature and moisture conditions can be very important in determining the level of weed control achieved with Tillam. For example, soil which is too dry promotes volatilization of Tillam into the atmosphere. A dry sand also tends to be warmer than a moist one and volatilization losses can be rapid. Some of the worst performance observed in research occurred when Tillam was applied to a soil that was on the dry side and the cultivator fluffed the soil, allowing the soil to dry even more.

In addition to volatilization, performance can be lost due to poor mixing. Soil moisture can play a significant role in this. A soil which is very dry does not “flow” as well through a disk or cultivator as does one with optimum moisture content. Good mixing is dependent upon the soil particles having some adhesion to one another so that the soil is more

easily turned and blended rather than moving more like a liquid as it does when it is too wet or dry. If the soil is wet, it becomes sticky and will not break apart as it is disturbed, moving around field cultivator sweeps or points much like butter would. This can result in uneven distribution of Tillam in the bed when the bed is formed which, in turn, can mean areas where weeds germinate and emerge. It is very difficult to mix dry soil; the soil tends to fall out of the disk blades prematurely and does not “turn over” when a field cultivator moves through it. Soil moisture should be adequate for good seed germination so that it mixes well when Tillam is incorporated and so the weed seed and tubers germinate quickly. Since about one-half the Tillam is present in the soil after 2 weeks, it is important that weed seed germinate and tubers sprout soon after application when the maximum amount of Tillam is present.

Nutsedge often becomes a problem on bed shoulders, even with the use of methyl bromide. This is because the shoulder gets hotter than most of the rest of the bed and pesticide loss is greater under higher temperatures. Tillam can exhibit the same behavior, presumably due to volatilization and faster degradation on shoulders.

Soil should be free of weeds and debris should be well decomposed, as it should be when applying methyl bromide. Some growers allow some weed growth to be disked into the soil at time of fumigation and expect good efficacy. While this often works with methyl bromide, it is a poor practice in which to engage when using any of the other fumigants and herbicides. Tillam will not control weeds once they have emerged from the soil and it is important that it be applied prior to germination and emergence. This is especially important with nutsedge. Fields should be clean cultivated for several weeks prior to Tillam application and all plant debris should have decomposed enough so that it is no longer recognizable.

Lastly, you should not expect Tillam to control ALL weeds. If you do not have nutsedge in your field, you may wish to select another herbicide. Herbicide selection should be based on weeds expected to be a problem. Thus, knowing the field history is important. The move away from methyl bromide will make maintenance of good soilborne pest records for individual fields invaluable for future planning purposes. Growers should begin practicing that now.

Importance of Grower Field Testing

In order to facilitate increased use of alternatives, substantial efforts on the part of Florida growers will be needed in future cropping seasons for the evaluation of efficacy of any alterative approach via actual field testing. Growers must realize that the appropriateness of the alternative must be considered and assessed as to the alternatives efficacy, ease of application, relevancy to climatic conditions, soils, and cropping patterns. To really determine the nature of crop response will require repeated testing in the same field, not only because of the long histories of repeated methyl bromide use but because some alternatives only have a limited spectrum of pest control activity. For example, chloropicrin is an excellent fungicide but generally lacks activity against nematodes and weeds, and additional measures will be needed to provide a full spectrum alternative system, tailored for or prescriptively developed to suit individual needs. As a result, some combination of treatments and or alternative tactics will have to be developed and evaluated over time to insure or achieve the same broad spectrum pest control and yields obtained with methyl bromide. Mistakes will be made and penalties can be harsh. To perform these field trials in the time remaining, a change of grower attitude is required regarding trial of alternative technologies. In our estimation, Florida growers only recently have begun to show interest in trying alternatives. The time has finally arrived in which corporate goals should be redefined to increase commitments of production acreage to evaluations of alternatives, and to fine tune the system for their own production practices (ie., to determine equipment requirements, time tables, etc). Benefits of this approach will ultimately lead to a reduction in methyl bromide use, increased reliance on an alternative, though still enough time in which to rely on the consistency of methyl bromide as a major component of their system. If farmers don't, then there may not be enough lead-time to develop and 'commercialize' their own systems.

The objective of a grower field trial is not only to obtain field experience with application but also to observe differences in crop response and pest control under the conditions present on the grower's farm. In preparation for field trialing of any alternative, growers should recognize that many factors serve to isolate and maintain certain pests only within particular field locations. Just as there are differences in crop production between farms and between individual fields on a farm, there can be differences within a given field. Most growers know this and recognize that comparisons of something, such as fertilizer rate, are difficult to make under these conditions. One way of minimizing this problem or effect is to repeat the comparison several times within a field. Thus, the different fertilizer rates are more likely to have an equal chance to be situated in the weaker as well as the stronger parts of a field. This same approach should be used with assessment of fumigant alternatives on a farm.

Soil factors also can influence crop growth response to fumigants and herbicides independent of pest presence and density. For example, wetter areas require longer aeration periods for the fumigant to dissipate from soil, and are thus areas where phytotoxic effects are frequently observed first. In any case the more areas in a field in which to directly compare the performance of the alternative with that of methyl bromide, the more information a grower will have to characterize problems, shortcomings, and to customize the overall system.

To conduct the test, a grower should first consider selection of a field with a previous history of soilborne pest problems, and or areas in which natural variation in soil type and moisture occur. Within these areas, the field test would then be organized as alternating strips of methyl bromide and an alternative treatment (Figure 5). The location of the test strips should be selected such that growers can relocate these same areas in following cropping seasons. The number and length of rows to be included in the test is determined by grower preferences, harvesting efficiencies, and or material requirements. Growers should also plan to harvest field strips separately so as to compare crop yields with that of methyl bromide. For example, a tomato grower who harvests the rows on both sides of a drive row at one time would want to apply the same fumigant to the two sections which would be harvested in one pass, thus not interrupting the normal 'flow' is operations. Any testing is best if it blends into the normal pattern of doing things as much as possible.

Use of Nematode Resistant Varieties

Use of host plant resistance is typically viewed as one of the foundation principals of an integrated, nonchemical, pest management approach to replace or minimize dependence on soil applied nematicides or biocides like methyl bromide. Numerous studies have shown host plant resistance as potentially offering considerable promise for both nematode management and maintenance of high yields in single and multi cropping production systems. There is also however, building evidence to show that use of nematode resistant cultivars should not be construed as a stand alone nematode management tactic, and that they may not be used universally because of various genotypic environmental interactions which contribute to reduced effectiveness. As one example, there is ample evidence to show that high soil temperature diminishes host plant resistance to nematodes in a number of crops such as tomato and pepper, and that in these crops, plants grown under warmer soil conditions become more susceptible to nematode infection. Since a large portion of Florida tomato and pepper production occurs in a hot, subtropical climate, the utility of root-knot resistant cultivars with thermal sensitive resistant genes has come into question. In areas such as Florida, use of these varieties may be of limited practical value because soil populations of root-knot nematodes probably would increase under such cultivars.

Given that most if not all of the resistant crop varieties have not elicited an immune response to all species and populations of root-knot nematode, the beneficial effects may also be reduced by selection pressures on select individuals within a population which do initially develop and increase in numbers to overcome the plant resistance.

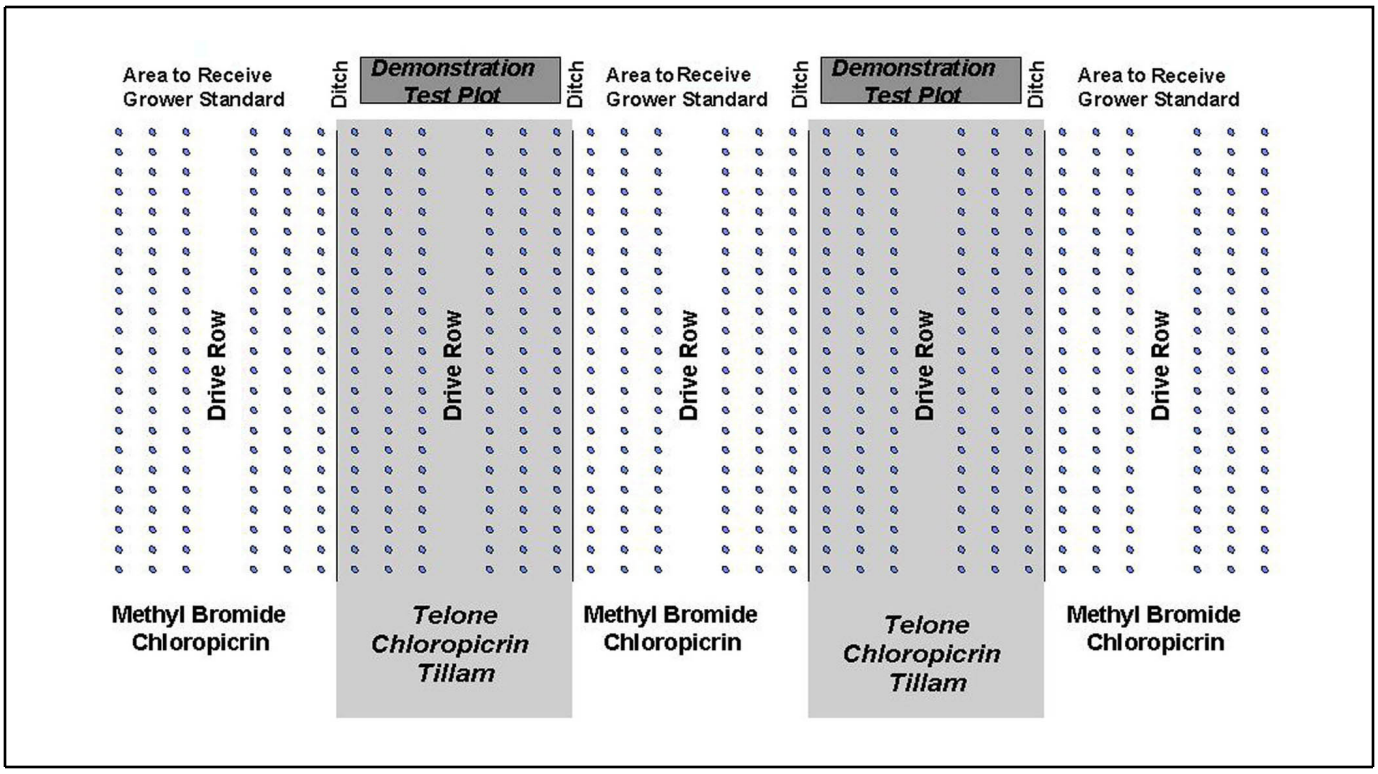

Figure 5. Example of grower directed field trial in which alternating treated strips forms the plot design to test alternatives to methyl bromide.

Evaluation of Nematode Resistant Tomato

Since the Fall of 1996, small plot field experiments have been conducted in Lake Alfred, FL to evaluate the new root-knot nematode resistant tomato cultivar 'Sanibel,' and to compare the resistance and plant yield response of this variety with a nematode susceptible cultivar, such as 'Agriset 761' or 'Florida 47.' The study has been repeated for five plantings to determine whether resistance could be broken by repeatedly selecting for soil populations of the root-knot nematode which could reproduce and cause significant yield loss to this new nematode resistant cultivar.

Results from these studies show that a naturally occurring virulent population of *M. incognita* was already present in soil, since some individuals within the population were able to parasitize and reproduce on the resistant gene-bearing 'Sanibel.' Even though reproduction was not assessed for all experiments, final harvest soil population densities of *M. incognita* remained low with 'Sanibel,' relative to the levels observed in susceptible 'Agriset' or 'Florida 47,' indicating an initial high level of nematode resistance. It was not until the conclusion of the fifth planting cycle during fall 1998, did final harvest soil populations of *M. incognita* increase to higher levels in the resistant 'Sanibel' compared to 'Florida 47.' At this same time (Fall 1998), root gall severity and relative yield losses were also higher with 'Sanibel' than 'Florida 47' (Figure 6).

These studies demonstrate that irrespective of nematode reproduction, a nematode resistant cultivar is not immune from incurring significant crop damage. During the first three planting cycles (Fall 1996 through Fall 1997), 'Sanibel' yield losses were on average 20% less than that of susceptible 'Agriset,' indicating a higher degree of plant tolerance to nematode parasitism by *M. incognita*. This expression of plant tolerance disappeared during the final two cropping cycles in which 'Sanibel' yield losses were on average 13% more than that of susceptible standard. Even with a resistant cultivar therefore, some consideration of preplant population levels of root-knot nematode in soil must be observed to minimize potential yield impacts.

Given tomato yield reductions of 30 to 40% over the course of these field experiments and at the highest soil population levels, combined efforts to

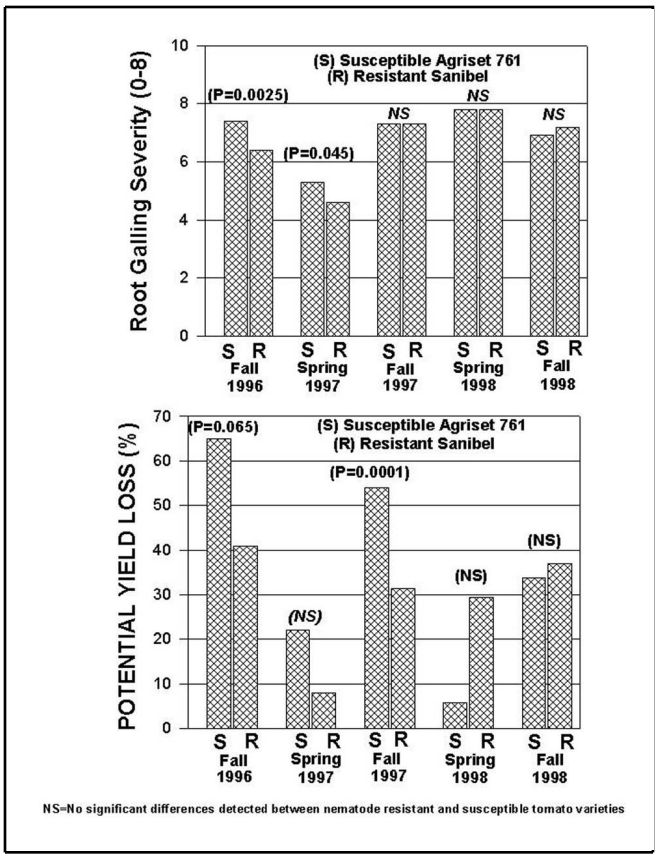

Figure 6. Responses in root galling and potential yield loss of root-knot nematode susceptible (Agriset 761) and resistant (Sanibel) tomato cultivars in each of five concurrent field trials from Fall 1996 through Fall 1998. UF/CREC, Lake Alfred, FL.

manage *M. incognita* to low levels still must be considered prior to planting. These studies have also demonstrated that use of a nematode resistant variety is not in itself a stand-alone replacement for methyl bromide soil fumigation, nor can the resistance be expected to last if some attempt is not made to preserve the resistance by alternating susceptible and resistance crop varieties in consecutive planting cycles. To be useful, and perhaps more durable, plant resistance as a nematode management tactic may require additional considerations for use in Florida. Given the temperature sensitivity of the resistance gene in tomato, use of these cultivars in Florida may have to be restricted to spring plantings when cooler temperatures initially prevail.

Similar studies conducted in Quincy, comparing resistant 'Sanibel' a nematode susceptible standard, have demonstrated quite the opposite of the above results. In these studies, no significant loss in yield, little or no root galling or reproduction of *Meloidogyne javanica* has been observed on 'Sanibel' roots.

Evaluation of Nematode Resistant Pepper

Fresh market bell pepper varieties (cultivars) with resistance to root-knot nematode currently are not commercially available as a tactic for nematode management. However, two newly USDA ARS developed root-knot nematode resistant varieties ('Carolina Belle' and 'Charleston Belle') have recently been released for field evaluation. As part of Florida methyl bromide alternative research efforts, these varieties were evaluated in small plot and commercial field research trials during spring 1998, fall 1998, and spring 1999 in west central and southwest Florida. Preliminary results from the grower field trial have demonstrated potential problems involving grower acceptance of these smaller, apparently lower yielding, open pollinated varieties.

It is also apparent from other field trials conducted in Lake Alfred, FL, that even highly resistant pepper varieties can suffer appreciable yield losses if initial root-knot nematode population densities are too high (Figure 7). In these studies, average pepper yield losses of 52% and 86% were observed among both susceptible and resistant varieties in the presence of the southern root-knot nematode, *Meloidogyne incognita*. Root gall severity was high for both resistant and susceptible pepper varieties. No resistance, ie. reduced nematode reproduction and soil population densities, was observed on either of the nematode resistant pepper varieties compared to that of the susceptible variety. Yield losses increased from the fall to spring planting as a result of nematode population increase during the fall crop.

The small plot research trials in Lake Alfred could not determine whether the significant yield losses or the high levels of nematode reproduction were associated with the apparent heat instability of the nematode resistance gene within these varieties. This group of experiments showed that a naturally occurring virulent population of *M. incognita* was native to the field, and based on the results of the initial spring 1998 experiment was able to parasitize, reproduce, and cause significant yield losses of 34 to

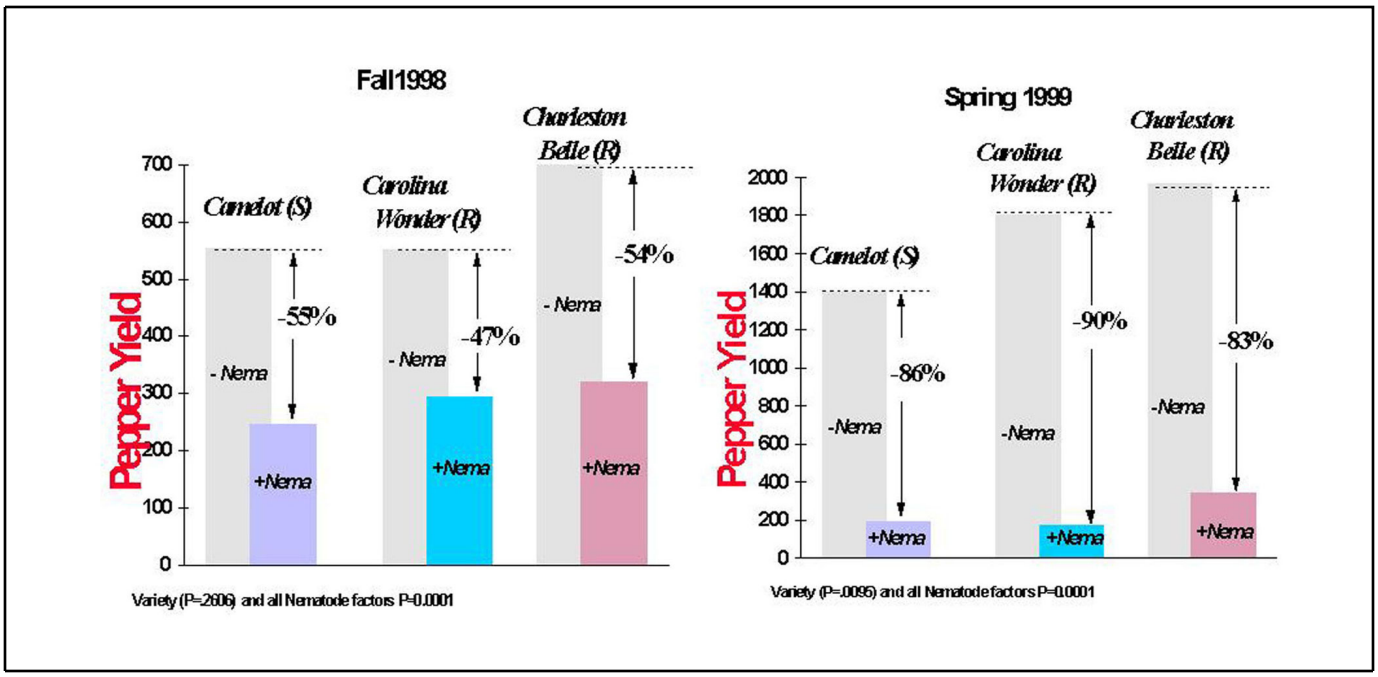

Figure 7. Yield of susceptible (S) and resistant (R) bell pepper cultivars grown in field microplots with (+nema) and without (-nema) the southern root-knot nematode, *Meloidogyne incognita*, during Fall 1998 and Spring 1999 at UF/CREC, Lake Alfred, FL.

45% on both N gene bearing resistant pepper cultivars. As recently demonstrated in similar studies evaluating use of a root-knot resistant tomato cultivar, some consideration of initial soil population level must still be observed prior to planting to minimize nematode induced yield impacts and to reduce selection pressures of developing biological races from the existing *Meloidogyne* population. Once again, these studies demonstrate that use of a nematode resistant pepper variety is not in itself a stand-alone replacement for methyl bromide soil fumigation at this time.

Use of Soil Amendments

The importance of organic matter to crop productivity, especially in sandy soils, has long been recognized for its ability to improve physical and chemical properties of soil, ie., water and nutrient retention and availability. In some cases, toxic metabolites or colonization by antagonists within the amended soils have also been shown to be responsible for direct suppression of soil nematodes. In Florida, various root-knot nematode (*Meloidogyne*) species are the primary nematode parasites of most high value vegetable crops. An alternative nonchemical strategy to methyl bromide for nematode control and maintenance of yield is to periodically apply composted organic materials as amendments to soil to suppress nematodes. Many different forms of amendments to soil have been used such as various agricultural and municipal composted residues, ie., composted bark, municipal solid wastes and waste water residuals. Other considerations for use of these soil amendments is to improve water and nutrient retention properties of sandy soils with an organic medium could also improve the management difficulties associated with drip irrigation for plants with limited root systems. Irrespective of pest management considerations, the use of organic amendments are frequently reported and promoted as a means of increasing crop tolerance or reducing the pathogenic impact of nematodes and disease on plant growth and yield. Tolerance is commonly used to describe the sensitivity of a host plant to nematode parasitism or amount of damage sustained, and is measured in terms of crop yield loss. An improvement in tolerance therefore implies that the host suffers less yield loss even when heavily infected with nematodes, whereas yield is greatly suppressed on a similarly infected intolerant cultivar.

Beginning Spring 1997, a series of four small plot experiments were initiated to assess the potential value of a single source of composted municipal waste to suppress soil populations of the southern root-knot nematode (*Meloidogyne incognita*) and to improve or maintain tomato yield in the presence of damaging soil populations of the pathogen. The CMW, obtained from Palm Beach County, FL consisting of yard trimmings and sludge, was applied at broadcast incorporated rates of 0, 15, 30, 60, 90, and 120 tons per acre. With the different amendment rates, tomatoes were then grown in either nematode free or nematode infested soil.

In general, the results of these four studies showed the potential for significant increases in tomato yield with amendment rate, particularly in the first tomato crop following CMW application (Figure 8). In some instances, the yield of tomato with the incorporated compost was near double (196%) the yield of the unamended control. The principal effect of the amendment was however never a result of direct suppression of *M. incognita* but an apparent increase in water and nutrient availability which resulted in improved tomato plant growth and yield. In addition to being nonnematicidal, use of this amendment did not enhance the ability of tomato plants to tolerate root infection by root-knot nematodes. Tomato yields were most always reduced by a constant amount by nematodes. In general as plant and root system size increased with amendment rate, so then did final harvest soil population densities of *M. incognita.* In the fall 1997 test, the effect of the amendment on nematode population buildup was so pronounced that tomato yields were unaffected and actually decreased with amendment rate. In general, the larger the plant, the more the food and the higher the end of season nematode population density. As has been reported in other recent soil amendment studies in Florida, use of at least this amendment proved not to be an effective alternative to methyl bromide soil fumigation, and unless nematodes come under biocontrol, may in fact increase management difficulty of soil nematode populations.

Use of Biorational Compounds

Beginning Spring 1998, a series of three small plot field experiments were initiated to evaluate the nematode suppressiveness of eleven biorational compounds and to determine any corresponding enhancement of tomato fruit yield (Table 2). The active ingredients of these compounds can best be described as either microbial agents or derived toxins, plant extracts or dried plant products, or simple blends of fatty acids, stabilized colloids, or secondary alcohols. In general, the results from these three studies showed that the biorational compounds evaluated provide little or only very weak nematicidal activity, and were always considerably less effective than the current industry standard, methyl bromide or of Telone C-17. For example, none of the biorationals produced a significant reduction in final harvest root gall severity compared to the untreated control during any season in which they were applied. In some cases, this occurred even though weekly applications of the compound were made rather than a single preplant treatment. On average, relative root gall severity of the biorational compounds on an experiment wide basis was within 10 to 15% of that of the untreated control. Whereas, an 80 to 95% reduction in final harvest root gall severity was achieved with either Telone C-17 or methyl bromide compared to the untreated control. Differences in tomato yield were usually directly related to severity of the formation of galls on roots. Highest tomato plant fruit yields were always associated with plants expressing little or no symptoms of root system galling. On average, tomato yield losses of 30 to 50% were observed with the biorational compounds compared to that of methyl bromide (Figure 9). In general these results suggest that suitable and or consistent nematode control and tomato yield enhancement cannot be achieved with the biorational compounds evaluated in these studies. Further research characterizing the utility of these compounds under different environmental conditions, and the ways and means in which to increase their effectiveness is necessary.

Crop Rescue / Post Plant Remediation

Nematode management must be viewed as a preplant consideration because once root infection occurs and plant damage becomes visible it is generally not possible to resolve the problem completely so as to avoid potentially significant

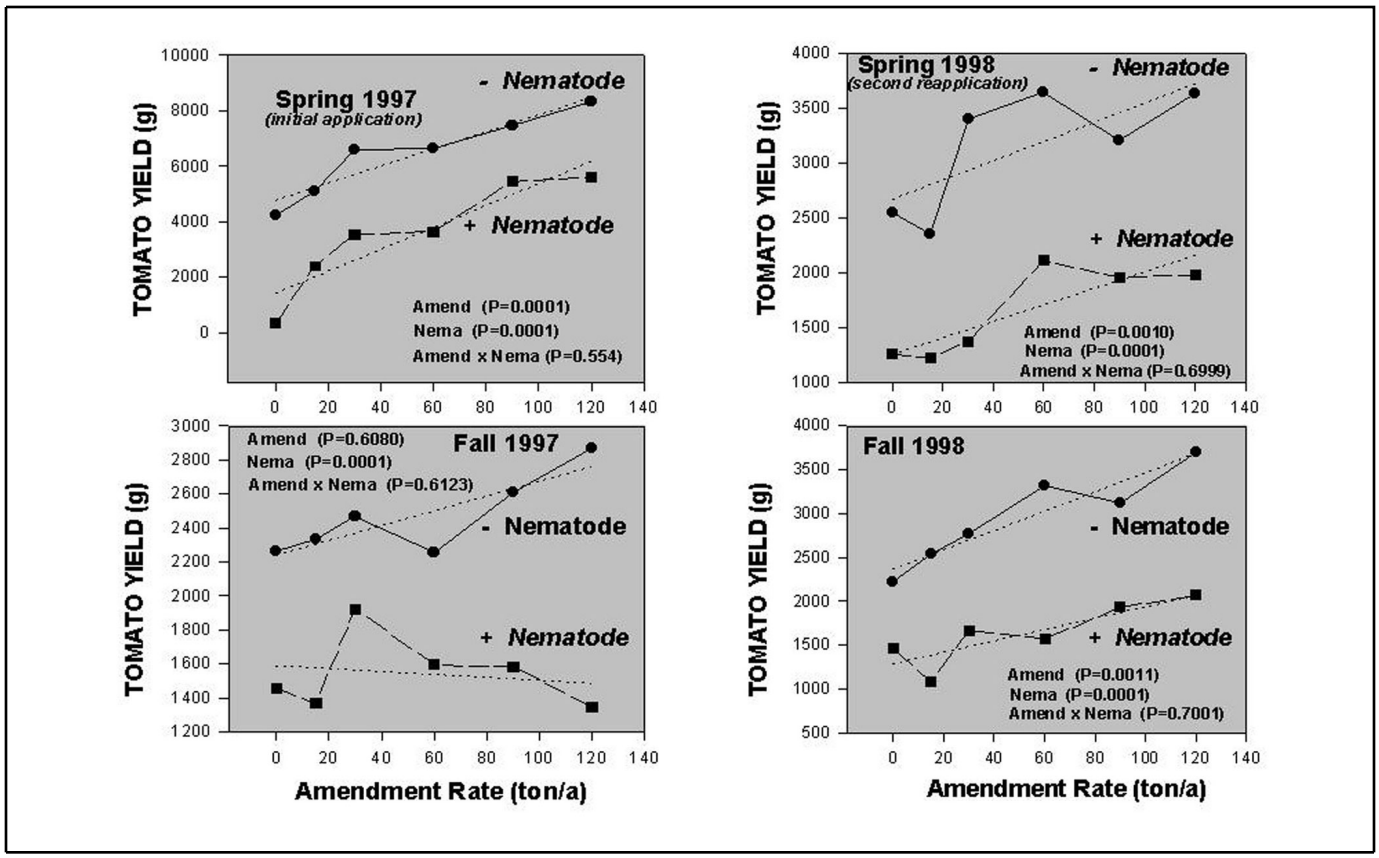

Figure 8. Long term expriment to evaluate the effects of increasing levels of municipal composted waste and biosolids on tomato yields with (+nema) and without (-nema) the southern root-knot nematode, *Meloidogyne incognita* in field microplots at Lake Alfred, FL.

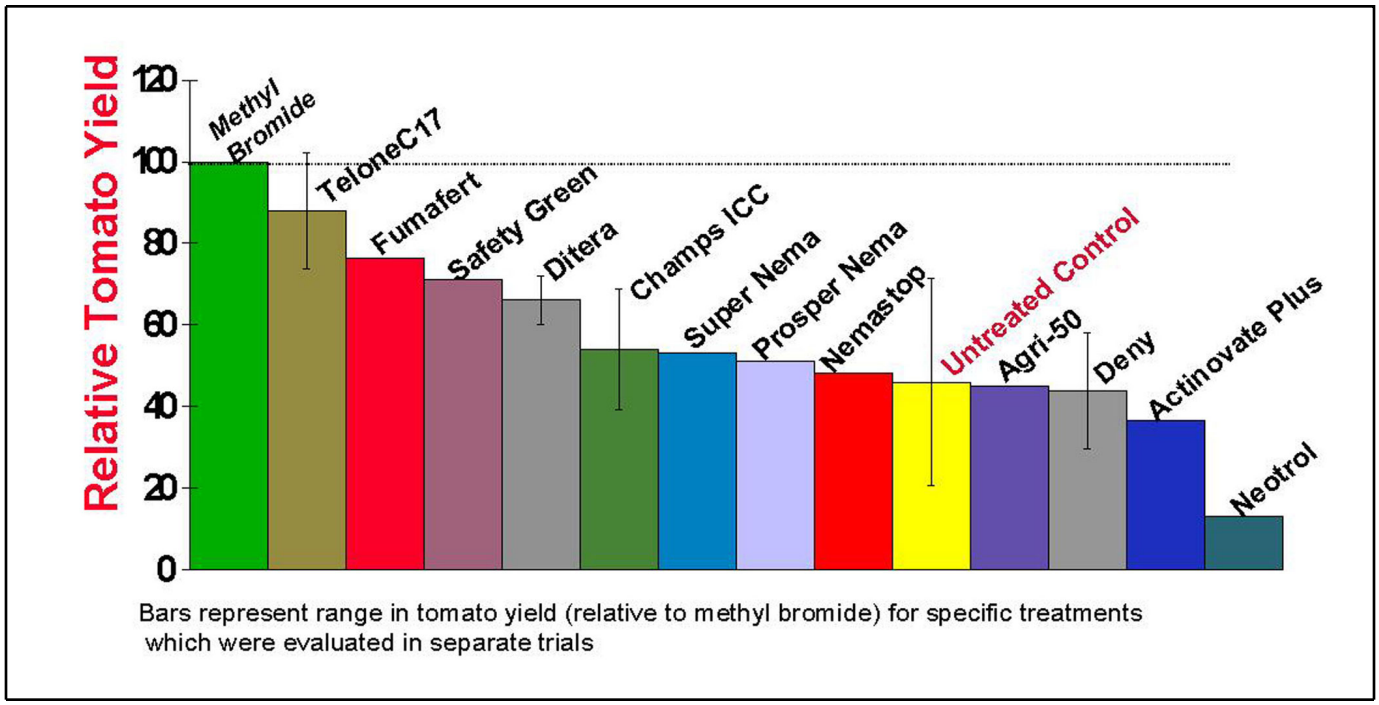

Figure 9. Effect of biorational compounds on tomato yield, relative to methyl bromide, in replicated tomato field microplot trials during Spring 1998, Fall 1998, and Spring 1999 at Lake Alfred, FL.

tomato yield losses. An experiment conducted during spring 1997 evaluated the extent to which tomato plant growth and yield could be 'rescued' from root-knot nematode via early detection and treatment by post plant applications of Vydate L (Oxamyl). In the experiment, tomato was planted into either nematode free or nematode infested microplots and soil treatments with Vydate L initiated 4, 6, 8 and 10 weeks prior to harvest. Vydate L application rates were held constant for all treatments at one gallon product per acre per season. Applications were made once per week as a soil drench or foliar treatment in one gallon of water resulting in concentrations of Vydate L in irrigation water of 20 to 57 ppm. The results of this experiment clearly showed that it was not possible to completely resolve the problem and avoid tomato yield losses with post plant applications of Vydate L (Figure 10). This was particularly obvious in tomato yield responses with foliar applications of Vydate L attempting to resolve a soilborne problem. If an attempt is going to be made to rescue the crop, the sooner the nematode problem is recognized and soil applications of Vydate L started, the greater the improvement in tomato yields relative to plants maintained nematode free.

Conclusion

In this paper we have tried to emphasize only a few of the various management tactics and transitional strategies currently being studied as replacements for methyl bromide in Florida. For the most part, we did not address crops other than tomato or numerous other crop and pest management tactics under evaluation around the state. Many of these tactics are only in a preliminary stage of research, and have not been studied in sufficient detail to predict either short or long term impacts. As research progresses, a discussion of these other crops and management tactics will be the subject of a subsequent article.

At the same time we have tried to make clear that none of the alternatives under investigation are without liabilities or shortcomings of one sort or another, and that the ultimate phaseout of methyl bromide will have tremendous impact, particularly if some federal and state regulations are not changed or even further limit the use of pesticide alternatives (ie., Telone buffer zones). Adoption of alternative chemical strategies and other IPM methods are also likely to be expedited only if appropriate guidelines and recommendations for their use are developed which minimize performance inconsistency and grower uncertainty. Unavoidably, some factors that affect the success or failure of the various tactics, such as the environment, may not be completely manageable or resolvable. For example, seasonal differences in temperature and rainfall patterns can adversely effect fumigant dissipation from soil, herbicide efficacy, and the function and utility of nematode resistant crop varieties, and thus reduce the value of many alternatives by causing treatment inconsistency.

We have tried to show that many strategies are not stand alone, direct replacements for methyl bromide and that some combination of treatments and alternative tactics will have to be used to insure or achieve similar broad spectrum pest control and high yields obtained with methyl bromide. Against this background, we recognize that mutlple-tactic IPM strategies will gain grower acceptance not by merely minimizing the undesirable environmental affects associated with methyl bromide use, but by addressing, as comprehensively as possible, the broad range of factors affecting performance and the economic costs and benefits obtained from each management practice. Given the limited time remaining and the additional 25% methyl bromide use reduction scheduled for January 1, 2001, we cannot overstate that substantial efforts on the part of Florida growers will be needed via actual field testing of new alternatives and the ways and means in which to use the new alternatives more effectively.

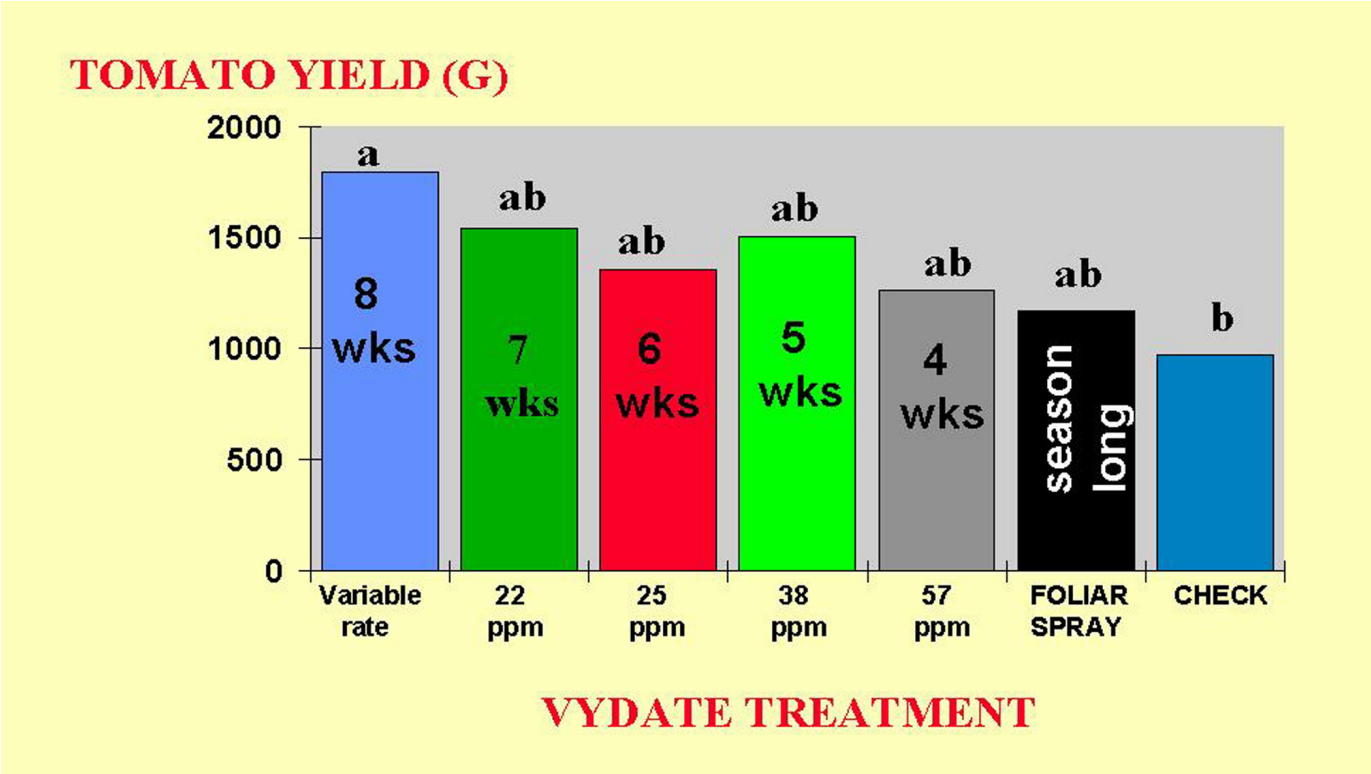

Figure 10. Response in tomato yields to post plant applications of Vydate L applied at different concentrations in irrigation water and initiated as weekly treatments at various times prior to final harvest in field microplots infested with *Meloidogyne incognita*. Spring 1997, Lake Alfred, FL.

Table 1. Summary of the effectiveness of various soil fumigants for nematode, soilborne disease and weed control.

FUMIGANT	NEMATODE	DISEASE	WEED
Methyl bromide	excellent	excellent	good to excellent
Enzone (experimental)	none	none	none
Vapam	erratic	erratic	erratic
Basamid	erratic	erratic	erratic
Chloropicrin	none to poor	good to excellent	none
Telone C-17	good to excellent	good to excellent	poor

Table 2. Biorational treatment list evaluated in field microplot trials at the University of Florida Citrus Research and Education Center, Lake Alfred, FL.

TREATMENT	COMPOSITION	RATE
Actinovate Plus	*Streptomyces lydicus*	16 oz/a @ wk
Agri-50	Stabilized colloid mixture	143 gal/a
Champon Insect Control Concentrate	Mixture pepper, mustard, & citrus oils	50-150 gal/a
Deny	0.6% *Burkholderia cepacia*	1 pt/a @ wk
DiTerra WDG	Toxin from *Myrothecium verrucaria*	100 lb/a @ wk
Fumafert	Mixture rapeseed meal & neem oilseed meal	916 lb/a
Methyl Bromide	Combination of methyl bromide & chloropicrin	400 lb/a
Nemastop	Liquid combination of plant extracts, fatty acids	20 gal/a
Neotrol	100% ground sesame plant	460 lb/a (2x)
Prosper Nema	Selected strains of mycorrhizal fungal spores	305 lb/a
Safety Green	Proprietary blend of secondary alcohols	2 pts/a
SuperNeem	Combination of humic acid, seaweed extract and neem concentrate	2 gal/a
Telone C-17	Liquid formulation of 1,3 dichloropropene and chloropicrin	35 gal/a
Untreated Control	----------	----------