

Nonchemical Management of Soilborne Pests in Fresh Market Vegetable Production Systems

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ABSTRACT

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Nonchemical methods including host resistance, organic amendments, crop rotation, soil solarization, and cultural practices have been used to control soilborne pests in fresh market vegetable production systems. Their suitability as alternatives to methyl bromide will depend on the approach to pest management used by the grower. Traditionally, methyl bromide is used in production systems that rely on the single application of a broad-spectrum biocide to disinfect soils prior to planting. Nonchemical methods are not suitable for a single tactic approach to pest management because they do not provide the same broad spectrum of activity or consistency as fumigation with methyl bromide. Nonchemical methods are compatible with an integrated pest management (IPM) approach, where multiple tactics are used to maintain damage from pests below an economic threshold while minimizing the impact to beneficial

organisms. However, adoption of IPM is hindered by the paucity of economically feasible sampling programs and thresholds for soilborne pests and by a reluctance of growers to commit additional resources to the collection and management of biological information. A novel approach to the management of soilborne pests is to design the crop production system to avoid pest outbreaks. Using this "proactive" approach, a tomato production system was developed using strip-tillage into existing bahiagrass pasture. By minimizing inputs and disruption to the pasture, growers were able to reap the rotational benefits of bahiagrass without cultivating the rotational crop. While minimizing the need for interventive procedures, a proactive approach is difficult to integrate into existing crop production systems and will require several years of testing and validation.

Additional keywords: ecologically based pest management, sustainable agriculture.

Nonchemical management of soilborne pests has been practiced for centuries (32). Only in the last 40 years have agricultural producers come to rely on synthetic chemicals for the control of soilborne pests. During this period, agricultural production systems were modified or redesigned to use newly available chemicals such as methyl bromide. Thus, the critical question facing vegetable producers who have relied exclusively on methyl bromide fumigation are (i) can soilborne pests be managed without chemicals in production systems designed around the use of broad-spectrum biocides to control them; and (ii) whether soilborne pests can be managed without chemicals by growers who have evolved in a culture based on the use of broad-spectrum biocides?

This paper first presents a brief discussion on vegetable production systems that account for the principal use of methyl bromide and of some of the factors contributing to its exclusive use, and three divergent approaches to the management of soilborne pests

and their potential for the use of nonchemical alternatives are explored. Examples of potential nonchemical methods for the management of soilborne pests are presented.

FACTORS CONTRIBUTING TO THE USE OF METHYL BROMIDE

Evolution of vegetable production systems. In the early 1960s, new production systems for fresh market vegetables evolved to take advantage of technological developments in plasticulture, fertilizer, pesticide application methods, and cultivars (29,30). To compensate for the lack of land suitable for these new production systems and for the corresponding increases in production costs, growing seasons were extended and continuous monocultures were practiced. With intensive cultivation practices came a dramatic increase in the incidence and severity of soilborne pests, commonly referred to as "old land syndrome" (51).

Broad-spectrum soil fumigants were soon introduced to control soilborne pests and the continued development of these production systems centered on the use of a single tactic, preplant application of a broad-spectrum biocide, to control all potential soilborne pests (31,38,73). Today, these production systems are used primarily for field production of fresh market tomato, pepper, and strawberry in the eastern United States and strawberry production in California, although many ornamental and cucurbit producers also use these systems (10,48).

Emergence of methyl bromide. As a soil fumigant, methyl bromide is unsurpassed in its ability to control myriad pests ranging from weeds to nematodes to fungi. When considered to-

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gether with other attributes, such as ease of application, low phytotoxicity, and effectiveness over a range of soil conditions, it is no surprise that growers who can afford the application costs have preferred to rely on methyl bromide for control of soilborne pests. Since its adoption in the 1960s, a generation of vegetable growers has come to depend on methyl bromide to alleviate the threat of soilborne pests. However, it should be noted that not all pests are controlled by methyl bromide. Fumigation with methyl bromide does not provide season-long control of bacterial wilt and Fusarium crown rot of tomato, Fusarium wilt of tomato and cucumber, and Phytophthora root rot of azalea and rhododendron (20,24, 37,60).

Despite its shortcomings, no other soil fumigant on the market today offers the same consistent level of control over a broad range of soilborne pests, environmental conditions, and cropping systems. In many areas of the world where intensive agriculture is practiced, the use of methyl bromide has become indispensable (70,73). By 1996, U.S. tomato, strawberry, and pepper producers accounted for 39% of the annual U.S. methyl bromide consumption and 12% of the global consumption (5). Without methyl bromide, production of tomato and pepper in Florida was projected to decline by 69%, resulting in losses exceeding \$450 million (6,61).

APPROACHES TO THE MANAGEMENT OF SOILBORNE PESTS

Three divergent approaches can be taken to develop programs for the management of soilborne pests. As outlined by Sylvia and Chellemi (66), there are a single tactic approach, an integrated pest management (IPM) approach, and a proactive approach.

Single tactic approach. The single tactic approach consists of a routine application of a broad-spectrum biocide to eradicate all potential pests. Applications are made on a regular basis using materials with a range of efficacy broad enough to remove the threat of all potential pests. The single tactic approach remains popular because it eliminates the need to obtain and manage information regarding pest biology and their population parameters in the field, thus simplifying the decision making process for growers. Determination of cropping sequences and application of materials is based on marketing constraints or a calendar date. Because the risks associated with damage from potential pests is reduced, growing seasons can be extended and the need for fallow periods or cultivation of a rotation crop is greatly reduced.

Several problems are associated with use of a single tactic approach. Industries that become dependent upon a single treatment to control all soilborne pests are vulnerable to any circumstances that impact the availability of the product. Such is the case with the Florida tomato, pepper, and strawberry industries, where regulatory actions threaten the continued use of methyl bromide (26). In addition, over-application of pesticides is common with the single tactic approach because applications are based on calendar dates or other nonbiological criteria, further increasing production costs and the potential for environmental disruption.

Integrated pest management approach. Integrated pest management (IPM) is defined as the coordinated use of multiple tactics to maintain damage from pests below an economic threshold while conserving beneficial organisms. The origin of IPM is rooted in the ecological principles of natural pest mortality factors, predator-prey relationships, genetic resistance, and cultural practices. Unfortunately, the practice of IPM is not always consistent with the theory of IPM (35). For example, as IPM was applied to the management of arthropod pests, its application in many instances became limited to pest scouting and precision application of insecticides. Ecologically based pest management (EBPM) has been proposed as an evolutionary progression of IPM. In EBPM, information on pest biology is used to integrate components that maximize the natural suppression of pest populations. Growers will rely primarily on inputs of pest biological

knowledge and secondarily on physical, chemical, and biological supplements for pest management (35).

Application of IPM or EBPM for the management of soilborne pests remains challenging. Economic thresholds have not been determined for many soilborne pests, and sampling methods are time consuming, expensive, and labor intensive. In addition, residual populations of soilborne pathogens are often below the level of detection for most methods. Combined with the explosive growth potential of many root pathogens, this often leads to the use of qualitative presence/absence designations rather than quantitative counts. Traditional deployment of an IPM strategy relies heavily on intervention after sampling thresholds have been reached. The soil medium makes uniform delivery of a tactic to mature root systems difficult to achieve. A limited number of chemical and biological treatments act systemically within the root system and even fewer with therapeutic affects.

Proactive approach. Proactive pest management is a strategy that seeks to minimize intervention through the avoidance of pest outbreaks. When incorporated into the design of the crop production system, this strategy can be very effective and can broaden the availability of pest management tactics not routinely considered by conventional growers. The most common example is the integration of soilless media into greenhouse production systems to avoid problems associated with soil infested with root pathogens. In another example, the benefits of crop rotation and minimum tillage were incorporated into the production system by designing a low-input production system for tomato using minimum tillage practices in existing bahiagrass pasture (16). Florida alone has over 2.5 million acres of improved bahiagrass pasture (11). Through a design that is compatible with pasture crops, the alternative system increases access to those pastures.

Other low-input production systems using minimum tillage techniques to plant vegetables into living or stubble mulches have been developed (2,3). Mulches were selected to improve soil tilth and reduce the impact of soilborne pests. In addition to reducing input costs, minimum tillage techniques conserved the integrity of the mulches. Reduction of windblown soil and rain splash dispersal by mulches will reduce the incidence of plant diseases (46,52,54).

To be effective and practical, a proactive strategy should be considered when designing the production system. This requirement precludes its application to existing production systems. Although a proactive pest management strategy may be desirable in theory, avoidance of all potential pests may not be practical and some flexibility in the strategy that permits intervention when needed is a more realistic approach. Finally, an outbreak of non-target pests or diseases may increase through the use of alternative production systems (16).

NONCHEMICAL METHODS FOR MANAGEMENT OF SOILBORNE PESTS

Numerous nonchemical methods have been used to control soilborne pests. In addition to biological control, some of the more successful methods have included host resistance, organic amendments, crop rotation, soil solarization, and other cultural practices.

Host resistance. Deployment of plants with pest resistance is a very powerful method for managing soilborne diseases and nematodes, but until recently this method has been largely underused, due in part to the success and availability of methyl bromide. Traditional plant breeding programs have concentrated on resistance controlled by a single dominant gene. Using this approach, commercial tomato hybrids that are horticulturally acceptable for the fresh market tomato industry and have resistance to Fusarium wilt (races 1, 2, and 3), Fusarium crown rot, three species of root-knot nematode, and Verticillium wilt (race 1) have been released by four major seed companies. Single dominant gene resistance to three species of nematode has also been identified in pepper, and

open-pollinated advanced breeding lines of bell and cayenne pepper have been released by four major seed companies and have been made available to breeders (22,27). However, to date, no hybrid bell pepper cultivars with commercially acceptable horticultural characteristics are available.

In tomato, sources of resistance to bacterial wilt (*Ralstonia solanacearum*) and southern blight (*Sclerotium rolfsii*) have been identified, but are mediated by multiple quantitative trait loci (43,68,71), making the development of commercially acceptable cultivars using traditional plant breeding methods highly unlikely. In pepper, a cultivar with resistance to Phytophthora blight has been released ('Paladin'; Novartis Seeds Inc., Rogers Brand, Boise, ID) but it does not have resistance to the foliar phase of Phytophthora blight, the principal means of dissemination during epidemics in high rainfall areas.

Even with established sources of genetic resistance, inherent risks and mitigating factors must be considered when deploying the resistant genotypes in the field. Expression of both the *Mi* and *N* genes, which confers root-knot resistance in tomato and pepper, respectively, is mediated by temperature (67), and field populations of "resistance-breaking" *Meloidogyne* spp. have been identified (40). Expression of disease resistance is often compounded by invasion by multiple pest species although the relationship is not always the same. For example, bacterial wilt and Fusarium wilt of tomato in susceptible cultivars are more severe when simultaneous invasion by root-knot nematode species takes place (1,18,39). In the presence of disease resistant cultivars, invasion of root-knot nematodes will break resistance to bacterial wilt but do not affect the expression of resistance to Fusarium wilt (1,18,39).

Traditionally, host resistance has been applied as a method to mitigate damage from plant pathogens and plant parasitic nematodes. Unfortunately, its application as a method to minimize economic losses from weeds has largely been ignored. The hypothesis that vegetable cultivars can be selected and bred for their ability to compete with weeds for water and nutrients has not been adequately addressed. This may be due in part to the success of methyl bromide fumigation for weed control, eliminating the need for such an approach, and because, until very recently many commercial breeding programs conducted their cultivar selections in methyl bromide-fumigated soil.

Systemic acquired resistance (SAR) and induced systemic resistance, whether chemically or biologically mediated, is rapidly evolving into a valid disease management method that has practical and commercial applicability. First reported in 1992 (72), the use of harpin proteins to initiate the signaling pathways that control the expression of genes responsible for activation of the plants natural defense system has shown promise. Recently, a product (Messenger, EdenBioscience, Bothell, WA) received registration for use in controlling Fusarium wilt and bacterial wilt of tomato and Phytophthora blight of pepper. Examples of chemically induced SAR include compounds belonging to the chemical class benzothiadiazole (33). Products developed from this class of chemicals include Actigard (Novartis Crop Protection, Triangle Park, NC).

Control of Fusarium wilt via induced systemic resistance has been achieved using nonpathogenic strains of *Fusarium oxysporum* (42,76) and plant growth-promoting rhizobacteria (PGPR) (44). The benefits of PGPR as inducers of disease resistance have been reviewed (69), and products using PGPR to promote plant growth and enhance resistance have been developed and field tested (BioYield, Gustafson LLC, Plano, TX).

Organic amendments. The prospects for composts as non-chemical alternatives to methyl bromide fumigation have recently been reviewed (19). Many individual examples of disease and nematode suppression using composts were noted, and there is strong evidence for the validity of the concept. Manures and sludge derived from animal or human wastes have also demon-

strated control of diseases, nematodes, and weeds (47,50). In a novel approach, municipal solid waste compost was banded in the row middles to suppress weeds in vegetable crops (58). Certain crop residues have been shown to suppress some soilborne diseases. Most recently, broccoli residues incorporated into field soils were shown to provide significant control of Verticillium wilt in cauliflower (65). Although disease suppression by broccoli residues were not realized in controlling root diseases of strawberry (59), subsequent testing of rotations with broccoli provided significant reductions of Verticillium wilt in strawberry in both conventional and organic production systems.

There are problems associated with the large-scale application of composts. Efforts must be made to standardize types of compost to improve the consistency of the physical and chemical composition of the material. Variation in the source of organic matter from which the compost is derived, the composting process itself, the maturity of the material, and the time and method of application all affect consistency. Often, this information is unavailable to the grower who purchases the material. Logistical problems are also associated with trucking and spreading of large amounts of material. Application of rates in excess of 75 t/ha are costly and time consuming, and are not likely to be conducted on large tracts of land unless the effects carry over many seasons. Variation in results can occur from site to site even when the same exact materials are used at the same rates (14). Only through a better understanding of the mechanisms of pest suppression by organic amendments can the potential for site variation be addressed before the material is applied. For those reasons, application of composts to control soilborne diseases is used most frequently in the containerized nursery industry and smaller, intensively managed vegetable and nursery operations.

Cover crops and rotational crops. Cover crops are those crops that are cultivated between the growing seasons of the main cash crop, e.g., tomatoes, peppers, or strawberries. To be effective, they must be able to establish a stand rapidly, compete with weeds and volunteers from the previous crop, and not pose a threat for regeneration as a weed species during the next cropping season. Cover crops are commonly used to conserve soil moisture and organic matter and to reduce pressure from soilborne pests. They include annual grains such as millet, rye, and sorghum-sudan hybrids and legumes such as vetch, clover, and cowpeas. Many candidates are effective in reducing but not eliminating overseasoning populations of plant parasitic nematodes (49). Additional cover crops uncommon to many production areas in the United States have also demonstrated potential in reducing populations of plant parasitic nematodes (55). When selecting cover crops on the basis of pest suppression, caution should be taken because the effects can be cultivar-specific (28). Some cover crops possessing excellent pest suppression properties, such as hairy indigo (*Indigofera hirsuta*), have become major weed pests in the fields following their introduction.

Rotational crops are those crops that are cultivated in place of the traditional cash crop for extended growing seasons. Their primary purpose is to eliminate soilborne pests and increase yields on future harvests of the cash crop. Crop rotation remains one of the oldest practices that can be used to eliminate the threat from soilborne pests (32). Many pasture grasses such as bahiagrass (*Paspalum notatum*), giant star grass (*Cynodon nlemfuensis*), and pangola grass (*Digitaria decumbens*) are very effective at suppressing populations of plant parasitic nematodes (4,21,36,56, 57). Additional benefits from these pasture grasses are suppression of foliar and soilborne diseases (8) and significantly improved soil tilth (7,9).

The main impediment to the use of crop rotation is the difficulty in stand establishment and the length of time required for pest suppression. Pasture grasses must be in pure stands for at least 2 years to suppress soilborne pests effectively (4,21,56). While some cash return can be realized by growers in the form of hay,

sod, or grazing, most growers cannot risk implementing a cover crop due to losses in farm income and marketing shares resulting from the reduction in acreage planted to the cash crop. Thus, most growers are still willing to risk crop loss by practicing a continuous monoculture (17).

Soil solarization. Developed in Israel in the middle 1970s by Katan and associates (41), soil solarization is a natural, hydrothermal procedure that uses transparent film to capture solar radiation in the soil. Heat generated in the soil can control many soilborne pests when the solarization period is extended over 6 to 8 weeks under intense solar radiation. Traditionally, soil solarization was applied to entire fields as continuous mulch (34) but was modified to permit compatibility with crop production systems used in humid, cloudy environments (15). Worldwide, solarization has gained popularity among greenhouse owners, who in Japan alone have solarized more than 5,000 ha (62). In the United States, commercial application of soil solarization for open field soil disinfestation has been limited to small areas in the central and southern desert valleys in California and in Florida (62) where soil temperatures can reach 69.5, 54.5, 48.0, and 40.6°C at 0, 5-, 10-, and 25-cm depths beneath clear, low density polyethylene plastic (12).

Soil solarization provides economic control of many soilborne pests (63) and is cost effective (15). However, reports of control of key soilborne pathogens are often conflicting. For example, there are numerous reports of failure to provide control of nutsedge (*Cyperus* spp.) (23). Yet in certain situations, solarization provided significant control of nutsedge (15). The same holds true for root-knot nematodes (*Meloidogyne* spp.) for which reports of effective control are also numerous (64), yet in key situations solarization did not provide control of root-knot nematode (15).

The variability in results can be attributed to the complex mode of action of solarization and the influence of ambient conditions. Solarization works through a combination of physical, chemical, and biological changes in the soil profile (62). Many of these changes depend on soil type, moisture, and resident microbial populations. Additionally, thermal inactivation is a function of time and temperature and varies depending on the ambient conditions during the time of solarization. Thus, it is not possible to prescribe a precise treatment period that will provide a broad level of control prior to application. This in turn creates a level of uncertainty among growers and remains one of the biggest factors impeding the widespread adoption of soil solarization.

Soil solarization should not be perceived as a stand-alone replacement to preplant fumigation with methyl bromide for soil disinfestations. However, in many locations soil solarization is compatible with most nonchemical methods for pest management and deserves serious consideration as a fundamental component of pest management programs that use the biological knowledge of pests to select and integrate tactics promoting safe, profitable, and durable pest management. Its importance and potential contributions to IPM programs is evident (13,63).

Cultural practices. While often overlooked, the cultural practices of growers can have a profound impact on many soilborne diseases. For example, the combination of high nitrate/low ammonium fertilizers and application of lime can provide significant control of Fusarium wilt and Fusarium crown rot of tomato and Fusarium wilt of chrysanthemum (25,74,75). Raising soil pH can control bacterial wilt of tomato (45,77). The severity of Phytophthora blight of pepper can be reduced by using site preparation, waterway systems, bed structures, transplanting, and irrigation procedures to minimize water accumulation in the fields and prevent over-saturation of soils (53).

SUMMARY

Fresh market vegetable producers account for a significant proportion of the U.S. consumption of methyl bromide. Their produc-

tion systems are designed to use a single application of a broad-spectrum biocide to disinfest soils prior to planting. While nonchemical methods, including host resistance, crop rotation, organic amendments, soil solarization, and cultural practices, have been used to control soilborne pests in vegetable production systems, they do not offer the same broad spectrum of control, consistency between sites and crops, and logistical compatibility as methyl bromide. Thus, it is highly unlikely that growers relying on a single tactic to manage soilborne pests will find a suitable nonchemical alternative to replace methyl bromide, although some nonchemical methods may be used to support less effective chemicals.

Nonchemical methods are ideally suited to an integrated approach to the management of soilborne pests. However, many of the components of IPM systems, including sampling programs and economic thresholds, are not available or economically feasible for many soilborne pests. In addition, growers who have relied on a single tactic approach for 30 years or more are hesitant to assume the additional responsibilities of managing biological information. Proactive pest management programs are based on the use of nonchemical methods and the biological information of soilborne pests and offer potential for the development of biologically sustainable pest management systems. Unfortunately, they will require redesigning crop production systems to minimize pest outbreaks, and it is highly unlikely that most growers will undertake that task.

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