Development and Deployment of Systems-Based Approaches for the Management of Soilborne Plant Pathogens

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ABSTRACT

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Biological suppression of soilborne diseases with minimal use of outside interventive actions has been difficult to achieve in high input conventional crop production systems due to the inherent risk of pest resurgence. This review examines previous approaches to the management of soilborne disease as precursors to the evolution of a systems-based approach, in which plant disease suppression through natural biological feedback mechanisms in soil is incorporated into the design and operation of cropping systems. Two case studies are provided as examples in which a systems-based approach is being developed and deployed in the production of high value crops: lettuce/strawberry production in the coastal valleys of central California (United States) and sweet basil and other herb crop production in Israel. Considerations for developing and deploying system-based approaches are discussed and operational frameworks and metrics to guide their development are presented with the goal of offering a credible alternative to conventional approaches to soilborne disease management.

Additional keywords: agroecology, crop rotation, microbial diversity, organic amendments, soil fumigation.

Post World War II production of high value crops including fresh herbs and soft fruits gravitated toward a singular approach of maximizing enterprise profitability through increased production (yield). Improved technology, access to irrigation, transportation, storage, and pesticides contributed to the creation of highly efficient crop production systems. Escalating input costs were offset by gains from economies of scale. Synthetic fertilizers replaced organic amendments as the principal source of plant nutrients, and routine pesticide applications were relied upon to control soilborne diseases, particularly to disinfect important and hard to eradicate soilborne pathogens. Extended monocultures of genetically uniform cultivars selected for increased yield and extended shelf life further intensified selection for soilborne pathogens. In recent years, mounting public concern regarding environmental degradation and human health risks associated with pesticides, escalating crop production costs, competition for diminishing natural resources, and the continued crop losses from disease outbreaks despite increased pesticide use have created an impetus to examine alternative approaches to pest management.

Integrated pest management (IPM) was developed as an alternative pest management approach incorporating ecosystem knowledge to balance the economic, environmental, and social consequences of remedial interventions. IPM is the coordinated use of multiple tactics to maintain damage from specific pests below an economic threshold, while conserving beneficial organisms and maintaining sustainability (Stern et al. 1959) and strives to manage pests by ecological principles of natural pest mortality factors, predator-prey relationships, genetic resistance, and cultural practices. Andrews (1983) indicated that integrated control should include three essential facets: (i) diversified controls coordinated to achieve an additive or, preferably, synergistic effect; (ii) economic (including aesthetic) analysis to the extent that action thresholds are developed to distinguish biological damage from economic damage (i.e., the amount of injury justifying a given increment of control); and (iii) ecological and environmental assessment to quantify, and subsequently minimize, a detrimental effect on nontarget organisms. By 2002, 66 additional definitions of IPM had been proposed (Bajwa and Kogan 2002; Kogan 1998). Entomologists pioneered the IPM concept that was later adopted by plant pathologists initially for foliar diseases followed by its adaptation to the management of soilborne pathogens.

In the case of IPM, the practice was not always consistent with the theory of IPM (Hardy 1996). For example, as IPM was applied to

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the management of arthropod pests, its application in many instances became limited to pest scouting and precision application of insecticides. Ecological processes at the landscape level, which can be used to understand and promote the inherent ability of ecosystems to limit pest outbreaks, were often deemphasized. Although IPM has made vast strides in the reduction of insecticides for control of arthropod pests, its adaptation to the management of soilborne pests has proven to be more difficult. Soil disinfestation must occur before the crop is planted, requiring assessment of economic injury and action thresholds well in advance of the current season. A paucity of systemic therapeutic interventions and the technical difficulties associated with the delivery of biocontrol agents to active infection courts further hamper the implementation of IPM for soilborne pests. Despite the many challenges of IPM for soilborne pests, its application to high value crops has been embraced following the mandated methyl bromide withdrawal from agriculture. The following IPM principles are suggested for the soilborne pathogens (Katan et al. 2012).

1. Accurate identification of the pathogens or other pests involved and consideration of the crop and soil pest history in the choice of management options.
2. Because IPM is a holistic approach, consideration to all sources of inoculum at all sites during the whole season, before, at and after planting should be given. The management tools for different pests need to be compatible with the relevant agricultural practices.
3. Combining management tools to improve the diversity and efficacy of pest control.
4. The impact of disease management on the soil and crop health, the agricultural and nonagricultural environments, natural resources, and human health should also be integral considerations.
5. Decision support systems enable the improvement in control effectiveness and curtail the dose and frequency of the applied measures. The relationships between pathogen inoculum density in soil and disease intensity, and between disease intensity and yield loss are integral to the success of these systems. These parallel the monitoring of pest population dynamics and thresholds developed by entomologists.
6. Issues such as economic, social, public, legislative, political, and local and international agreements and regulations should again be fundamental to the IPM program.
7. Since the soilborne pathogens survive in the soil, the long-term effects of the management options and soil reinfestation by pathogens should be considered.
8. Since IPM is an integrated approach, and has to be adapted for a variety of potential uses, technology transfer systems should be developed for each specific IPM program.

Even if the techniques for disease suppression are only partially effective and can only be used under specific conditions, they may still be effective when combined with other methods. This is particularly relevant for soilborne pathogens given that the management options are limited. If these options retain or improve the natural suppressiveness in a given soil, they have the potential to improve the overall system sustainability. This can be achieved by minimizing drastic measures or by reducing the frequency of applying these measures. Whenever possible, enriching the soil organic matter should remain a disease management goal.

As a matter of fundamental principle, the application of external corrective actions into a system can be effective in the short term. A more sustainable, robust solution with direct application to the management of soilborne pests is to redesign crop production systems to mitigate pest outbreaks through natural processes that promote ecosystem stability while minimizing the need for therapeutic intervention. Systems-based approaches to pest management evolved from the IPM concept to emphasize incorporation of

agricultural practices into the design and operation of cropping systems that promote pest and disease suppression through natural biological feedback mechanisms (Lewis et al. 1997). A systems-based approach to the management of soilborne plant disease consists of four pillars: (i) prevent the introduction and spread of pathogens into the cropping system; (ii) reduce high pathogen populations to levels where they can be managed through natural biological feedback mechanisms; (iii) incorporate activities into the cropping system design to promote disease suppressive soil microbial communities; and (iv) minimize the impact of disruptive actions (pesticides, bio-pesticides, and other agents) through the use of an integrated approach for pest control which optimizes their use at relevant crop stages to interfere with the different stages of the pathogen life cycle. Implicit in this last item is the development of application technologies to assure maximum impact on the target pathogen, and to reduce populations to levels where they can again be regulated naturally. This review will explore the potential of systems-based approaches for management of soilborne diseases using two examples where this approach is being evaluated.

SYSTEMS-BASED APPROACH FOR SOILBORNE DISEASE MANAGEMENT

The concept of self-organizing ecosystems is pivotal to the development and deployment of systems-based disease management approaches. In agroecosystems, fluctuations in the density and composition of soil biological communities are the norm, particularly where natural or anthropogenic disturbances are key features. The degree of oscillation is governed by complex interactions involving soil edaphic factors, plant hosts, competing macro- and microbiological communities, and anthropogenic disturbances. Resilience (the capacity to self-organize into desirable steady states) and homeostasis (the maintenance of desirable steady states) are achieved through a series of continuous negative biological feedback loops. While far too complex to be measured in any precise way (Cabell and Oelofs 2012; Darnhofer et al. 2010), agroecosystems share a key similarity to other systems; they consist of networks nesting within other networks, all interacting within themselves and among themselves (Robinson 2007). Recognition of simultaneous interactions at multiple trophic levels is fundamental to the design and implementation of systems-based approaches to pest management (Levins 1986; Lewis et al. 1997). The reader is directed to Ashby (2001), Camazine et al. (2001), and Robinson (2007) for additional information on self-organizing agroecosystems.

Naturally occurring disease suppressive soils exemplify self-organization within agroecosystems. As defined by Baker and Cook (1974), disease suppressive soils are “soils in which the pathogen does not establish or persist, establishes but causes little or no damage, or establishes and causes disease for a while but thereafter the disease is less important, although the pathogen may persist in the soil.” Natural suppression of plant pathogens and phytoparasitic nematodes in soil is well documented (Hornby 1983) and largely attributable to the composition of resident soil microbial communities they interact with (Mendes et al. 2011; Weller et al. 2002). Some well-known examples of naturally suppressive soils are listed in Table 1. Other than the examples of specific disease suppression (Weller et al. 2002), the mechanisms by which resident microbial communities suppress pathogens and nematodes is not well understood and suppression most likely results from combinations of specific and general disease suppression mechanisms. What is evident is the resilience of soil microbial communities and negative feedback loops they employ to suppress disease. For general disease and nematode suppression, beneficial shifts in microbial community composition can occur despite prior soil fumigation when organic production practices including crop rotations, organic amendments, and soil solarization are implemented (Chellemi et al. 2012, 2013). For specific disease suppression, reductions in soilborne disease may also occur after

repeated monoculture (Lucas et al. 1993; Rovira and Wildermuth 1981). Cultivation of the same plant host year after year is often considered the bane of sustainable crop production due to associations with increased outbreaks of plant pests and diseases, because of augmented pest or pathogen populations. For example, regional monoculture of cotton increased arthropod pest pressure in 13 of 15 published studies (Andow 1983) and was also attributable to increases in soilborne diseases of cotton (Shipton 1977). Yet, wheat monocultures are commonly associated with reductions in soilborne disease and also reduced arthropod pest populations in 7 out of 10 published studies (Andow 1983). The conflicting outcomes point to a need to further define the operational mechanisms of self-organizing ecosystems.

CASE STUDIES

Verticillium wilt in the coastal valleys of central California (United States). *The cropping system.* Strawberry and leafy greens are the dominant agricultural commodities in the coastal valleys of central California. Approximately 65,000 ha of lettuce and other leafy greens generate over U.S. \$1.2 billion in farm gate value (USDA-NASS 1998 to 2012, 2014). Iceberg (crisphead) was the dominant lettuce type prior to the 1990s, but a significant proportion of the acreage has been replaced in recent years by Romaine and leaf lettuce, and to a lesser extent leafy greens including endive (*Cichorium endivia* L.), radicchio (*Cichorium intybus* L.), arugula (*Eruca vesicaria* L.), spinach (*Spinacia oleracea* L.), beet tops, red Swiss chard (*Beta vulgaris* L.), mache (*Valerianella locusta* (L.) Laterr.), mizuna, and tatsoi (*Brassica rapa* L.). Strawberry (*Fragaria* × *ananassa* Duchesne) contributes 88% of the fresh market and 94% of the processed strawberries produced in the United States (USDA-NASS 2014). Approximately 15,819 ha generated \$2.6 billion in harvested revenue. Of those hectares, 1,239 ha were certified organic (California Strawberry Commission 2014 Acreage Survey) (2014). Strawberry production employs raised bed-plastic mulch systems, using mostly bare root seedlings from plants harvested from high elevation nurseries and transplanted into fumigated soil. The lettuce/strawberry rotation has dominated agricultural land use in the Salinas and Pajaro Valleys of the California central coast for decades and continues to be the backbone of the economic stability of the region.

Vulnerability to soilborne pathogens. A recent shift in lettuce production practices impacted existing lettuce diseases (Wu et al. 2011) and compromised lettuce to Verticillium wilt caused by *Verticillium dahliae* (Atallah et al. 2011; Subbarao et al. 1997), a disease to which lettuce was previously considered immune. Affected lettuce fields have suffered near-total losses (Atallah et al. 2011; Subbarao et al. 1997) and in strawberry, losses of up to

75% have been recorded in absence of soil fumigation (Wilhelm and Paulus 1980). Soil fumigation with methyl bromide and chloropicrin was developed in the late 1950s specifically to control Verticillium wilt of strawberry (Wilhelm et al. 1961) and was the industry standard for decades. In recent years, soil fumigation with mixtures of chloropicrin and 1,3-dichloropropene have replaced methyl bromide. This shift in soil fumigants has been associated with increased incidence of Fusarium wilt caused by *Fusarium oxysporum* f. sp. *fragariae* and charcoal rot caused by *Macrophomina phaseolina* (Koike et al. 2013). Commercially acceptable lettuce cultivars with resistance to Verticillium wilt are not yet available, and strawberry varieties exhibit limited levels of tolerance to the disease in the field, limiting the use of host resistance as an effective disease management tool.

Lettuce growers with Verticillium wilt-affected fields prefer to rotate with strawberry, where preplant fumigation with methyl bromide and chloropicrin until this year was a routine practice but other fumigants are registered and continue to be available. This allows growers to recover the cost of fumigation through a strawberry crop, and piggy-back on the residual fumigation effects when rotating back to lettuce production. The benefits of the residual fumigation effects, however, are short-lived as Verticillium wilt typically returns with greater severity following the second consecutive lettuce crop (Fig. 1) (Atallah et al. 2011; Short et al. 2015b).

Sources of inoculum. *V. dahliae* survives in soil in absence of a host for at least 14 years (Wilhelm 1955) owing to microsclerotia, which are clusters of specialized, thick-walled and highly melanized fungal cells (Fig. 2). Inoculum dispersal is facilitated by tillage practices, particularly involving infected crop residues at the end of the harvest season (Fig. 2). Plant infection is initiated when microsclerotia germinate and produce one to several hyphae that extend toward host roots (Fitzell et al. 1980). The pathogen is also capable of multiplying on several monocot plant species and dicot weed species common to both lettuce and strawberry production systems, including *Capsella bursapastoris* L., *Solanum sarra-choides* Sendtner, *Sonchus oleraceus* L., and *Senecio vulgaris* L. (Vallad et al. 2005) and those that serve as asymptomatic hosts (Krikun and Bernier 1987; Mathre 1989; Vallad et al. 2005). Seed transmission of *V. dahliae* occurs in lettuce (Vallad et al. 2005) and spinach (du Toit et al. 2005; Snyder and Wilhem 1962). Crop rotations with several *Brassica* species including broccoli and Brussels sprouts have been shown to reduce *V. dahliae* microsclerotia populations in soil and the subsequent incidence of Verticillium wilt (Fig. 3) (Subbarao et al. 2007).

Components of the systems-based approach. The systems-based approach is predicated on creating a soil environment supportive of biological regulation of pathogen populations through natural negative feedback mechanisms. To accomplish this, pathogen

TABLE 1
Examples of the suppression of plant pathogens and nematodes by indigenous populations of soil microorganisms

Plant pathogen/nematode	Host plant	Reference
<i>Aphanomyces euteiches</i>	<i>Pisum sativum</i>	Persson et al. 1999
<i>Cricodemella xenoplax</i>	<i>Prunus persica</i>	Kluepfel et al. 1993
<i>Fusarium oxysporum</i> f. sp. <i>lanatus</i> and f. sp. <i>lycopersici</i>	<i>Citrullus lanatus</i> , <i>Solanum lycopersici</i>	Alabouvette 1990; Larkin et al. 1996
<i>Gaeumannomyces graminis</i> var. <i>tritici</i>	<i>Triticum aestivum</i>	Rovira and Wildermuth 1981
<i>Heterodera schachtii</i>	<i>Beta vulgaris</i>	Westphal and Becker 1999
<i>Meloidogyne incognita</i> , <i>M. javanica</i>	Multiple plant hosts	Weibelzahl et al. 1996
<i>Thielaviopsis basicola</i>	<i>Nicotiana tabacum</i>	Stutz et al. 1986
<i>Phytophthora cinnamomi</i>	Multiple plant hosts	Ko and Shiroma 1989
<i>Rhizoctonia solani</i>	<i>Triticum aestivum</i>	Lucas et al. 1993

populations must be present in levels that do not undermine the biological capacity of soils to regulate disease. There are five primary components.

1. Prevent the introduction of pathogens, in particular *Verticillium* species, into fields. The use of clean seed and transplants is recommended. While the lettuce, spinach, and strawberry industries have taken great strides to clean up infested seed through improved pathogen indexing programs, introduction of *Verticillium* species through infected spinach seed lots continues to be problematic (du Toit et al. 2005; Short et al. 2015a). This is because of the long-term survival of *V. dahliae* microsclerotia in soil once introduced.
2. When pathogens are present in numbers high enough to cause significant disease losses, soil disinfestation using chemical fumigants or other means is recommended.
3. Integrate beneficial crop rotations into long-term land management plans.
4. Make the most of the combined use of organic amendments and crop rotations to create beneficial shifts in soil microbial community composition associated with suppression of *Verticillium* wilt.
5. Mitigate inoculum build-up and dissemination, including microsclerotia, resulting from tillage of infected plants after harvest. This is accomplished by crop termination treatments immediately after harvest using a material that prevents both additional inoculum formation on infected plants and reduces viable pathogen propagules residing in the rooting zone.

A schematic diagram is presented in Figure 4 to serve as a template for implementing a systems-based approach. Over the 3-year cropping cycle, one strawberry crop and two lettuce crops are

FIGURE 1

Fluctuation in number of microsclerotia of *Verticillium dahliae* per gram of soil detected in soil samples from an infested lettuce field in coastal California over two successive crops within a year, and requiring fumigation at the end of the second lettuce crop. Reproduced, with permission, from Atallah et al. (2011).

FIGURE 2

A, *Verticillium* wilt of crisphead lettuce. **B**, *Verticillium dahliae* microsclerotia on infected lettuce. **C**, Aerosol dispersal of soil infested with *V. dahliae* during tillage of infected lettuce crop. Neighboring field is susceptible strawberry.

cultivated. Soil sampling for *V. dahliae* populations and soil fertility following each crop is essential to gauge the progress of the disease management approach. Adjustments to the system should be made accordingly. For example, cropping cycles can be extended if pathogen populations do not decline sufficiently. Alternatively, crop termination applications and/or organic amendments can be omitted if pathogen populations decline below detectable thresholds. Versions of this systems-based approach are being evaluated on commercial farms in the Salinas Valley.

Record of success. An example is provided from a farm with a history of strawberry/lettuce rotations, soil fumigation, and recurrent epidemics of Verticillium wilt. Prior to initiating a systems-based approach, the incidence of Verticillium wilt ranged from 11 to 35% on the strawberry crop. Termination of the infected strawberry crop was accomplished using allyl-isothiocyanate (AITC, Dominus, ISAGRO USA, Morrisville, NC) applied at 155 kg ha⁻¹ through the drip system (Fig. 5). Use of AITC-derived products has an added benefit as it occurs naturally in broccoli and Brussels sprouts, two crops common to the coastal valleys of central California and associated with suppression of Verticillium wilt (Harborne and Baxter 1993; Njoroge et al. 2011). Endemic soil microbial communities have been exposed to AITC for decades from the decomposing crops and have had ample time to adapt it as a carbon source. Successive broccoli crops, augmented with chitin-rich crab/feather meal (RootGuard, Agricultural Solutions, Plant City, FL) at 1.1 t ha⁻¹ incorporated to a 12 cm depth, were compared with an adjacent area subjected to the broccoli rotations but not receiving the

AITC crop termination treatment or chitin-based organic amendments. Crisphead lettuce was grown following the broccoli rotations and the soil density of *V. dahliae* microsclerotia monitored by collecting multiple samples along two transects and determining the number of microsclerotia per gram of soil using the technique described by Subbarao et al. (2007). Figure 6 depicts the initial decline of *V. dahliae* microsclerotia populations following the AITC application and subsequent oscillations in microsclerotia densities during the broccoli rotations. The oscillations are attributed to the redistribution of microsclerotia in the soil profile resulting from tillage practices. Resumption of crisphead lettuce led to an increase in microsclerotia density from <1.0 to >8.06 g⁻¹ of soil in the section subjected to the broccoli rotation only (Fig. 6). In the section receiving the AITC crop termination treatment and applications of crab/feather meal in addition to the broccoli rotation, microsclerotia remained below 1.0 g⁻¹ of soil. Thus, carefully designed cropping patterns as part of the systems-based approaches in each region or field can be a very successful strategy of soilborne disease management.

Sweet basil and other herb crops in Israel. *The cropping system.* Herb crops are grown commercially in Israel for export of fresh produce. Many species and cultivars are grown both in open field and greenhouses that meet the demand for high quality produce year round. The main crops include sweet basil, chive, tarragon, sage, thyme, rosemary, and others. To maintain a steady supply of herbs, production has expanded to areas with diverse climatic conditions, soils, and artificial substrates. The increase in

FIGURE 3

Microsclerotia of *Verticillium dahliae* present in the soil at Watsonville during vegetable-strawberry rotation system from 1997 to 2000. V = vegetable rotation seasons, S = strawberry production seasons, BRL = broccoli rotation plots, and BSP = Brussels sprouts rotation plots. Adapted with modifications, by permission, from Subbarao et al. (2007).

FIGURE 4

Framework for systems-based management of Verticillium wilt in the coastal valleys of central California.

herb production has caused the inevitable increase in the occurrence of new and existing pathogens on these crops (Gamliel and Yarden 1997). These include diseases caused by nematodes and parasitic weeds, which have wide host ranges and their inoculum augmented by previous susceptible crops. Additionally, new pests and pathogens have been introduced (e.g., *Fusarium* wilt of basil, downy mildew of basil; Gamliel et al. 1996). Apart from the expansion and intensification of herb crop production, the changes in cultural and harvesting practices are likely contributors to the increase in disease incidence. These changes have had devastating effects on herb production.

Vulnerability to soilborne pathogens. Many of the herb crops which are grown commercially in Israel are vulnerable to polyphagous soilborne pathogens. A majority of the crops are attacked by root

knot nematodes and damping-off pathogens. In addition, the parasitic weed broomrape (*Phelipanche egyptiaca*) is widespread in both open field and closed production systems. *Sclerotinia sclerotiorum* is the most devastating disease causing both root and canopy rot. Its damage is evident during the cool seasons at peak herb production and marketing. Additionally, new pathogens have also emerged in specific crops. *Phyrenochaeta terrestris* is a known pathogen causing pink root in onions. Chive (*Allium schoenoprasum*) is also susceptible to this pathogen with similar symptoms and damage. *Fusarium* wilt and root rot of sweet basil (*F. oxysporum* f. sp. *basilicii*) were introduced during the early 1990s. This pathogen is characterized by soilborne and airborne inoculum and can also be disseminated by infected seeds. The ability of various pathogens to infect other crops indicates that a

FIGURE 5

Strawberry field in the Salinas Valley with *Verticillium* wilt where allyl isothiocyanate applied through the drip irrigation was used to terminate the crop and mitigate production and redistribution of microsclerotia during tillage.

FIGURE 6

Comparison of temporal fluctuations in *Verticillium dahliae* microsclerotia populations in adjacent Salinas Valley fields.

Zone 2 included an addition application of allyl isothiocyanate through the drip irrigation system to terminate the strawberry crop and two applications of crab/feather meal incorporated prior to transplanting broccoli at 1.1 t ha⁻¹. Zone 3 subjected to a strawberry-broccoli-broccoli-lettuce rotation only.

systems-based approach must target all the crops grown in a field since infection on one crop serves as the source of the inoculum for the following herb crop.

Sources of inoculum. The sources of inoculum for the above pathogens are diverse. Polyphagous soilborne pathogens (e.g., *S. sclerotiorum*, *Rhizoctonia solani*, *P. terrestris*, and *Meloidogyne* spp.) and others (*F. oxysporum* f. sp. *basilicii*, seeds of broomrape) survive on the debris from different crops and form resting structures in soil. Ascospores of *S. sclerotiorum* from germinating sclerotia in adjacent fields, dumping sites, and other sources are spread by wind and infect indoor and open field crops. Similarly, *F. oxysporum* f. sp. *basilicii* produces spores, which can be spread by air, infect adjacent crops, and survive in the soil. It also remains in the greenhouse structure and becomes a source of the inoculum (Gamliel et al. 1996). Organic manure can harbor propagules of *R. solani* and *Meloidogyne javanica*. *F. oxysporum* f. sp. *basilicii* and *S. sclerotiorum*. *F. oxysporum* f. sp. *basilicii* is also transmitted by seeds. This diversity of inoculum sources dictates that a system-based approach address all sources to minimize transmission of the pathogens from their sources of inoculum into crop production fields.

Available management tools and the components of the systems-based approach. Herb crops can serve as a good model for a systems-based approach for a number of reasons. Herb farms combine different types of crops, which can be rotated to prevent the establishment of host-specific pathogens. Furthermore, some of the herb crops, e.g., wild rocket, can be incorporated at the end of the season to serve as organic amendments to control existing soilborne pathogens in the soil (Klein et al. 2011). Such organic amendments may also increase soil suppressiveness and prevent or delay reestablishment of a pathogen. Many herb crops are grown in closed structures, which enables effective soil disinfestation treatments such as the combination of solarization with reduced dosage of fumigants, combination of solarization with organic amendments, and also solarization of the structure to eliminate airborne propagules and propagules which survive on the structural components of the closed system. The following is an example of a system-based approach for the management of *F. oxysporum* f. sp. *basilicii* in basil crop. It consists of the following pillars.

1. During the first season, a crop that can serve also as organic amendment is grown in the field. The spectrum of the available crops is wide and includes wild rocket, rosemary, sage thyme, oregano, and others. These crops are grown commercially and produce marketable products.
2. At the end of the season, the crop provides significant biomass that is chopped and incorporated into the soil with a rototiller to serve as an organic amendment. The field is then mulched with transparent polyethylene to provide the conditions for solarization combined with organic amendments. This procedure is accompanied by structural solarization to eliminate the inoculum on the structure.
3. During the second season, sweet basil is planted by using pathogen-free seeds of cultivars that are resistant to *F. oxysporum* f. sp. *basilicii*.
4. During sweet basil production, monitoring to locate diseased plants and their removal is done to prevent aerial spore spread.
5. At the end of the crop, all the crop debris are removed from the greenhouse and destroyed in a compost site. The soil and the greenhouse structure are solarized.
6. A different crop that can serve for organic amendment purposes is planted during the third season.

Records of success (area, seasons, and crops). This approach is now adopted by most but not all herb growers for all the cropping systems and has proven successful for the following reasons.

1. Crop rotation does not involve change in practice or introduction of new crops. It also does not need changes in technology.

2. The organic amendments are already available on site and are easy to use.
3. The approach is cost effective as it does not require additional inputs, and obviates the need for fumigation.
4. It applies to many other herb crops in addition to sweet basil.
5. Soil suppressiveness to plant disease is frequently improved and contributes to the overall system sustainability.

Challenges and difficulties.

1. This approach is not fully adopted by farmers that grow a limited range of crops or is less flexible in rotating limited number of crops in a limited area of production fields.
2. Using solarization has its own limitations, such as scheduling the crop and treatments.
3. Solarization of soil and structure is less effective in net houses, which comprise an important part of herb production. In such structures, intensity of solar radiation inside the structure is low and thus the efficacy is also low.

KEY CONSIDERATIONS FOR SYSTEMS-BASED APPROACHES

Systems-based approaches for managing soilborne diseases will continue to evolve as new scientific and technical advances become available. Regional cropping systems will change as markets, economics, and availability of natural resources fluctuate, necessitating changes to the systems approach. New disease and pest outbreaks will emerge, requiring further changes to the system and reprioritization of goals and objectives. It is naïve to assume that all assumptions pertaining to ecosystem and anthropogenic effects on plant pathosystems will be met or are correct in the design of the present system. Thus, it is imperative to guide development and deployment of systems-based approaches using a framework and associated metrics to assess progress.

Grower practices often contribute to the incidence and severity of soilborne diseases but are difficult to address from a management perspective. Grower decisions are determined by factors affecting enterprise profitability. Excluding instances where recent epidemics resulted in direct economic loss, soilborne pathogens are not an immediate concern and their consideration is often secondary. For example, manipulation of planting schedules to coincide with harvest periods generating increased profits often take precedence over timing of planting schedule to mitigate disease outbreak. Extending the growing season to gain additional returns through delayed harvests can lead to increased inoculum reservoirs in soil as the pathogen continues to reproduce on infected host plants. Finally, lack of revenue associated with cover crops, increased land values and higher nonharvest costs limit the adoption of crop rotations and promote the continuation of monocultures.

Effective management of the key economic soilborne plant pathogens responsible for yield and quality reduction is the goal. However, entire pest complexes will set the course of action for decision-making as the impact of primary pathogens to plant health can be exacerbated through interactions with secondary pathogens (i.e., root nibblers) and soil-inhabiting arthropods. The significant role of nematodes in the development of soilborne diseases is well documented (Back et al. 2002). The role of vesicular-arbuscular mycorrhizal fungi in soilborne disease is more complex, increasing the incidence of disease in some instances and decreasing in others (Dehne 1982). The role of mycorrhizal fungi on plant growth and elevated plant tolerance to stresses should be also considered (Gamliel et al. 2002).

Pathogen detection. Managing soilborne plant diseases within a systems-based approach requires a broad, multidisciplinary perspective. Soilborne pathogens are cryptic, limiting the economic and technical feasibility of soil sampling programs. To reliably

ensure pathogen populations below the damaging thresholds, multiple samples must be collected and processed, escalating sampling costs and taxing the physical resources needed for their collection and assay. New polymerase chain reaction (PCR)-based detection methods offer potential to reduce costs and significantly shorten processing time. For example, detection of *V. dahliae* using real-time PCR based on the ribosomal DNA intergenic spacer reduced processing times to 2 to 3 days compared with the 6 to 8 weeks common for the traditional dry or wet sieving techniques (Bilodeau et al. 2012; Termorshuizen et al. 1998). A practical, farm-based alternative is to survey disease in susceptible crops at season's end, when it is easier to detect pathogen presence and prior to redistributing infective propagules through the soil profile via tillage practices incorporating crop residue.

Risk mitigation. Systems-based ecological approaches to pest management operate under the premise that indigenous biological communities limit pest outbreaks through naturally occurring, self-regulating ecological feedback mechanisms. A defining feature of this approach is the de-emphasis of remedial interventions, whether biological, chemical, or physical (Levins 1986; Lewis et al. 1997). While attractive in theory, consistently achieving the desirable biological balance to mitigate outbreaks of a single pest species is difficult. Achieving the correct biological balance to simultaneously manage multiple pests at differing trophic levels is especially challenging, particularly on a regional scale. Multiple crops susceptible to the same pathogen complex can occur in proximity to each other. Neighboring farmers often have differing expectations of what constitutes acceptable levels of pest control. Risk mitigation drives the decision-making process for growers of high value crops because financial assistance is often required due to high, fixed and variable costs associated with crop production. From a risk perspective, application of broad-spectrum biocides including soil fumigants is an appealing option and often required as a prerequisite by the financial lending institution.

Financial costs. Despite extended time frames and increased costs associated with developing disease suppressive soils, the long-term benefits of minimizing pesticide use, improving soil fertility and reducing environmental impacts outweigh the costs and efforts. However, it is difficult to put a monetary value on those savings or amortize them over longer time frames as it also depends on the crop values over time. This precludes inclusion of systems-based approaches during the strategic planning process associated with future crop production. More attention to quantitative assessments of the financial costs and benefits associated with systems-based approaches is needed. While many organic farmers have embraced this concept, the majority of conventional growers are reluctant to integrate naturally occurring disease suppression mechanisms into crop production systems because the horticultural and pest management benefits do not outweigh the cost and time required to implement and manage them.

Spread of pathogens naturally and by other means. Plant pathogen populations in soil are dynamic. They are exposed to continuous spatial and temporal biotic, abiotic, and agricultural modifications (Short et al. 2015a). Their populations are supplemented by external sources arriving through infested seed, propagation material, contaminated equipment, and directly from field workers. The influx of newly described or exotic pathogens and hypervirulent strains of established pathogens further complicates the pathogen dynamics (Atallah et al. 2010; Short et al. 2014, 2015a). The issue of emerging and reemerging pathogens presents a paradox as well (Subbarao et al. 2015). However, detection and management tools are continuously improving. Molecular techniques enable the detection of extremely low levels of pathogens with greater accuracy and reliability. In contrast, the globalization and the associated rapid and large scale movement of agricultural products for trade and travelers all over the world impede our attempts to prevent such invasions. New

diseases are continuously reported from various parts of the world, e.g., *F. oxysporum* f. sp. *radicis-cucumerinum* (Vakalounakis 1996), *F. oxysporum* f. sp. *lactucae* (Hubbard and Gerik 1993), *Verticillium dahliae* (Subbarao et al. 1997), and others are such examples. Whatever is the source of the inoculum for these pathogens, they have a devastating potential (see case studies for further discussion on this issue).

Strategies and tactics for the management of soilborne pathogens. Pest control has come a long way from the primary goal of simply killing the pathogen. Thus, at last, "management" replaced "control" not only as a term but also as a concept. IPM assembles various measures under one roof. The special features of soilborne pathogens with regard to their biology, ecology, and survival in the soil present both difficulties and options for their management (Katan et al. 2012). The pathogen's existence in the soil makes the application of control measures very difficult, necessitating the use of drastic and soil penetrating measures, such as fumigants or heat, which while expensive also have adverse effects on beneficial organisms and the environment. On the plus side, the existence of pathogen inoculum in the soil prior to planting enables predicting the expected disease level and making decisions accordingly.

Many soilborne pathogens have multiple mechanisms of survival and dissemination, resulting in multiple sources of inoculum, all of which need to be identified and managed to ensure soil and crop health. The soil inoculum of soilborne pathogens is not the only source of infestation and paradoxically, in some cases is not even the major cause of infection. Aside from the soil in which the pathogens live, the various sources of inoculum include, infected propagation material, contaminated water, spreading of infested soil, insects and animals, inoculum adhering to the greenhouse structure or farm equipment and personnel, weeds and other hosts, as well as aerial propagules produced on the canopy of plants and spread through the air, as shown with various formae speciales of *F. oxysporum*. The above-ground aerial phase of the soilborne pathogens are usually overlooked, putting an additional burden on their management. Thus, the amount of inoculum left untreated will finally determine the degree of success or failure of the management actions. Therefore, the basic management strategies include physical, chemical, biological, cultural, physiological, and genetic approaches. These are reflected in tactics such as soil disinfestation (chemical, physical, solarization, and biological disinfestation), pesticides, breeding for resistance, grafting, induced resistance, sanitation, biological control, organic amendments, and others. Disease management in the greenhouse should also include the management of pathogens adhering to the structural components of the greenhouse (Gamliel et al. 2012) as well as the disinfestation of irrigation water.

CONCLUDING REMARKS

High input, conventional production systems have had a very successful reign in offering an efficient, secure, and stable food supply over many decades. Disease management under these systems has also relied on extensive inputs. Mounting public concerns regarding environmental degradation and human health risks associated with pesticides, escalating crop production costs, competition for diminishing natural resources, and the continued crop losses from disease outbreaks despite increased pesticide use have created an impetus to examine alternative approaches to soilborne disease management. While conventional approaches to manage diseases will continue to dominate in the near-future, over the long term, the systems-based approaches will undoubtedly offer a credible alternative. This paper has offered the necessary background for designing systems-based approaches to soilborne disease management and has illustrated such a system using two case studies.

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