

Plant Disease Prevention and Management in Sustainable Agricultural Systems

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1 Introduction

Plant disease management strategies have been dominated by the use of “silver bullet” products to control plant disease outbreaks. Unfortunately, most of these therapeutic strategies are effective only for a short time. Long-term plant disease preventative strategies that are based on the ecological understanding of pathogens have been explored and studied extensively, but its implementation is restricted by economic consideration for large scale farming. Crop losses due to arthropods, diseases, and weeds have increased on a world basis from 34.9% in 1965 to 42.1% in 1990 (Oerke et al. 1994; Lewis et al. 1997). Despite the intensification of developing modern technologies for pest control, today’s crop loss caused by arthropods, diseases, and weeds remains at 20–40% (Oerke 2006). Worldwide, herbicide use ranked highest among all the pesticide usage in the agriculture sector, followed by insecticide/miticide and fungicide use (Grube et al. 2011). Based on recent pesticide usage statistics conducted by the United States Environmental Protection Agency, nematicide or fumigant usage is actually second to herbicide use (200 mil kg), with 49 mil kg being used in agriculture sectors in the U.S. (Grube et al. 2011), higher than insecticide (29.5 mil kg) and fungicide (20 mil kg) use. One positive sign of this statistic is that the amount of organophosphate insecticides used in the U.S. has declined more than 60% since 1990, from an estimated 38.6 million kg in 1990 to 15 million kg in 2007 (Grube et al. 2011). This reduction is somewhat encouraging as organophosphates are among the most acutely toxic pesticides still used.

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Much of these acute toxic pesticides are now slowly replaced by biologically based pesticides. At the end of 2001, there were approximately 195 biopesticide active ingredients and 780 products registered in the U.S. (i.e. 25% are biopesticides). Today, there are 330 registered biopesticide active ingredients out of 1100 products registered in the U.S. (i.e. 30% are biopesticides) (Meister and Sine 2012). However, this shift in pesticide use still did not avoid a common paradigm of those “therapeutic pesticides” used. Two of the main concerns of therapeutic pesticides are the buildup of pesticide resistant pest populations that might lead to the pesticide treadmill, and broad-spectrum effects of pesticides that will harm non-target beneficial organisms and humans.

A total systems approach for developing sustainable pest management strategies for plant disease management was thoroughly reviewed more than a decade ago (Cook et al. 1995; Cook and Baker 1983; Hornby 1990). Most of these literature reviews focused on managing bacteria, fungi and nematodes. To achieve sustainable pest management, we must go beyond replacing toxic chemicals with sophisticated, biologically based agents. This chapter focuses on sustainable pest management approaches for tropical plant diseases through environmentally friendly and renewable strategies. Particularly, we are focusing on managing nematodes, fungi, bacteria and insect vectored plant viruses. Based on ecological knowledge about targeted pests/pathogens, their associated natural enemies, and their interactions with hosts, we recommend integrating five sustainable approaches for plant disease management. These approaches are: (1) enhancing high biological diversity through polyculture instead of the conventional preference of monoculture cropping systems; (2) increasing ecosystem community stability by promoting natural enemies of multiple pests and pathogens; (3) stimulating inherent plant defenses; (4) improving plant health by maintaining nutrient cycling and energy flow; and (5) targeting vulnerable stages of pests or pathogens through the understanding of their ecology. The use of pesticides or even biocontrol agents as ‘therapeutic’ approaches are unsustainable and should be the last resort in developing a sustainable plant disease management program. While managing multiple pathogens in an agroecosystem involves multi-disciplinary studies and would be very comprehensive, we chose to start by reviewing sustainable pest management approaches recommended for plant-parasitic nematodes, followed by how these approaches can be extended to or complement plant fungal and viral disease management.

2 Sustainable Pest Management for Plant-Parasitic Nematodes

The life cycle of most plant-parasitic nematodes is rather typical, consisting of the egg, four juvenile stages, and the adults, usually parasitizing plant roots. One might suggest that root infecting plant-parasitic nematodes can be managed by the same approach across genera. In reality, management strategies for plant-parasitic nematodes could differ significantly based on the amount of time they spend inside the plant roots vs outside of roots (i.e. endoparasitic vs ectoparasitic), whether they are

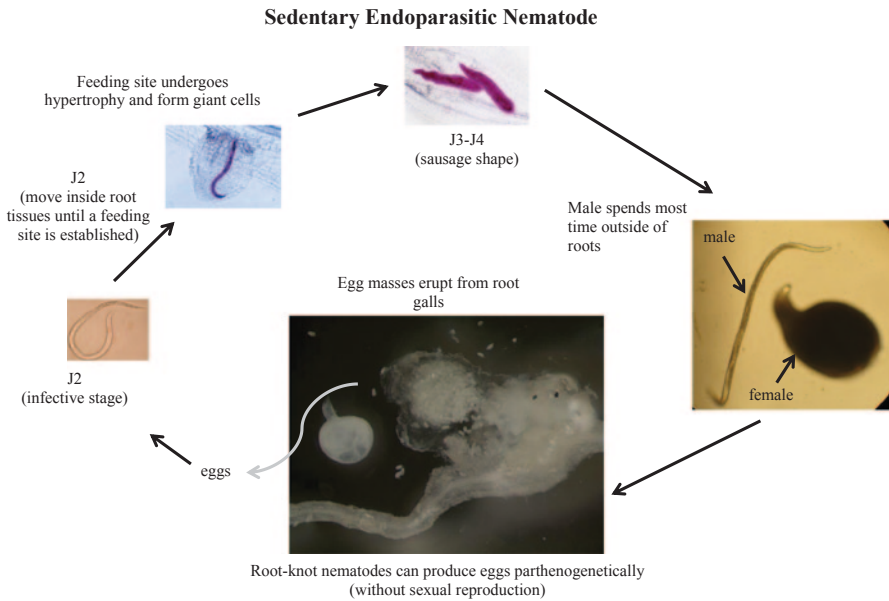


Fig. 1 Life cycle of root-knot nematode, *Meloidogyne javanica*, showing the vulnerable stage of the nematode being the vermiform second stage juvenile (J2). Other stages of the nematode are buried inside the root system, and are thus less prone to chemical exposure, parasitism or predation by its natural enemies. Eggs of root-knot nematodes though exposed outside of the root gall are protected by a gelatinous matrix, making them less prone to predation but can often be parasitized by nematode egg parasites. (Pictures by M. Davilla and K.-H. Wang)

sedentary or migratory after infecting the roots, if they produce eggs protected by egg masses or not, and if they have the capability to transform into an anhydrobiotic stage. Examples of some of the most economically damaging and commonly found plant-parasitic nematodes with distinct life cycle patterns are root-knot nematode (*Meloidogyne spp.*) (Fig. 1), reniform nematode (*Rotylenchulus reniformis*) (Fig. 2), lesion (*Pratylenchus spp.*), and burrowing nematode (*Radopholus similis*) (Fig. 3). Knowing the nematode distribution in the plants and their survival strategies help to determine the best management approaches.

A thorough review on managing plant-parasitic nematodes in sustainable and subsistence agriculture in the tropics and subtropics has been published by Bridge (1996). In that review, Bridge described how to prevent the introduction and spread of nematodes by the use of nematode-free planting materials through heat treatment, production of seedlings in nematode-free seedbeds, surface soil burning of plant debris, soil solarization, adjust planting time, flooding, postharvest removal of infected crop residues, and soil cultivation between crops. Bridge (1996) also provided some insight on encouraging naturally occurring nematode antagonistic organisms through the use of soil amendments and designing multiple cropping and multiple cultivars in tropical and subtropical climates to increase plant resistance or

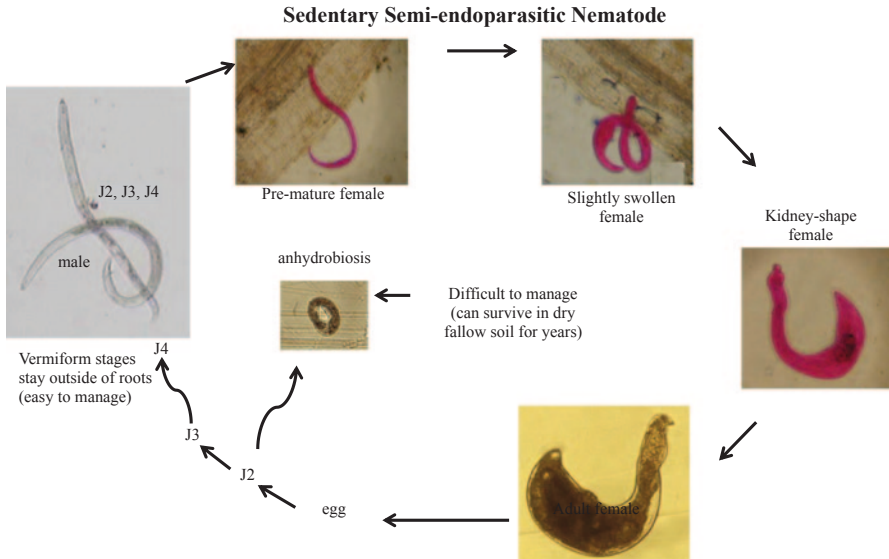


Fig. 2 Life cycle of reniform nematode, *Rotylenchulus reniformis*, showing the vulnerable stages of the nematode: vermiform juvenile stages (J2, J3, and J4) as well as the male. Females of the nematode partially penetrate the roots. Although most life stages of reniform nematodes are prone to chemical exposure or parasitism and predation by its natural enemies in the soil, this nematode can survive in harsh environments without the presence of a host plant in a form of anhydrobiosis. During anhydrobiosis, the nematodes curl up their bodies and remain dormant. (Pictures by K.-H. Wang)

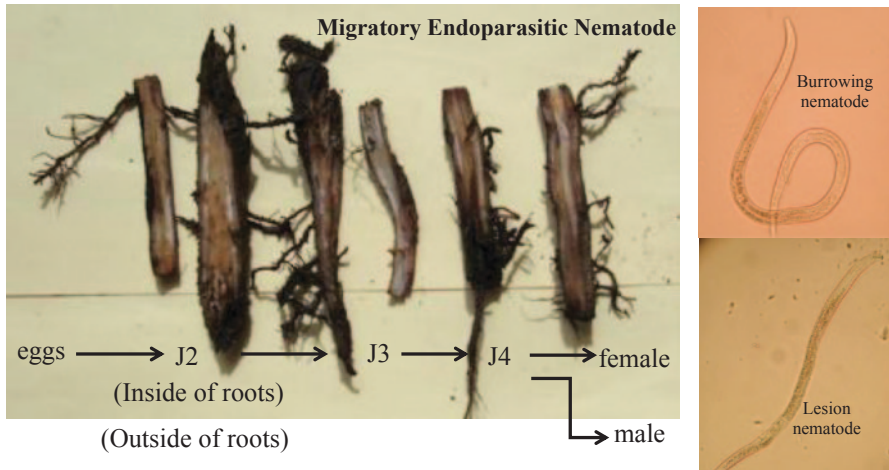


Fig. 3 Life stages of burrowing (*Radopholus similis*) and lesion nematodes (*Pratylenchus* spp.). These migratory endoparasitic nematodes burrow into root tissues soon after hatching, spend most of their life cycle inside the roots of the host plant. Only male nematodes migrate out of the roots when mature. Females lay eggs inside of roots. (Pictures by K.-H. Wang)

tolerance to nematodes. The current chapter will focus on four sustainable farming approaches for nematode management.

2.1 Increasing Host Plant Diversity in a Cropping System

Many plant-parasitic nematodes commonly found in tropical climates tend to have a wide host range, making crop rotation practices rather challenging to design. In addition, host plant resistance against nematode pests for minor crop production in the tropics is also rare. Thus, planting cover crops with allelopathic compounds against nematode pests offer a good alternative strategy. Integrating cover crops into conventional cropping systems for managing plant-parasitic nematodes has been extensively researched and has shown great potential for crops commonly grown. For example, rye (*Secale cereal*), wheat, sorghum (*Sorghum bicolor*), hairy vetch (*Vicia villosa*), sunn hemp (*Crotalaria juncea*), cowpea (*Vigna unguiculata*), and marigold (*Tagetes* spp.) effectively suppressed root-knot nematodes (*Meloidogyne* spp.), one of the most important plant-parasitic nematodes of vegetable and field crops in tropical and subtropical climates (McSorley et al. 1994; Ploeg and Maris 1999). In general there are four possible mechanisms that may play a role in nematode suppression by cover crops: (1) non or poor host effect; (2) nematicidal or nematostatic effect in which the cover crop produces volatile and nonvolatile toxic compounds; (3) enhancement of nematode antagonists (e.g., parasites, predators); and (4) “dead end” trap crop effect, in which cover crop roots are penetrated by nematodes but the nematodes are not capable of reproducing (Gardner and Caswell-Chen 1994; Ploeg 2000; Ploeg and Maris 1999; Wang et al. 2001).

A list of the most well-known cover crops with allelopathic properties against specific plant-parasitic nematodes is summarized in Table 1. Some of these cover crops suppressed multiple nematode pests. For example, sunn hemp was found to significantly reduce root-knot (*Meloidogyne* spp.) (McSorley et al. 1994), reniform (*Rotylenchulus reniformis*) (Charchar and Huang 1981; Wang et al. 2001), lance (*Hoplolaimus* spp.) (Charles 1995), and burrowing (*Radopholus similis*) (Birchfield and Bristline 1956) nematodes. Sunn hemp was found to suppress plant-parasitic nematodes when incorporated into soil. Similarly, marigold suppresses a wide range of plant-parasitic nematodes (up to 14 genera) (Suatmadji 1969). However, the nematicidal effect of marigold varies according to marigold and nematode species, cultivar, and soil temperature (Ploeg and Maris 1999). *Tagetes patula* ‘Single Gold’ consistently suppressed a diverse range of plant-parasitic nematodes. Only living marigold root systems exhibit nematicidal properties. Incorporation of ‘Single Gold’ residues into the soil would not suppress root-knot nematode (Ploeg 2000; Suatmadji 1969; Jagdale et al. 1999). The critical stage for the marigold suppressive effect to occur is during its growth. Thus, to maximize its nematicidal effect, marigolds should not be terminated until late after establishment. Sipes and Arakaki (1997) found that *T. patula* was the most effective cover crop for improving

Table 1 Cover crops with allelopathic compounds against plant-parasitic nematodes in tropical and subtropical regions

Cover crop	Common name	Effect on nematode pests
Brassicacea	Rapeseed Mustard Oil radish	When incorporated into soil, their residues contain glucosinolates that will break down into isothiocyanates and nitriles that suppress nematodes. These cover crops were known to suppress stubby root (<i>Paratrichodorus</i> sp.), lesion (<i>Pratylenchus</i> sp.), and root-knot (<i>M. incognita</i>) nematodes (Brown and Morra 1997)
<i>Sorghum bicolor</i> × <i>Sorghum arundinaceum</i> var. <i>sudanense</i>	Sorghum × Sudan grass	When incorporated into soil, releases dhurrin that degrades into hydrogen cyanide, which is nematocidal (Widmer and Abawi 2000)
<i>Sesamum indicum</i>	Sesame seeds	As a rotation crop with cotton, peanut, and soybean, it suppressed peanut root-knot (<i>M. arenaria</i>) and southern root-knot (<i>M. incognita</i>) nematodes but not Javanese root-knot (<i>M. javanica</i>) (Starr and Black 1995). It is made into commercial products Dragonfire™ (oil), Ontrol™ (seed meal) (Poulenger, USA), and Nemastop™ (ground up sesame plant) (Natural Organic Products) ^a
<i>Crotalaria juncea</i>	Sunn hemp	Act as a poor host of root-knot, reniform, soybean cyst (<i>Heterodera glycine</i>) nematodes, etc. When incorporated into soil, it releases monocrotaline that is nematostatic (immobilizes the movement of nematodes) (Wang et al. 2001; Warnke et al. 2008)
<i>Tagetes</i> spp.	Marigold	There are 14 genera of plant-parasitic nematodes suppressed by marigold, among which root-knot and lesion nematodes are most consistently suppressed (Hooks et al. 2010). Gommers and Bakker (1988) suggested that marigold as a standing cover crop (not after incorporation), releases α -terthienyl (nematocidal compound) when the roots are penetrated by nematodes. Marigold roots also enhance activity of endophytic bacteria that might be responsible for nematode suppression (Sturz and Kimpinski 2004). Unfortunately, marigold is good host to many ectoparasitic nematodes include sting (<i>Belonolaimus</i>), stubby root (<i>Paratrichodorus</i>), and lance (<i>Hoplolaimus</i>) nematodes
<i>T. erecta</i>	African marigold ('Cracker Jack')	Suppressed lesion nematodes when in rotation with potato (Ball-Coelho et al. 2003). However, it is a good host to reniform nematodes (Wang et al. 2003)
<i>T. patula</i>	French marigold ('Single Gold')	Suppressed many root-knot nematode species (Ploeg 2002; Ploeg and Maris 1999)
<i>T. minuta</i>		More tolerant of warm summer temperatures in Florida than the more commonly used marigold species

Table 1 (continued)

Cover crop	Common name	Effect on nematode pests
<i>Tagetes</i> hybrid 'Polynema'		Suppressed many root-knot nematode species if soil temperature is below 30 °C (Ploeg and Maris 1999)
<i>Mucuna pruriens</i> var. <i>utilis</i>	Velvetbean	Velvetbean has been shown to suppress some weed species in tropical production systems. In addition, it also releases nematicidal compounds against many plant-parasitic nematodes including root-knot nematodes (Zasada et al. 2006)
<i>Canavalia ensiformis</i>	Horsebean	It contains lectins, such as concanavalin A, which may disrupt nematode behaviors in host-finding (Marban-Mendoza et al. 1989). Co-cultivation of <i>C. ensiformis</i> with tomato reduced root galling caused by <i>M. incognita</i> and <i>Nacobbus aberrans</i> (Marban-Mendoza et al. 1989)

^a Mention of a trade product does not imply a recommendation by the University of Hawaii

taro (*Colocastia esculenta* L.) yields among the 22 cover crops tested in *M. javanica* infested fields in Hawaii.

On the other hand, brassica crops such as rapeseed (*Brassica napus*), oilseed and mustard are used as green manure to suppress root-knot and lesion nematodes. When green manure is incorporated into soil, glucosinolates in tissues of brassica break down into isothiocyanates and nitriles that suppress nematodes. Thus, rapeseed should be incorporated prior to cash crop planting to produce allelopathic compounds against plant-parasitic nematodes (Cardwell and Ingham 1996). In Bangladesh, populations of the rice root-knot nematode (*Meloidogyne graminicola*) can be reduced significantly on deep water rice by growing rice after oilseed crops, such as mustard and sesame (Rahman 1990).

Velvetbean (*Mucuna pruriens*) is another leguminous cover crop suitable for use as a green manure to reduce some important nematode species such as *Meloidogyne* spp. and *Heterodera glycines* (Weaver et al. 1998; Ritzinger and McSorley 1998). Two alcohols, which inhibited *M. incognita* hatching, were isolated from the velvetbean (Nogueira et al. 1996). Another leguminous plant known to be suppressive to plant-parasitic nematodes in the tropics is horsebean (*Canavalia ensiformis*). It contains lectins, such as concanavalin A, which may disrupt the capability of nematodes to locate a host (Marban-Mendoza et al. 1989). Co-cultivation of *C. ensiformis* with tomatoes reduced root galling caused by *M. incognita* and *Nacobbus aberrans* (Marban-Mendoza et al. 1989). For more information about other plant extracts capable of suppressing plant-parasitic nematodes, please refer to Oka (2010). Most recently, a new biopesticide registered by Monterey AgResources as a nematicide was extracted from the soap bark tree, *Quillaja saponaria*, and has been used for controlling plant-parasitic nematodes in vineyards, orchards, field crops, turf and ornamentals (Meister and Sine 2012).

Beside cover crops, another organism known to produce allelopathic compounds suppressive to plant-parasitic nematodes is the oyster mushroom (*Pleurotus*

ostreatus). The mushroom exudes a toxin from the fungal hyphae, known as trans-2-decenedioic acid (Kwok et al. 1992). This toxin paralyzes the nematode on contact, which allows the hyphae to move into the nematode to colonize and digest the nematode. Studies on the effects of nematodes have been predominantly in vitro. Thorn and Barron (1984) screened 27 species of mushrooms for toxicity against nematodes in vitro and found that 5 species of *Pleurotus*, 5 species of *Hohenbuehelia*, and one species of *Resupinatus*, all of which were classified in the family of Pleurotaceae, were capable of destroying nematodes. Complete control of *M. incognita* by *P. ostreatus* compost amended at 0.5% in soybean pots has been reported in Nigeria (Okorie et al. 2011). More research is needed to investigate the potential of using mushroom compost waste for managing plant-parasitic nematodes in agriculture production systems.

However, performance of cover crops or mushroom compost to suppress plant-parasitic nematodes could vary based on cover crop or mushroom compost quality and quantity, cultural practices, history of the crop site, and time of planting. Several approaches can be used to integrate cover crops or mushroom compost into a cropping system: (1) incorporating mushroom compost or cover crops as a soil amendment or green manure prior to cash crop planting; (2) strip-till cover cropping system, where only the rows for planting the cash crop are tilled under and the remaining cover crop remains on the soil surface as a living or hay mulch; (3) no-till system where the cover crop is destroyed by chemical or physical means (e.g. flail mower, cover crop roller), prior to planting the cash crop with a no-till planter; or (4) as a dying mulch in which the cash crop is planted into a senescing cover crop. Understanding the mechanism of action on how a particular cover crop suppresses plant-parasitic nematodes is critical in deciding how the cover crop or compost should be integrated into a cropping system.

Based on a review of research using rotation crops and cover crops for root-knot nematode management in the Southern United States, McSorley (2011) concluded that the performance of rotation crops or cover crops was similar to clean fallow in most studies. This review suggested that rehabilitation of heavy nematode infested sites is difficult, and could require several years of crop rotation to achieve economic benefits. These results are discouraging for sustainable farming systems that rely heavily on crop rotation and cover cropping. Marahatta et al. (2012a) provided evidence that the effects of the allelopathic cover crops suppressing plant-parasitic nematodes are more efficient if targeting the vulnerable stage of the nematodes. For example, marigold suppressed *Meloidogyne* spp. if planted when these nematodes are in their active stage. This means that marigold would suppress *Meloidogyne* more effectively if planted right after a susceptible crop rather than planted in fields that had been dry fallow for some time. Similarly, Marahatta et al. (2012b) also documented that soil incorporation of *C. juncea* suppressed *R. reniformis* more efficiently in soil previously planted with a susceptible host (e.g. cowpea, *Vigna unguiculata*) than in soil being dry fallowed for 3 months. This is most likely due to the fact that dry fallow can trigger *R. reniformis* to transform into their survival or anhydrobiotic stage, and caused the eggs of *Meloidogyne* to remain unhatched. Future work should examine how to manipulate cropping systems to allow effective

use of nematode antagonistic cover crops so as to target the vulnerable stage of the nematodes.

2.2 *Increasing Ecosystem Community Stability by Promoting Antagonists of Nematodes*

Nematode antagonists encompass diverse organisms that include natural enemies such as parasites and predators, but also organisms that produce antibiotics, extracellular enzymes, or induce host plant systemic resistances (Stirling 2011). Numerous organisms that are capable of reducing populations of plant-parasitic nematodes include egg parasitic fungi, endoparasitic fungi, fungal endophytes, parasitic bacteria, predatory nematodes, actinomycetes, and plant growth promoting rhizobacteria. A thorough review for each of these groups of nematode antagonists has been published in the book “Biological control of plant-parasitic nematodes: progress, problems and prospects” (Stirling 1991). Although nematode suppressive soils do occur naturally (Westphal and Becker 1999), it often takes time to build up without initial economic yield loss.

Stirling (2011) reminds us that “nematode biological control is a normal part of a properly functioning soil ecosystem, with plant-parasitic nematodes only becoming pests when they are no longer constrained by the biological buffering mechanisms that normally keep them in check”. Common agricultural practices that rely on soil tillage, application of pesticides for various pest control, and synthetic fertilizer are generally unfavorable for the establishment of nematode suppressive soil. Conventional farming practices that attempt to introduce nematode antagonists of plant-parasitic nematodes back into human intervened intensive farming systems tend to conduct augmentative biological control where biocontrol agents are isolated, mass produced and introduced to a targeted area. Despite the high numbers of nematode antagonists of plant-parasitic nematodes that have been commonly isolated and identified (Stirling 2011), they are only four bacteria or fungi that were registered as biopesticides for nematode control by the United States Environmental Protection Agency as listed on the Crop Protection Handbook of 2012 (Meister and Sine 2012). Among which, *Myrothecium verrucaria* is prepared as fermented materials with killed mycelium, whereas *Paecilomyces lilacinus*, *Bacillus firmus*, and *Streptomyces saraciticus* are prepared as live biological control agents. *Pasteuria* is another nematode biological control agent that is commercialized, but with specificity against target species. Worldwide, there are more commercialized nematode biological control agents, but they are all challenged by the same dilemma, i.e. their inconsistent performance in the field.

Therefore, recently there has been more work focused on approaches that can be used to restore, maintain or enhance the natural nematode suppressive mechanisms that should operate in all agricultural soils (Timper 2014). These types of practices that enhance naturally occurring biocontrol agents through cultural prac-

tices are known as conservation biological control. A thorough review on the use of the conservation biological control approach for nematode management is recently published by Timper (2014). In summary, these approaches include: (1) providing a supplemental food source for nematode antagonists, (2) identifying the host plants that are compatible with the colonization or establishment of nematode antagonists, (3) integrating the host plants that are favorable for the expression of antibiotics from nematode antagonistic bacteria, and (4) reducing cultural practices that could disturb the establishment of nematode antagonists.

Stirling (2011) categorized the supplemental food source for nematode antagonists into two distinct groups: carbon (C) or nitrogen (N) dominated organic matter. Organic matter that are N dominated such as animal manures, oil-cakes, and residues from leguminous crops (Muller and Gooch 1982; Rodriguez-Kabana 1986; Stirling 1991) are thought to release nematicidal levels of ammonia during the decomposition process, killing nematodes in a short period of time. However, the effect is usually short lived, and requires frequent application if the nematode problem persists. Accumulation of nitrite and nitrate would be a great concern when relying on N dominated organic matter. Oka and Pivonia (2003) found that adding chitin or cottonseed amendments to N dominated soil organic matter could serve as a nitrification inhibitor by slowing the oxidation of ammonia to nitrite and nitrate and allowing ammonia concentrations to build up for an extended period, and thus extending the nematode suppressive period.

The second group of organic matter is dominated by C content. In contrary to N dominated compounds, nematode suppressive effects provided by wood chips, yard waste, or grassy crop residues (such as sugarcane residues) tend to build up slowly (McSorley and Gallaher 1996; Stirling et al. 1995). Often taking years, the mechanisms involved are usually biological based, and the effects often last much longer than the N dominated soil amendments (Stirling et al. 2005). The nematode-trapping fungi (NTF) and several genera of wood-decaying basidiomycetes are commonly found in habitats rich in cellulose and lignin and are thought to have evolved the capacity to scavenge for additional N in low N environments by preying on nematodes (Barron 1992).

Exceptional responses of nematode suppressiveness by organic matter with different C:N ratios do occur. For example, Wang et al. (2002) demonstrated that when the leguminous cover crop sunn hemp (*Crotalaria juncea*) was grown prior to a pineapple crop, population densities of nematode-trapping fungi increased significantly compared to two non-leguminous cover crops, marigold (*Tagetes erecta*) and rapeseed (*Brassica napus*), and most significantly to a weed fallow treatment. Later, Ching and Wang (2012) compared sunn hemp (SH) to oats (O) (*Avena sativa*), and a mix of sunn hemp and oats (SH+O) as preplant cover crops prior to a no-till planting of eggplant. They monitored NTF over a 10 month period after eggplant was planted, and found that SH (whether SH alone or SH+O) had higher numbers of NTF propagules per gram of root than treatments without SH (O alone and bareground). This is probably due to the fact that SH alone contains tissues that are made of different C:N ratios, ranging from C:N of 11 in the leaves to 48 in stem tissues (Marshall 2002). However, although SH could enhance NTF significantly

in this system, abundance of NTF was only positively correlated ($r=0.26$, $P=0.05$) with total abundance of plant-parasitic nematodes, indicating a density dependent relationship between nematode prey and NTF, and not necessary resulted in suppression of the nematode pests.

Clearly, integrating augmentative and conservation biological control strategies together might offer a more versatile approach to promote nematode-antagonistic microorganisms in a sustainable agriculture system. For example, Stirling (2008) integrated crop rotations, reduced tillage, residue retention, more frequent cover cropping, and regular inputs of animal manures and organic wastes into a sugarcane farming system and found that damage caused by *M. javanica* and *Pratylenchus zae* was reduced due to enhancement of natural biological control mechanisms against these pests (Stirling 2008). More work will be needed to develop integrated approaches for different cropping systems specific for different regions. Thus, the era of the “silver bullet” approach needs to be adjusted to allow for more efficient and sustainable use of natural enemies.

2.3 Stimulating Inherent Plant Defenses Against Nematode Pests

The availability of natural host plant resistance against nematode pests relies on traditional plant breeding or through genetic recombination, both of which are time consuming. These technologies are mostly available for highly profitable or intensive farming crops. Most of the minor crops grown in the tropics might not be economically significant. One alternative is to induce resistance in the host plant. Systemic induced resistance is an enhanced defensive capacity throughout the plant that is triggered by a specific stimulus such as a chemical inducer, a pathogen or insect, or a non-pathogenic microorganism (van Loon et al. 1998). There are two recognized types of induced resistance, systemic acquired resistance (SAR) and induced systemic resistance (ISR) that are differentiated by their signal transduction pathways (van Loon et al. 1998). These induced resistances often lead to the systemic expression of a broad spectrum and long lasting disease resistance that is efficient against bacteria, fungi, Oomycetes, nematodes, viruses (Durrant and Dong 2004; Zinovieva et al. 2013) as well as insect transmitted viruses (Zehnder et al. 2000). ISR occurs not only in place of an elicitor exposition or a penetration of the pathogen (local resistance), but also in remote areas of the plant induced systemic resistance. ISR in plants activate the same defense mechanisms that operate in genetically determined resistance, but unlike this degree of protection, usually, it does not exceed 30% of the regular host plant resistance (Zinovieva et al. 2013). None-the-less, it still provides a form of plant disease management that would reduce risk to the environment and be more compatible with sustainable pest management.

Although ISR is dependent on jasmonic acid and ethylene signaling in the plant, ISR differs from SAR in that resistance can be induced by the rhizobacterium, particularly *Pseudomonas* and *Bacillus* (Kloepper et al. 2004; Van Loon 2007). This type of rhizobacteria is referred to as plant growth-promoting rhizobacteria (PGPR). PGPR are naturally occurring soil bacteria that colonize plant roots and

benefit plants by promoting plant growth and/or reducing disease or insect damage. Lugtenberg and Kamilova (2009) recently reviewed works on PGPR and listed all the mechanisms responsible for PGPR to promote plant growth and protect plants from pest damage. In recent years, increasing numbers of PGPR species have been identified. *Azotobacter*, *Pseudomonas*, *Azospirillum*, *Klebsiella*, *Enterobacter*, *Alcaligenes*, *Arthrobacter*, *Burkholderia*, *Bacillus*, and *Serratia* are among the most commonly found (Pathma and Sakthivel 2013). These bacteria either induced ISR, produce siderophore bacteria or antibiotics, improve nutrient acquisition of plants, or produce phytohormones.

One sustainable agriculture approach that can enhance PGPR and subsequently lead to ISR is through the use of vermicompost tea extract. Vermicompost is the product of accelerated bio-degradation of organic matter by earthworms through mesophilic decomposition. It generally has higher concentrations of plant available nutrients (NO_3^- , exchangeable Ca, P and soluble K) and significantly larger and more diverse microbial populations than thermophilic compost (Tognetti et al. 2005). Vermicompost tea (VCT) is a water-based extract of vermicomposts through aerated and non-aerated procedures. Aerated VCT is usually prepared by adding vermicompost into a porous container, then suspending it in a water containing vessel, typically 1 part compost to 10–50 parts water. Constant mechanical energy input is used to provide aeration either by air injection directly into the water or by re-circulation of the water, typically for 12–24 h. Non-aerated compost tea is prepared by mixing 1 part compost with 3–10 parts water in an open container, where it remains with or without daily stirring, for at least several days (often for 1–3 weeks) (NOSB 2004). VCT may supply microbial biomass, fine particulate organic matter (POM), organic acids, plant growth regulator like substances and soluble mineral nutrients to plant surfaces (Edwards et al. 2006; Scheuerell and Mahaffee 2002). These properties of vermicompost tea might serve as a means to enhance the soil food web structure that eventually leads to a plant tolerance to stress (Arancon et al. 2004). VCT increased seedling vigor and plant growth, as well as N content, total carotenoids, and total glucosinolates in plant tissue as compared to no VCT treatment (Pant et al. 2011). In addition, they also measured dehydrogenase activity and soil respiration and found that increased VCT concentration increased total soil microbial activities.

Vermicompost tea extract has been shown to suppress plant pathogens including nematodes (Edwards et al. 2007). Wang and Radovich (2012) found that weekly application of chicken manure based VCT (10%) suppressed root-knot nematode population densities initially and improved crop yields of squash. Besides direct suppression of plant-parasitic nematodes, Wang and Radovich (2012) also reported that drenching of VCT resulted in a significant increase of predatory nematode numbers within one cropping system of zucchini (<30 days after transplanting), thus showing an improvement in soil food web structure in a short period of time. Many have documented that the microbial population found in compost teas or extracts is responsible for suppressing soil-borne pathogens (El-Masry et al. 2002; Scheuerell and Mahaffee 2002; Zmora-Nahum et al. 2008). Future work needs to examine the performance of different formulations of VCT for targeted nematode pests.

2.4 Improving Plant Tolerance to Plant-Parasitic Nematodes by Maintaining Soil Nutrient Cycling and Energy Flow

Plant-parasitic nematodes cause damage to plant roots, resulting in root systems which are less able to take up nutrients and water. Enhancing soil nutrient availability not only supplies nutrients for plant uptake, but also provides plants with materials needed to grow functional roots, thus increasing the plant's tolerance to nematode damage. On the other hand, a great resource in most soil ecosystems for suppressing plant-parasitic nematodes is the pool of natural enemies of nematodes in the soil. Thus, maintaining a complex soil food web would increase plant tolerance to nematode pests.

When organic matter is first added into the soil, it is in a form that is unavailable for plant uptake until it is decomposed by bacteria or fungi. After initial decomposition, some organic matter will be converted into an inorganic form that plants can utilize. However, these same bacteria or fungi can immobilize nutrients in the soil until they are grazed by bacterivorous and fungivorous nematodes. However, overgrazing by these nematode groups can reduce the overall activity of decomposers. Fortunately, in the hierarchy of the soil food web, predators such as predatory nematodes and mites, feed on these bacterivorous and fungivorous nematodes, thus allowing more nutrients to be released into an inorganic form for plant uptake. Thus, an increase in predatory nematodes may contribute to increased nutrient mineralization. Ferris et al. (2012) recently reviewed the studies of nematode ecology since the beginning of 1980s, and revealed the importance of free-living nematodes in the soil food web (Fig. 4).

Availability of nutrients from soil organic matter to plants relies on the mineralization (release) of nutrients from the organic matter (immobilized forms). Nematodes have higher respiration rates, lower N needs, and lower growth efficiency than bacteria. Therefore they can release a majority of both the C and N that they consume from bacteria into nutrients available for plants. Grazing of nematodes may contribute up to 19% of soluble N in soil (Neher 2001), much higher than that contributed by bacteria in soil ecosystems. In general, increases in bacterial and fungal feeding nematodes are associated with higher N availability to plants.

In addition to N mineralization, populations of free-living nematodes, especially bacterivorous, omnivorous, and predatory nematodes, have also been found to correlate with concentrations of most of the other soil nutrient elements including P, K, Na, Ca, Mg, Fe, Cu, Mn, Zn, and cation exchange capacity (Wang et al. 2003). This suggests that nematodes are also responsible for the mineralization of other soil nutrients. Therefore, nematodes play important roles in soil nutrient cycling.

Unfortunately, nematode communities in an agroecosystem, especially those in the higher hierarchy of the soil food web, are often too disturbed by human intervention, such as frequent tillage, pesticide applications, etc. (McSorley et al. 2007). Several attempts have been made to use cover crops in combination with conservation tillage practices to reduce soil disturbances and increase the abundance of soil organisms higher in the soil food web hierarchy (DuPont et al. 2009;

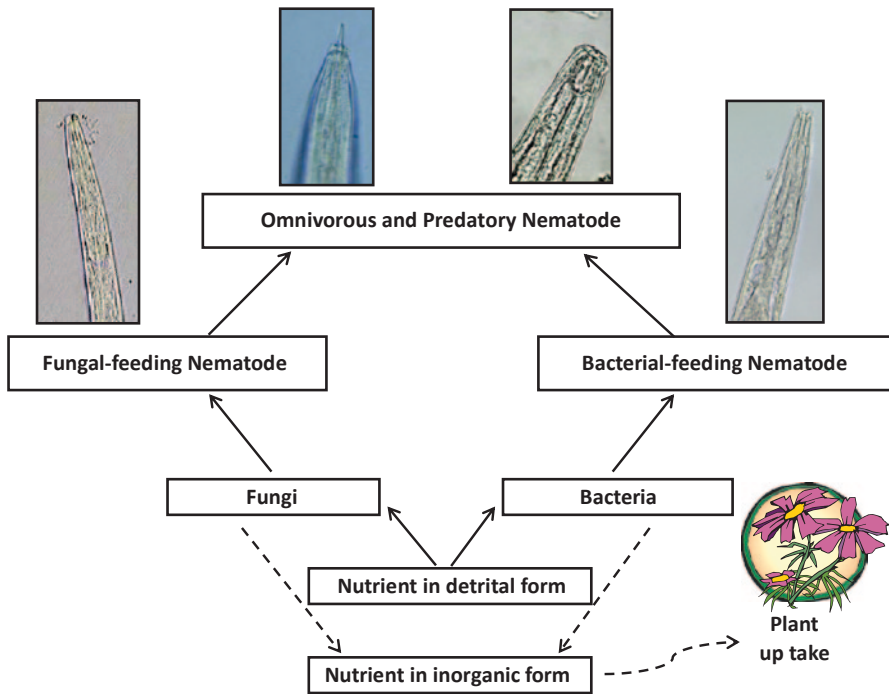


Fig. 4 Functional groups of free-living nematodes in a soil food web in relation to soil nutrient cycling. (Pictures by K.-H. Wang)

Sánchez-Moreno and Ferris 2007). However, these studies generally found that long term conservation tillage (more than 2 years) is required before enhancement of omnivorous or predatory nematodes can be observed. Alternatively, adding resources such as organic matter into the soil fuels the food source for free-living nematodes, and thus, can also enhance nematodes that are of higher hierarchy in the soil food web. Using these concepts, growing sunn hemp (*Crotalaria juncea*) as a leguminous cover crop in a strip-till cover cropping system (STCC) followed by periodic clipping of the living mulch intercropping between vegetable cropping rows and added as organic surface mulch (SM) provide an approach to reduce soil disturbance, while fueling organic materials to the soil food web over a longer period of time than a conventional cover cropping system (Wang et al. 2011).

Another approach to improve the soil food web structure in short-term agroecosystems is to enrich the soil with vermicompost tea extract, as mentioned in Sect. 2.3. VCT enhanced microbial biomass and improved soil structure (Edwards et al. 2006; Scheuerell and Mahaffee 2002). These properties of vermicompost tea might be responsible for the significant increase of abundance in predatory nematodes within one cropping cycle of zucchini, drenched weekly with chicken manure based VCT (Wang and Radovich 2012). Other approaches to enrich crop rhizosphere with microbial biomass and improve soil structure might obtain similar results and should be integrated into sustainable pest management planning.

3 Sustainable Pest Management for Plant Fungal and Oomycete Pathogens

Similar to management of other groups of plant pathogens in a sustainable agriculture system, sanitation of planting materials or growing media should be the first line of a preventative measure against fungal or Oomycete caused diseases. This chapter will mainly focus on biological and cultural practices that are compatible with the five approaches listed in the introduction section. Natural enemies of fungal or Oomycete pathogens are mostly fungi or bacteria. Some of the most commonly found fungal and Oomycete biocontrol agents are *Trichoderma*, *Gliocladium*, *Acremonium*, *Geotrichopsis*, *Pythium*, *Verticillium*, *Coniothyrium*, *Piptocephalis*, *Kuzuhaea*, *Melanospora*, and many others. However, most of these are not commercially available. In general the pathogenic relationships that have evolved between the biocontrol antagonist and the fungal pathogen are often highly specific. Through the understanding of the mechanisms of how these potential biocontrol agents suppress fungi or Oomycetes, perhaps better ecologically based management strategies could be developed. In general, five mechanisms could be involved between the fungal biological control antagonist and the plant pathogen as reviewed by Jeffries and Young (1994).

Toxin producers: Production of extracellular metabolites (e.g. toxins) that diffuse from the antagonist that harm the plant pathogen. For example, *Stereum* species that attack plums are inhibited by the antagonist, *Hypomyces aurantius*. When the *Hypomyces* is grown near the *Stereum*, the *Hypomyces* releases substances that cause lipid (component of fat, waxes, etc) bodies to accumulate, or that lead to destruction of the membranes in the energy producing mitochondria, or that cause membrane disruption of the endoplasmic reticulum, needed for internal transport, and this causes the cell membrane to withdraw from the cell wall (Kellock and Dix 1984). The cell membrane is crucial to the survival of all cells and regulates what enters and leaves the cell. Thus disruption of these systems in the *Stereum* results in cell death of the pathogen. In another example, fungal pathogen destruction was observed when grown with *Trichoderma* species that are common biocontrol agents. Thus between the use of *Hypomyces* and *Trichoderma* biocontrol species, plum diseases caused by *Stereum* can be controlled.

Hyphal cell interference: Ikediugwu and Webster (1970) described hyphal interference as any process that occurs when two different fungi are grown close together and the plant pathogen is harmed by the antagonist, when substances diffuse from the antagonist to the pathogen and reduce its growth rate and cause cytoplasm disruption. When studied using an electron microscope, a marked change in the permeability of the cell membrane of the pathogen can be observed. There is loss of turgor pressure with granulation and vacuole formation in the pathogen cytoplasm. These cells then die. The substances are able to diffuse across a cellophane membrane and this implies that the substance is a small molecule and not a large enzyme molecule (Ikediugwu and Webster 1970).

This process has been documented for the ability of *Phanerochaete gigantea* to control infection of the pine tree by *Heterobasidion annosum*. When pine trees are harvested, the stumps are rapidly infected with *Heterobasidion*, the bracket fungus. This highly destructive fungus can grow from one tree to another using the connected root systems, infecting hundreds of trees. If the *Phanerochaete* is sprayed on the freshly cut stumps, infection by *Heterobasidion* is prevented. Research has shown that the *Phanerochaete* occupies the sites needed by the *Heterobasidion* for infection and that the interference reaction prevents respiration (energy metabolism) of the *Heterobasidion* (Ikediugwu 1976). This has been a highly effective biocontrol for the pine forest industry.

Rhizoctonia solani is a very common worldwide pathogen of roots and some foliar disease (thread blights). It can be controlled by the biological control agent *Arthrobotrys oligospora*, another fungus common in soil (Persson and Baath 1992). When the *Arthrobotrys* hyphae grows adjacent to *Rhizoctonia* hyphae, the *Arthrobotrys* forms numerous membranous structures indicating that following contact, serious metabolites are formed by the *Arthrobotrys* that trigger the lyses and cell death of *Rhizoctonia*.

Haustoria formers: In these cases the mycelium of the antagonist remains on the outside of the pathogen but grows closely with it. Appressoria, or cushion shaped hyphal tips are formed and firmly anchored to the plant pathogen. An infection peg is produced from the appressoria and it enters the pathogen hyphae. Inside the hyphae, it inflates to form a balloon like structure, the haustoria. This haustoria releases enzymes that disrupts the cells contents and cause them to degrade and die. Nutrients are released and the haustorium absorbs these nutrients and transports the nutrients back to the antagonist mycelium for further growth. Haustoria formers are common in biological control of fungi. Commonly, several methods of attack occur. For example, pathogen control of onion diseases uses interference principles, and then enzymes are formed for wall degradation and growth of the antagonist in the mycelium of the *Botrytis*, that destroys the pathogen. The cells of the plant pathogen *Botrytis alli*, which attacks onion, are killed when the biocontrol *Gliocladium roseum* are grown with it. The series of events that occur are: (1) the close growth of the *Gliocladium* and *Botrytis* hyphae or threads, (2) the *Gliocladium* produces toxins that diffuse into the *Botrytis*, (3) the cells of the *Botrytis* are killed, (4) cell wall degrading enzymes are then produced by the *Gliocladium* which enters the *Botrytis* and feeds on it (Pachenari and Dix 1980).

Invasive necrotrophs: These biological control agents penetrate the hyphae of the pathogens they invade. Following penetration, there is a huge amount of lyses of the cell walls and destruction of the pathogen cytoplasm and finally death of the pathogen. These necrotrophs can invade the entire pathogen structure but are more commonly associated with the hyphae, spores, or surviving sclerotia. A well-known necrotroph, *Schizophyllum commune*, lives on stumps of felled trees. It attacks the nematode destroying fungus, *Arthrobotrys oligospora*, parasitizing *Rhizoctonia solani* and species of *Cunninghamella*, *Rhizopus*, and *Zygorhynchus*. *Schizophyllum* coils around the pathogen and other fungi it infects, develops appressoria and pegs, and penetrates the host. The parasitized hypha collapses and is destroyed (Tzean and Estey 1978).

Pythium species can be plant pathogens but some are also mycoparasites, which have been well studied. Mycoparasitic species include *P. acanthicum*, *P. mycoparasiticum*, *P. nunn*, *P. oligandrum* and *P. periplocum* (Deacon et al. 1991). *Pythium oligandrum* has been frequently isolated from agricultural soils and is known to be an aggressive pathogen of significant plant pathogens (Deacon 1976; Deacon and Henry 1978). The fungal pathogens differ in susceptibility with *Trichoderma aureoviride* and *Fusarium oxysporum* as highly susceptible, *Botrytis cinerea*, *Fusarium culmorum*, *Rhizoctonia solani* and *Botryotrichum piluliferum* as moderately susceptible and *Pythium graminicola* and *P. vexans* as highly resistant (Laing and Deacon 1990). Susceptible pathogens are rapidly lysed with total destruction of the pathogen while those that are more resistant degraded at slower rates and lysed are not consistent.

Intracellular Biotrophs: Although many types of relationships exist, one that is unique is the total movement of the biological control agent into the host. This occurs as the zoospore of the biological control agent becomes an endobiotic body within the pathogen's cytoplasm. Several species of the *Oomycota* and *Chytridiomycota* are involved. The invading biotroph does not seem to cause damage to the pathogen initially, and there appears to be a close relationship of the parasite wall and the endoplasmic reticulum of the host (Powell 1982).

However a few successes in using fungal biocontrol agents against fungal or Oomycete pathogens have been developed and more are in the process of being improved. For detailed examples, please visit Jeffries and Young (1994). In general, fungal biocontrol agents that are resistant or compatible with fungicide application are recognized as effective biocontrol agents. For example, *Pythium oligandrum* is being considered for commercial production now that isolates resistant to Benlate were found (Lewis et al. 1989). Effective control of damping-off was attained with the use of *P. oligandrum* and lower rates of the fungicides. Another example is *Trichoderma*. *Trichoderma* was predicted to be a good source of biocontrol because it grows rapidly in soil, is able to use low levels of nutrients, and is able to grow in acidic and alkaline soils (Jeffries and Young 1994). It was also found that some strains were resistant to fungicides used to control pathogens (Papavizas 1985). Today there are nine species/strains of *Trichoderma* listed as biocontrol agents, and these include *Trichoderma harzianum* (no specific strain; some mixed with *T. viridie*, available as Ecosom, Trisan, others), *T. harzianum* (strain T-22, Rootshield), *T. harzianum* (strain T-39, Trichodex) *T. virens* (SoilGard), *T. viride* (Bioderma, Ecfosom, Bio-Cure, and Tricho-shield), *T. harzianum/polysporum* (BINAB T) (Meister and Sine 2012). These types of biocontrol agents could be used in Integrated Pest Management Programs to control plant diseases.

Bacteria as biocontrol agents: In addition to the use of fungi to control fungal diseases, bacterial species have also been employed to control fungal rots. Three species of *Bacillus* are used to control fungal diseases. For example *B. subtilis* is used to control fungal pathogens on seeds of barley, peanuts, wheat, cotton, soybean and other leguminous crops, while *B. pumilus* controls mildew and rust on cereals, roses, strawberries, and vegetables. *Bacillus pumilus* is sold in the USA as Ballad or Yield Shield, and available in Brazil as Sonata. *Bacillus subtilis* is widely available

from many companies and is sold as Serenade, Kodiak, Companion and others. *Streptomyces candidus* is used to control *Phytophthora* and *Pythium* on fruits and vegetables. It is sold as BioAid and Sun Mycan. Other *Streptomyces* species are used to control fungal diseases such as damping-off, root rots and wilt of herbs, vegetables, ornamentals, and landscape plants. For *S. lydicus*, it is marketed as Actinovate AG, Actinovate Sp, or others. *Pseudomonas fluorescens* can be used to control root rots, banana wilt, diseases of chickpeas, soybean, tomatoes, and sheath blight on rice, many other diseases of cereals, cotton fruits and vegetables. It is available as Bio-cure-B and Biomonas. *Pseudomonas syringae* is employed to control post-harvest diseases of citrus, cherries and pomes fruits. It can be purchased as Bio-Save 10LP and should be kept refrigerated (Meister and Sine 2012).

None-the-less, introducing biocontrol agents is still considered as a therapeutic approach for pest management. Integrating multiple species of biological control agents to complement each other would be an effort to increase biodiversity to keep pathogenic fungi or Oomycete in check.

3.1 Increasing Ecosystem Community Stability by Promoting Antagonists of Fungal and Oomycete Pathogens

In reality, root systems of agricultural crops are often exposed to multiple soil-borne or foliar fungal pathogens. Introducing biocontrol agents that specifically target a single pathogen will be too time consuming and costly. Amending soil with organic matter could enhance multiple beneficial indigenous soil organisms that might lead to natural suppressive soils. For example, broad-spectrum control of *Pythium*, *Phytophthora* and *Rhizoctonia* was reported in peat and compost-based soilless container media (Hoitink et al. 2001); *Pythium* was suppressed in Mexican fields following the application of large quantities of organic matter over many years (Lumsden et al. 1987); *Phytophthora* root rot of avocado in Australia was suppressed by the use of cover crops, organic amendments and mulches (You and Sivasithamparan 1994, 1995); similarly, suppression of the same disease with eucalyptus mulch was reported in California, USA (Downer et al. 2001).

One drawback of using organic amendments is that when pathogens are good saprophytes but poor competitors (e.g. *Pythium* and *Fusarium*), they may multiply on organic amendments before being suppressed. Similarly, use of organic amendments is also problematic in *Rhizoctonia* infested soil. This is because *Rhizoctonia* has a high capacity to degrade cellulose as well as simple sugars, making it a good saprophyte that can proliferate in soil with high organic matter. Thus, organic-matter mediated general suppression might not be sufficient to achieve control and specific antagonists may also be required (Stone et al. 2004).

However, van Bruggen and Termorshuizen (2003) compared disease severity in organic and conventional farming systems from various studies conducted in the U.S. and Europe, root diseases are generally less severe in organically than conventionally managed soils. Although specific mechanisms of this phenomenon are

not totally understood, sometimes positive correlation between soil N availability and disease severity was found (Tamis and van den Bink 1998; Daamen et al. 1989; El Titi and Richter 1987). Another possible reason for lower disease severity in organic farming systems compared to conventional farming systems is the higher diversity and abundance of non-pathogenic fungi with antagonistic properties. For example, the density of non-pathogenic *Fusarium* species with antagonistic properties towards *F. culmorum* was significantly higher in an established organic farm than in a neighbouring conventional farm (Knudsen et al. 1999). Bulluck and Ristaino (2002) documented that southern blight (caused by *Sclerotium rolfsii*) was suppressed in plots receiving organic amendments rather than synthetic fertilizers, and they attribute this to higher microbial biomass and activity in organic plots. In addition, van Bruggen and Termorshuizen (2003) also concluded that crop protection in organic farming is generally not directed at controlling particular pathogens or pests but at management of the environment so that plants are able to withstand potential attacks.

Similar to the sustainable approaches for nematode management, sustainable farming practices to promote soil suppressiveness against fungal and Oomycete pathogens are long, balanced crop rotations, organic amendments and reduced tillage, all geared towards maintenance of the soil organic matter content and fertility. Unfortunately, conversion from a disturbed, conventional farming system to disease suppressive organic farming system often takes times. Roget (1995) demonstrated that after conversion from regularly tilled to no-till wheat production, *Rhizoctonia* root rot increased initially, but this increase was followed by a decline in this disease after about 5 years of no-till.

3.2 Stimulating Inherent Plant Defenses against Fungal or Oomycete Pathogens

Examples of ISR to suppress fungal or oomycete pathogens is also present. For example, *Pseudomonas* sp. strain WCS417r was found to induce ISR against *Fusarium* wilt of carnation (Wei et al. 1991). In addition, induction of systemic resistance of cucumber to *Colletotrichum orbiculare* by selected strains of plant growth-promoting rhizobacteria (PGPR) have also been reported (Wei et al. 1991). Commercially available chemicals are also available to induce ISR against this group of pathogens. For example, Acibenzolar-S-methyl (ASM), which is commercially available as Actigard, contains a Harpin protein, has been used successfully in some ornamental crops such as Fuchsia (Titus 2012) and is sold as Messenger or Employ. It was effective in boosting the health of plants, which were more vigorous following treatment, and grew at a faster rate. Harpin protein is obtained from the bacterium *Erwinia amylovora* which activates plant physiology. Better growth and vigor is the major effect but minor, weak pathogens may be inhibited as well (see bacterial biocontrol with Actigard).

3.3 Plant Extracts to Control Fungal Diseases

A few compounds have been extracted from plants which demonstrate disease control characteristics. An extract from *Reynoutria sachalinensis*, sold as Regelia in the U.S. A., has been commonly cited as a control for powdery mildew and leaf spots on greenhouse grown ornamentals, strawberries and vegetables. Much research is still needed for specific crops, as well as, the optimal methods of application and the timing of these extracts to be applied. Clove oil is reported to reduce silver scurf and sprouting of potatoes. It is sold as Matratec, Matran and Biox. Other oil based compounds used are anise, canola, jojoba, rosemary, wintergreen, lemongrass, mint, orange, rapeseed, soybean, thyme and others. These are sold as Armorex, Deter, Ecotec, EcoTrol, Organocide, and Pest Out (Meister and Sine 2012). Many compounds have some effect but do not completely prevent or “cure” diseases. Still they offer growers alternatives to harsh chemical controls.

4 Sustainable Pest Management for Insect-Vectored Plant Viruses

In terms of plant viruses, breeding for virus resistant hybrids is available on several crops, but these approaches are time consuming. This is especially challenging when dealing with crops that are susceptible to multiple plant viruses, as well as, other pathogens. Managing insect vectors such as aphids, thrips, and whiteflies that transmit plant viruses serve as a preventative measure for this type of virus disease. Rear and release of biological control agents against virus insect vectors has become of great interest to farmers that are considering the sustainable pest management approach. A wide range of therapeutic bioinsecticides are available (Meister and Sine 2012), and more are being developed with modern technology. Therapeutic approaches play a valuable role in ecologically based pest management strategies, but they could potentially be disruptive to natural enemies. For example, although spinosad is considered a reduced-risk insecticide, it is harmful to *Trichogramma* wasp (*T. exiguum*), and slightly harmful to a predatory mite, *Iphiseius degenerans* (Charles et al. 2000; Van Driesche et al. 2006) and bumble bees (Johnson 2004; Morandin et al. 2005). Azadirachtin (neem) reduced life table parameters of *T. exiguum* (Saber et al. 2004), and harmed a soil predatory mite, *Hypoaspis aculeifer*, when applied to soil (Thoeming and Poehling 2006). Upon contact, neem seed extract reduced the population densities of parasitoids, *Encarsia* sp. and *Al-eurodiphilus* sp. (Price and Schuster 1991). Both natural and synthetic pyrethrins are harmful to green lacewing (*Chrysoperla carnea*) and multicolored Asian lady beetle (*Harmonia axyridis*) (Huerta et al. 2003; Kraiss and Cullen 2008). Insecticidal soap is moderately lethal to first and third instars of *H. axyridis* (Kraiss and Cullen 2008). Another U.S. National Organic Program (NOP) compliant pesticide, sulfur, is moderately harmful to the predatory mite *Phytoseiid* sp. (James 2005) and harmful to *Trichogramma cacoeciae* (Grutzmacher et al. 2004). Frequent use of

Bacillus thuringiensis (Bt) on diamondback moth (*Plutella xylostella*) has resulted in resistance developing in that population (Liu et al. 1996). *Beauvaria*, a biocontrol agent with minimal non-target impact, is unfortunately very costly and requires frequent application.

A thorough review on developing sustainable pest management strategies against insect pests can be found in an article by Lewis et al. (1997). This article will again focus on some of the key sustainable pest management approaches.

4.1 *Enhancing High Biological Diversity and Promoting Natural Enemies of Insect Pests*

Intercropping cash crops with trap crops or insectary plants is compatible with the approaches on enhancing high biological diversity and promoting natural enemies of multiple pests. Insectary plants are plants that attract beneficial insects by providing nectar and pollen sources for many predatory insects (Cowgill et al. 1993; Lavandero et al. 2005; Hogg et al. 2011); and supplemental food for spiders (Taylor and Pfannenstiel 2008). Conventional farming practices that involve intensive tillage, monoculture, and extensive weed control, or even some innovative alternative farming practices such as high tunnel shade house crop production, hydroponic and aquaponic practices often lack the insectary plant resources beneficial to agroecosystems. Introducing insectary plants into these systems could be one approach to attract beneficial insect allies back into our farming systems.

Natural enemies of insect pests that are of interest to attract into agroecosystems to protect plants from insect transmitted viruses include hoverflies, various insect parasites or parasitoids (e.g. Tachinid fly, Trichogramma, Braconid wasp, etc.), lady beetles, lacewings, spiders, assassin bugs, minute pirate bugs, and ground beetles. Careful timing of the planting of insectary plants can help enhance population densities of predatory insects or insect parasitoids that could result in a reduction of insect transmitted viral diseases (Mandanhar et al. 2009).

Some criteria on selecting insectary plants include: (1) attractiveness to beneficial insects; (2) an early and long blooming period; (3) low potential to host plant viruses; (4) ability to out-compete weeds; (5) low potential to become a weed; (6) low attractiveness to pest species; and (7) low cost of seed and establishment (Hogg et al. 2011).

Families of plants commonly found to be attractive to various beneficial insects mentioned above include, but are not limited to, Apiacea (Umbelliferae), Astera-cea (Compositae), Lamiaceae and Fabaceae. Apiacea includes fennel (*Foeniculum vulgare*), dill (*Anethum graveolens*), cilantro or coriander (*Coriandrum sativum*), carrot (*Daucus carota* subsp. *sativus*), wild carrot or Queen Anne's-lace (*Daucus carota* subsp. *Carota*). These Apiacea are excellent insectary plants as they provide great numbers of tiny flowers required by parasitic wasps.

Asteracea known to be attractive to parasitoids include zinnia (*Zinnia peruviana*), creeping zinnia (*Sanvitalia speciosa*), marigold (*Tagetes* spp.), sunflower (*Helianthus annuus*), etc. These plants produce showy composite flowers that are

Table 2 Natural enemies of insect pests or beneficial arthropods and plants that attract them (insectary plants). (Wang 2012)

Beneficial arthropods	Insectary plants
Various parasitoids and predators	Fennel, dill, coriander (cilantro), parsley, carrot, wild carrot (Queen Anne's-lace), angelica, yarrow (milfoil), sow thistle, dandelion, zinnia, tansy, marigold, sunflowers
Predatory wasps, hoverflies	Sweet alyssum, buckwheat, mustard, Cuban oregano, sage, salvia, lavender, oregano, thyme, marjoram, perilla
Lady beetles	Dill, marigold, Mexican tea, morning glory, oleander, yarrow
Lacewing	Carrot, oleander, red cosmos, wild lettuce, tansy
Minute pirate bug	Carrot, Mexican tea, oleander, sunn hemp, cowpea
Ground beetles	Low-growing plants: thyme, rosemary, mint or mulches
Spider	Marigold, yellow-sweet clover, white clover

favorable for many parasitoids as well as predatory insects. Lamiaceae (mint family) includes many herbs such as basil (*Ocimum basilicum*), mint (*Mentha* spp.), rosemary (*Rosmarinus officinalis*), sage (*Salvia officinalis*), marjoram (*Origanum marjorana*), oregano (*Origanum vulgare*), thyme (*Thymus* spp.), lavender (*Lavandula spica*), and perilla (*Perilla frutescens*). These plants attract wasps, hoverflies and other beneficials. Planting these insectary plants may provide additional economic incentive for farmers to set aside land for harvestable herbs. In addition, low-growing Lamiaceae such as thyme, rosemary, or mint also provides shelter for ground beetles that are predators of insect pests or weed seeds. Among Fabaceae, sunn hemp (*Crotalaria juncea*), cowpea (*Vigna unguiculata*), white clover (*Trifolium repens*), and yellow sweet clover (*Melilotus officinalis*) are most commonly used as cover crops in Hawaii. White clover and yellow sweet clover has been documented to increase the abundance of spiders when planted as living mulch, intercropping with broccoli (Hooks and Johnson 2004). At the flowering stage, sunn hemp and cowpea increased numbers of beneficial insects such as the Trichogramma wasp and the minute pirate bug when planted as living mulch in corn fields (Manandhar, personal communication). In addition to serving as insectary plants, this plant family is the most favorable cover crop group as it fixes nitrogen, reducing the need for additional nitrogen inputs into the agroecosystem.

One factor to take into consideration when selecting for insectary plants, is the length of time needed for plants to reach blooming. Buckwheat (*Fagopyrum esculentum*) and mustard are early blooming plants, but their flowering period is short. On the other hand, wild arugula and tansy phacelia might take a longer time to bloom, but their flowering period lasts for a longer time (Hogg et al. 2011). Table 2 summarizes natural enemies of insect pests that are attracted to but not limited to these insectary plants.

Understanding the benefits of enhancing various beneficial organisms can provide incentive for farmers to incorporate cover cropping into their farmscapes. Many approaches to integrate cover cropping with cash crop production have already been practiced. These include planting cover crops as a (1) border crop or barrier crop, (2) living mulch intercropping with cash crop, (3) undersown ground cover in an orchard system, (4) pre-plant rotation crop followed by conservation tillage, i.e.

serve as surface mulch or organic mulch after mowing, crimping or natural die back of cover crop, (5) preplant cover crop followed by strip tilling, and clipping for surface mulch, and (6) trap crop. Farmers can select cover cropping practices based on target insect vectors, occurrence of beneficial organisms, and compatibility of the cover crop to their cash crop production practices.

Various research projects conducted in the tropics on the use of cover crops to manage insect transmitted viruses have shown promising results. Hooks et al. (1998) has demonstrated that intercropping buckwheat (*Fagopyrum esculentum*) with zucchini reduced population densities of whiteflies and aphids, thus reducing silver leaf symptoms and aphid transmitted viruses such as papaya ring spot virus on zucchini. They supported that this was partly due to the “virus sink theory” (Mandanhar and Hooks 2011) where insect vectors that transmitted non-persistent, non-propagative viruses lost the virus after visiting a border crop. In addition, cover crops could also provide niches for generalist-type of insect predators. For example, when sunn hemp or marigold (*Tagetes patula*) were intercropped with cucumber in a strip-till system as a living mulch followed by clipping to provide organic mulch (Wang et al. 2011), abundance of spiders in the agroecosystem were higher in these cover crop plots than cucumber planted in the bare ground plots.

4.2 *Stimulating Inherent Plant Defenses Against Insect Pests*

Plants grown with high levels of N supplements resulted in larger infestations of insect pests (Dixon 1969; House 1965). Conversely, inadequate N availability increased consumption rates of plant tissues by insects (Hamilton and Moran 1980). Radovich and Arancon (2011) suggested that vermicompost provides plants with balanced nutrients through gradual decomposition of organic matter and slower mineralization rates of nutrients, and could suppresses various insect pests and diseases in greenhouse and field conditions. Vermicomposts are produced by mesophilic decomposition and stabilization of organic matter by certain earthworms and microorganisms. Solid vermicompost produced significant suppression of mealy bug infestations (*Pseudococcus* sp.) on cucumbers and tomatoes, two-spotted spider mite attacks (*Tetranychus urticae*) on bush beans and eggplants, and aphids (*Myzus persicae*) on cabbages at low application rates (Arancon and Edwards 2004; Arancon et al. 2005a, b). Yardim et al. (2006) reported the suppression of tomato hornworms and cucumber beetles by solid vermicomposts.

When Radovich and Arancon (2011) applied food-waste based vermicompost water extract at 10 and 20% every week, they found that aphid populations on tomatoes and cucumbers decreased with time as compared to water control. Several mechanisms have been proposed to explain the pest resistance induced by vermicompost. Organic and inorganic nutrition affects plant growth such as the onset of senescence, lignification of the epidermal cells, increased sugar concentrations in the apoplasts, amino-N in phloem sap, and levels of secondary plant compounds (Patriquin et al. 1995). Water-soluble phenols in VCT extracted during the brewing have been proposed to be the most likely ingredients in VCT to contribute to insect

pest suppression (Arancon et al. 2004; Arancon and Edwards 2004). Several soil microorganisms associated with vermicompost including *Trichoderma hamatum*, *Pseudomonas fluorescens*, *P. putida*, *Xanthomonas maltophilia*, *Bacillus subtilis* etc. (Hoitink and Fahy 1986; Dowling et al. 1996; O'Sullivan and O'Gara 1992) have also been shown to induce ISR by secretion of hydrolytic enzymes (chitinase, protease, and β -1,3 glucanase).

5 Sustainable Pest Management Approaches Against Bacterial Pathogens

Given a highly susceptible host, a bacterial disease is nearly impossible to control with conventional methods. The task of using sustainable methods becomes even more challenging. The best method is to prevent introduction of the disease. This requires knowledge of the severe bacterial diseases of the crop being grown. Great efforts need to be made to purchase seeds and plants that are free of bacterial disease. For many horticultural crops, stocks that are free of bacterial (and other diseases) are available. Investment in these clean crops is worth the cost. Once the crop is contaminated, it is nearly impossible to significantly reduce the level of disease, especially in a tropical environment. In Hawaii, after the bacterial blight on anthurium entered the State, growers refused to discard diseased anthurium, and over 75% of the industry was lost. Thus, prevention is the best approach. For a few crops that are grown even with the bacterial pathogen present, options such as the following are available: growing the crop under solid cover while using minimal irrigation, use of drip systems and avoiding splash irrigation that wet the foliage. Applying copper sulfate (Phyton-27), copper hydroxide (Kocide, Champ), and other compounds that reduce bacterial reproduction and spread. In Florida, Actigard with mode of action to induce SAR provide leaf spot control on tomato but the crop yield was not increased. Sprays needed to be made weekly and begun early in the crop cycle (Vallad 2013; Vallad and Goodman 2004). Cool environments are not conducive to bacterial diseases. Any plant with resistance is also beneficial. Antibiotics can be applied but overall they are expensive. For bacterial diseases, a common sense approach using prevention, sanitation, dry environments, and clean stock are the best approaches.

6 Future Prospects of Sustainable Pest Management for Plant Diseases

The sustainable pest management approaches emphasized in this chapter focus on ecosystem management, induced host plant resistance, while finding alternatives to replace conventional therapeutic plant disease management approaches. The use of therapeutic approaches, whether biological, chemical, or physical, is not compatible with the five fundamental approaches for sustainable pest management. More

efforts should be devoted to developing farming practices that can: (1) enhance high biological diversity through polyculture instead of the conventional preference of the monoculture cropping system; (2) increase ecosystem community stability by promoting natural enemies of multiple pests and pathogens; (3) stimulate inherent plant defenses; (4) improve plant health by maintaining nutrient cycling and energy flow; and (5) target the vulnerable stage of pests or pathogens through the understanding of their ecology. Successful examples have been observed for each of the key plant pathogens that met these approaches. While there are more sustainable pest management approaches, this chapter only listed some that are known to be successful. An article on “Research on Plant Disease and Pest Management is Essential to Sustainable Agriculture” published by Cook et al. (1995) about two decades ago mentioned that while new technologies are needed, traditional methods for plant disease management need to be strengthened. Decades later, this statement still holds true. We now have more documentation on the importance of maintaining ecosystem biodiversity, sustaining the function and integrity of the soil food web, and ensuring the continuation of natural suppressiveness in our agroecosystems. Yet, more work remains to be done to reveal the nature of the myriad of interactions between pathogens and their antagonists, before biological control can be successful in managing targeted pathogens. The study of biological control of insect pests has provided much of the theory and principles available to understanding and predicting the predatory-prey relationships in the environment. To encourage biological control agents to be more widely used for plant pathogen management, sustainable approaches reviewed by Lewis et al. (1997) should be referenced. In addition, the study of plant disease management for sustainable agricultural systems should integrate with other disciplines. For example, information from the study of plant disease epidemics has provided much theory for predicting genotype changes of microorganisms. This could address the issues of constant resistance buildup of plant pathogens against pesticides or resistant cultivars. Research on a single disease in a monoculture system, or under artificial laboratory conditions is not applicable for sustainable crop production. Thus, future work should look into developing cultural practices that can be suppressive to multiple pathogens concurrently in an agroecosystem while protecting our environmental health, economic profitability, and social and economic equity.

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