Chapter 5
Plant-Parasitic Nematode Problems in Organic Agriculture

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Abstract Crop protection approaches differ widely among organic growers both globally and regionally, yet organic farming faces the same plant-parasitic nematode (PPN) issues as conventional farming. Due to the restrictions on use of synthetic chemical inputs and the limited number of options for nematode management in organic fields, organic producers are often at greater risk to nematode problems than their conventional counterparts. While worldwide estimates of crop losses of about 12 % annually of food and fiber due to nematode damage are reported in the literature, such information for organic farming systems is scarce. Comparative studies of organic and conventional farming systems and surveys conducted in organic farms in distinct regions show that the genera of nematodes attacking organic crops are similar to that in conventional fields, including species of root-knot (*Meloidogyne* spp.), cyst (*Heterodera* and *Globodera* spp.), and root lesion (*Pratylenchus* spp.) nematodes, among others. For PPN management, organic farmers employ practices such as crop rotation, use of cover crops or resistant crop cultivars, and soil amendments. In many instances, however, these methods may not be sufficient for PPN management. Although resistant cultivars of some crops are available for root-knot and cyst nematodes, they are resistant to only a few races or species of nematodes and new races develop over time. Biological control, using microbial pathogens, endophytes, or antagonists may help control PPNs in organic production of some crops but have had limited commercial success. In contrast, use of soil amendments has provided some level of suppression of PPNs under field conditions. Increased populations of predatory nematodes or other beneficial species grazing microbial films and stimulating soil nutrient mineralization have been observed in organic systems, indicating an improvement in the soil health. Further studies are needed to estimate yield losses caused by the

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economically important PPN species in organic systems and to develop suitable nematode management strategies given for organic farming.

Keywords Nematodes · Organic agriculture · Implications · Management

5.1 Introduction

Nematodes are unsegmented, bilaterally symmetric roundworms, usually microscopic in size in the phylum Nematoda. They are one of the most important and abundant groups of animals and are essentially aquatic, living in water, moisture films, or host tissues. Plant-parasitic nematodes (PPNs) are obligate parasites which feed mainly on plant roots with common aboveground symptoms of stunting, yellowing, wilting, and yield losses and belowground root malformation due to direct feeding damage. In general, nematode bodies taper toward both head and tail, but females of some of species may be pear, lemon, or kidney-shaped. All major food crops are damaged by at least one species of nematodes, and the economic consequences of nematode infestations are many and varied, reducing crop quality and yield (Norris et al. 2003; Agrios 2005). Feeding of many PPNs creates entryways into plant roots for secondary pathogens, while feeding of some species directly transmits plant viruses (Rowe and Powelson 2002).

Organic farming has increased significantly worldwide over the last several years and is expected to grow further (Moyniham 2010). Briefly, organic farming is a set of plant and animal production practices that emphasize reliance on sustainable and renewable biological processes. Nutrients are supplied through the decomposition of cover crops of nitrogen-fixing legumes or animal manures or products. Pest management relies on an integrated approach of promoting plant health, vegetation management, and biological control (van Bruggen and Semenov 2000; McSorley 2011a). No synthetic inputs (such as broad spectrum fumigants) are allowed, leaving soil biological activities intact while the incorporation of plant and animal-derived organic materials enhances the soil food web. Soil food webs of organic farming systems are generally more diverse in terms of species richness and abundance compared to conventional systems (Ferris et al. 2001; Mäder et al. 2002; Aude et al. 2004). Organic farming practices also affect the abundance of PPNs (Hallmann et al. 2007; Chen et al. 2012; Adam et al. 2013).

Limited information is available on PPN densities and their damage in organic farming systems. Therefore, to illustrate the potential for nematode damage and opportunities or constraints for their management in organic agriculture, we discuss studies comparing conventional and organic farming systems and surveys of organic farms in different geographic locations. Although the majority of comparative studies showed reduction in the number of PPNs in organic farming compared to conventional systems (Griffiths et al. 1994; Ferris et al. 1996), results differed among nematode species within studies. For example, higher population densities of plant-parasitic root lesion nematodes (*Pratylenchus* spp.) were observed in organic plots than conventional fields (Clark et al. 1998; Neher and Olsen 1999; Berkelmans et al. 2003). In another study, root-knot nematode populations increased under organic tomato production conditions (van Bruggen and Termorshuizen 2003). Recent surveys have found increased populations of several genera of PPNs in fields under organic production (Hallmann et al. 2007; Chen et al. 2012; Adam et al. 2013). These studies demonstrate that organic farming has plant-parasitic nematode problems the same as conventional farms and that under certain circumstances, organic farms may experience even higher nematode pest pressure compared to conventional production systems. Higher densities of weeds, use of legumes to enhance nutrients, and continuous cropping to prevent nutrient leaching on organic farms provide perpetual hosts for several potentially damaging groups of nematodes.

5.2 Plant-Parasitic Nematode Problems in Organic Agriculture

For detailed information on the important PPN species, worldwide crop losses from nematodes, and options for their management for general crop production, see Chen et al. (2004), Luc et al. (2005), Perry and Moens (2006), Perry et al. (2009), and Stirling (2014a). Broadly, PPNs are categorized into two groups based on their feeding strategies. Ectoparasitic nematodes feed on roots without entering the root tissue, while endoparasites undergo at least one stage of development inside the plant host. Symptoms of feeding of PPNs on plant roots can be confused with symptoms of nutrient or water deficiency. Aboveground symptoms of nematode damage include stunting, yellowing, wilting (Fig. 5.1), and yield loss, while belowground indicators are malformations of roots (Fig. 5.2) such as galls, lesions, and distortions depending upon the type of nematode specie. Several genera of PPNs including both ectoparasites and endoparasites are observed in fields under organic production (Chen et al. 2012; Hallmann et al. 2007; Adam et al. 2013). However, little attention is being paid to the detrimental effects of PPNs can cause to the organic cropping systems, and it is now that farmers have started to realize nematodes as being pests in their organic fields (Hallmann et al. 2007).

Here, we briefly review PPNs, concentrating on the most economically important species reported from organic farming systems. Additional species, not discussed here, may also cause losses to some organic crops. Nematodes of greatest importance in organic crops appear to be sedentary endoparasites in the family *Heteroderidae* including the cyst nematodes (e.g., species of *Heterodera* and *Globodera*) and root-knot nematodes (*Meloidogyne* spp.), and migratory endoparasites of family *Pratylenchidae* (*Pratylenchus* spp.). Cyst nematode species including soybean cyst, potato cyst, and cereal cyst nematodes causes huge crop

Fig. 5.1 Above ground symptoms of nematode damage: patchy and stunted growth of barley crop due to cereal cyst nematode infestation (*Courtesy* Shabeg Briar, CARC, Montana State University)

Fig. 5.2 Below ground symptoms of root nematode damage. Distorted tomato root system due to knot formation (*Courtesy* Jack Kelly Clark, Univ. of California Statewide IPM Program)

losses (Wrather and Koenning 2006; Mai 1977). Cyst nematode-infected plants may develop bushy roots system, and individual roots may have knotted appearance with several females at each knot. Root-knot nematode (*Meloidogyne* spp.) are economically important polyphagous obligate plant parasites, distributed worldwide, and are known to parasitize nearly every plant species of higher plants (Moens et al. 2009). As a result of feeding of root-knot nematode, small to large galls or "knots" can form throughout the root system of infected plants. In contrast, root lesion nematodes (*Pratylenchus* spp.) are migratory endoparasites and feed within the root system. They are distributed worldwide and have wider host ranges, and several species are reported to cause economic injury to the crop plants (Thompson et al. 1999). As the name implies, root lesion nematodes produce characteristic necrotic lesions (darkened areas of dead tissue) on the surface and throughout the cortex of infected roots.

5.3 Nematode Management: Options and Constraints for Organic Agriculture

Basic methods of nematode management are exclusion, eradication, and protection (Norris et al. 2003; Agrios 2005). The concept of integrated pest management relies on a combination of approaches with minimum or judicious use of synthetic pesticides. Plant protection in organic agriculture, however, relies primarily on creating a favorable ecological equilibrium among soil biota without the use of synthetic pesticides (Delate et al. 2003). Letourneau and van Bruggen (2006) outlined three basic approaches for pest management in organic crops, including preventing pest colonization, regulating the abundance of pests or pathogens at low levels through biological processes, and employing curative materials permitted in organic farming, through which crop protection is generally achievable.

Nematodes can only move very short distances and are therefore unable to spread from one field to another on their own. They are usually transported to other locations by farming machinery, in plant material, on animals, or by water or wind. Routine practices such as sanitation of farm equipment and clean planting material can prevent their spread. Crop rotation with non-hosts and planting time adjustments can prevent the colonization and establishment of PPNs. All these steps to prevent nematode spread and establishment are practiced in both organic and conventional farming systems. However, measures to prevent nematode entry into fields under organic production are more critical because of restrictions on the use of curative synthetic chemicals such as fumigants. Similar to other soil-borne pathogens, PPNs once introduced and established into the field are difficult to eradicate and their ongoing management will then be necessary. Among methods for nematode management, we discuss application of organic amendments, cover crops, crop rotation, nematode trap crops, antagonistic crops, and biological control.

5.3.1 Soil Organic Amendments

Application of animal and plant by-products into the soil is best known for crop management especially where synthetic inputs are not permitted. Although the primary reason for using soil amendments is to enhance nutrient supplement, increase organic matter levels, and improve soil structure, numerous amendments have been assessed and recommended for the management of PPNs (Akhtar and Alam 1993; Akhtar and Malik 2000; Oka 2010; Rodríguez-Kábana and Ivey 1986; Trivedi and Barker 1986). Organic amendments can be divided into two broad categories: (a) amendments that are cultivated in situ and are incorporated into the soil such as green manure, cover crops, or trap crops and (b) the amendments transported from elsewhere into the field such as composted animal manure and composted yard material or animal waste.

Several mechanisms have been proposed for the probable cause/s for nematode suppression using organic amendments and have been reviewed in detail by McSorley (2011a). The effects of amendments in general are accepted as indirectly causing the nematode suppression through enhanced activity of naturally occurring antagonists (such as bacteria, fungi, and predatory nematodes) (Akhtar and Malik 2000; Oka 2010). Various antagonistic fungi and bacteria have been observed in compost including species of *Trichoderma*, *Penicillium*, *Aspergillus*, *Bacillus*, *Pseudomonas*, *Pantoea*, and *Actinomycetes* (Hoitink and Boehm 1999) which help control soil-borne pathogens and PPNs (Sharon et al. 2001; Kluepfel et al. 2002; Mekete et al. 2009). Additionally, plant residues and other organic amendments such as composted animal manure may release nematicidal compounds such as ammonia directly lethal to nematodes (Oka 2010; Thoden et al. 2011; Rodríguez-Kábana and Ivey 1986; Rodriguez-Kabana et al. 1987).

5.3.1.1 Cover Crops

Cover crops and green manure crops (intended for soil incorporation prior to maturity) are grown between cash crop cycles primarily to improve soil fertility and soil structure and prevent soil from erosion. Various grassy and legumes as cover crops appear to suppress nematodes in soil, including the following cover crop/nematode combinations: (1) sun hemp (*Crotalaria juncea* L.)/root-knot nematode (*Meloidogyne incognita*) (Wang et al. 2004), (2) velvet bean (*Mucuna pruriens*)/root-knot nematode (*Meloidogyne incognita*) (Quénéhervé et al. 1998), (3) sorghum or Sudan grass (*Sorghum bicolor*, *S. sudanense*)/root-knot nematodes (*Meloidogyne* spp.) (McSorley et al. 1994), and (4) pearl millet (*Pennisetum glaucum*)/root lesion nematodes (*Pratylenchus* spp.) (Bélair et al. 2005). Some of the green manure cover crops have also been identified for their antagonistic or allelopathic effects on PPNs. For example, root exudates of marigold (*Tagetes* spp.) possess nematicidal properties and helped in the suppression of several genera of PPNs (Siddiqui and Alam 1987).

The selection of a cover crop in the rotational sequence depends on the economics and its adaptability to a specific region (McSorley 1998, 2011b). The best choice, however, would be a crop that is poor host or non-host for the PPNs prevalent in the field. Therefore, care should be taken in selecting a cover crop in organic farming, as a crop resistant to one species of nematode may be a good host for other type of nematode (McSorley et al. 1994). More often, cover crops are mechanically incorporated into the upper layers of the soil using heavy tillage operations thereby leaving negative impacts on the soil food web and especially detrimental to the disturbance of sensitive predatory organisms (Briar et al. 2007). An alternate would be to apply the amendments on the soil surface as mulches which may be less detrimental to soil food web and also help in the suppression of PPNs (Wang et al. 2008).

5.3.1.2 Animal Manures

Composted animal manure is one of the most popular organic amendments for soils. Poultry or livestock manure has been tested for nematode management (Nahar et al. 2006; Akhtar and Alam 1993; Akhtar and Malik 2000; Rodríguez-Kábana and Ivey 1986; Trivedi and Barker 1986). Numerous studies have found positive correlations between the addition of compost and suppression of PPNs including the economically important species such as root-knot and root lesion nematodes (e.g., Marull et al. 1997; LaMondia et al. 1999; McSorley and Gallaher 1994, 1995, 1996; Everts et al. 2006; Kaplan et al. 1992). The degree of nematode suppression, however, is variable depending upon factors such as the type of manure, application rate, and natural microflora in it (McSorley 2011a).

5.3.2 Crop Rotation and Other Cultural Practices

As described previously in this chapter, nematodes do not move long distance on their own and by reducing their population below the damaging levels may result in increased crop yield. Planting non-host crop in the rotation would remove food source for the PPNs and consequently decline in their population below the damaging levels (Rodríguez-Kábana and Ivey 1986; LaMondia 1999). However, the effectiveness of rotation in suppressing PPN population depends upon the type of the nematode specie/s present in the field, host range, and the duration of time pest nematode can survive in the field in the absence of the host (Halbrendt and LaMondia 2004). In general, for specialized host-specific plant-parasitic nematode (such as root-knot and cyst nematodes species) selection of non-host crop is relatively less difficult as compared to the nematode with a wider host range (such as root lesion nematode) (LaMondia 1999). Nevertheless, accurate identification of plant-parasitic nematode/s prevalent in the field would help in selecting a non-host crop and planning a long-term rotation with a focus on nematode management in organic farming.

Other cultural practices to prevent colonization and establishment of plant-parasitic nematodes such as sanitation, nematode-free vegetative-propagating materials, adjustment of planting time, and removal of host weeds are recommended for both organic and conventional agriculture. However, they are even more important for organic farming, because curative measures such as synthetic fumigant nematicides applications are restricted (Letourneau and van Bruggen 2006). Prophylactic measure such as nematode-free planting material, cleaning equipment, and quarantine measures would help in minimizing the chances of nematode entry into the field and further spread. Adjustment of planting date (early or late) to coincide with the conditions when the temperature is too low or too high for nematode infection and development has been shown to be effective method for nematode management in vegetable cropping systems (Bridge 1996). Soil solarization using transparent polyethylene sheets to trap solar heat is usually considered effective method in hot and arid climates. For example, solarization experiments in Israel and tropical India were helpful in suppressing population of root-knot, cyst, and root lesion nematodes (Oka et al. 2007; Sharma and Nene 1990). Trapping solar energy for raising soil temperature to the level detrimental to nematodes appears to be effective, and the only disadvantage would be that it may not be cost-effective and feasible for large-scale farming systems.

5.3.3 Host Plant Resistance

Host resistance is often the most cost-effective tool for nematode management for organic farming systems. Resistant plants are defined as those that support lower levels of nematode reproduction compared to susceptible plants (Roberts 2002; Cook and Starr 2006), and the extent of nematode-resistant crop varieties has been reviewed (e.g., Roberts and Ulloa 2010; Williamson and Roberts 2009; Starr and Roberts 2004; Starr et al. 2010). Progress has been made in identifying genes for resistance to the economically important nematode species (Williamson and Kumar 2006). These include the *Hs1pro-1* gene that provides resistance to the sugar beet cyst nematode (*Heterodera schachtii*), the *Mi* gene that affects several species of root-knot nematodes in *Meloidogyne*, and the *Gpa2* gene that confers resistance against some isolates of the potato cyst nematode (*Globodera pallida*) (Williamson 1998, 1999). Nematode-resistant plant carrying resistant genes is either characterized by a rapid localized cell death that occurs near the anterior end of the nematode in the region of the root where feeding site initiation occurs or neither the feeding site nor the nematode is able to progress to the next developmental stage (Branch et al. 2004; Williamson 1999).

Ideally, resistance should be broad in nature, affecting many nematode species. For instance, the *Mi* gene confers resistance against four species of root-knot nematode (Huang et al. 2006). Most genes for resistance, however, provide effective suppression against only single specie or even just particular race of plant-parasitic nematode (Williamson and Roberts 2009). The continual emergence of new and more virulent races of PPNs sometimes leads to failure of resistant crop varieties planted over a longer period of time. In some cases, resistance is sensitive to temperature. Resistant crops developed in a colder region may be susceptible to the same pest nematodes in warmer regions of the world (Williamson and Roberts 2009). Another constraint in choosing resistant cultivars for organic farming is that some of the commercially available nematode-resistant cultivars also possess a modified gene for herbicide tolerance and are therefore not permitted in organic agriculture. Chen et al. (2012) observed higher numbers of soybean cyst nematode in fields under organic production as compared to conventional fields where genetically modified cultivars resistant to soybean cyst nematode were planted. A system of integrated control with a rotation of resistant and non-resistant crop varieties to slow selection for new virulent races is recommended for different cropping systems where limited numbers of resistant cultivars are available, and this approach seems to be effective for organic farming as well. In addition, optimizing plant health with adequate nutrition helps sustain high plant productivity, while suppressing PPNs and maintaining efficacy of resistant cultivars over a longer period of time (Williamson and Roberts 2009).

5.3.4 Biological Control

Because organic growers do not, by definition, choose to use synthetic nematicides, they must maximize beneficial organisms in soils to help manage PPNs together with cultural practices. Curative biological control can sometimes be accomplished through inundative releases of selected biological control agents obtained from commercial suppliers (Stirling 2014c). Microbial pathogens, endophytes, and antagonists are important in the regulation of PPNs, independent of farming system (Kerry 1990; Siddiqui and Mahmood 1996, 1999; Morton et al. 2004; Hallmann et al. 2009; Stirling 2014c). However, the introduction of beneficial organisms to the soil for nematode management via augmentative biological control has had limited success (Sikora et al. 2008). There are few commercial biological control products for nematode management are available in the market that might be considered for use in organic farming. Biological control agents along with their advantages and disadvantages are discussed and enlisted recently by Hallmann et al. (2009) and Stirling (2014c).

5.3.4.1 Bacterial Pathogens and Antagonists

Several types of saprophytic bacteria that occur in the soil, rhizosphere (in the root zone), or endorhiza (inside roots) have been shown to be antagonistic to nematodes, with their unique modes of action. The most widely studied group of beneficial bacteria resides on the plant rhizosphere, and its members are commonly considered as plant growth-promoting rhizobacteria (PGPR). Some rhizobacteria are able to enter the root system, colonize, and become endophytic (Hallmann et al. 2001). Among the dominant genera (*Bacillus* and *Pseudomonas*), there are several species such as *Bacillus subtilis*, *B. sphaericus*, and *Pseudomonas flourescens* producing metabolites toxic to PPNs (Sikora 1992; Hallmann et al. 1999; Kloepper et al. 1991). A number of different mechanism have been proposed for nematode control by rhizobacteria including direct antagonism through release of nitrogenous compounds toxic to nematodes, induced systemic resistance, interference with plant–nematode recognition, and plant growth promotion. These mechanisms are reviewed in detail by Tian et al. (2007).

The Gram-positive obligate endoparasitic bacteria of the genus *Pasteuria* are parasites of all the economically important genera of PPNs. Different species of *Pasteuria* have been reported, which differ in their host ranges and pathogenicity against PPNs (Trudgill et al. 2000; Timper 2009). Among them, the most widely studied is *Pasteuria penetrans,* parasitic on root-knot nematodes (*Meloidogyne* spp.) (Sayre and Starr 1985; Stirling 2014c). This bacterium has been successfully mass produced either in vivo (on nematode hosts) or in vitro in quantities only suitable to add to small-size microplots or in pots for nematode control (Stirling 1984; Trudgill et al. 2000; Hewlett et al. 2004). Since high application rates of pasteuria-based products are necessary for achieving effective nematode control, it may still not be cost-effective to apply at large-scale cropping areas (Stirling 2014b).

5.3.4.2 Fungal Pathogens and Antagonists

A wide range of fungi are known to parasitize PPNs and possess the potential for biological control of nematodes (Kerry 1990; Stirling and Smith 1998; Kerry 2000; Sayre and Walter 1991; Kerry and Hominick 2002; Sikora et al. 2008; Stirling 2014c). In particular, important for the purpose of controlling PPNs are nematophagous fungi, which may be either obligate or facultative parasites. Obligate fungal parasites species such as *Catenaria auxilaris* and *Nematophthora gynophila* use their spores to initiate infection either by adhering to the body of the nematodes or by being ingested and then penetrating the gastrointestinal tract. These fungal species have been reported to parasitize cyst nematode (Kerry and Crump 1980, 1998). Facultative parasites grow saphrophytically in the soil and parasitize nematodes by either way of specialized adhesive spores or trapping structures such as knobs, rings, or net structures that trap nematodes and kill them. Important fungal species in this group include *Dactylella* spp., *Dactylaria candida*, *Arthrobotrys botryospora*, *Paeciliomyces liliacinus*, *Verticillium chlamydosporium*, and *Hirsutella rhossiliensis* have been studied further in detail and possess the potential to be developed into biological control products (Hallmann et al. 2009; Stirling 2014c).

Although considerable progress has been made in the area of inundative application of fungal organisms for nematode control, the number of biotic and abiotic factors still limits their effectiveness in the field. For example, the biggest constraint in using nematophagus fungi for biological control is the difficulty in overcoming the competition from other resident soil organisms (Stirling 2014c). Abiotic factors such as soil texture, moisture, nutrients, organic matter, and pH also affect their survival and establishment directly and indirectly after their application (Chen and Dickson 2004).

5.3.4.3 Plant-Parasitic and Entomopathogenic Nematode Interactions

A number of entomopathogenic nematodes (EPNs) species (e.g., *Steinernema carpocapsae*, *S. feltiae*, *S. riobraveare*, *Heterorhabditis bacteriophora*, *Xenorhabdus nematophilus*) are better known than PPNs and are widely used to manage insect pests in agro-ecosystems (Grewal et al. 2005). However, their use for the management of PPNs is controversial, and the ecology of their interactions with PPNs is still not fully understood (Lewis and Grewal 2005). Only a few studies have observed EPNs to be antagonistic to PPNs and to consequently suppress them under field or greenhouse conditions (Bird and Bird 1986; Ishibashi and Kondo 1986; Grewal et al. 1999). Possible mechanism responsible for the suppression of PPNs seems to be either the allelochemicals produced by the EPNs itself (Grewal et al. 1999) or the antagonistic effects that are from the bacterial symbiont of the EPNs (Samaliev et al. 2000). Other studies have observed little or no effect on the suppression of PPNs (LaMondia and Cowless 2002; Nyczepir et al. 2004). Currently, there seems to be little realistic potential to use EPNs to manage PPNs cost-effectively, and growers would not consider relying on this method, especially if they are applying them with the sole goal of achieving PPN management under field conditions.

5.4 Conclusions

Conditions such as no application of synthetic inputs, higher levels of weed infestation, cultivation of leguminous crops in rotation for nutrient management, and lack of vegetation-free periods necessary to prevent nutrient leaching may be contributing to higher levels of nematode buildup over a longer period of time (Hallmann et al. 2007). For disease management, organic farming relies on cultural practices that may not be sufficient for nematode management under certain circumstances. Resistant cultivars of selective crops are usually resistant to only a few races or species of nematodes and may not last long due to the development of new races over time. Moreover, some of the commercially available resistant cultivars also possess genetically modified genes against herbicides which preclude their use in organic agriculture. Biological control measures involving the use of microbial pathogens, endophytes, and antagonists may play an important role in nematode management in organic crop production, but have shown limited success in their management at a commercial level due to higher cost, and their application may not be yet feasible in large-scale farming systems. Therefore, the emphasis should be on the conservation and enhancement of the existing pool of biological control agents through farming practices that support the survival and reproduction of natural enemies of PPNs in the soil (Stirling 2014b). For example, the addition of organic amendments to the soil has been shown to have some level of suppression of PPNs under field conditions.

A combined approach is needed for nematode management in organic farming systems. Measures such as appropriate crop rotation with less susceptible crop species and green manure crops, soil amendments with antagonistic crops, and consistent weed control are effective when used in together in concert (Hallmann et al. 2007). Identification of prevalent PPN specie/s through nematode diagnostic services should be considered for choosing non-hosts before planning long-term crop rotation for organic farming. Additional research is needed most in the development of resistant cultivars suitable for organic farming, nematode-free vegetative-propagating materials, and further steps in commercialization of biological control products permitted in organic farming systems.

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