Chapter 4
Nematodes of Agricultural Importance in Indiana, Illinois, Iowa, Missouri and Ohio

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4.1 Agriculture in Indiana, Illinois, Iowa, Missouri and Ohio

These five states comprise portions of the southern part of the North Central Region of the U.S. They all are located at the southern portion of the Mississippi River Drainage Basin at surprisingly little elevation above sea level ranging from 200 to 300 m. Precipitation is distributed throughout the year allowing for efficient dryland farming on fertile soils that are largely glacially impacted in their origin. Except for Ohio, the states mostly receive summer rains, and total annual precipitation is declining from East to West. Agricultural production is focused on combine crops, foremost soybean, *Glycine max*, and corn, *Zea mays* (Table 4.1).

Indiana, Illinois, Iowa, Missouri and Ohio constitute the central part of the "corn belt" of the United States. Soybean and corn occupy large proportions of the entire acreage, and remaining lands are used for wheat, vegetable production, and minor areas for crops like fruit trees and vines. Based on this production pattern and climatic conditions of medium hard winters and mostly rainy summers, plant parasitic nematodes of the major crops are of greatest concern. The production emphasis on the two large-area combine crops results in narrow crop rotations, and market forces partially lead to monoculture cropping. Although plant parasitic nematodes are recognized in corn, foremost *Pratylenchus* sp. (Norton 1984), more attention is afforded for nematode problems in soybean. Production conditions are characterized by

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S. A. Subbotin, J. J. Chitambar (eds.), *Plant Parasitic Nematodes in Sustainable Agriculture of North America*, Sustainability in Plant and Crop Protection,
https://doi.org/10.1007/978-3-319-99588-5_4

Table 4.1 Acreage of the large acre crops of Illinois, Indiana, Iowa, Missouri and Ohio in 2017 (in 1000,000 hectare)

State	Soybean	Corn
Illinois	4.3	4.5
Indiana	2.4	2.2
Iowa	4.0	5.4
Missouri	2.4	1.4
Ohio	2.1	1.4

https://quickstats.nass.usda.gov

maturity grouping of the crops. Flower induction is day length sensitive in soybean, limiting the cultivar pool to the maturity groups capable of producing high yields in this area. Similar restrictions apply for corn cultivars that are also limited by maturity groupings fitting in particular areas. To some extent, genetic resources are confined within these maturity groupings and are not easily exchanged with other production areas. This biological background increases the challenge of providing new cultivars fit for production in these states quickly and frequently.

4.2 Plant Parasitic Nematodes

4.2.1 Soybean Cyst Nematode, Heterodera glycines

In this region, the by-far most damaging and costly nematode parasite is the soybean cyst nematode (SCN), *Heterodera glycines* (Tylka and Marett 2017) (Fig. 4.1). While it is not fully understood if one or several introductions of the nematode to the U.S. occurred, one of the hypotheses includes the following: When soybean seed was first introduced to the U.S., plants lacked vigor and performance. To overcome this growth depression, soil was introduced from Asia, e.g. Japan where soybean had been cultivated and vigorously produced. The expected benefits and reasoning for this practice were strictly empirical at the time. Plants just performed more vigorously when amending fields with imported soil. From today's view, the material, probably unbeknownst, transferred rhizobium bacteria for the critical legume nodulation. This group of bacteria forms a symbiosis with the plants, in that the bacteria benefit from the plant host by obtaining photosynthates for nourishment while mineralizing atmospheric nitrogen that the plant can use for its growth. Using such type of soil amendments became standard practice to increase yields. Ignorant of other possible soil-borne culprits, the story goes that the soybean cyst nematode was also introduced with such inoculum soil. But the first official report of soybean cyst nematode in the U.S. was made in 1954 in North Carolina in a field where soybean was grown after several years of growing flower bulbs of planting material imported from Japan (Winstead et al. 1955). The current consensus is that the soybean cyst nematode has continuously spread throughout soybean production areas while early after its discovery, some discussions persisted that the nematode would be endemic to the U.S. (Noel 1992).

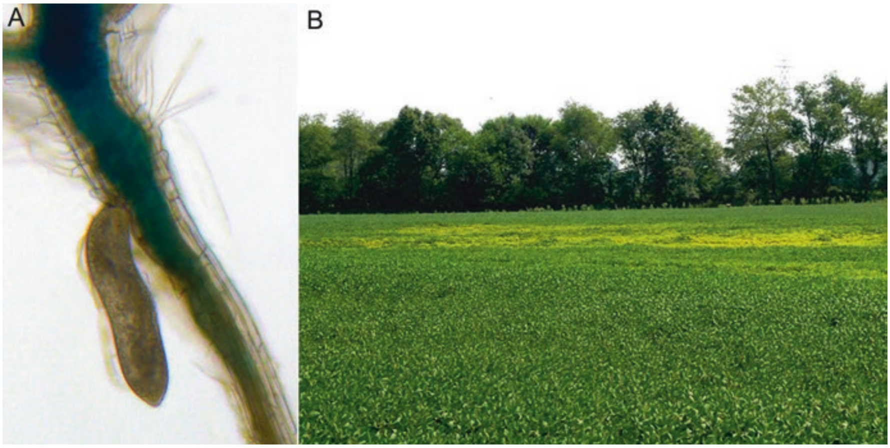

Fig. 4.1 (**a**) Plant root infected with soybean cyst nematode; note the vascular swelling of the developing nematode feeding site (syncytium) (Credit: Xiaoli Guo, Division of Plant Sciences and Bond Life Sciences Center, University of Missouri). (**b**) Field view of a soybean field with patches of yellow and stunted soybean caused by soybean cyst nematode (Credit: Purdue University)

Surveys in the different states, confirmed the wide distribution of SCN in Missouri, (Niblack et al. 1994) and Ohio (Riedel and Golden 1988), however, its spread throughout the region is now fully recognized (Niblack 2005). For years, collaborative efforts of nematologists, extension specialists and others in the respective states have documented its spread and damage potential. Over the years, the soybean cyst nematode has excelled in being one of the most important plant pests of soybean on an annual basis (Allen et al. 2017; Koenning and Wrather 2010; Wrather and Koenning 2009).

A soil-borne problem like soybean cyst nematode requires multiple management approaches (Niblack 2005). Utility of some practices may be reduced because of environmental/climatic conditions and economic forces. In the here-covered states, economic returns of the soybean and corn crops clearly favor their production over alternative crops. The most effective vegetation period from April to September is used for growing these cash crops, thereby minimizing opportunities for alternative or cover crops.

Based on these production constraints and interactions with other soil-borne maladies, a strong research focus is on the development of resistant soybean germplasm, and the search continues (Arelli et al. 2015). Crop rotation and cover cropping are investigated along with clean field strategies, and so involve removal of alternate hosts during the soybean crop and outside the vegetation period of the cash crop. The use of naturally occurring nematode population density regulation has received noteworthy attention, but further comprehensive studies are indicated to implement their use. Chemical seed and in-furrow treatments find interest but are limited because of the typically small margins of the return to investment for such strategies. In detail the following aspects are discussed:

4.2.1.1 Interactions of *Heterodera glycines* with Soil-Borne Fungi on Soybean

In the 1990s, the new symptomology of the so-called "sudden death syndrome" (SDS) of soybean was observed in soybean fields. Depending on the epidemiology, symptoms are most often observed after onset of reproductive stages. The etiology was traced to *Fusarium virguliforme* (Aoki et al. 2003), formerly *F. solani* f. sp. *glycines* (Roy et al. 1997). SDS typically occurs at the beginning of reproductive stages of the soybean crop and is evidenced in the field as varying areas of premature defoliation. Single leaves initially have interveinal chlorosis and later necrosis before these toxin-induced symptoms result in leaf abortion (Westphal et al. 2008). Early in the discovery of the disease the interrelationship of the fungal pathogen with *H. glycines* was discovered (McLean and Lawrence 1993). This interrelationship was later described as a truly synergistic disease complex (Xing and Westphal 2013). In contrast to nematode damage that can be conspicuous and allow for apparently normal growth but severely reduced yields, SDS symptoms are obvious and trigger "catastrophic" fears when plants in infected fields rapidly and prematurely defoliate (Westphal et al. 2008). Though yield losses can be extreme, they may not be as large as the symptomology suggests if the disease is occurring late in the season. A similar interactive disease complex was also described for *H. glycines* and *Phialophora gregata* in the development of brown stem rot (Tabor et al. 2003). If the diseases are likely to occur in the same region, proper diagnostic is essential to take the proper remedial actions (Tabor et al. 2018).

4.2.1.2 Host Plant Resistance Including Considerations for Virulence Differences of *Heterodera glycines*

Use of host plant resistance against *H. glycines* has been recognized as one of the key options in managing these soil-dwelling worms. Large efforts have been made to find sources of resistance to this parasite. This resulted in the discovery of several resistant sources. Challenges remained because host plant resistance was detected in soybean lines with otherwise undesirable agronomic characteristics. For example, the seed color was dark in some of the lines, or the plant lacked overall vigor. This required additional back-crossing efforts to high yielding soybean lines. This lengthy process was only partially overcome, and initially resistant cultivars experienced the so-called "yield drag". A phenomenon described as yield inferiority of a resistant cultivar compared to the susceptible high-yield cultivar under non-infested conditions. Experimentally, this can be demonstrated when *H. glycines*-resistant and susceptible cultivars are exposed to different nematode infestation levels (Koenning 2000). This characteristic of early resistant cultivars slowed adoption of the resistant cultivars.

Shortly after the introduction of resistant lines, occasional failures under *H. glycines*-infested conditions were observed. Plant damage and nematode reproduction were detected in single fields while the same cultivars fared well in other infested fields. This led to the hypothesis that *H. glycines* populations vary in virulence. It became obvious that this variability was encumbering the utility of the new resistant cultivars. Thus, a system for capturing this variability was developed. Initially, a race system was developed that used arbitrary classification schemes of nematode reproduction on resistance sources of soybean (Riggs and Schmitt 1988). Nematode reproduction was measured on the resistant lines and compared to a susceptible standard. An arbitrary 10% reproduction compared to reproduction on the susceptible was used as cut-off for calling the nematode-host plant interaction resistant. Based on such classification, a race was assigned to specific nematode populations (Riggs and Schmitt 1988). Because it was difficult to quickly translate the race information into useful information for cultivar choice, and because of other shortcomings of the system due to the high variability of nematode reproduction, an improved classification system was needed. In the HG-type system, population notifications were greatly improved (Niblack 1992b). For example, the indexing gives unambiguous notification on what resistance source a population of *H. glycines* can overcome, and the seed description clearly indicates the utility of the cultivar. In this latter system, similar classification cut-offs are used but the index gives a direct lead to what sources of resistance are ineffective against certain field populations (Niblack et al. 2002). Both classification systems were first introduced to describe field populations for pure biological observations, but especially the modernized system does allow for guidance in the cultivar choice when the soybean cyst nematode is present in specific fields. These very practical considerations also feed back into the development of new genetic resources to generate broader breeding strategies. For example, the generation of broader germplasm has been reported to allow for efficient future selection efforts (Cianzio et al. 2018)

Knowledge of the specific virulence pattern of *H. glycines* is important because this nematode is not only spread in different virulence groups but can also change its virulence pattern when observed over periods of decades. For example, resistance in the source PI88788 has been excessively used for generating soybean cultivars with resistance to *H. glycines* while few other sources were used for decades (Tylka 2017). In a comparison of virulence patterns of *H. glycines* of historical data and those of the early 2000s, populations had changed in their capacity to infect soybean lines with resistance derived from PI88788 (Niblack et al. 2008). This observation, confirmed in Missouri (Howland et al. 2016) and Iowa (McCarville et al. 2017), illustrated the need to use different sources of resistance, and that the simple recommendation to at least rotate the resistant cultivars. Even if alternate cultivars were based on the same PI88788 resistance, thus probably insufficient to avoid the selection pressure for higher virulence on this resistance source, some benefit of the supporting genetics was surmised. Hypothetically, this overuse of one resistance source on large areas of nematode populations favored nematode populations of virulence patterns that can overcome the resistance of PI88788 (Niblack et al. 2008). Other resistance sources have more side-effects possibly of less agronomically desirable traits. The soybean line ‘Hartwig’ derived from PI437654 has high levels of resistance to multiple *H. glycines* populations (Anand 1992). Careful breeding experiments of Hartwig with the highly susceptible

‘Williams 82’ coupled with molecular work, identified molecular markers (Faghihi et al. 1995), and methods for molecular tracing during breeding have been patented (Vierling et al. 2000). The promise of these lines is the lack of undesirable traits not being transferred during the breeding efforts. Lines developed with this technology were marketed as CystX cultivars. Success of this technology is still evaluated.

Great hope is set on understanding the infection process more comprehensively, and to find novel ways to interfere with the infection process. A recent summary has been given on respective improvements of understanding the infection process of *H. glycines,* and other sedentary plant parasitic nematodes could contribute in the long-term to improve methods for nematode management (Hewezi and Baum 2017).

4.2.1.3 Cultural Methods for Managing *Heterodera glycines*

Host plant resistance is one of the cornerstones of management of *Heterodera glycines*. Use of crop rotation and cover cropping has received some attention. In many areas of these states, options for crop rotations are minimal because soybean and corn comprise the majority of the acreage. A rotation to the non-host corn is aimed at taking advantage of the natural decline of the population densities when reproduction cannot occur. Presumably, spontaneous hatch and the reduction by natural enemies reduces the population densities of *H. glycines*. Unless the soil has extraordinarily high activity of nematode antagonist (see discussion below on nematode suppressive soil) these decline rates are often insufficient to reduce nematode population densities below economic threshold levels. One or 2 years of corn are insufficient to reduce nematode population densities below threshold levels (Tylka 2016). Accordingly, a rotation scheme of rotating resistant soybean with corn, then a susceptible soybean, again corn, and then back to resistant soybean has been proposed. Anecdotally, the resistant soybean reduces the population densities together with the 1 year of the non-host corn to protect the high-yielding susceptible cultivar. It is surmised that the interspersing of the susceptible line reduces the selection pressure on the nematode population thereby preserving the desirable resistance characteristic. This is a wide-spread recommendation though with little data foundation. Some benefit for production has been documented where winter wheat can be produced and harvested early enough to allow for a soybean crop right after wheat harvest. While this “double-cropping” is a strategy mostly feasible in the southern counties of the respective states, it appears that the incidence of SDS is reduced and the per-acre productivity increase (Von Qualen et al. 1989).

Because changes to the overwhelming crop rotation of alternating soybean with corn annually are difficult to implement, other agronomic practices have found research interest. For example, the use of cover crops that may have benefits for the cropping system. A co-cropping was employed to overcome the challenges of limited growing periods outside the production cycle of the cash crops (Chen et al. 2006). Winter covers may have potential but options are limited for specific cover crop species in the northern counties of the states after harvest of the soybean or corn crop after the middle of September (Villamil et al. 2006). In concert with using plantings of potentially nematode-antagonistic plants, the avoidance in permitting volunteer vegetation as alternate hosts has been intensively studied in multiple states. Reports of very high reproductive rates of *H. glycines* under controlled greenhouse conditions (Venkatesh et al. 2000), and the positive confirmation of reproduction of *H. glycines* on fall volunteer purple henbit (Creech et al. 2007) illustrated the interest in these plants, and subsequently, a variety of greenhouse, field and microplot experiments were conducted to investigate the role of this volunteer vegetation (Wong and Tylka 1994). Even after several years of differential weed control, no differences of nematode population densities were found (Mock et al. 2012). In summary, these projects demonstrated that not field hygiene, though important in preventing transfer of infested soil from infested fields into non-infested fields, but weed management in the fallow period for nematode management strategies, often plays a minor role.

In large-acre crops, tillage is another obvious agronomic practice that could be altered if it was beneficial to the production strategy. Minimum, and especially no-tillage practices have shown potential to suppress population increases of *H. glycines* (Westphal et al. 2009). But multiple factors go into decisions of tillage operations. Even within the five states, agroecological conditions may vary sufficiently to modify how tillage intensity affects nematode population densities and other soil-borne pests and diseases. For example, no-tillage was foremost beneficial to reduce *H. glycines* population densities in Indiana but was detrimental in Southern Illinois where no-tillage increased the severity of SDS. One is to speculate that the winter freezes in the north impact the soil edaphon differently than the constantly non-frozen conditions in the southern counties of Illinois. So, careful implementation at the area of interest is indicated.

4.2.1.4 Biological, Chemical Control and Suppressive Soils for Managing *Heterodera glycines*

Cyst nematodes persist in the soil for many years before the contents of the dead but protective female body are depleted. During this time, the cysts plus content are exposed to a multitude of soil organisms that can feed on them. Early work by Carris and Glawe has accumulated a wonderful pictorial account of fungi found in these nematode propagules (Carris and Glawe 1989). Similarly, work in Arkansas had found a sterile hyphomycete fungus that later was found to be related to *Dactylella oviparasitica*, a very effective female parasite of *H. schachtii* which is a close relative of *H. glycines* (Kim et al. 1998; Yang et al. 2012). Because of the large-acre set-up of these crops, the interest of studying suppressive soils has constantly increased. There are various forms of soil suppressiveness of which the most studied is "… where a pathogen establishes at first, causes damage, and then diminishes with continued culture of the crop" (Cook and Baker 1983). Hypothetically, this type of suppressiveness is microbially incited, and thus it may be possible to manipulate the soil environment for evolution of this natural population density regulation. In studies in Indiana, such soil suppressiveness developed in random fields that had come out of soybean-corn rotations when they were mono-cultured to susceptible soybean (Westphal and Xing 2011). Comparisons were made between non-treated and methyl-bromide fumigated plots both infested with the SDS pathogen. Over the time course of 5 years, *H. glycines* populations increased several-fold in pre-plant fumigated plots and remained low in the non-treated plots illustrating some biological reduction of nematode reproduction and concomitant reduction of SDS severity. In these field experiments, SDS also was suppressed. The suppressive phenomenon only developed when at least *H. glycines* was naturally present at initiation of the experiment. In such growing contexts, nematode population densities probably were kept low by microbial antagonists. A program in the neighboring State of Minnesota has examined microbial effects and tested the effects of tillage and crop sequence on the dynamics of soil suppressiveness (Chen 2007). Unfortunately, these early studies were not followed up thoroughly, and the use of novel sequencing approaches to describe the soil microbiome was only initiated a decade later and at rather random patterns (Srour et al. 2017).

In studies at the University of Illinois, the obligate nematode parasite *Pasteuria nishizawae* was discovered under soybean monoculture. Transfer studies with soil provided the proof of concept that this bacterial nematode parasite was effectively reducing cyst nematode population densities (Atibalentja et al. 1998). This obligate bacterial nematode parasite was successfully grown in culture in the early 2000s, and subsequently commercialized. This allowed developing *P. nishizawae* into a biological seed treatment. Based on the expense and the biology of the nematode and the bacterium, seed treatments have been the preferred choice (Anon 2018). Other control options rely on seed treatments with Avicta (abamectin), Votivo (a mixture of a chemical and *Bacillus firmus*), and Clariva (*P. nishizawae*) (Tylka 2016). Older chemistries of in-furrow treatments have mostly left the market place partially because of regulation.

4.2.2 Root Knot Nematodes, Meloidogyne *spp.*

4.2.2.1 Root Knot Nematodes *Meloidogyne* Species on Soybean and Corn

Root knot nematodes (RKN) have a much broader host range than soybean cyst nematodes, suggesting that much greater problems could be expected to occur in the States of Indiana, Illinois, Iowa, Missouri and Ohio (Fig. 4.2). At the same time, root knot nematodes cause more prevalent damage in sandy soils. There is good evidence that *Meloidogyne* spp. prefer pore spaces provided by such soil texture. Many soils of this region are fine-textured and may, for that reason, be less prone for root knot nematode infestations. Although corn and soybean are hosts for different *Meloidogyne* spp., reports on RKN problems in soybean and corn in the five states are rare. The species of *Meloidogyne* in these states is probably *M. incognita*. Because of the overwhelming importance of soybean cyst nematode, only few deep-going surveys have been conducted to see if other species also occur. Just a few surveys have been conducted in Illinois and Indiana (Allen et al. 2005; Kruger et al.

Fig. 4.2 Soybean infected with root knot nematodes. Note the infestation hot spot surrounded by more vigorously growing soybean

2007) in contrast to challenges with RKN in southern states, e.g., Georgia, where large screening efforts of soybean lines were established for years and new sources for resistance were identified (Harris et al. 2003). More recent work demonstrated the damage potential on corn in southern states (Bowen et al. 2008). Against previous general perception of monocot plants being poor hosts to RKN species, corn can be a supportive host of RKN. Maybe because of its hybrid vigor and confusion with other soil-borne issues, RKN are rarely diagnosed. As both soybean and corn are hosts for RKN but rarely examined for their responses, problems can occur when these field crops are cropped in rotation with vegetable crops. Such problems were frequently observed in Southern Indiana where rotations of corn, soybean, and watermelon are frequent, and more comprehensive evaluations of crop sequences are necessary when the valuable cash crop is to be grown in a Midwest crop sequence where soybean and corn may be susceptible to root knot nematodes (Westphal 2011). In the southwest of Indiana, a defined area of sandy soil is used for specialized vegetable production. Foremost, watermelon is the crop of choice in this area. In this region *Meloidogyne* spp. were easily detected in a survey (Kruger et al. 2007). Choice of resistant cultivars of soybean (Kruger et al. 2008) was proposed as a mitigation strategy in rotations with watermelons where all current cultivars are susceptible and sensitive to RKN infection.

4.2.2.2 *Meloidogyne* spp. on Vegetable Crops

In vegetable crops, because of the higher per acre crop value, chemical remedies are used against the soil-dwelling culprits. For example, soil fumigation is often used in preparation of watermelon plantings. The unstable weather typical for this area of the Midwest can make such applications challenging, and has led to variable results when cool and wet soils are treated with 1,3-dichloropropene (1,3-D). After the loss or use restrictions of carbamates and organophosphate resulting from the Food Quality Protection Act (FQPA), novel chemistries are just slowly gaining registration in vegetable crops. These new chemistries have very different modes of action for suppressing nematodes, but are much less toxic to the user and the environment.

Cover cropping against root knot nematodes was of some success in Europe. There, similar strategies for the management of the sugar beet cyst nematode are implemented. In these systems, the nematodes are attracted to the host plant roots. They penetrate these roots, and then fail to reproduce if the host plant is resistant to the particular nematode species. The cover crop serves as a trap crop because this process leads to active reduction of the nematode population density. Cultivar choice is critical to ensure the reduction of nematode numbers versus an unwanted increase of population densities if the nematodes were to reproduce on the cover crop. Cover cropping of nematode-reducing plants in Midwest vegetable production has not been widely adopted, and instead the moderately supportive host rye is often grown in non-crop periods. When planted in fall, this cereal crop is used for erosion control during winter and left as windbreaks when the majority of the field is prepared for watermelon seedbeds. Investigations have demonstrated the risk for nematode increases under this cover crop, resulting in a treatment need that potentially could be avoided by cover cropping with nematode-resistant plant species (Westphal et al. 2006).

4.2.3 Root Lesion Nematodes, **Pratylenchus** *spp.*

Lesion nematodes are more often a problem on perennial plants, both woody and herbaceous. Several *Pratylenchus* species occur in the five states: *Pratylenchus penetrans, P. alleni, P. crenatus, P. hexincisus, P. neglectus* and *P. scribneri* (Brown et al. 1980; Anon 1999). More than 50% samples collected in Ohio contained *Pratylenchus* spp. (Wilson and Walker 1961). Over 80% of the corn and soybean fields sampled in Ohio are infested with lesion nematodes. *Pratylenchus penetrans* is most often found in nurseries, orchards, and strawberry fields in Illinois. In the Eastern United States, *P. penetrans* has been responsible for severe decline and replant failure in many cherry, apple, and peach orchards, and is one of the most common species of plant parasitic nematodes found on corn in the United States. *Pratylenchus penetrans* can affect the host directly or through interactions with other organisms in disease complexes such as those involving fungi, including *Fusarium* spp., *Rhizoctonia solani*, *Verticillium albo-atrum* and *Verticillium dahliae*. The two other *Pratylenchus, P. hexincisus* and *P. scribneri* are also commonly associated with field crops in Illinois. *Pratylenchus scribneri* also caused yield losses of potato in Ohio (Wheeler and Riedel 1994). These two species often occur in mixed populations and have been associated with damage and yield loss in corn and soybeans. Host suitability studies indicated that corn and potato were good hosts for both *Pratylenchus* species, whereas alfalfa and red clover were non-hosts. Wheat and rye were better hosts for *P. hexincisus* than *P. scribneri*, whereas sorghum, soybean, tomato and white clover were better hosts for *P. scribneri* (Anon 1999).

For the management of root lesion nematode, several procedures have been recommended. (i) Maintain optimum growing conditions. The greatest damage by lesion nematodes occurs to plants under stress. (ii) Crop rotation. Despite the wide range of hosts for lesion nematodes, crop rotation can provide control in some instances. The use of crop rotation depends on the species involved and the economic feasibility of such rotations. (iii) Treat propagation material with heat. A hot water treatment is an effective method of eradicating lesion nematodes from the roots of transplants. Temperatures of 45–55 °C sustained for 10–30 min are commonly used. Before making a large-scale treatment, treat several plants of each variety to make sure that heat damage will be, at most, minimal. (iv) Treat the soil with dry or moist heat. Nematodes are killed by exposure to temperatures of 40–52 °C, depending on the species. Aerated steam is the most efficient method but baking small quantities of soil in an oven at 82 °C for 30 min or 71 °C for 60 min is also effective, especially for the homeowner who needs a small quantity of soil. (v) Apply nematicides. The use of chemical fumigants to control lesion nematodes can be effective and economical, especially where high-value crops are involved. Preplant fumigation with nematicides may be necessary in order to control replant and other lesion nematode diseases in orchards, nurseries, strawberry beds and other areas (Anon 1999). Seed treatments containing the nematicide abamectin in combination with fungicides can also reduce root infection by root lesion nematodes (da Silva et al. 2016).

4.2.4 Foliar Nematode, Aphelenchoides fragariae

Foliar nematode causes serious damage to alfalfa, strawberries, *Lamium*, and many ornamentals in nursery and landscape enviroments and during the last decades, has emerged as an important pest of hosta and ornamentals in North America (Jagdale and Grewal 2002). In the United States, the cultivation and production of hosta is a multimillion-dollar industry and nurseries grow and sell over 1000 selections representing 10 different hosta species and their hybrids (Grewal and Jagdale 2001). As hosta foliage offers a variety of leaf shapes, textures and colors, there is a growing concern among growers and nursery managers about leaf damage caused by foliar nematodes. This nematode was found in many nurseries in Ohio and Illinois (Noel and White 1994; Grewal and Jagdale 2001). Many studies on the biology and management of this nematode have been made in Ohio by Heinlein (1982), Grewal and Jagdale (2001), Jagdale and Grewal (2002, 2004, 2006), An et al. (2017). These nematodes infect young leaves through stomata and feed on the mesophyll cells, causing large sections of the leaf to become chlorotic and subsequently turn necrotic.

The necrotic lesions are usually bounded by large veins. In the Midwest, typical symptoms of foliar nematodes on hosta can first be observed in July (Grewal and Jagdale 2001). Jagdale and Grewal (2006) showed that foliar nematode overwinters as juveniles and adults, but not as eggs in soil, dry infected leaves, and dormant crowns, but not in the roots. These authors also revealed that survival of *A. fragariae* in soil and dormant buds was influenced by the location of plants. It has been found that higher numbers of nematodes survived in soil collected from a polyhouse than those collected from plants held under polythene cover or plants in the bare ground in a home garden.

Control of foliar nematodes has been problematic as most of the standard chemical nematicides have been banned by the United States Environmental Protection Agency (US EPA) under the implementation of FQPA. Some effective nematicides and fumigants including methyl bromide have been phased out due to their broad spectrum toxicity and the threat to the degradation of the ozone layer (An et al. 2017). Use of hot water as a preventive treatment to manage foliar nematodes may provide an environmentally safe alternative to nematicides. Jagdale and Grewal (2004) evaluated the effects of hot and boiling water on growth parameters of hosta and ferns and concluded that the application of a 90 °C water drench as a preventive treatment in autumn or spring could prove effective in reducing foliar nematode infection of hosta without affecting plant vigor.

Many efforts have been made to search for alternative products for management of foliar nematodes affecting ornamental and horticultural plants. Jagdale and Grewal (2002) tested a biological agent, *Pseudomonas cepacia*, two plant products (clove extract and Nimbecidine) and twelve chemical pesticides for the control of *A. fragariae*. They found that only diazinon EC, trichlorfon SP, oxamyl GR and ZeroTol™ were effective in reducing nematode population in soil and leaves. However, diazinon EC, trichlorfon SP and oxamyl GR were banned by the US Environmental Protection Agency. ZeroTol™ was therefore suggested as a useful product for managing foliar nematodes in soil, however, it did not provide acceptable levels of control in the leaves because of limited contact with nematodes and its short persistence (Jagdale and Grewal 2002).

An et al. (2017) used a three-stage approach to evaluate 24 products for their potential to control foliar nematodes *Aphelenchoides fragariae* in hosta. Out of the 24 products screened, Pylon (24% chlorfenapyr) and Nemakill (32% cinnamon oil, 8% clove oil, 15% thyme oil mixture) showed the highest nematicidal activity against foliar nematodes in the aqueous suspension, soil drench, and leaf-disc spray assays even at the low concentrations (20-fold dilution) tested. These two products were significantly more effective than ZeroTol™ in the leaf disc assays. There was no evidence of phytotoxicity from Pylon and Nemakill regardless of being applied through spray or soil drench. The authors concluded that these two products have potential for foliar nematode management and can be recommended for further field evaluations.

4.2.5 *Stem and Bulb Nematode,* **Ditylenchus dipsaci**

An infestation of the stem nematode was discovered in onion fields in Cook County, Illinois, in 1954 (Edwards and Taylor 1963). It has been demonstrated that snap bean, soybean, pea and tomato were excellent and good host for this nematode. Weed hosts may also be of importance in survival of *D. dipsaci* in the field. Of the weeds demonstrated to be capable of functioning as hosts in this study, *Hibiscus trionum, Solanum nigrum*, and *Polygonum persicaria* were observed to be infected with *D. dipsaci* in infested onion fields. The stem nematode is also a key pest of garlic. Although garlic is not a major crop in Ohio, this crop is grown in diversified vegetable production systems. In July 2013, diseased garlic bulbs were received from a grower in Lorain County, OH, from a field with wide symptom distribution. Bulbs were discolored, exhibited splitting, and had basal plate damage including reduced roots. Nematodes were extracted for examination by placing bulb slices in water (Testen et al. 2014).

4.2.6 *Needle Nematode,* **Longidorus breviannulatus**

Longidorus breviannulatus is one of the most damaging nematodes in corn in highly sandy soils (Malek et al. 1980). It causes root pruning of seedlings resulting in severe stunting and greatly reduced yields. The nematode has been found in most sandy fields examined in the central and southwestern counties of Iowa where corn has been grown continuously for a few years (Norton 1989). This species was also detected in association with the perennial grasses *Miscanthus* spp. plot and corn in Havana, Illinois (Ye and Robbins 2004; Mekete et al. 2009). The occurrence of this species was associated with severe damage to the fibrous root system, including stunting and necrosis of grasses.

4.2.7 *Spiral Nematodes,* **Helicotylenchus** *spp.*

Spiral nematodes were the most frequently found plant parasitic nematode (Table 4.2), present in 77% of the soil samples collected from corn in Iowa. The spiral nematode also was present at the highest maximum population density (2340 nematodes per 100 cm^3 soil) and with the greatest mean population density (87 per 100 cm^3 soil) of all nematode genera identified in the samples. A damage threshold of 500–1000 nematodes per 100 cm^3 soil were proposed (Tylka et al. 2011). *Helicotylenchus* spp. were found in Ohio in 14.6% samples (Wilson and Walker

Table 4.2 Some plant parasitic nematodes reported from agricultural fields, pastures and golf courses in Indiana, Illinois, Ohio, Iowa and Missouri

Species	States	Crop or plants	References
Aphelenchoides fragariae	Illinois, Indiana, Iowa	Strawberry	Logsdon et al. (1968)
A. ritzemabosi	Illinois, Indiana, Iowa	Ornamentals	Logsdon et al. (1968)
Discocriconemella inarata	Iowa	Prairies	Powers et al. (2010)
Ditylenchus destructor	Indiana	Potato	Logsdon et al. (1968)
Helicotylenchus cornurus	Illinois	Bentgrass	Davis et al. (1994a)
H. digonicus	Iowa	Prairies	Norton and Schmitt (1978)
H. dihystera	Missouri, Iowa	Soybean, prairies	Norton and Schmitt (1978) and Niblack (1992a)
H. platyurus	Illinois	Peach	Walters et al. (2008)
H. peudorobustus	Missouri, Illinois, Indiana, Iowa	Soybean, peach, corn	Ferris et al. (1971), Norton (1977), Lawn and Noel (1986), Niblack (1992a), and Walters et al. (2008)
Heteroanguina graminophila	Iowa, Ohio	*Calamagrostis canadensis*	Norton et al. (1987)
Heterodera glycines	Missouri, Iowa, Indiana, Illinois, Ohio	Soybean	Anon (1984), Niblack et al. (1993), and Willson et al. (1996)
H. trifolii	Missouri	Soybean	Niblack (1992a)
H. ustinovi	Ohio	Grasses	Joseph et al. (2018)
Hoplolaimus galeatus	Iowa, Illinois, Indiana, Missouri	Prairies, cotton, corn	Logsdon et al. (1968), Norton and Hinz (1976), Norton and Schmitt (1978), and Wrather et al. (1992)
Longidorus breviannulatus	Iowa, Illinois	Corn	Malek et al. (1980) and Norton et al. (1982)
Meloidogyne hapla	Missouri, Iowa, Illinois, Indiana	Soybean	Logsdon et al. (1968) and Niblack (1992a)
M. incognita	Missouri, Illinois	Soybean, cotton	Anon (1984), Niblack (1992a), and Wrather et al. (1992)
M. naasi	Illinois	Grasses	Michell et al. (1973)
Mesocriconema curvatum	Illinois, Iowa	Bentgrass	Logsdon et al. (1968) and Davis et al. (1994a)
M. xenoplax	Illinois, Indiana, Iowa	Peach	Logsdon et al. (1968), Reis et al. (1979), and Walters et al. (2008)
Nanidorus minor	Iowa	Corn	Norton et al. (1982)
Paratrichodorus allius	Ohio	Corn	Lopez-Nicora et al. (2014)

(continued)

Table 4.2 (continued)

Species	States	Crop or plants	References
Paratylenchus neoamblycephalus	Ohio	Soybean	Ankrom et al. (2017)
P. projectus	Missouri, Illinois, Indiana	Soybean, peach	Ferris et al. (1971), Lawn and Noel (1986), Niblack (1992a), and Walters et al. (2008)
Pratylenchus agilis	Missouri	Soybean	Niblack (1992a)
P. crenatus	Ohio	Potato, corn	Brown et al. (1980)
P. hexincisus	Missouri, Iowa	Soybean, corn	Norton and Hinz (1976) and Niblack (1992a)
P. neglectus	Ohio	Potato	Brown et al. (1980)
P. penetrans	Ohio, Missouri, Illinois, Indiana	Potato, soybean, peach, peppermint	Mai et al. (1977), Brown et al. (1980), Niblack (1992a, b), Wheeler and Riedel (1994), and Walters et al. (2008)
P. scribneri	Missouri, Ohio, Illinois	Soybean, potato, cotton	Lawn and Noel (1986), Niblack (1992a), Wrather et al. (1992), and Wheeler and Riedel (1994)
P. thornei	Ohio	Potato	Brown et al. (1980)
P. vulnus	Missouri, Illinous	Cotton, peach	Wrather et al. (1992) and Walters et al. (2008)
Rotylenchulus reniformis	Missouri	Cotton	Wrather et al. (1992)
Quinisulcius acutus	Iowa, Missouri, Illinois, Indiana	Corn, soybean	Ferris et al. (1971), Norton (1989), and Niblack (1992a)
Tylenchorhynchus annulatus	Illinois	Peach	Walters et al. (2008)
T. agri	Iowa, Illinois	Corn, soybean	Norton (1989)
T. claytoni	Iowa, Missouri, Illinois	Corn, soybean, peach	Norton (1989), Niblack (1992a), and Walters et al. (2008)
T. maximus	Iowa, Missouri	Lowland prairies, turf, soybean	Norton and Schmitt (1978), Norton (1989), and Niblack (1992a)
T. martini	Illinois	Soybean	Lawn and Noel (1986)
T. nudus	Illinois, Iowa	Bentgrass, corn, prairies	Norton and Schmitt (1978), Norton (1989), and Davis et al. (1994a)
Xiphinema americanum sensu lato	Missouri, Iowa, Illinois, Indiana, Ohio	Soybean, prairies, peach, alfalfa, red clover	Logsdon et al. (1968), Ferris et al. (1971), Norton and Schmitt (1978), Norton et al. (1982), Niblack (1992a), and Walters et al. (2008)
X. chambersi	Iowa	Prairies	Norton and Schmitt (1978)

1961) and also in almost all corn fields surveyed in Ohio. This genus was found in 94% of the fields sampled, at a mean population density of 90 nematodes per 100 cm^3 soil. It has been concluded that the spiral nematode was not a major threat to corn production in most Ohio corn fields. However, further research will be needed to determine how damaging this plant parasitic nematode genus really is under conditions in Ohio (Niblack 1992a)

4.2.8 Stunt Nematodes, **Tylenchorhynchus** *spp.*

Taylor et al. (1963) sampled 26 putting greens from six golf courses in Illinois and determined that *Tylenchorhynchus* spp. were the most abundant plant parasitic nematodes present. An unidentified *Tylenchorhynchus* sp. was also recovered from all putting greens, with an average 284 nematodes recovered per 125 g of soil. Nematodes of the genus *Tylenchorhynchus* were also recovered from 22% of putting greens sampled in an Ohio study (Safford and Riedel 1976). It has been shown in experimental study that *T. nudus* suppresses root growth of both bentgrass and annual bluegrass (Davis et al. 1994b, c). *Quinisulcius acutus* and *T. martini* were found in soybean fields in Illinois and Indiana (Ferris et al. 1971).

4.3 Conclusion

In summary, nematode problems exist in the herein discussed states. Reports include isolated challenges of specialty crops. Most vulnerable are the large-acre crops soybean and corn, in which relatively narrow genetic bases lead to large production areas with crop cultivars of similar susceptibilities. Examining these highly intensive production systems illustrates how ensuring sustainability of production systems relies on vigilant and constant search for alternative production strategies and genetic improvements. Management strategies already in use against nematode threats to crop production in the five states represent on-going, integrated, sustainable approaches to nematode management and due to restrictions on nematicides, the use of biological and cultural alternatives will continue to challenge future development of sustainable nematode management practices in the region.

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