Managing Nematodes, Cover Crops, and Soil Health in Diverse Cropping Systems

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Summary: In recent years, there has been increasing reference to nematodes, soil health, and cover crops in the scientific and popular media. The intertwined nature of these subjects and the mounting science in the literature can sometimes be overwhelming. For example, the science gaps within the subjects and the information scattered mostly across disciplinary lines make it difficult to understand. To give stakeholders some level of integrated information they can use to make informed and integrated decisions, this bulletin summarizes information about soil health, nematodes, and cover crops in three sections. The first section gives an overview of soil health and composition and reproductive strategies of nematodes and the ways they contribute to soil health and nutrient cycling through the soil food web functions. The second section focuses on the effects of good agricultural practices (GAPs) on soil health and nematodes with particular emphasis on tillage and cropping systems, soil amendments, and cover crops. The last section, encompassing half of this bulletin, looks into the future by considering gaps in the science and current soil health and nematode management practices. Specific emphasis is given to a) nematode biology, b) use of cropping systems to exploit weaknesses in the biology of harmful nematodes *with proven practices*, and c) asking agronomic, economic, and systematic questions before making nematode and soil health management decisions.

1.0. Overview of soil health and role of nematodes:

1.1. What is soil health and where do nematodes fit in? The simplest United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) definition of soil health is “the capacity of a soil to function” (2). Soil health has biological, physiochemical, nutritional, structural, and water-holding components that need to be kept in balance and functioning at all times. When the belowground biological and physiochemical processes are functioning, as an example, they deliver the desirable ecosystem services such as nutrient cycling, regulation of life forms, and crop yield (2, 6, 13, 17, 18, 19, 26, 27, 42, 44). The biological component of soil health has many single- and multi-cellular organisms that are part of the soil food web (SFW). The SFW drives the belowground biological and physiochemical processes that deliver the desirable ecosystem services. Nematodes are small, nonsegmented worm-like organisms present in all ecosystems and a critical part of the SFW (7, 16, 17). An estimated abundance of more than 57 billion nematodes for each human being on the planet (25) and their presence in all ecosystems make nematodes excellent indicators of changes in soil and global ecosystems (7, 45).

1.2. Composition and characteristics of nematodes: Nematodes are classified into six trophic groups based on their food sources (52). These include *bacterivores* (bacterial feeders), *fungivores* (fungal feeders), *plant parasites* or *herbivores* (plant feeders), *predators* (those that feed on nematodes and other life forms), *omnivores* (those that feed on a range of soil organisms), and *animal parasites* (those that feed on vertebrates and invertebrates). Examples of what some of the herbivore, bacterivore, fungivore, predator, and omnivore mouth parts look like are shown in Figure 1. Animal parasites are important from the veterinary, medical, and biological control points of view. Herbivores use a *stylet,* which resembles a hypodermic needle, to pierce roots *(root parasites)* or leaf tissue *(shoot parasites)* to obtain nutrition. They are harmful pests that cause crop yield loss. Bacterivores, fungivores, omnivores, and predators are all beneficial and pertinent to nutrient cycling and maintaining healthy soils (13, 19, 32, 35). *Herbivorous nematodes exist in the same soil ecosystems as bacterivores, fungivores, omnivores, and predators.* Unfortunately, few selective, broadly applicable, and sustainable beneficial and harmful nematode management tools are available to growers.

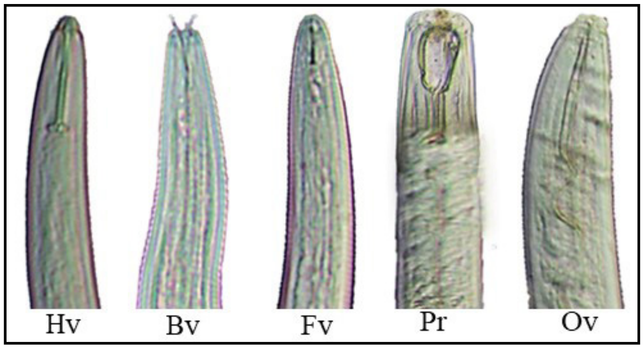

Figure 1. Examples of mouth parts of an herbivore (Hv), bacterivore (Bv), fungivore (Fv), predator (Pr), and omnivore (Ov). (Credit: Isaac Lartey, Agricultural Nematology Laboratory).

1.3. Reproductive strategies of nematodes: All nematodes have life histories and reproductive strategies that fall into five categories commonly known as colonizer-persister (c-p) groups (7, 52). These range from c-p 1, *fast reproducing and tolerant to disturbance,* to c-p 5, *slow reproducing and sensitive to disturbance* (7, 17). By analogy, c-p 1 reproduce like mice and c-p 5 like elephants. You can find a complete list of the c-p classification for all of the nematode functional groups at http://nemaplex.ucdavis.edu/Uppermnus/topmnu.htm#. The c-p groups have different functions. A healthy soil should contain all c-p groups of all beneficial nematodes.

1.4. How do nematodes contribute to soil health? Not all soil nutrients are available in forms that plants can readily absorb. Nutrients become available as a result of belowground biological and physiochemical processes driven by the SFW (1, 8, 14, 45). As shown in this open-source USDA-NRCS figure, the SFW is like an elaborate soup with ingredients coming from actions of five trophic levels (Figure 2). Level I are the photosynthesizers; Level II, decomposer and parasites; Level III, shredders; Level IV, predators; and Level V, higher level predators. In simple terms, the desired ecosystem services from a functioning SFW are the predator-prey and excretions of many micro- and macro-organisms operating across five trophic levels (27). By feeding on or being food for other organisms, nematodes contribute to nutrient cycling in Levels II, III, and IV of the SFW. As an example, bacterivorous nematodes feeding on bacteria alone excrete nitrogen that meets about 30% of crops' nitrogen needs (26).

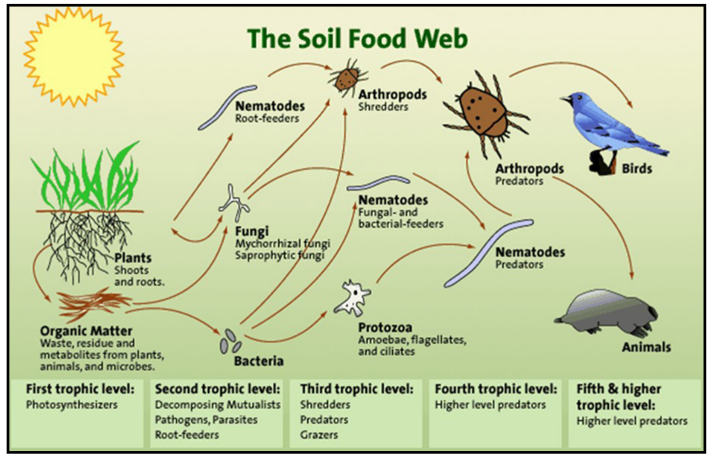

Figure 2. The five trophic levels of the soil food web. (USDA-NRCS) https://www.nrcs.usda.gov/wps/portal/nrcs/photogallery/soils/health/biology/gallery/?cid=1788&position=Promo.

1.5. Translating nematode numbers and functions into practical decision-making: Knowing that nematodes are key players in the SFW functions and nutrient cycling may be easy to understand. However, converting the numbers and functions into practical application is not. Current management recommendations are based on whether a treatment resulted in an increase or a decrease in beneficial nematodes, harmful nematodes, or both. Unfortunately, no benchmarks exist for how many nematodes and functional groups result in a desired level of soil health. Studies to link nematode numbers and functional guilds—to draw practical applications in Michigan agriculture—are ongoing.

2.0. Effect of good GAPs on soil health and nematodes:

2.1. Role of GAPs in altering soil health conditions: Use of appropriate organic and inorganic forms of nutrient amendments, mulching, tillage, crop rotation, and cover crops are among the most commonly used GAPs to achieve healthy soils in crop production systems (3, 9, 14, 22, 35, 42, 53). Desirable characteristics of healthy soil include improved nutrient cycling, soil structure, and soil environment as well as low harmful nematodes, pests, and disease-causing microbes. While there is a substantial volume of mostly discipline-based knowledge on the characteristics of healthy soil in scientific and popular media, the desirable and undesirable outcomes do not align as expected for a given crop, GAP, and soil type over time (6, 11, 12, 23, 24, 33, 34, 41, 43, 46-51). *Under these circumstances, localized knowledge of the effects of GAPs on the desirable and undesirable outcomes is helpful.* Examples of the effects of tillage and cropping systems, soil amendments, and cover crops on nematodes and soil health in Michigan agriculture follow.

2.2. Effects of tillage and cropping systems on nematodes and soil health: Many combinations of tillage and cropping systems have shown variable effects on soil health, beneficial and harmful nematodes, pest and diseases in short- and full-season crops in Michigan and in the U.S. Midwest (11, 20, 21, 33, 42, 43). The effects of tillage and crop rotation on nematodes may be direct or indirect, and soil type is a major influencer. Generally, disturbed soils favor fast-reproducing nematodes more than the slow-reproducing kinds because the latter group is slow to recover from disturbance. What is less known is how nematodes, such as the soybean cyst (SCN), a c-p 3 reproductive strategist and a menacing pest of soybeans, respond relative to beneficial nematodes in the same environment. A field study investigated the relationship between an introduced SCN population and the soil nematode community under tillage (chisel plow and no-till) and mono-cropping of either maize (C), SCN-resistant (R), SCN-susceptible (S) soybean, or RCRC or SCSC rotations in a sandy loam soil with a texture of 60.6% sand, 20.5% silt, and 13.2% clay at the Michigan State University (MSU) campus. The study revealed three important points (Figure 3; 11, 33). First, SCN remaining barely detectable six years after it was introduced at damaging levels suggests that there is a lag period between introduction and establishing to reach damaging levels. Second, SCN establishment was less in no-till than in tilled conditions. This suggests that no-till could be a tool that contributes toward keeping SCN population density low. Third, the conditions that favored SCN also favored fast-reproducing bacterial-feeding nematodes (11), which are central to nutrient cycling and nitrogen availability to plants. This suggests that many changes in soil biology as a function of GAPs need to be elucidated in order to develop SCN and beneficial nematode management strategies in the same environment.

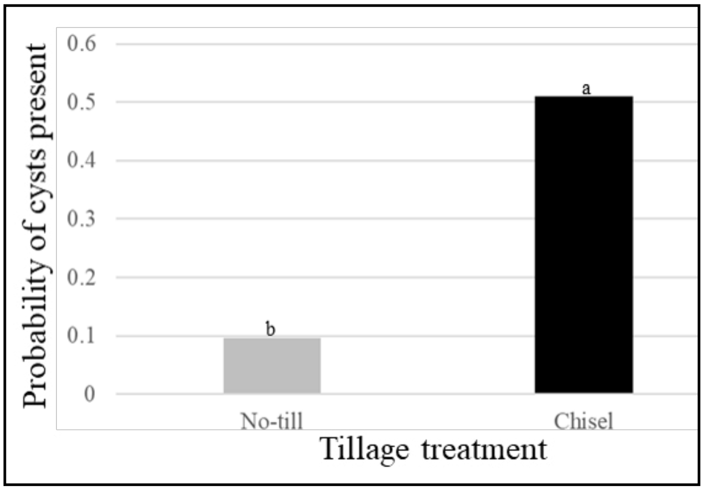

Figure 3. The probability of SCN cyst detection in no-till and chisel-plowed sandy loam soil six years after it was introduced at damaging levels into a sandy loam soil. (Modified from Melakeberhan et al., 33).

2.3. Effect of soil amendments on nematodes and soil health: Soil amendments include composted animal manure and plant litter (23), mulching (35), green manure (36, 37, 38), synthetic fertilizers (9, 29), and many combinations. While outcomes vary by location, soil type, crop and form of amendment, benefits of increasing soil organic matter, nutrient cycling, and beneficial nematodes, microbial biomass, and crop quality and yield have been demonstrated (6, 9, 17, 13, 19, 23, 29, 30, 51, 53). Many factors contribute to variable outcomes; two of them are soil amendment and time. The amount of soil amendment needed to supply the nutrient levels for optimal soil health for a soil type and crop is unknown, and the nutrients are not available from the time of application. This is particularly important for compost and green manure amendments because it will take time for the materials to break down and release nutrients or pest regulating compounds. The process of getting the nutrients released, in turn, is dependent on temperature, soil biology, and soil type. The second factor is the time it takes to get consistent and improved soil health outcomes from applying the soil amendments. For example, it took three years of repeated application of animal- and plant-based compost in carrot production on the same location to improve soil health in a Colwood-Brookston sandy clay loam soil with texture of 54% sand, 25% silt, and 21% clay (23). This may not be practical under current practices, but points to the challenges of achieving healthy soils in cropping systems.

2.4. Effects of cover crops and cropping systems on nematodes and soil health: Much ongoing and past research and publicity covers this topic with still more questions than answers on the impact of cover crops on nematodes, soil health, or both (3, 10, 14, 15, 21, 22, 24, 28, 32, 33, 34, 43, 44. 46-49). MSU hosts the U.S. Midwest Cover Crops Council website (http://mccc.msu.edu/covercroptool/covercroptool.php; 28). Cereals, legumes, and brassicas are the most commonly used cover crops in the U.S. Midwest. Cereals include barley, oats, triticale, and wheat planted either as a winter or spring crop, annual rye grass, cereal rye, pearl millet, and sorghum-sudangrass. Legumes include alfalfa, clover species (Berseem, Crimson, Red, and Sweet), hairy vetch, and sunn hemp. The brassicas include oil seed radish, mustard, rapeseed/canola, kale, turnip, field pennycress, and winter camelina. There are many varieties of these cereals, legumes, and brassicas with varying properties and responses to pests and diseases in different localities. *A list of crops and ways they can be used to develop site-specific management practices relative to harmful nematodes is provided at the end of Section 3.0 (Table 3).* When considering cropping system-based nematode and soil health management strategies, growers will face two major challenges.

The first challenge is that beneficial and harmful nematodes exist in the same environment and many of the cover and rotation crops are suitable hosts to many plant-parasitic or harmful nematodes. For example, Grabau et al. (2017) (21) tested the effects of 1) fallow control, 2) oats, 3) oilseed radish cv. Defender, 4) a mixture of oats and 'Defender' radish, and 5) oilseed rape cv. Dwarf Essex on the nematode community in Michigan carrot production in Grattan Sand (94% sand, 1% silt, 5% clay) soil. The study showed that bacterivorous nematodes increased in carrot season following oats or radish cover crops compared to the control. Unfortunately, population densities of root-lesion nematode were increased by Defender radish compared to other cover crops or fallow control during cover-crop growth and carrot production. This presents growers with making careful tradeoff decisions in their cropping system management.

The second challenge is that successful use of cropping systems for nematode and soil health management depends on knowing what and how each of the cover-, rotation- or main-crops changes in the nematode community structure. Depending on the farming system in question, a main crop could be a cereal, vegetable, legume, or root crop. Any of these crops could be a rotation crop. Independent of whether a crop is used as a cover, rotation, or main crop, it has a footprint on the soil that needs to be standardized for a given location. Figure 4 shows a 2-year study of how oilseed radish and mustard, soybean, corn, and sugar beet varieties affected soil nematode trophic (left side) and c-p groups (right side) in a sandy clay loam sugar beet field in the Saginaw Valley (32). While none of the crops significantly altered the population dynamics of the trophic (left side) or c-p (right side) groups, the proportions had similar variations to what is reported in the literature. Moreover, the study highlighted four points (32):

a. Herbivore (harmful) nematodes were about 20% to 30% of the population and root-lesion was the most dominant genus present.
b. Omnivores and predators, generally slow-reproducing kinds, are present in very low numbers.
c. The majority of nematodes present are c-p 2 group, the fast-reproducing types.
d. Collectively, these results mean that the soil system is disturbed and stressed, and provide basis for how future studies may improve soil health using cropping systems.
e.

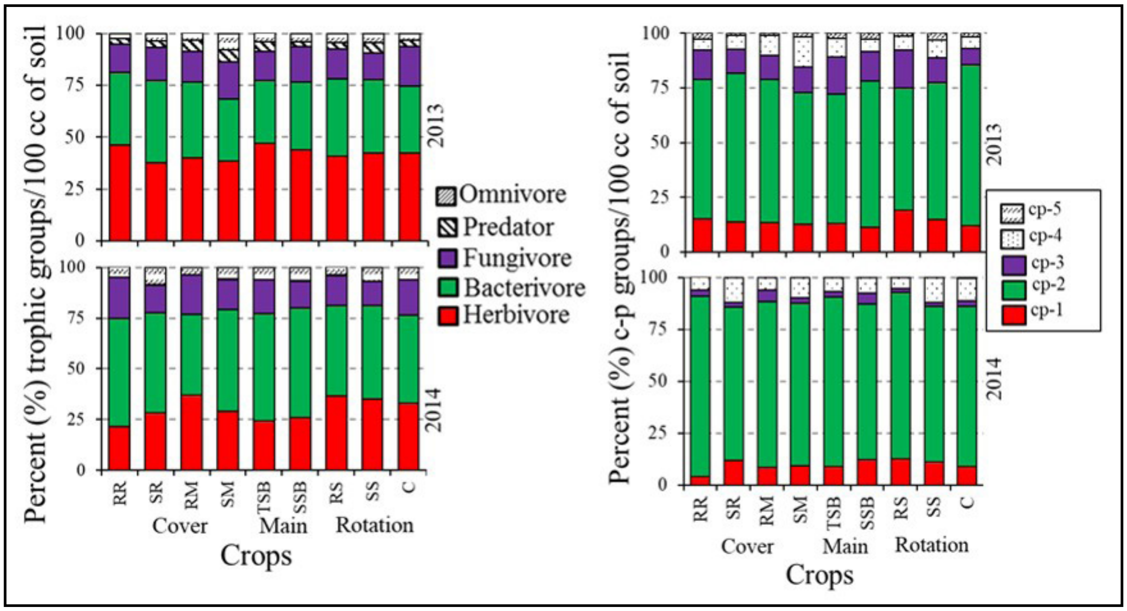

Figure 4. Composition of herbivore, bacterivore, fungivore, predator, and omnivore nematodes (left side) composition of c-p groups 1 to 5 of the trophic groups (right side) under cover crops (oilseed radish and mustard), main crop (sugar beet), and rotation crops (soybean and corn [C]) grown in the same sandy clay loam field in 2013 and 2014 growing seasons. The cover crops were sugar beet nematode (SBCN) resistant (RR) and susceptible (SR) oilseed radish and resistant (RM) and susceptible (SM) mustard. The sugar beets were SBCN tolerant (TSB) and susceptible (SSB) and the soybean cyst nematode resistant (RS) and susceptible (SS). (Modified from Melakeberhan, et al., 2018, [32]).

3.0. Future challenges and opportunities for integrated nematode and soil health management:

3.1. We need a paradigm shift: Achieving sustainable nematode and soil health in cropping systems is a moving target. There needs to be a recognition of key hard facts to make necessary adjustments. **First,** aligning desirable and undesirable ecosystem services to achieve and sustain optimal soil health conditions in a production system remains difficult, in part, due to gaps in the science and the lack of interdisciplinary integration. **Second,** the complex relationships among crops, cropping systems, and beneficial and harmful nematodes make soil health management decisions difficult in several ways. For example, harmful and beneficial nematodes live in the same soil environment, few selective control measures exist, and *little data is published that show an ideal ratio of beneficial nematodes and harmful nematodes that equal a desirable soil health outcome.* Another challenge is that practicing cropping systems is important for soil health, but most harmful nematodes have a broad host range of cover, rotation, and main crops as well as weeds. Under these circumstances, soil health management decisions are likely to be location specific and need to consider multiple factors simultaneously. **Third,** in order to develop a soil health management strategy that addresses the challenges and fits the local production system conditions, an integrated consideration of all of the cover, rotation, and main crops in use and their status against harmful nematodes will be needed. *However, the large volume of discipline-based and highly variable information on nematodes and cropping systems is spread across many publications and is difficult to integrate even for scientists.* The following subsections summarize how to consider and exploit the biology of nematodes (Sections 3.2–3.7) and the types of systematic questions that a grower needs to ask (Section 3.8) before developing a soil health management plan that accounts for harmful nematodes and cropping systems to solve location-specific problems (Section 3.9). With this approach, growers will have the power to make integrated and potentially sustainable nematode and soil health management decisions suitable to their production systems.

3.2. Consider expanded nematode sampling frequency: Management decisions are based on the numbers of nematodes, which vary by soil types, land use practices, agricultural inputs (fertilizers, pesticides, etc., 29), and growing season. In the absence of peer-reviewed analyses of nematodes across time in Michigan agricultural ecosystems and soil types, Figure 5 provides a snapshot of abundance and proportions of beneficial and harmful nematodes in some of the common soils found in Michigan. These results are from 62 soil samples collected within a month in 2013 in urban, field crop, and vegetable soils, and in well-maintained soils under till and no-till and corn-soybean rotations for over 10 years. The differences within and among soil types and cropping systems are an example of how variable nematode abundance could be and that complicates nematode-based soil health management recommendations. *One size does not fit all.* Because nematodes reproduce at different rates and have multiple generations during a growing season, their population densities are likely to have peaks and valleys. In this case, management decisions based on one sampling time may not be capturing the reality in the field, that is, samples collected at the peaks and valleys will skew recommendations and management decisions. To minimize such events, have at least three sampling points during a growing season that correspond with seedling, reproductive, and harvest stages of the crops. Consult your local extension educators and consultants for a sampling plan and the location to send samples to be analyzed. Find instructions to submit samples to MSU Plant & Pest Diagnostics and associated charges at this website: https://www.canr.msu.edu/pestid/submit-samples/.

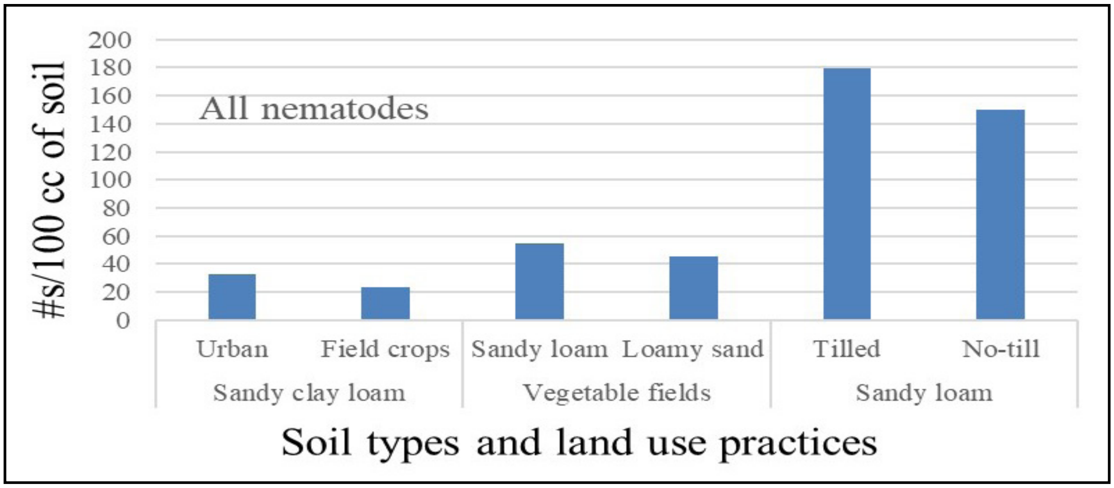

Figure 5. Numbers of nematodes/100 cc of soil present in samples collected around the same time in sandy clay loam soil from demolished houses in Detroit and mixed field cropping in Saginaw Valley (two left bars), sandy loam and loamy sand vegetable fields in Hart/Shelby area (two center bars), and sandy loam under long-term till and no-till conditions (two right bars) at the MSU campus in 2013. (Unpublished data).

3.3. Know your nematode host range terminology: Broadly speaking, crops are either resistant (R), tolerant (T), susceptible (S), or immune to nematodes. In a nematode-resistant crop, only a limited number of nematodes invade and grow, and cause no or little yield loss. The difference between nematode-susceptible and -tolerant cultivars is that the latter do not suffer crop yield loss as much as the former. Otherwise, nematode reproduction is high in both. Immune means no nematodes invade, but such crops lack other good agronomic qualities. A crop can also be a trap if it does not allow the harmful nematode to complete a life cycle (31). Any susceptible plant can be used as a trap crop for certain nematodes if it is terminated before the nematode completes a life cycle (see Section 3.6).

3.4. Know what harmful nematodes are in your fields: Knowing what nematodes are in your field is as important as knowing which crops the nematodes feed on. Depending on the crop, many herbivorous nematodes are commonly known to be present and some at damaging levels in Michigan and U.S. Midwest agriculture (4, 5, 28, 39, 40, 41, 50). These include Dagger (DN), Needle (NN), Stubby root (SRN), Spiral (SPN), Sheath (SHN), Stem and foliar (STFN), Pin (PN), Stunt (STN), Root-lesion (RLN), Northern root-knot (NRKN), False root-knot nematode (FRKN), Carrot cyst (CCN), Clover cyst (CLCN), Hop cyst (HCN), soybean cyst (SCN), and sugar beet cyst (SBCN) nematodes (Table 1). Find out which of these nematodes are present in your field(s).

Table 1. Harmful Nematodes Present in Michigan and the U.S. Midwest.

Common Name	Acronym	Genus/Species Name
Dagger	DN	*Xiphinema* spp,
Needle	NN	*Longidorus* spp.
Pin	PN	*Paratylenchus* spp.
Sheath	SHN	*Hemicycliophora* spp.
Spiral	SPN	*Helicotylenchus* spp.
Stem and foliar	STFN	*Ditylenchus* spp.
Stubby root	SRN	*Trichodorus* spp.
Stunt	STN	*Tylenchorhynchus* spp.
Root lesion	RLN	*Pratylenchus* spp.
Carrot cyst	CCN	*Heterodera carotae*
Clover cyst	CLCN	*H. trifolii*
False root-knot	FRKN	*Nacobbus batatiformis*
Northern root- knot	NRKN	*Meloidogyne hapla*
Soybean cyst	SCN	*Heterodera glycines*
Hop cyst	HCN	*H. humuli*
Sugar beet cyst	SBCN	*H. schachtii*

3.5. Know the biology of the harmful nematodes in your fields: Depending on the way these nematodes enter their host plant root or tissue, they can be classified as either ecto-parasites, migratory endo-parasites, or sedentary endo-parasites (Table 2). **Ecto-parasites** feed by inserting their stylet into a root, remaining mobile, and laying their eggs in the soil. **Migratory endo-parasites** enter host tissue at all infective stages, move through cortical (roots) or parenchyma (leaves and stems) tissue, and lay eggs inside or outside the host. **Sedentary endo-parasites** have an infective-stage, usually the second-stage juvenile, that enters the host, and establishes a suitable feeding site by modifying plant cells. Then the host supplies these nematodes with enhanced nutrition. All of the feeding behaviors weaken or destroy normal host cell functions of water and nutrient transport, thereby limiting the host's photosynthetic capacity and crop yield. In addition, sedentary endo-parasites derive their nutrition directly from the plant vascular tissue by ingesting photosynthate, important for plant growth and crop yield.

Table 2. Common Herbivore Nematodes in Present Michigan and U.S. Midwest, Their Mode of Parasitism and Host Cell Damages.

<table>
<tr><td colspan="4">Mode of Parasitism</td></tr>
<tr><td>Ecto-parasites</td><td colspan="3">Endo-Parasites</td></tr>
<tr><td rowspan="2"></td><td>Migratory</td><td colspan="2">Sedentary</td></tr>
<tr><td></td><td>Non-cyst forming</td><td>cyst forming</td></tr>
<tr><td>DN, NN, PN, SPN, SHN, STN, STFN, SRN</td><td>RLN</td><td>NRKN, FRKN</td><td>CCN, CLCN, HCN, SCN, SBCN</td></tr>
<tr><td colspan="2">Destructive (cells leak and die)</td><td colspan="2">Modified (cells become sinks)</td></tr>
<tr><td colspan="4">Mode of host cell damage</td></tr>
</table>

Common herbivore nematodes, their mode of parasitism as ecto- and migratory or sedentary endo-parasites, and the host cell damages that they cause once inside the root. Common name abbreviations are as shown in Table 1. For extended nematode biology, visit: http://nemaplex.ucdavis.edu/IndexFiles/common%20names.html.

3.6. Exploit the harmful nematodes' mode of host cell destruction against them: Ecto- and migratory endo-parasites are capable of moving to new roots if the root on which they are feeding dies (Table 2). Management strategies that are likely to get best outcomes against ecto- and migratory endo-parasites are those that reduce the population density of *all* life stages of the nematode in question. *Sedentary endo-parasites are sitting ducks* that cannot migrate once they successfully establish a feeding site. If the root on which they are feeding dies, they die as well. *Disrupting their life cycle before they reach adulthood and produce eggs is the weak link that management strategies should focus on.* (See green-shaded part of Table 3.) Use of trap cropping is an example.

3.7. Know what beneficial nematodes are in your fields: A healthy soil needs to have *bacterivore*, *fungivore*, *predator*, and *omnivore* nematodes (7, 16). The proportion of the harmful nematodes should be as low as possible compared to the beneficial kinds (Figure 6). If all of the beneficial nematode trophic groups are not present in your soils, you will know that the system is out of balance and it will be difficult to develop a sustainable soil health. Thus far, few published examples demonstrate where specific beneficial nematodes have been introduced to establish in new locations and to improve soil health in an agricultural system.

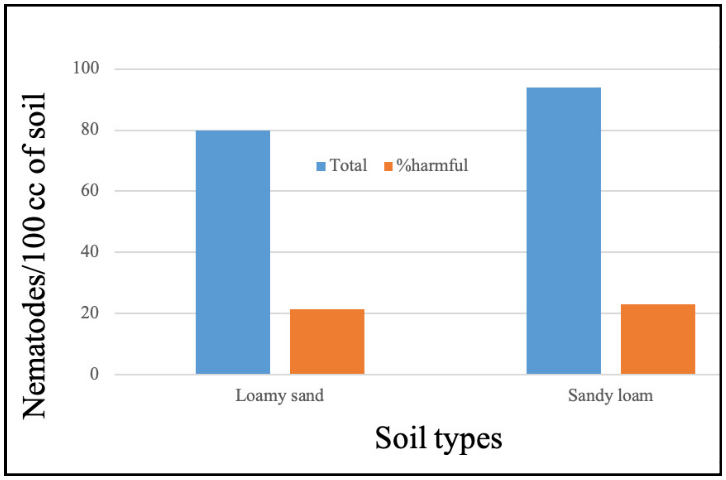

Figure 6. Numbers of all nematodes present in 100 cc of loamy sand and sandy loam vine production soils in southwestern Michigan in 2019 and percentage of harmful nematodes. (Unpublished).

3.8. Ask systematic questions before making decisions about nematode and soil health management: Management decisions are as good as the breadth, depth, and integrated impact of the information that they are based on. *Nematodes may be the primary focus, but they are unlikely to be the only problem in a given soil.* ***Also, know that all of the GAPs have direct or indirect impact on nematodes.*** Therefore, asking sets of hard questions before developing a plan of action is important.

The first set of questions relate to production practices. These questions are designed to help balancing agronomic benefits and effects on nematodes.

1. What are your main crops (Table 3) and their impact on the soil? For example, cereals (*nitrogen scavengers*), legumes (*nitrogen enrichers*), root crops (*varying impact on soil structure)*, and others.
2. What is your rotation system?
3. What are the cover crops that you use?
4. How long do the cover crops stay on the ground?
5. What are your weed management practices? Many weeds are hosts to harmful nematodes.
6. What are your tillage practices? Among other things, tillage affects all nematodes and not always in desirable ways.
7. What is your soil fertility management practice? Soil amendments affect nematodes (9, 23).

The second set of questions relate to harmful nematodes.

1. Based on sampling (Section 3.2), what harmful nematodes do you have (Table 1)?
2. Are your main, cover, or rotation crops host to harmful nematodes (Table 3)? The chances are that they are suitable hosts to one or more harmful nematodes because of the lack of broad-spectrum nematode-resistant crops.
3. Are population densities of the harmful nematodes considered low, medium, or high? There is little peer-reviewed science that shows a known number of nematodes result in a known percent yield loss in a given soil type or production practice.

The third set of questions relate to beneficial nematodes. Is the priority to manage beneficial nematodes, harmful nematodes, or both? The simple answer is both because they co-exist in the same environment. This means developing a location-specific management strategy will require carefully weighing the purpose of using cover and rotation crops, the biology of the harmful nematodes (Table 2), and the host suitability database (Table 3). Then look for *combinations* that increase the total numbers of bacterivore, fungivore, predator, and omnivores. An outcome that resembles Figure 4 is an indication that something is out of balance in that system.

The fourth set of questions relate to affordability.

What can you afford to do now or across a planned period? In the end, it comes down to economics.

The fifth set of questions relate to your management and decision-making.

What is your management philosophy? Answering this set of questions will help growers evaluate whether or not they were applying information purely on a disciplinary basis or in integrated ways. This, in turn, will lead to making necessary adjustments to apply an integrated approach so that multiple limiting factors can be addressed simultaneously and more efficiently.

3.9. Develop a nematode and soil health management plan that fits your cropping system: With the knowledge of the types and biology of the nematodes (Sections 3.2, 3.4, 3.5, and 3.7); crops and cropping systems (Section 2.4); the crops' R, S, or T status against the harmful nematodes (Section 3.3.); and answers to the systematic questions (Section 3.8); a grower will have enough information to develop an integrated nematode, cover crop, and soil health management plan. As part of developing an integrated and location-specific nematode and soil health management plan *using proven practices* of trap-, rotation-, and cover-cropping systems, growers can use Table 3 as a template to make decisions.

What Table 3 contains: Table 3 provides a partial list of the major crops and harmful nematodes present in the U.S. Midwest (4, 5, 10, 20, 28, 39, 41, 50). The crops' common and scientific names are listed in groups of cereals, legumes, root crops, brassicas. and vegetables. Many of these crops have varieties with different traits and status against harmful nematodes. The nematodes are listed by acronym as described in Table 1 and further divided into mobile or ecto- and migratory endo-parasites (*those that move inside or outside host tissue*) and sedentary (green shade, *those that don't move after establishing a feeding site*) as described in Table 2. Like many of the crops, nematodes such as SCN have populations with varying appetites to varieties of soybeans.

How to use Table 3: You know what crops and cropping systems you practice or plan to (Table 3, http://mccc.msu.edu/covercroptool/covercroptool.php). From doing a survey (Section 3.2), you will know what harmful nematodes are in your fields (Table 1). From the information in the websites listed at the bottom of Table 3 and internet search, you will get the status of your crops to the harmful nematodes that are in your fields. Depending on the grower, compiling this information may require input from expertise at MSU and MSU Extension's statewide educator network or elsewhere as needed. Finally, fill out the R, S, or T status of your crops relative to the harmful nematodes present in your fields. The information that goes into Table 3 is likely to change frequently depending on peer-reviewed and popular publications. Up-to-date information about crops, nematodes, and crop suitability to harmful nematodes can be accessed in the websites listed at the bottom of Table 3. While you can search the internet for nematodes and crops, the information may not be as organized as in the listed websites.

How to make decisions based on the information on Table 3: Depending on the R, S, or T combinations across the crops and harmful nematodes, you will likely have many options where targeted trap-, rotation- or cover-crop systems to manage nematodes and soil health can be applied. If nematodes in the green-shaded columns are present, for example, you know that a carefully timed trap cropping will be an option (Section 3.6). Destroying and incorporating the plants into the soil before the nematodes complete a life cycle will add organic matter that will also benefit the good nematodes and soil health. Another example is scaling up management decisions across locations. Depending on the enterprise, a grower could have farms across counties with the same or different problems. *This approach allows for scaling up on the basis of similarities of location-specific problems rather than one-size-fits-all and with little regard to differences among locations.* As growers make a habit of keeping these records year after year and realize the advantages from the level of integration presented herein, they will likely identify other factors that may be incorporated into their soil health management strategies.

Table 3: Partial List of the Crops, Cover Crops and Harmful Nematodes Present in the U.S. Midwest.

			Nematodes and their mobility															
Crop groups		Scientific name	Mobile									Sedentary						
			DN	NN	PN	SPN	SHN	STN	STFN	SRN	RLN	NRKN	FRKN	CCN	CLCN	HCN	SCN	SBCN
Cereals	Annual/Perennial rye grass	*Lolium multiflorum*																
	Corn	*Zea mays*																
	Pearl millet	*Pennisetum glaucum*																
	Sorghum-Sudangrass	*Sorghum bicolor x Sorghum bicolor* var. Sudanese																
	Spring/winter barley	*Hordeum vulgare*																
	Spring/winter oats	*Avena sativa*																
	Spring/winter wheat	*Triticum aestivum*																
	Spring/winter triticale	*Triticum x Secale*																
	Winter rye	*Secale cereal*																
Legumes	Alfalfa	*Medicago sativa*																
	Berseem clover	*Trifolium alexandrinum*																
	Crimson clover	*Trifolium incarnatum*																
	Dry beans	*Phaseolus vulgaris*																
	Hairy vetch	*Vicia villosa*																
	Red clover	*Trifolium pretense*																
	Soybean	*Glycine max*																
	Sunn Hemp	*Crotalaria juncea*																
	Sweet clover	*Melilotus* spp.																
Brassicas	Field pennycress	*Thlaspi arvense*																
	Kale	*Brassica napus* var. *pabularia*																
	Mustard	*Brassica* spp.																
	Oil seed radish	*Raphanus sativus*																
	Rape seed/Canola	*Brassica napus*																
	Turnip (forage type)	*Brassica rapa*																
	Winter camelina	*Camelina sativa*																
Root/ tuber	Carrot	*Daucus carota*																
	Potato	*Solanum tuberosum*																
	Sugar beet	*Beta vulgaris*																
Vegetables	Asparagus	*Asparagus officinalis*																
	Arugula	*Eruca vesicaria*																
	Cabbage	*Brassica oleracea*																
	Celery	*Apium graveolens*																
	Lettuce	*Lactuca sativa*																
	Onion	*Allium cepa*																
	Pumpkin	*Cucurbita pepo*																
	Tomato	*Solanum lycopersicum*																

Managing Nematodes, Cover Crops, and Soil Health in Diverse Cropping Systems

Acronyms are as shown in Table 1 and nematodes are grouped as mobile (those that move if host cell dies) and sedentary (those that will die if host cell dies, Table 2). Green-shaded nematodes are those where trap cropping will be most effective. You can access up-to-date information on nematodes and crops on the following websites:

Midwest Cover Crops Council Cover Crop Decision Tool: http://mccc.msu.edu/covercroptool/covercroptool.php;

MSU Extension Cover Crops: https://www.canr.msu.edu/cover_crops/species/;

University of California–Davis Nemaplex Index to Common Names: http://nemaplex.ucdavis.edu/IndexFiles/common%20names.html;

University of Minnesota Extension Cover Crops: https://extension.umn.edu/soil-and-water/cover-crops.

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