Chapter 3
Nematodes and Nematologists of Michigan

George W. Bird and Fred Warner

3.1 Introduction

The known glacial history of Michigan began about 2.4 million years ago (Gillespie et al. 1987). It involved six glaciations. The last was the Wisconsin Glacier. It retreated and the entire watershed was free of ice by 9000 years ago. Glaciation resulted in three major geological features. These include the Michigan Basin of the Lower Peninsula and eastern part of the Upper Peninsula, the southern margin of the Canadian Shield in the western part of the Upper Peninsula and the Great Lakes. Glaciation also resulted in a diversity of soils and local climates. This allowed for the pre-agricultural evolution of Eastern Deciduous, Spruce-Fir and Tall-Grass Prairie biomes. Today, Michigan farms produce more than 300 different commodities. These contribute $13 billion to the overall food and agriculture industry (MDARD 2017). They include agronomic crops, fruit, vegetables and ornamentals. In addition, Michigan has the largest state forest system in the USA. There are three national forests and more than eight hundred thousand hectares of private forest land. Plant parasitic nematodes are known to be associated with the vast majority, if not all of Michigan agricultural and forest systems. In addition, the roles of bacterial and fungal feeding nematodes have been documented. This would not have been possible without the diversity of nematologists that have studied the nematodes of Michigan. The objectives of this chapter are to: (1) summarize the history of Michigan nematology, (2) document the occurrence and distribution of plant

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parasitic nematode taxa known to be present in Michigan, (3) describe Michigan's contributions to understanding their biology and ecology and (4) outline the history and current state of integrated nematode management in the state.

3.2 Nematologists and Michigan Nematology

Michigan nematology began in 1910 with the arrival of Professor Ernst A. Bessey at Michigan Agricultural College. This was one year before he published his Nematological Classic entitled, *Root knot and Its Control*. The document includes a forward from the Honorable James Wilson, Secretary of the United States Department of Agricultural and William A. Taylor, Acting Chief of the Bureau of Plant Industry (Bessey 1911). It contains a list of the 480 species and subspecies known to be hosts of *Heterodera radicicola* (the 1910 taxonomic name for root knot nematodes). The nematode control section is divided into perennial and annual crops. The described practices included chemicals, fertilizers, flooding, drying, trap crops, steam, fallowing, non-susceptible crops and breeding for host-plant resistance. This was followed in 1915 with publication of Farmers Bulletin No. 648 entitled, *The Control of Root knot* (Bessey 1915). Prior to coming to Michigan, E. A. Bessey differentiated between summer crimp and spring crimp bud disease of strawberries. In 1942, J. R. Christie named *Aphelenchoides besseyi* (Christie 1942) in his honor. Bessey Hall is a constant reminder of E. A. Bessey's impact of the stature of biology at Michigan State University (Table 3.1).

In 1913, Margaret V. Cobb conducted a nematology survey of the Douglas Lake region of Michigan. Her findings included 12 known species and 11 new species (Cobb 1915). One of the new species was *Dolichodorus heterocephalus* (awl nematode), the first record of a plant parasitic nematode reported in Michigan. Seven additional species from the collection were described by N. A. Cobb (1914). In 1920, Professor Gerald Thorne made his first of several visits to Michigan to survey for *Heterodera schachtii*. This nematode, however, was not detected in Michigan until 1948 (Bockstahler 1950). In 1953, the Director of the Michigan Agricultural Experiment Station hired B. G. Chitwood to conduct a 6-month survey of Michigan nematodes (Chitwood 1953). This initiative included nematode surveys of vegetable, orchard, vineyard, berry, cover crop, nursery, florist and forest systems. In 1954, Dr. John Knierim was hired as Michigan State University's first full-time nematologist.

Throughout the years, a total of 22 professional nematologists have worked in Michigan (Table 3.1). This resulted in the training of a significant number of M.S. and Ph.D. students and their research forms a large portion of the knowledge base for this chapter. Most of these individuals have gone on to have successful careers in nematology. Michigan State University has offered both introductory and advanced courses in nematology, in addition to having nematology lectures included in plant pathology, horticulture, agronomic crop and soil science courses. Since the arrival of Dr. Charles Laughlin at Michigan State University in 1969, Extension

Table 3.1 Michigan Nematologists, positions and dates

Nematologist	Position	Dates
E. A. Bessey[a]	MSU, Professor, Chair, Dean	1910–1945
M. V. Cobb	University of Michigan Student	1913–1915
N. A. Cobb	USDA Nematologist	1914–1915
Gerald Thorne	MSU, Visiting Nematologist, Consultant	1920, 1962–1966
H.W. Bockstahler	USDA/ARS/Technician	1950
B. G. Chitwood	MSU, Visiting Nematologist	1953
John Knierim	MSU, Assistant Professor	1954–1980
Natalie Knobloch	MSU, Taxonomist and Diagnostician	1962–1978
Paul Wolley	MSU, Director, Nematology Program	1963–1968
Charles Laughlin	MSU, Associate Professor	1969–1973
John Davenport	MSU, Applied Research Technician	1972–2007
George Bird	MSU, Professor	1973-present
Lindy Rose	MSU, Nematode Diagnostician	1978–1981
Alma Elliott	MSU, Instructor	1979–1981
Loraine Graney	MSU, Nematode Taxonomist/Diagnostician	1982–1989
Linda Mansfield	MSU, Dis. Professor, Large Animal Clinic	1990-present
Fred Warner	MSU, Nematode Diagnostician	1990-present
Haddish Melakeberhan	MSU, Associate Professor	1994-present
Angie Tenney	MSU, Associate Diagnostician	1999-present
Todd Ciche	MSU, Assistant Professor	2006–2012
Jared Ali	MSU, Assistant Professor	2012–2015
Marisol Quintanilla	MSU, Applied Research and Extension Nematologist	2017-present
Kristin Poley	MSU, Applied Research Technician	2017-present
Jeff Shoemaker	MSU, Applied Research Technician	2017–2018

[a]Bessey Hall. There are three Bessey Halls at Big Ten Universities. The one at Michigan State University is named after E. A. Bessey (1877–1957), B.S., 1896, Univ. NE., M.S., 1898, Univ. NE. and Ph.D., Halle Univ., Germany (1904). The Bessey Halls at Iowa State University and the University of Nebraska are named after C. E. Bessey (1845–1915, E. A. Bessey's father), Michigan Agricultural College, Class of 1869, Horticulture; Professor, Iowa State University, Professor and Academic Dean, University of Nebraska.

nematology has been the primary focus of the program. Between 1962 and 1974, Michigan State University processed about 6000 extension samples for nematodes (Knobloch and Bird 1981). Ninety-four taxa of plant parasitic nematodes have been detected in Michigan (Table 3.2). In addition, at least ten formal nematode surveys were conducted in Michigan between 1913 and 2017. During the last 35 years, Michigan nematology has played an active leadership role in the evolution of the domains of integrated pest management, sustainable agriculture, sustainable-equitable development and soil health biology (Bird 2003; Bird and Smith 2013) (Table 3.3).

Table 3.2 Plant parasitic nematodes of Michigan: 1913–2018

Nematode species	Crop and plants	Reference
Aphelenchoides ritzemabosi	Chrysanthemums	Knierim (1963)
Atylenchus decalineatus	Blueberry	Tjepkema (1966)
Cactodera milleri	Lambs quarter	Graney and Bird (1990)
C. weissi	Smartweed	Chitwood (1953)
Criconema fimbriatum	Spruce	Knobloch and Bird (1981)
C. mutable	Unknown	Knobloch and Bird (1981)
C. permistum	Spruce	Knobloch and Bird (1981)
C. petasum	Unknown	Knobloch and Bird (1981)
C. princeps	Spruce	Knobloch and Bird (1981)
C. sphagni	White birch	Knobloch and Bird (1981)
Crossonema menzeli	Spruce	Knobloch and Bird (1981)
Ditylenchus dipsaci	Creeping phlox, onion	Schnabelrauch et al. (1981)
D. destructor	Potato	Chitwood (1953)
Dolichodorus heterocephalus	Beach grass	Cobb (1914)
Geocenamus longus	White birch	Knobloch and Bird (1981)
Gracilacus acicula	White birch, spruce	Knobloch and Bird (1981)
Helicotylenchus californicus	Willow	Knobloch and Bird (1981)
H. crenacauda	Willow, iris	Knobloch and Bird (1981)
H. digonicus	Clover, onion, potato	Chitwood 1953
H. platyurus	Phlox, onion	Knobloch and Bird (1981)
H. pseudorobustus	Phlox, willow	Knobloch and Bird (1981)
Hemicycliophora similis	Oak, clover	Chitwood (1953)
H. uniformis	Maple	Knobloch and Bird (1981)
H. vaccinium	Blueberry	Knobloch and Bird (1981)
H. vidua	Maple	Knobloch and Bird (1981)
Heterodera avenae	Wheat	Bernett (1986)
H. carotae	Carrots, Queen Anne's lace	Berney and Bird (1992)
H. glycines	Soybean	Warner and Golden (1987)
H. humuli	Hop	Warner et al. (2015)
H. orientalis	*Miscanthus* sp.	Warner and Handoo (pers. comm.)
H. pratensis	Turfgrass	Stouffer-Hopkins et al. (pers. comm.)
H. schachtii	Sugar beet, cabbage	Bockstaller (1950)
H. trifolii	Alfalfa	Brzeski and Laughlin (1971)
H. ustinovi	Bentgrass	Knobloch and Bird (1981)
Hirschmanniella gracilis	Beech, maple	Knobloch and Bird (1981)
Hoplolaimus galeatus	Maple, cherry	Chitwood (1953)
Lobocriconema thornei	Oak, maple	Knobloch and Bird (1978)
Longidorus breviannulatus	Corn	Corn extension samples
L. elongatus	Celery, onion	Knobloch and Bird (1981)
Meloidogyne arenaria	Celery, maple	Chitwood (1953)

(continued)

Table 3.2 (continued)

Nematode species	Crop and plants	Reference
M. hapla	Lettuce, celery, ornamentals	Chitwood (1953)
M. incognita	Greenhouse ornamentals	Knobloch and Bird (1981)
M. microtyla	Maple	Knobloch and Bird (1981)
M. naasi	Turfgrass	Knobloch and Bird (1981)
M. nataliei	Grape	Diamond and Bird (1994)
Merlinius brevidens	Sugar beet, onion	Knobloch and Bird (1981)
M. joctus	Ornamental nursery	Knobloch and Bird (1981)
M. macrodorus	Lily	Knobloch and Bird (1981)
M. tessellatus	Unknown	Knobloch and Bird (1981)
Mesocriconema axeste	Moss	Knobloch and Bird (1981)
M. curvatum	Grass, strawberry	Knobloch and Bird (1981)
M. ornatum	Unknown	Knobloch and Bird (1981)
M. reedi	Woods	Knobloch and Bird (1981)
M. serratum	Grass	Knobloch and Bird (1981)
M. simile	Peach, wormwood	Chitwood (1953)
M. xenoplax	Peach	Knobloch and Bird (1981)
Nacobbus batatiformis	Sugar beet	Knobloch and Bird (1981)
Nanidorus minor	Onion	Knobloch and Bird (1981)
Ogma cobbi	Willow, birch	Knobloch and Bird (1981)
O. octangularis	Maple	Chitwood (1953)
Paratrichodorus atlanticus	Unknown	Knobloch and Bird (1981)
P. pachydermus	*Dahlia* sp.	Knobloch and Bird (1981)
P. porosus	Potato	Knobloch and Bird (1981)
Paratylenchus hamatus	Celery, onion	Knobloch and Bird (1981)
P. projectus	Corn, alfalfa	Knobloch and Bird (1981)
Pratylenchoides laticauda	Mint	Knobloch and Bird (1981)
Pratylenchus crenatus	Corn, soybean, wheat	Knobloch and Bird (1981)
P. neglectus	Apple, Corn, soybeans, wheat	Chitwood (1953); Knobloch and Bird (1981)
P. penetrans	Fruits, vegetable crops	Knobloch and Bird (1981)
P. pratensis	Cherry	Chitwood (1953)
P. scribneri	Corn, soybean, wheat	Chitwood (1953)
P. vulnus	Cherry	Chitwood (1953)
Punctodera punctata	Turfgrass	Knobloch and Bird (1981)
Quinisulcius acti	Potato, corn	Knobloch and Bird (1981)
Q. acutus	Unknown	Knobloch and Bird (1981)
Q. capitatus	Unknown	Knobloch and Bird (1981)
Radopholus similis	*Miscanthus*	Warner (pers. comm.)
Rotylenchus buxophilus	Woody ornamentals	Knobloch and Bird (1981)
Rotylenchus robustus	Ornamental hedge	Knobloch and Bird (1981)
Trichodorus primitivus	Boxwood	Knobloch and Bird (1981)

(continued)

Table 3.2 (continued)

Nematode species	Crop and plants	Reference
T. proximus	Boxwood	Knobloch and Bird (1981)
T. similis	Turfgrass	Knobloch and Bird (1981)
Trophonema arenarium	*Spuria* sp.	Knobloch and Bird (1981)
Tylenchorhynchus agri	Unknown	Knobloch and Bird (1981)
T. clarus	Unknown	Knobloch and Bird (1981)
T. claytoni	Potato	Chitwood (1953)
T. dubius	Peach, pine, turfgrass	Chitwood (1953)
T. martini	Willow	Knobloch and Bird (1981)
T. maximus	Sugar beet	Knobloch and Bird (1981)
T. nudus	Turfgrass	Knobloch and Bird (1981)
T. parvus	Peach	Knobloch and Bird (1981)
Xenocriconemella macrodora	Wood lot	Knobloch and Bird (1981)
Xiphinema americanum	Elm, peach, apple, turfgrass	Chitwood (1953)
X. diversicaudatum	Greenhouse roses	G. Bird (pers. comm.)
X. rivesi	Grapes	Ramsdell et al. 1995

Table 3.3 Frequencies of detection and maximum counts per 100 cm^3 soil for plant-parasitic nematodes recovered from survey samples of turfgrasses collected in 2017 (n = 100) and 1993 (n = 106)

Nematode	Frequency of detection (%)		Maximum counts	
Year	2017	1993	2017	1993
Ring	97.0	69.7	6440	1400
Stunt	86.0	76.1	3280	880
Spiral	86.0	61.5	2160	2040
Root knot (j2)	22.0	16.5	300	55
Heterodera spp. (cyst)	21.0	10.1	141	41
Lance	19.0	22.0	330	399
Stubby root	8.0	0.9	100	1
Punctodera punctata (cyst)	7.0	0.0	17	0
Needle	3.0	3.7	50	1
Lesion	2.0	49.5	40	140
Sheath	2.0	6.4	460	60
Pin	0.0	17.4	0	99
Dagger	0.0	4.6	0	20

3.3 Plant Parasitic Nematodes

The ninety-four currently known taxa of plant parasitic nematodes in Michigan include sedentary endoparasites, migratory endoparasites, ectoparasites and virus vectors.

3.3.1 Cyst Nematodes

Michigan has eleven documented species of cyst nematodes. These include *Cactodera milleri, C. weissi, Heterodera avenae, H. carotae, H. glycines, H. humuli, H. pratensis, H. schachtii, H, trifolii, H. ustinovi (=H. iri)* and *Punctodera punctata,* as well as one tentatively identified species, *H. orientalis* (Handoo, USDA/ARS, pers. comm.). Many species of cyst nematodes are serious pathogens of agronomic crops. In Michigan, *Heterodera glycines* and *H. schachtii* are major limiting factors in the production of soybeans and sugar beets, respectively. *Heterodera carotae* can reduce carrot yields, but its impact has not been fully determined. Due to the number of cyst nematode species detected, Michigan is often referred to as the Cyst Nematode Capital of the U.S.

3.3.1.1 *Cactodera* spp.

The two species of *Cactodera* found in Michigan are of no agricultural importance. *Cactodera weissi* has existed in Michigan for at least 60 years and its type host is Pennsylvania smartweed, *Polygonum pennsylvanicum.* This weed is very abundant in the lower peninsula, hence we believe this nematode species is also widely distributed throughout this region. *Cactodera weissi* was first reported in Michigan in a 1971 (Brzeski, pers. comm.). It is found at an annual frequency of up to 1% in samples submitted to Michigan State University (MSU) Diagnostic Services. The type host for *C. milleri* is common lambsquarters, *Chenopodium album*. *Cactodera milleri* was described by Graney and Bird (1990). Other species of *Chenopodium* also serve as hosts for *C. milleri.*

3.3.1.2 *Heterodera avenae*

In a 1983, USDA/APHIS-sponsored a national cereal cyst nematode survey. *Heterodera avenae* was detected in a few locations in Tuscola County, Michigan. All of the sites had a similar production system history and ownership (Bernett 1986). A state-wide survey conducted soon after its initial discovery, revealed no additional detections although many economically significant hosts for this nematode grow in Michigan. Field trials in Michigan in 1986 indicated small grain yield losses can be associated with the presence of *H. avenae* (Bernett 1986). The farms with the original infestations were all managed with the same equipment. Although there are many hosts for this nematode in Michigan, no additional detections have been reported in the last three decades.

3.3.1.3 *Heterodera carotae*

The carrot cyst nematode, *Heterodera carotae,* was found in 1979 during a survey of organic soil (histosol) carrot/onion fields (Graney 1985). Results of surveys conducted in 1986 and 1988 to delineate the distribution of the carrot cyst nematode in Michigan indicated *H. carotae* was widely distributed in the major carrot production areas and had a frequency of detection of roughly 68% in the 43 fields surveyed (Berney and Bird 1992). *Heterodera carotae*, however, has never been detected in mineral soil carrot production systems in Michigan. In addition, *H. carotae* is often detected concomitantly with *Meloidogyne hapla,* so its impact on field-grown carrots is difficult to determine. For soil samples collected the fall prior to carrot, nematode control is recommended if *H. carotae* egg counts exceed 500/100 cm^3 soil. This threshold is essentially the same as that established by Oostenbrink (1972). Berney (1994) found that *H. carotae* had two root exudate mediated peaks of egg hatch. Hatch was common at 10 °C, complete at 15 °C and reduced at both 5 °C and 20 °C. No hatch occurred at 25 °C. Beginning in the early 1990s, however, much of the carrot production in Michigan began shifting from histosols to mineral soils.

3.3.1.4 Soybean Cyst Nematode, *Heterodera glycines*

The initial detection of the soybean cyst nematode (SCN), *H. glycines,* was in Gratiot County in April 1987. Random surveys of soybean fields were performed for SCN in 1992 and 1993 (Warner et al. 1994a). A statistically valid survey was conducted in 2010–2011 (Schumacker-Lott 2011). The Warner and Schumacher-Lott surveys indicate that slightly more than 50% of the 890 thousand Michigan soybean hectares are infested with *H. glycines*. In addition, Michigan has a SCN sampling program funded by the Michigan Soybean Promotion Committee. Over 22,000 samples have been submitted as of 2017, with 41 counties testing positive for SCN. The results covered 50 counties and indicated that on an annual basis, between 45% and 70% of the samples test positive for *H. glycines*.

Soybean cyst nematode is the most important plant pathogen of soybean in the U.S. If a grower opts to use an SCN-susceptible soybean variety on a site where SCN exists, 50% or greater yield loss can occur. Estimates in Michigan place yield loss at 5%, which costs growers about $40,000,000 annually. The Gratiott County location of the first Michigan detection was not harvested the previous year due to the low yield caused by SCN. At another site, bean yields were frequently below 70 kg/ha. In 1999–2000, Chen et al. (1995a) demonstrated both inter and intra-specific competition between *Glycines max* and *Chenopodium album* in the presence of *H. glycines*. Avendano (2003) conducted a comprehensive spatial distribution characterization in a Michigan soybean field. The nested design at 1-month intervals revealed a strong correlation between soil texture, pH, calcium and *H. glycines*. Bates (2006) reported that specific oilseed radish and Oriental mustard cultivars may have potential for use as trap crops for *H. glycines* and that some populations of this species appear to be aggressive in regard to PI 88788 as a source of resistance. In 2010 and 2011, Schumacher-Lott (2011) found significant greater yields in SCN-infested fields planted to PI 88788 and PI 437654-derived cultivars, compared to SCN-susceptible cultivars. Currently, HG and SCN Type testing are performed in the Diagnostic Lab at MSU (Warner et al. 2016). From 2014 to 2017, 97 SCN type tests were conducted. Approximately 95% of the SCN populations tested developed on the indicator line PI 88788 (SCN Type 2 populations), which is the source of resistance present in close to 98% of all SCN-commercially available SCN resistant varieties in maturity groups 0–3 soybeans. This a strong indication that a significant portion of Michigan *H. glycine* populations have become highly aggressive. A potential SCN trap crop blend of a trap crop legume, Wheeler rye and Maximus oilseed radish was tested in 2017–2018.

3.3.1.5 Hop Cyst Nematode, *Heterodera humuli*

The hop cyst nematode, *Heterodera humuli* was first detected in Michigan in 2012. It was found in a sample submitted to Diagnostic Services from an unthrifty hop planting. The site of the single detection of the hop cyst nematode yielded 241 *H. humuli* cysts/100 cm^3 soil. Michigan has a long history of hop production. It is highly probable that *H. humuli* exists in other hop yards.

3.3.1.6 Sugar Beet Cyst Nematode, *Heterodera schachtii*

The second plant parasitic nematode documented in Michigan was the sugar beet cyst nematode *Heterodera schachtii* (SBCN) (Bockstahler 1950). In a 1999 nematode survey of Michigan's sugar beet industry, Miller et al. (1999) found *Heterodera schachtii* widely distributed in six Michigan counties in the Thumb region (East Central Michigan). This nematode was also reported by Brzeski (pers. comm). in 1971. Three surveys for SBCN have occurred over the past 20 years: 1998, 2007 and 2012. The results have been similar in that SBCN occurs in 20–25% of samples collected from sugar beet fields. Michigan has a long history of sugar beet production, with roughly about 61,000 ha of beets grown annually. SBCN occurs in all of the major sugar beet producing areas and historically reduced beet yields 10,000–45,000 kg/ha. Muchena (1984) showed there were three generations of *H. schachtii* per year on *Brassica oleracea* cv. *Capitate*. Bates (2006), confirmed the potential of oilseed radish cvs Adagio and Colonel as trap crops for *H. schachtii*. Caswell's et al. (1986) model of *H. schachtii* remains one of, if not the most, comprehensive of all nematode simulation models.

3.3.1.7 Clover Cyst Nematode, *Heterodera trifolii*

The clover cyst nematode is detected at 5–20% in samples collected from forage legume fields in Michigan. It has never been considered an economic issue in Michigan in commercial production systems. This species was first reported to be present in an unpublished report by Brzeski (pers. comm.) in 1971. Relatively little is known about the biology and ecology of the clover cyst nematode in Michigan. In 2014, a greenhouse trial was conducted with alfalfa (Foregrazer), crimson clover, two varieties of red clover (Dynamite and Gallant), white clover (Domino), yellow sweet clover and rape (Dwarf Essex). Gallant red clover was the best host tested. *Heterodera trifolii* females and cysts were recovered from all of cultivars tested, but not from alfalfa or dwarf Essex rape.

3.3.1.8 *Heterodera ustinovi*

This species of cyst nematode occurs on golf greens where creeping bentgrass, *Agrostis stolonifera*, is grown. Detection of *Heterodera ustinovi* is 10–15% in samples submitted to Diagnostic Services from golf courses. In a 1993 survey of golf courses, *H. ustinovi* was recovered from about 10% of 106 samples. Creeping bentgrass is a good species for use on golf greens in temperate climates, but many greens are now dominated by annual bluegrass, *Poa annua. Heterodera ustonovi* prefers *Agrostis* sp., whereas, a second species of turfgrass nematodes, *Punctodera punctata*, prefers *Poa* plants. Most of the detections of *H. ustinovi* have occurred on golf courses and country clubs near metropolitan Detroit. Evidence suggests that nematode-infested sod was used for construction of the greens. Like many of the other plant parasitic nematodes associated with turfgrass, formal pathogenicity studies have not been conducted. Occurrence of this nematode, however, is usually associated with symptoms of foliar necrosis not attributed to other causes.

3.3.1.9 *Heterodera orientalis*

In the spring of 2000, a sample of *Miscanthus sinensis* was submitted to MSU Diagnostic Services. Numerous cysts were extracted from the soil. We attempted to identify these cysts to species using Mulvey and Golden's (1985) key to the cyst-forming genera and species of Heteroderidae. After two unsuccessful attempts, the cysts were sent to Dr. Z. Handoo (USDA-ARS, Beltsville, Maryland), who tentatively identified them as *Heterodera orientalis.* Unfortunately, we were not able to maintain a greenhouse culture of this nematode. The tentative identification, therefore, stands. We have not isolated this nematode from any other samples of grasses submitted for analyses since the initial detection.

3.3.1.10 *Punctodera punctata*

This species of cyst nematode was first identified in Michigan by Brzeski (pers. comm.) in 1971. White females were observed on the roots of Kentucky bluegrass, *Poa pratensis,* collected from a home lawn near Grand Rapids. The nematode was identified as *H. punctata*. Until recently, *P. punctata* had only been found associated with *P. pratensis* in Michigan. It was found in samples collected from home lawns and sod farms at a frequency of up to 5%. The first detection on a golf green was in 2012. *Punctodera punctata* is now recovered in about 5–10% of the samples collected from golf greens in MI. In a 1992 survey of golf courses, *P. punctata* was recovered from about 10% of 106 samples. Annual bluegrass now is the dominant grass species on many of golf greens, at least in the southern portion of the lower peninsula. While formal pathogenicity tests have not been conducted, anecdotal evidence suggests its feeding results in the development of necrotic symptoms on annual bluegrass golf greens.

3.3.2 Root Knot Nematodes

In his 1953 nematode survey, B. G. Chitwood identified twenty-eight taxa of plant parasitic nematodes including *Meloidogyne* spp. associated with vegetable and specialty crops (Table 3.2). *Meloidogyne hapla* is by far the most common of the four species of root knot nematodes currently recognized in Michigan. It is common (20–50%) in diagnostic samples from vegetables, brassicas, legumes, stone fruit, pome fruit, grapes and field-grown herbaceous perennials; infrequent (5–20%) on soybeans, dry beans, strawberry, raspberry, and field-grown woody ornamentals; rare (1–5%) on sugar beets and never (0%) on grains grasses/turf and blueberry.

Meloidogyne incognita and other *Meloidogyne* spp. are often associated with greenhouse crops and imported transplants. The fourth species, *M. naasi,* is not uncommon on turfgrass.

Under Michigan field and greenhouse environments, the northern root knot nematode, *M. hapla* and the southern root knot nematode, *M. incognita,* cause typical root galls, resulting in both necrotic and hypoplastic shoot system symptoms.

Slinger and Bird (1978) conducted a comprehensive study of the ontogeny of the carrot tap root in regards to pathogenesis by *M. hapla*. In addition to deformation of the tap root, plant maturity was delayed about 14 days. Kotcon (1979) found that both rotation crops and weeds impacted the population densities of predaceous nematodes in organic soil, but was not able to show a relationship between *M. hapla* and predaceous nematodes. Olsen (1984) demonstrated the benefits of having corn in crop rotations in *M. hapla* infested sites. MacGuidwin (1983) reported a single annual generation of *M. hapla* association with onions, and a negative linear relationship between mid-season *M. hapla* population density and onion bulb yield (MacGuidwin et al. 1987). The relationship generally resulted in yield losses less than those associated with other Michigan vegetable crops. *M. hapla* population development was similar in both *Glomus fasciculatum*-infected and non-mycorrhizal onion plants (MacGuidwin et al. 1985). The symbiont enhanced onion biomass in the absence, but not in the presence of *M. hapla*.

Meloidogyne nataliei (Michigan grape root knot nematode) is a highly unique taxon with a known global distribution limited to five townships in Southwest Michigan. This species has unique morphology, cytogenetics and biology (Golden et al. 1981). White females and egg masses are readily observable in November, under Michigan growing conditions. This species has a very limited host range (Diamond and Bird 1994) and a known distribution limited to a small geographical area in Michigan (Bird et al. 1994). "Studies of oogenesis and spermatogenesis revealed that *M. nataliei* is a diploid amphimictic species with four (n), relatively large chromosomes, and possibly with an XX (female)-XY (male) mechanism of sex determination. It differs considerably from all other amphimictic or meiotically parthenogenetic species of *Meloidogyne* which have 13–18 smaller chromosomes" (Triantaphyllou 1985). It is a species that needs to be studied in greater detail in regards to its overall relationship to the evolution of the Meloidogyninae.

3.3.3 Root Lesion Nematodes

Pratylenchus penetrans is considered the most common plant parasitic nematode in Michigan. While other *Pratylenchus* spp. exist, no recent survey at the species level has been undertaken. A highly aggressive population of *P. penetrans* exists in mineral soil in West Central Michigan. A 1988 survey of Michigan's potato industry found *Pratylenchus*, predominately *P. penetrans*, in more than 50% of the fields surveyed. There are about 80 described *Pratylenchus* spp. of which some are highly pathogenic, whereas, others have very little impact on host ontogeny. For several decades in Michigan, *P. penetrans* has been referred to as the "Penetrans Root Lesion Nematode". The 1980 study of *P. penetrans* associated with navy beans (*Phaseolus vulgaris*) demonstrated aggregate distribution of this nematode under field conditions. It also showed the variability among different plant cultivars in both nematode population development and plant symptoms associated with this host-parasite relationship. Olsen (1984) demonstrated the wide host range of *P. penetrans* associated with Michigan crops. As the predisposition agent for the Potato Early-Die Disease Complex, potato tuber yield losses are about 50% and range from 5500 to 22,500 kg/ha. Chen (1995) partitioned the below-ground potato biomass into eight components: seed piece, below-ground stem, stolons, basal roots, nodal roots, stolon roots, tuber roots and tubers in regards to *P. penetrans* population development. This species parasitized basal root, nodal root, stolon root, tuber root and stolon tissues. Basal root tissue was damaged as early as 21 days after planting and highly correlated with final tuber yield. Chen et al. (1995a, b) significantly reduced risk to the potato early-die disease complex and increased tuber yields with 2 years of rotation with a legume. Wernette (2011) studied the vertical distribution of *P. penetrans* and found it more common in the upper 30 cm of soil than at a

Pratylenchus penetrans Risk	*Verticillium dahliae* Risk					
	0	1	2	3	4	5
0	0	1	2	3	4	5
1	1	1	2	3	4	5
2	2	2	3	4	5	5
3	3	3	4	4	5	5
4	4	4	5	5	5	5
5	5	5	5	5	5	5

Risk	RLN / 1.0 g root +100 cc Soil	*V. dal*. Dil. Plate / g Soil	*V. dal*. Wet Siev. /10 g Soil
0	0	0	0
1	1-25	2	1-15
2	26-75	4	16-35
3	76-150	6	36-60
4	151-300	8-16	61-100
5	>300	>16	>100

Fig. 3.1 Michigan potato early-die disease complex risk matrix

Fig. 3.2 Carrot symptoms associated with an extremely aggressive population of *Pratylenchus penetrans*

30–60 cm soil depth. A potato early-die risk matrix is used in Michigan for making management recommendations in regards to this infectious disease (Fig. 3.1). The highly aggressive population of *P. penetrans* that exists in West Central Michigan is known to reduce marketable carrot yields by 50% (Fig. 3.2).

Elliott used a holistic approach to study the ecology of *P. penetrans* associated with navy beans. She detected it in aggregate distributions in 68% of Michigan bean fields, with a pathogenic relationship with cv. Sanilac. Cultivars Gratiot, Saginaw and Kentwood exhibited tolerance (Elliott and Bird 1985). Pathogenic severity and nematode population development was impacted by soil texture, moisture and temperature. Mycorrhizal associations appeared to be minimal in this system (Elliott et al. 1984a). Aldicarb provided effective control (Elliott et al. 1984b) and was used in this system for almost three decades.

Noling et al. (1984) used three population densities of *P. penetrans* and three population densities of the Colorado potato beetle (*Leptinotarsa decemlineata*) to study the joint action of these key limiting factors in potato production in Michigan. Root population densities of *P. penetrans* were significantly less in plants grown in the presence of *L. decemlineata*, compared to those maintained in the absence of this insect.

Studies on the joint impact of soil nutrition and *P. penetrans* in Michigan potato production began in 1980 and had a significant impact on the evolution of the concept of soil health and soil health biology in regards to overall Michigan agriculture (Vitosh et al. 1980; Bird and Smith 2013; Snapp et al. 2016). *Pratylenchus penetrans* was included among bacterial canker, nutrition, soil pH and winter injury, as factors associated with the decline of sweet cherry trees in Michigan (Melakeberhan et al. 1993). Melakeberhan et al. (1994) described the impact of *P. penetrans* on cherry rootstock growth and development and in a 1995 study, Melakeberhan et al. (1997) described the relationship between *P. penetrans* and the nutrition of *Prunus avium* rootstocks.

3.3.4 **Pratylenchoides** ***spp.***

Historically, a species of the false root lesion nematode was commonly associated with mint production in organic soils in Michigan. It resulted in stunted plants and reductions in oil quantity. Because of this and other issues association with organic soil degradation, most of the Michigan mint industry has moved to mineral soils. *Pratylenchoides laticauda* has not been detected in Michigan in mineral soils.

3.3.5 Stubby Root Nematodes

In his 1953 nematode survey, B. G. Chitwood detected trichodorids associated with vegetable and specialty crops. While seven species classified in the Trichodoridae have been reported from Michigan (Table 3.2), their frequency of occurrence and population densities appear to have declined during the past two decades. Wernette (2011) studied the vertical distribution of *Paratrichodorus pachydermus*, a vector of Corky Ring Spot Disease of potato caused by *Tobacco rattle virus.* Its occurrence was more common at a soil depth of 30–60 cm, compared to a 0–30 cm soil depth.

3.3.6 Dagger Nematodes

The 1953 Michigan nematode survey by B. G. Chitwood detected *Xiphinema* sp. associated with Michigan orchards, vineyards, berries, cover crops, nurseries, florists and forests (Table 3.2). The 1966 nematode survey of Michigan cultivated blueberry plantings showed an association between *Xiphinema americanum* and *Necrotic Ring Spot Virus* symptoms (Tjepkema 1966). Other important virus diseases of Michigan crops associated with *X. americanum* as the vector include *Tomato Ring Spot Virus* disease of grapes, union necrosis of cherry and stem pitting of cherry (Ramsdell et al. 1995). *Xiphinema americanum* is commonly associated with tree fruit orchards, vineyards and other sites throughout Michigan. *Xiphinema rivesi* is also detected in these ecosystems on a less frequent basis. Both species serve as important vectors of *tomato ringspot virus* disease associated with apple, cherry and grape production. In addition, *Xiphinema diversicaudatum* was recently identified by the junior author of this chapter from a soil sample from roses grown in a Detroit greenhouse. It was previously detected from greenhouse rose samples in 1966.

3.3.7 Needle Nematodes

Longidorus elongatus is not uncommon in Michigan in both mineral and organic soils. It can be a serious problem in celery production. *Longidorus breviannulatus* is present, but limited to corn production in very coarse-textured sandy soils. Yield losses associated with this nematode can be extensive.

3.3.8 Other Ectoparasites

In his 1953 nematode survey, B. G. Chitwood detected criconematid species associated with Michigan orchards, vineyards, berries, cover crops, nurseries, florists and forests. The 1966 survey of 30 commercial blueberry farms by Tjepkema, detected *Atylenchus decalineatus*, *Nanidorus minor, Mesocriconema* spp., *Hemicliophora* spp., *Hoplolaimus galeatus*, *Tylenchorhynchus claytoni*, and *T. joctus*. Species of the Criconematinae, Paratylenchinae and stunt nematode taxa are currently common throughout Michigan agriculture and forest ecosystems. Both ring and stunt nematodes exist in a diversity of genera and species, whereas, known *Paratylenchus*

Table 3.4 Results of 32 years (1974–2015) of nematicide research for control of the potato early-die disease complex

Nematicide (rate and number of years of data)	Mean tuber yield
Non-treated control (32 years of data)	255 cwt/A
Metam (37.5 gal/A, 15 years of data)	387 cwt/A
Oxamyl (4.0 lbs. a.i/A, 11 years of data)	324 cwt/A
Ethoprop (6 years of data)	324 cwt/A
Telone (5 years of data	316 cwt/A
Aldicarb (17 years of data)	306 cwt/A

spp. are limited to *P. hamatus* and *P. projectus. Paratylenchus hamatus* is common in organic soils; whereas, *P. projectus* is common in mineral soils (Knobloch and Bird 1981b). *Lobocriconema thornei* was described by Knobloch and Bird (1978) from a forest location.

Michigan is home to approximately 900 golf courses. Two surveys of golf greens have been conducted; one in 1993 (Warner et al. 1994b) and another in 2017. Turfgrass species grown on golf greens are hosts to many genera of plant parasitic nematodes. At least 12 genera were identified without attempting to separate the stunt nematodes (*Merlinius, Quinsulcius* and *Tylenchorhynchus*) into their appropriate genera. Ring, spiral and stunt nematodes are, by a wide margin, the most frequently detected plant parasitic nematodes in golf green soil in Michigan (Table 3.4). The other genera/species of nematodes that are detected at frequencies >10% in turf samples from Michigan golf greens are *Hoplolaimus galeatus, Meloidogyne naasi,* and *Pratylenchus* spp.

3.3.9 Stem and Foliar Nematodes

In his 1953 nematode survey, B. G. Chitwood detected *Ditylenchus destructor* associated with vegetable and specialty crops. While known to be present in the past, the potato rot nematode, *Ditylenchus destructor* has not been detected in Michigan during the last 40 years. The stem and bulb nematode, *Ditylenchus dipsaci,* also known as the onion bloat nematode, is the most common shoot system tissue-feeding nematode in Michigan. It is frequently associated with herbaceous perennial ornaments. In the past, it was commonly associated with onions, and with garlic in more recent years. Schnabelrauch et al. (1980) reported evidence for four generations of *Ditylenchus dipsaci* associated with *Phlox subulata* during the first year of their study. This was followed by a significant population decline under field or storage conditions and only a single generation the following year. The chrysanthemum nematode, *Aphelenchoides ritzemabosi* is often associated with the greenhouse flower industry.

3.4 Management

At least 45 nematicides have been registered for use in Michigan (Table 3.5). In the late 1950s, halogenated hydrocarbon insecticides were used extensively on the Michigan State University (MSU) campus. This resulted in a serious robin-mortality problem. It also served as a catalyst for Rachel Carson's, land-mark book entitled, *Silent Spring* (Carson 1962). It resulted in a dynamic transdisciplinary team of MSU faculty working with scientists from Cornell University, University of California-Berkeley and Texas A&M University on the development of the philosophy and practices of Integrated Pest Management (IPM). While overall leadership for the MSU portion of this initiative came from the Department of Electrical Engineering and Systems Science, MSU nematology was responsible for the Extension-outreach component. In October of 1974, MSU hosted the Second U.S.A.-U.S.S.R. Symposium. It was entitled *Modeling for Pest Management: Concepts, Techniques and Applications* (Tummala et al. 1976). Volume 30 of BioScience (1980) was dedicated to Pest Management and included an article by Bird and Thomason (1980) entitled, *Pest Management, a Nematological Perspective.* This was expanded by Bird et al. (1985) in Volume II of Sasser's *Advanced Treatise on Meloidogyne*. Nematology continued to play an important role in IPM. In 1979–1980, Ivan Thomason of the Department of Nematology at the University of California-Riverside did a sabbatical leave at MSU. This resulted in development of the California State-Wide IPM Program. In addition, it became recognized that IPM had significant social and political attributes (Bird and Ikerd 1993). *The Integrated Pest Management Experience* (in) *Reform and Innovation of Science and Education Planning for the 1990 Farm Bill* was written from the view of a nematologist (Bird 1989). Much of the original U.S. IPM legislation is still in pace in 2017.

The IPM philosophy was incorporated into the Low Input Sustainable Agriculture (LISA) legislation of the 1985 Farm Bill which evolved into the Sustainable Agriculture Research and Education (SARE) legislation in the 1990 Farm Bill (Bird 1992). This was the stimulus for development of the highly popular Extension Bulletin entitled, *Michigan Field Crop Ecology*, which contains multiple chapters on nematodes (Cavigelli et al. 1998; Bird et al. 1998). The next steps included pioneering involvement in the soil health movement (Sanchez et al. 2003; Yao et al. 2005) and social aspects of conventional, alternative and organic agriculture systems (Francis et al. 2006; Kirschenmann and Bird 2006). The four fundamental strategies of Integrated Nematode Management (INM) include (1) exclusion/avoidance, (2) containment, (3) plant parasitic nematode population reduction and (4) do nothing. The current available tactics are essentially the same as described by Bessey in 1911. Recommendations of control of plant parasitic nematodes associated with fruit, vegetable and ornamental crops are published in MSU Extension Bulletins E-154 and E-312 (Bird and Warner 2015a, b). The objective of the Management Section of this chapter is to describe the current state of INM in Michigan.

Table 3.5 Nematicides marketed in Michigan 1973–2017

Common name	Active ingredient	Company
Aveo EZ	*Bacillus amyloliquefaciens* strain PTA-4838	Valent U.S.A. Corp.
Avicta Duo Corn	12.4% Abamectin; 28.1% Thiamethoxam	Syngenta
Avid 0.15EC	2.0% Abamectin	Syngenta
Avid 0.15EC	2.0% Abamectin	Sygenta
Basamid	99% Tetrahydro-3,5,-dimethyl-2H-1,3,5-thiadiazine-2-thione	BASF
BIOst Nematicide 100	94.46% *Burkholderia* spp. Strain A396 (heat killed)	Albaugh
Brom-O-Gas	96.75% Methyl bromide	Great Lakes Chemical Co.
ClandoSan 618	crustacean exoskeletons (10.4 lbs. N per 100 lbs. product)	IGENE Biotechnology, Inc.
Clariva	*Pasteuria nishiwazae*	Syngenta
Counter 20G	20% terbufos (OP)	AMVAC
Curfew EC	97.5% 1,3-dichloropropene	Dow AgroSciences, LLC
Nemagon 8.6 EC	1,2-Dibromo-3-chloropropane (8.6 lbs./gal)	Shell
DiTera DF	90% *Myrothecium verrucaria* strain AARC-0255 w/w	Valent Biosciences
Divanem 0.15 EC	2.0% Abamectin	Syngenta
Dursban 50W	50% chlorpyrifos (OP)	Dow AgroSciences, LLC
Dylox 80	80% Trichlorfon	Bayer
EarthMAX	4.2% humic acid	Harrell's
EDB	Ethylene-dibromide	Shell
Fumazone 70E	70% 1,2-Dibromo-3-chloropropane	Dow
Furadan	10% Carbofuran	FMC
ILevo	48.4% fluopyram	Bayer
Indemnify	34.5% fluopyram; 7.7% 1,2-propanediol	Bayer
Kontos	22.4% Spirotetramat	OHP, Inc.
K-PAM HL	54% potassium N-methyldithiocarbamate	AMVAC
Lorsban 15G	15% chlorpyrifos	Dow AgroSciences, LLC
Luna Tranquility		Bayer
Majestene	94.46% *Burkholderia* spp. Strain A396 (heat killed)	Marrone Bio Innovations
MeloCon WG	6% *Paecilomyces lilacinus* strain 251	Certis
Mocap 15G	15% Ethoprop (OP)	AMVAC
Mocap EC	69.6% Ethoprop (OP)	AMVAC
Movento	22.4% Spirotetramat	Bayer
Multiguard protect 90EC	90% furfural	Agriguard Co. LLC
NemaKILL	32% cinnamon oil; 8% clove oil; 15% thyme oil	Cisco

(continued)

Table 3.5 (continued)

Common name	Active ingredient	Company
NemaStrike	Tioxazafen, a disubstituted oxadiazole	Monsanto
Nematec	0.56% plant extract	Sci Protek, Inc.
Nematode control	Geraniol oil, egg powder and lecithin	Growers Trust
Nem guard gold	3.33% *Bacillus chitinosporus*	Agro Research International
Nimitz	40.0% fluensulfone	Adama
Nortica	5% *Bacillus firmis*	Bayer
Poncho/votivo	40.3% clothalandin; 8.1% *Bacillus firmis*	Bayer
Pylon	21.4% chlorfenapyr	OHP, Inc.
Sectagon	54% potassium N-methyldithiocarbamate	Tessenderlo Group
Telone C-17	81.2% 1,3-dichloropropene; 16.5% chloropicrin	Dow AgroSciences, LLC
Telone C-35	63.4% 1,3-dichloropropene; 34.7% chloropicrin	Dow AgroSciences, LLC
Telone II	97.5% 1,3-dichloropropene	Dow AgroSciences, LLC
Temik 15G	15% Aldicarb (carbamate)	Bayer
Thimet 20G	20% Phorate	AMVAC
Vapam HL	42% methyl dithiocarbamate	AMVAC
Velum	15.4% fluopyram; 22.2% imidacloprid	Bayer
Velum Prime	41.5% fluopyram	Bayer
Vorlex	1,3-D, 1,2-D and methyl isothiocyanate	Agrevo
Vydate L	24% Oxamyl (carbamate)	Dupont

3.4.1 Cysts Nematodes

In general, cyst nematodes have been more difficult to manage than other plant parasitic nematodes under Michigan conditions.

3.4.1.1 *Heterodera carotae*

Because of the extremely narrow host range of *Heterodera carotae*, risk of infestations can be avoided or reduced through rotations with non-host crops. Movement of the majority of the Michigan carrot acreage from high value organic soil used primarily for vegetable production, to mineral soils suitable for agronomic crop production, significantly increased the potential for rotations with non-host crops. Growers with a previously documented *H. carotae* problem or low marketable yields are encouraged to submit soil samples to MSU Diagnostic Services each fall before the next carrot crop. Carrot production systems with *H. carotae* in organic soil use both fumigant (Telone II and metam sodium) and non-fumigant nematicides (oxamyl) for control of this nematode.

3.4.1.2 *Heterodera glycines*

Crop rotation is recommended to reduce the risk of sites not infested with *H. glycines* from becoming infested and maintaining population densities below the damage threshold for this host-parasite relation. Soil analysis for *H. glycines* population dynamics determination is recommended on a 3-year basis. The length of any rotation should be based on the number of eggs/100 cm^3 soil. Soybeans should not be grown if SCN egg counts exceed 10,000/100 cm^3 soil. For predictive purposes, we estimate declines of 50% annually in SCN population densities in the presence of non-host crops. Producers should avoid growing SCN-susceptible soybean varieties if this nematode is detected in any soil sample. Use of soybean cultivars derived from the PI 88788 source of *H. glycines* resistance is common. Sites with yields less than 1350 kg/ha are expected with a susceptible cultivar, while, yields greater than 3000 kg/ha are expected with a resistant cultivar.

While growers are encouraged to rotate sources of *H. glycines* resistance, sources other than PI 88788 have not been readily available in recent years. This has resulted in an increase in highly aggressive populations, referred to as SCN or HG Types 1, or 1.2, reducing the yield potential enhancement of PI 88788-derived varieties (Warner et al. 2016). Soybean growers are experimenting with chemical, biological and plant health regulator seed treatments. These, however, are only designed for use with resistant varieties. Several new chemical nematicides for soil application are also in the development stage. To manage SCN, soybean producers grow SCN-resistant soybean varieties and rotate to non-host crops. The results of an SCN Type test can aid growers in selecting the best sources of SCN resistance found in commercial varieties. SCN Type testing provides growers information about the aggressiveness of their SCN populations. Most Type 2 populations are slightly or moderately aggressive at this time. A comprehensive analysis of SCN management is included in the 2018 book chapter entitled, "Role of Population Dynamics and Damage Thresholds in Cyst Nematode Management" (Bird et al. 2018). Michigan Farm Bureau, Michigan Agribusiness Association, Michigan soybean Promotion Committee and Michigan State University Extension have formed a Michigan SCN Resistance Management Coalition Partnership with more than twenty other states and eight industry partners. In addition to these partners, funding for this unique Coalition has been made available from the United Soybean Board and the North Central Soybean Research Program.

3.4.1.3 *Heterodera humuli*

While no research on hop cyst nematode management has been conducted in Michigan, Warner et al. (2015) were requested to write the nematode section of a Hop Production Bulletin. The following is a condensation of their recommendations. Avoidance/prevention is the key management strategy. This is primarily achieved through planting hop cyst nematode-free crowns. If a site does become infested, it is imperative that the nematodes are contained to that site, avoiding any activities that move soil and transport nematodes. Always be sure to clean equipment free from soil if working with soil infested with cyst nematodes. Mocap EC (ethoprop) is labeled for use on hop as a pre-plant and post-plant insecticide/nematicide. Cyst nematodes, however, can be difficult to control chemically and there is no information available to suggest that Mocap use results in population reductions of hop cyst nematodes as the product is recommended for insect control. Hop cultivars differ in their susceptibilities to hop cyst nematodes, but in general, most appear to support the nematodes quite well. Improving soil health can be beneficial because as the diversity and numbers of beneficial organisms in the soil increase, often the numbers and impacts of plant pathogens including nematodes, decrease. If hop cyst nematodes are detected in a hop yard, growers must then learn to optimize crop growth and yields in the presence of these nematodes because of the long-term persistence of cyst nematodes.

3.4.1.4 *Heterodera schachtii*

Historically, sugar beet cyst nematode management in Michigan was based on crop rotation. Since production is controlled by the sugar companies, beets were only allowed to be planted in non-infested sites once every 3 years. Fields with known *H. schachtii* infestations were limited to 5-year rotations. A few growers used soil fumigant (Telone, Vorlex) or non-fumigant (aldicarb) nematicides. Muchena and Bird (1987) evaluated the role of fenamiphos as a nemastat for control of *H. schachtii.* Subsequently, the crop rotations were shortened, resulting in increases in *H. schachtii* problem sites. Infested sites often yielded less than 25 tons per hectare, whereas, non-infested sites yielded double this amount. The development and availability of *H. schachtii* tolerant cultivars, in addition to other management changes, significantly enhanced beet yield potentials. Yields greater than 75 tons per hectares are not uncommon. It is recommended that growers sample their fields for SBCN either in the fall prior to a sugar beet crop or during an existing beet crop. Since the release of the first SBCN-tolerant (resistant) beet varieties in the mid to late 1990s, Michigan's sugar beet yields have increased significantly and awareness of SBCN is greatly elevated. Bird, Tylka and Zasada included an economic spreadsheet for SBCN decision-making in their 2018 book chapter entitled, "Role of Population Dynamics and Damage Thresholds in Cyst Nematode Management".

An additional important innovation is the use of a *H. schachtii* trap crop following wheat, pickles (Michigan grows pickles, not cucumbers) or peas, in the year prior to sugar beets. The trap crops are limited to *Raphanus sativus oleiferus* (oilseed radish) and are cultivar specific (e.g. Adagio, Colonel, Defender and Maximus). *Raphanus sativus longipineatus* (Daikon-type radish) is not a trap crop for *H. schachtii*. The *H. schachtii* trap crops attract second-stage juveniles. After root penetration, the nematode signals (cross-talk) for the plant to produce nurse cells. The plant fails to respond to the signal and the nematode dies without producing a next generation. The R-value (reproductive factor) for the *H. schachtii* trap crop ranges from about 0.01–0.10. Michigan sugar beet growers are also experimenting with biological seed treatments. The sugar beet industry has become one of the leaders in development of the concept of soil health.

3.4.1.5 *Heterodera ustinovi* and *Punctodera punctata*

Heterodera ustinovi has a strong preference for creeping bentgrass cv. Toronto. It does not develop well on bluegrasses and fescues. Rotation of grass species, however, is not an option for turf managers. Annual bluegrass is becoming more dominant on creeping bentgrass greens in Michigan, which does not favor *H. ustinovi.* This transition, however, has resulted in the presence of *Punctodera punctata* on these greens. A number of new nematicides including Divanem®, Indemnify® and Nimitz® have been registered for nematode control on turf. They have not, however, been evaluated for control of *H. ustinovi* and *P. punctata* under Michigan growing conditions. Experience indicates that cyst nematodes can be difficult to control with chemical nematicides. Obtaining a further understanding of the biology and parasitic habits of these two species may aid in the proper timing of nematicide applications.

3.4.2 Root Knot Nematodes

3.4.2.1 *Meloidogyne hapla*

Whenever possible, northern root knot nematode is managed through rotation with non-host crops such as corn, wheat or other small grain. Unfortunately, no resistant cultivars for *Meloidogyne hapla* susceptible crops are available. Soil fumigation with 1,3-D or metam is common for high cash value crops. 1,3-D, however, can be difficult to obtain. Most growers that use these fumigants are certified applicators and have their own application equipment. Methyl bromide is used on an emergency exemption basis in the production of field-grown herbaceous ornamental plants. This chemical is usually applied by a professional soil fumigation company. The most commonly used non-fumigant chemical nematicide is oxamyl. New supplies of this product, however, were not available for the 2016 and 2017 growing seasons. A number of new and old biological nematicides and plant health regulators are being evaluated by Michigan growers. Farms with highly susceptible *M. hapla* crops or problem sites are generally well aware of the situation and maintain formal or information crop yield, nematode management and soil sample records.

3.4.2.2 Michigan Grape Root Knot Mematode, *Meloidogyne nataliei*

In 1980, the Michigan grape root knot nematode became a state-mandated regulatory species for eradication. Known infestation sites were treated with shallow and deep high dosages of ethylene dibromide (EDB). Two decades later, EDB was detected in groundwater at the sites treated with this soil fumigant. In 2017, active populations of *Meloidogyne nataliei* were collected from at least two of the original infestation (eradication) sites.

3.4.2.3 *Meloidogyne incognita* and *M. naasi*

The southern root knot nematode is managed under greenhouse conditions through the use of soil sterilization, use of nematode-free propagation stocks and nematicides. Although *Meloidogyne incognita* has never been shown to survive Michigan winter conditions, Michigan potato enterprises have southern root knot nematode problems as far north as Indianapolis, Indiana. Additional climate change has the potential to allow for the over-wintering of *M. incognita* in the southern tier of Michigan agricultural counties. Nematicides are currently being evaluated for control of *M. naasi* in turf.

3.4.3 Root Lesion Nematodes

3.4.3.1 *Pratylenchus penetrans*

As the most common plant parasitic nematode in Michigan, control measures are required for a significant number of both annual and perennial crops. Before losing their registrations, use of EDB (Ethylene di-bromide) and DBCP (1,2-Dibromo-3-chloropropane) was common for management of *Pratylenchus penetrans*. Klonsky and Bird (1981) used a computer simulation to show that while the short-term economic loss of these fumigants in tree fruit production would be negligible, the long-term impact would depend on the availability of viable alternatives. Pre-plant applications of soil fumigants, primarily Telone II and metam sodium, are used where warranted for tree fruit, small fruit/grapes, vegetables and ornamentals. When aldicarb (Temik) was first registered for specific commodities, it immediately became the nematicide of choice. When its registrations were cancelled, there was a return to soil fumigation. The rate of 350 l/ha of metam sodium is used for potato early-die management. Some growers changed to other non-fumigant nematicides, predominately oxamyl and ethoprop. The results of 41 years of potato nematicide research clearly demonstrate the impact of these chemicals on tuber yield (Table 3.4).

3.4.4 Turfgrass Biological Control of Ecto and Migratory Endo-Parasitic Nematodes

In a turfgrass trial with *Heterorhabditis bacteriophora* applied through irrigation water, population densities of a mixture of ecto and endoparasitic nematodes were lower in the presence of the entomopathogenic nematode, compared to the absence of this biological control species (Smitley et al. 1992). Until recently, phenamiphos was the most common turf grass nematicide used in Michigan. A significant number of new chemical and biological products are currently being investigated.

3.4.5 Virus Vectors

3.4.5.1 *Xiphinema* spp.

In the presence of *Xiphinema americanum* and *X. rivesi*, new and replant orchard and vineyard sites undergo 1 or 2 years of soil preparation before planting. Ramsdell et al. (1983) evaluated the role of superimposed deep and shallow soil fumigation to control *X. americanum* and *peach rosette mosaic virus* re-infection in a "Concord" vineyard site. Historically, management has involved planting sudax as a cover crop. Recently, the recommendation has changed to Essex rape, because it is a poor to non-host for *X. americanum*. In addition, soil fumigants (Telone II and metam sodium) are used on a pre-plant basis. This is especially used in tart cherry orchards. *Xiphinema americanum* is the key target virus vector. Research has been funded by the Michigan tart cherry industry to find a replacement for soil fumigation. Cover crop blends that contain Essex rape appear promising.

3.4.5.2 *Paratrichodorus pachydermus*

Crop rotation and deep-shallow soil fumigation is used for control of *Paratrichodorus pachydermus* in locations known to be infested with this nematode. Growers have designed and built custom soil fumigant equipment designed to apply metam sodium at both 20 and 40-cm soil depths.

3.4.6 Shoot-System Nematodes

3.4.6.1 Stem and Bulb Nematode, *Ditylenchus dipsaci*

Both aldicarb and oxamyl reduced foliar symptoms of creeping phlox and population densities of *Ditylenchus dipsaci* during the first year after treatment, throughout winter storage and most of the second year (Schnabelrauch et al. 1981). In recent years, seeding, instead of planting bulb sets, is recommended for control of the bulb and stem nematode in onion systems. Crop rotation and use of nematode-free planting stock is essential for *D. dipsaci* management in garlic plantings. This nematode can be a key limiting factor in creeping phlox production. Crop rotation, use of nematode-free planting stock and soil fumigation are recommended and commonly used.

3.4.6.2 Foliar Nematode, *Aphelenchoides ritzemabosi*

Avoidance is by far the best strategy or foliar nematode management. Planting stock and planting media including field soil, should be free of *Aphelenchoides ritzemabosi*. This may require in-house quarantine to assure that crowns are nematode-free. Crop rotation, soil sterilization, foliar nematicides and hot water treatments can all be used as control tactics in specific situations. Hot water at 46 °C for 5–15 min is often adequate. Overhead watering should be avoided to prevent nematode dissemination to non-infested tissue.

3.5 Conclusions

Michigan's highly variable agriculture and nematodes (Table 3.2) evolved in conjunction with the state's great diversity of soils, local climates and talents of immigrant farmers. This fostered a leadership role in the evolution of the concepts of Integrated Pest Management, Sustainable Agriculture, Sustainable and Equitable Development and Soil Health. Today, large specialized farms are highly knowledgeable about nematodes and other associated production technologies. An emerging group of new small farms are having their initial experiences with both plant parasitic and other types of nematodes. In addition, there has been a significant increase in organic agriculture in Michigan (Bird 2017). These developments provide key challenges for nematologists, since the Nematodes of Michigan will always be evolving in response to the dynamics of their associated ecosystems.

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