Chapter 8
Plant Parasitic Nematodes of North Dakota and South Dakota

Guiping Yan and Richard Baidoo

8.1 Introduction

Nematode studies began in the States of North Dakota and South Dakota only in the mid-twentieth century when nematologists were first employed by different state research institutions. Since then, a number of surveys and experiments have been conducted to annotate occurrence, abundance, economic importance and develop management strategies for different plant parasitic nematodes in the Dakotas. This chapter devotes to plant parasitic nematodes which limit or potentially threaten crop production in these states and their management strategies in sustainable agriculture.

8.2 Economically Important Crops in North Dakota and South Dakota

Production agriculture is the largest sector of the economies of both North and South Dakota making up to 25% of their economic bases (USDA-NASS 2015a, b). In North Dakota, the value of crop production in recent years has been estimated at $7–10 billion, with an economic impact of $20–30 billion (Anonymous 2016; USDA-NASS 2016b).

Major crops produced in North Dakota include soybean, wheat, sunflower, corn, dry edible beans, sugar beet and canola. Soybeans, corn, wheat, sugar beet and canola are the top revenue-producing cash crops for the state (USDA-NASS 2016b). The state maintained its position as the top U.S. producer of spring wheat, durum

G. Yan (✉) · R. Baidoo
Department of Plant Pathology, North Dakota State University, Fargo, ND, USA
e-mail: guiping.yan@ndsu.edu

S. A. Subbotin, J. J. Chitambar (eds.), *Plant Parasitic Nematodes in Sustainable Agriculture of North America*, Sustainability in Plant and Crop Protection,
https://doi.org/10.1007/978-3-319-99588-5_8

wheat, dry edible beans, pinto beans, canola and flaxseed in 2015 (Table 8.1). These crops are produced not only for their numerous food and industrial uses, but also for export, contributing immensely to the economy of the state.

About 94% of the soybeans produced in North Dakota is shipped to other states, whereas, approximately 70–75% of the soybeans are exported out of the country. Soybeans are used as food products, animal feed, and hundreds of industrial applications including productions of vegetable oil, margarine, inks, paints, biodiesel fuel, solvents and hydraulic fluids. The canola biodiesel facility at Velva, North Dakota is capable of producing 322 million liters of biodiesel annually. Corn ethanol is also a growing industry in North Dakota. Ethanol plants currently in operation

Table 8.1 Major crops produced in North and South Dakota (2015)

	Planted hectares ($\times 10^6$)	Harvested hectares ($\times 10^6$)	Production in kilogram ($\times 10^9$)	Sales in $ ($\times 10^6$)	U.S. rank (2015)
Soybean	2.44	2.42	6.22	2,253.45	8
Corn	–	1.38	15.93	1,627.48	9
Wheat	3.07	2.99	8.99	1,544.51	1
Canola	0.59	0.59	1.64	436.04	1
Hay	–	1.01	2.57	312.41	9
Beans, dry edible	0.25	0.23	0.55	245.86	1
Potato	0.03	0.024	1.28	210.08	4
Sunflower	0.27	0.27	0.71	205.96	2
Barley	0.29	0.26	0.94	192.96	1
Pea, dry edible	0.23	0.22	0.76	131.21	1
Sugar beet	0.08	0.08	7.74	–	3
Lentil	0.12	0.12	0.23	104.86	2
Flaxseed	0.14	0.13	0.21	64.15	1
Oat	0.12	0.05	0.11	16.34	4
South Dakota					
Corn	2.3	2.22	28.67	2,642.98	6
Soybean	2.10	2.09	6.91	2,328.83	8
Wheat	0.91	0.87	3.0	439.63	6
Sunflower	0.23	0.22	0.66	178.67	1
Sorghum	0.10	0.09	0.99	42.47	7
Oats	0.12	0.04	0.13	17.59	1
Millet	0.02	0.01	0.04	4.76	3
Safflower	0.008	0.008	0.01	3.64	1
Flaxseed	0.004	0.004	0.004	1.15	3
Hay and alfalfa	–	0.03	0.60	–	3

'–' Means data is not available
Source: USDA-NASS (2016a, b)

produce nearly 1.5 billion liters of ethanol annually. North Dakota is number one in the production of two wheat classes: hard red spring and durum. Hard red spring is known for its gluten strength used for the production of high quality bread flours. Durum wheat is used for making spaghetti, lasagna and, at least, 350 other pasta shapes. North Dakota's production of spring wheat and durum wheat in 2014 accounted for 53% and 52% of the total U.S. production, respectively. Canola accounted for 87% and flaxseed accounted for 92% of what was produced in Minnesota. North Dakota produced nearly 45% of the nation's sugar beet crop. Monetary contribution from the sales of the sugar beet produce to the economies in the two states in 2014 were estimated at $2,066 per hectare or $544.6 million.

South Dakota's agriculture industry has more than 7 million ha of cropland and 9 million ha of pastureland and $25.6 billion of economic impact each year, constituting more than 30% of the state's total output (Anonymous 2014). Revenue generated from crop production and further processing alone is more than $13.3 billion annually and is responsible for 70,104 jobs (Anonymous 2014; USDA-NASS 2016a).

South Dakota consistently ranked amongst the top ten states for production of several crops including spring wheat, flaxseed, hay, oat, rye and sunflower seeds. Corn, soybean, oat and wheat are South Dakota's major cash crops; sunflowers, sorghum, flaxseed and barley are also grown. In 2015, total planted area of principal crops including hay, was 3.9 million ha (USDA-NASS 2015a, 2016a). The most economically important crops within the top ten in the US ranking and their production acreages, total production or total sales in 2015 for both states are summarized in Table 8.1.

8.3 Common Plant Parasitic Nematodes in North and South Dakota Fields

8.3.1 Historical Perspective

In 1949, Chitwood discovered the grass cyst nematode, *Punctodera punctata,* during routine soil inspections of potato fields for the golden cyst nematode in Pembina County, North Dakota (Chitwood 1949). This was the first record of this species in the United States. Following this, a *Cactodera* sp. (former *H. cacti* group) was discovered in a soil sample from North Dakota (Spears 1956). In 1958, *Heterodera schachtii* was reported in a soil sample from Cass County (Caveness 1958) but the occurrence of the nematode in the state was not confirmed at that time. From 1963 to 1968, several other nematode genera were detected during surveys in commercial fields of barley, wheat and forage grasses in North Dakota. The plant parasitic nematodes were identified from the genera *Tylenchorhynchus*, *Aphelenchoides*, *Xiphinema*, *Heterodera*, *Pratylenchus*, *Paratylenchus, Meloidogyne*, *Hoplolaimus*, *Tetylenchus*, *Helicotylenchus* and *Trichodorus* (Pepper 1963, 1968).

Tylenchorhynchus spp. were commonly associated with cereals and grasses showing marked root damage, but the cause of the root damage was not ascertained. The associated *Meloidogyne* sp. was identified as *M. incognita* and was detected in greenhouse flower beds adjacent to underground steam lines at the North Dakota State University (NDSU) campus at Fargo, probably since it could not survive North Dakota winter temperatures (Pepper 1963, 1968). Since then, several other plant parasitic nematodes surveys have been conducted and suggested that only selected nematode genera are frequently encountered in North and South Dakota fields (Thorne and Malek 1968; Donald and Hosford 1980; Krupinsky et al. 1983; Bradley et al. 2004; Nelson et al. 2012).

Recent nematode surveys conducted at the North Dakota State University (NDSU) on field crops such as corn, wheat, barley, potato and pea also resulted in detections of *Paratylenchus* spp., *Pratylenchus* spp., *Helicotylenchus* spp., *Tylenchorhynchus* spp. and *Xiphinema* spp. as the most common genera of plant parasitic nematodes in North Dakota agricultural fields (Plaisance and Yan 2015; Upadhaya et al. 2016; Yan et al. 2015b; Yan and Plaisance 2016). These findings corroborate the previous assertion that only specific adapted groups of plant parasitic nematodes are present in the state. In another survey, soybean fields or fields with history of soybean cyst nematode (SCN) were selected to ascertain the incidence and abundance of plant parasitic nematodes and their possible association with SCN. The nematodes identified per 200 g soil were *Helicotylenchus* spp. (incidence: 49%; highest density: 1800 specimens; average density: 174 specimens), *Tylenchorhynchus* spp. (41%; 340; 30), *Paratylenchus* spp. (37%; 2480; 151), *Pratylenchus* spp. (19%; 245; 9), *Xiphinema* spp. (7%; 180; 4), *Paratrichodorous* spp. (4%; 60; 1), *Hoplolaimus* spp. (3%; 140; 2), *Mesocriconema* spp. (1%; 300; 2), SCN juveniles from soil (24%; 1200; 46) and SCN eggs from cysts (56%; 21,540; 501). Interestingly, these nematodes had no or poor association with SCN in the 155 fields surveyed in 2015 (Yan and Plaisance 2016). A summary of plant parasitic nematodes identified in North and South Dakota and their associated crops are presented in Table 8.2.

8.3.2 Soybean Cyst Nematode, **Heterodera glycines** *in North Dakota*

8.3.2.1 Detection and Distribution

The soybean cyst nematode is considered the most damaging pathogen of soybeans in the USA and by far, the most economically important nematode in North Dakota. Heavily infested fields show patchy yellowing of the foliage (chlorosis), stunting of plants, and thin stands with swollen females and cysts attached to roots. The females first appear as lemon-shaped, cream-colored cysts, which later turn brown while still attached to plant roots (Fig. 8.1a, b). Losses of up to 30% have been reported

Table 8.2 Plant parasitic nematodes identified in North Dakota and South Dakota and their associated host plants

Nematode	Host and rhizosphere soil	Reference
Cactodera sp.	Potato	Spears (1956)
Criconema permistus	Grasses	Donald and Hosford (1980) and Donald (1978)
Geocenamus tenidens	Prairie sod	Thorne and Malek (1968)
Helicotylenchus digonicus	Red clover	Donald (1978) and Donald and Hosford (1980)
H. dihystera	Sugar beet	Caveness (1958)
H. erythrinae	Sugar beet	Caveness (1958)
H. exallus	Grasses, corn	Donald (1978) and Krupinsky et al. (1983)
H. glissus	Grasses	Krupinsky et al. (1983)
H. leiocephalus	Unknown	Krupinsky et al. (1983)
H. microlobus	Soybean	Yan et al. (2017c)
H. pseudorobustus	Grasses, red clover	Donald and Hosford (1980), Donald (1978), and Krupinsky et al. (1983)
Helicotylenchus sp.	Grasses, barley, wheat	Caveness (1958), Donald (1978), and Plaisance et al. (2016a, b)
Hemicycliophora sp.	Alfalfa	Caveness (1958) and Donald (1978)
Heterodera glycines	Soybean	Bradley et al. (2004), Smolik (1995), and Baidoo et al. (2017)
H. schachtii	Sugar beet	Caveness (1958) and Nelson et al. (2012)
Heterodera sp.	Grasses	Donald (1978), Pepper (1968), and Krupinsky et al. (1983)
Hoplolaimus galeatus	Grasses	Krupinsky et al. (1983)
H. stephanus	Soybean	Yan et al. (2016a)
Hoplolaimus sp.	Sugar beet	Caveness (1958) and Plaisance et al. (2016a)
Meloidogyne incognita	Flower bed, NDSU	Pepper (1968)
Merlinius lineatus	Barley	Pepper (1968)
Mesocriconema raskiensis	Grasses	Donald and Hosford (1980), Donald (1978), and Thorne and Malek (1968)
M. xenoplax	Grasses	Krupinsky et al. (1983)
Nagelus aberrans	Prairie sod	Thorne and Malek (1968)
Neodolichodorus pachys	Grasses	Thorne and Malek (1968) and Krupinsky et al. (1983)
Paratylenchus hamatus	Alfalfa, grasses	Donald and Hosford (1980) and Donald (1978)
Paratylenchus sp.	Barley, sugar beet	Caveness (1958) and Pepper (1968)
Paratrichodorus allius	Potato	Yan et al. (2016e) and Huang et al. (2017a, b)
Pratylenchus agilis	Prairie sod	Thorne and Malek (1968)
P. minyus	Sugar beet	Caveness (1958)
P. neglectus	Wheat	Yan et al. (2016d)

(continued)

Table 8.2 (continued)

Nematode	Host and rhizosphere soil	Reference
P. scribneri	Potato	Huang and Yan (2017) and Yan et al. (2016c)
P. vexans	Grasses	Donald and Hosford (1980), Donald (1978), and Tylka and Marett (2014)
Pratylenchus sp.	Grasses, soybean	Krupinsky et al. (1983) and Yan et al. (2017d, e)
Punctodera punctata	Potato, wheat	Chitwood (1949), Pepper (1968), and Spears (1956)
Quinisulcius acutus	Barley, sugar beet, wheat	Caveness (1958), Pepper (1968), and Thorne and Malek (1968)
Q. acutoides	Unknown	Donald (1978) and Pepper (1968)
Rotylenchus spp.	Sugar beet	Caveness (1958)
Trichodorus sp.	Barley	Pepper (1968)
Trophurus minnesotensis	Unknown	Thorne and Malek (1968)
Tylenchorhynchus canalis	Grasses	Krupinsky et al. (1983)
T. claytoni	Barley, sugar beet, wheat	Pepper (1968)
T. cylindricus	Barley, wheat	Pepper (1968)
T. latus	Barley	Pepper (1968)
T. macrurus	Barley	Pepper (1968)
T. maximus	Grasses	Donald (1978) and Krupinsky et al. (1983)
T. nudus	Barley, corn, grasses, sage	Donald (1978), Peper (1968), and Krupinsky et al. (1983)
T. robustus	Grasses	Krupinsky et al. (1983)
Tylenchorhynchus sp.	Grasses, barley, wheat, sugar beet	Donald (1978), Pepper (1968), and Plaisance et al. (2016a, b)
Xiphinema americanum	Barley, wheat, shelter belt trees, cottonwood	Caveness (1958), Donald (1978), and Plaisance et al. (2016a, b)
Xiphinema sp.	Barley	Pepper (1968)

even when there are no obvious above-ground symptoms (Nelson et al. 2012; Niblack et al. 2004).

Since its first detection in 1954 in North Carolina, USA (Winstead et al. 1955), the nematode has spread to other soybean producing areas in many states (Tylka and Marett 2014) and was reported in 2003 from Richland County in North Dakota (Bradley et al. 2004). By 2012, the nematode had been confirmed in 12 other counties of North Dakota (Berghuis 2016), and currently is present in 19 soybean-producing counties in the eastern half of the state (Berghuis 2016; Yan et al. 2015a, b) (Fig. 8.1d).

In 2013, a grower-based SCN sampling program, sponsored by the North Dakota Soybean Council, was established to increase SCN awareness and to monitor its occurrence and distribution in North Dakota. The participants receive prepaid sampling bags at their County Extension office, the North Dakota Soybean Council

Fig. 8.1 (**a**) Soybean field showing patchy distribution of chlorotic foliage as a result of soybean cyst nematode infestation. (Courtesy of Smolik J. D., SDSU); (**b**) Soybean roots showing soybean cyst nematode cysts. Cream-colored cysts (vertical arrow) and one nodule on soybean roots (horizontal arrow); (**c**) Brown cysts on soybean roots (vertical arrow). (Courtesy of Sam Markell, NDSU.); (**d**) Detection year and distribution of *Heterodera glycines* (SCN) in North Dakota. (Credit: Dr. Sam Markell, NDSU)

offices, field days and other events and submit the samples to Agvise Laboratories (Benson, MN, USA) for analysis. The number of samples submitted in 2013, 2014, and 2015 were 193, 579, and 943 respectively. Approximately, 30% of the samples submitted had, at least, 50 eggs/100 cm^3 soil of which approximately 50% had more than 200 eggs/100 cm^3 and 10% exceeded 10,000 eggs/100 cm^3. Between 2013 and 2015, sampling was done in 39 of the 53 North Dakota counties and resulted in 19 counties being positive for SCN. The highest SCN population densities (≥2,000 eggs/100 cm^3 soil) occurred in Cass, Richland and Trail Counties (Berghuis 2016). Previously, higher numbers of 550–20,000 eggs per 100 cm^3 soil were detected in Richland County, North Dakota (Bradley et al. 2004). A SCN distribution map for North Dakota was then generated based on the data. The spread of the nematode from the southeastern part across the mid and northeastern parts of the state strongly suggests that preemptive control measures against this species need to be implemented.

During surveys, samples with low level of egg densities (<50 eggs/100 cm^3) were excluded due to the possibility of false positives. This is due to the fact that it is always difficult to morphologically differentiate soybean cyst nematode eggs from those of other cyst-forming nematodes. Therefore, investigators report counties as positive only if multiple samples typically have over 50 eggs/100 cm^3 of soil. Undoubtedly, the morphological diagnostic approach used in such investigations has the potential to underestimate the number of counties with positive SCN in North Dakota. New technologies that sensitively and specifically detect SCN directly from soil with low densities, have been developed (Baidoo et al. 2017; Yan and Baidoo 2017). Such molecular-based detection techniques undoubtedly provide a viable alternative or compliment the traditional diagnostic methods. The spread of the nematode from the southeastern part across the mid and northeastern parts of the state indicates prophylactic control measures against this nematode are necessary.

8.3.2.2 Variation in Virulence Phenotypes

Soybean cyst nematode populations are either classified into different races or HG types. The race test was based on resistance or susceptible reaction to four SCN differential lines: Peking, Picket, PI 88788, and PI 90763, and standard susceptible check, Lee 74 (Golden et al. 1970; Riggs and Schmitt 1988; Riggs 1988). However, as more soybean differential lines were introduced, not only did race-based characterization become more complicated, but variability of SCN populations were not fully characterized by the race system. A new system of characterizing SCN populations was developed known as the *Heterodera glycines* (HG) type test (Niblack et al. 2002). With the HG type test, SCN populations are characterized by their ability to reproduce on soybean indicator lines with seven different sources of genetic resistance. HG typing considers phenotypic diversity and SCN reproduction differences on soybean lines PI 548402 (Peking), PI88788, PI 90763, PI 437654, PI 209332, PI 89772, and PI 548316 (Cloud) with respect to a standard susceptible check (Niblack et al. 2002). HG type determination not only reveals the diversity of the SCN populations, but can provide information of resistance sources that are effective against SCN. After a SCN population has been characterized using the HG type test, a grower can determine which sources of resistance to grow that would minimize the buildup of SCN in a particular field. Thus, the knowledge of the occurrence and distribution of virulent phenotypes (HG types) provides valuable information regarding sustainable and effective use of resistant cultivars.

The HG type 0, previously known as race 3, was the only SCN type reported in North Dakota until 2016 (Bradley et al. 2004). Soil samples collected in 2015 and 2016, and HG type tests conducted at the North Dakota State University suggested that other HG types are present in North Dakota (including HG type 0, 7, 2.7, 2.5, 5, and 2.5.7.) even though the HG type 0 and 7 are the most predominant populations. Interestingly, some North Dakota SCN populations were able to reproduce on the most widely used resistance, PI 88788 (Chowdhury et al. 2016 2017). The SCN populations in North Dakota are increasing in virulence diversity, as reported for other states (Niblack et al. 2002). As HG types diversify in North Dakota, the use of resistance for management of this nematode may no longer be sustainable.

8.3.2.3 Management of Soybean Cyst Nematode in Soybean Fields in North Dakota

Management of SCN in fields begins with soil sampling to determine egg levels. Once SCN is detected, the most common practices include the use of SCN resistant varieties and crop rotation. These two methods have been found to be most effective (Mathew et al. 2014).

8.3.2.3.1 Resistant Varieties

The use of resistant varieties is a major SCN management tool. SCN reproduction is inhibited on roots of SCN-resistant varieties. In North Dakota, early maturing varieties are being developed with SCN resistance and varieties containing the two common sources of resistance, PI88788 and Peking that are still effective against SCN. Each year, the North Dakota State University (NDSU) evaluates nearly 40 soybean varieties for SCN resistance under greenhouse and field conditions at three to four locations within the state. This program is funded by the North Dakota Soybean Council. Thereafter, information on SCN resistance is made available to growers through an annual bulletin of NDSU Extension Service publication A843, "*North Dakota Soybean Performance Testing*."

It is important to note that while varieties may have the same source of resistance, the degree of resistance in each variety varies. Thus, varieties marketed as SCN-resistant may be truly resistant or have only low to moderate levels of resistance. Therefore, selection of the most resistant variety possible and subsequent monitoring of the field for SCN are important. Previously, only HG type 0 (Race 3) was known in ND, but other HG types have recently been reported. Interestingly, the HG type 2.5.7 population of ND could reproduce on the most widely known source of resistance PI88788 which suggests that new sources of resistance are needed, in the future, for sustainable management of this nematode.

8.3.2.3.2 Crop Rotation

Crop rotation is another critical component of SCN management. Rotation of soybean varieties with different sources of resistance or non-host crops is imperative for long-term management. Common rotational crops such as wheat and corn, are used by growers to reduce population levels of SCN in North Dakota. Continuous reductions in SCN population levels can be achieved over years of planting non-host crops, but the greatest reduction in egg levels occurs the first year a non-host is planted, meaning that many years of crop rotation with non-hosts may be required to reduce high egg levels to low levels. On the other hand, when susceptible crops are grown sequentially, egg levels can become high enough so that growing soybeans may not be practical. Also, the pathogen may overcome resistance if soybean varieties with the same source of resistance are sequentially planted. A minimum of a 2-year rotation is critical for SCN management, although a rotation out of soybean for 2 years is beneficial.

Dry bean is an excellent host for soybean cyst nematode, but canola, dry edible peas, alfalfa, corn, forage grasses, sorghum and sugar beet are considered non- or poor- hosts. Soybean cyst nematode can reproduce on some weeds. Henbit and field pennycress, allow substantial reproduction of SCN. About 31 weed species are known to support SCN reproduction in North Dakota (Poromarto et al. 2015). These weed species and other crop hosts in North Dakota and Northern Minnesota that potentially support SCN reproduction can undermine the effectiveness of SCN management by crop rotation.

A recent study revealed that annual ryegrass (variety not stated: VNS), camelina (Bison), carinata (VNS), Ethiopian cabbage (VNS), faba bean (VNS), foxtail millet (Siberian), radish (Daikon), dwarf essex rape, red clover (Allington), sweet clover (VNS), triticale (Winter 336) and winter rye (Dylan) do not support SCN reproduction (Acharya et al. 2017). However, cowpea (VNS), crimson clover (Dixie) and turnips (Purple Top, Pointer), Austrian winter pea (VNS), field pea (Aragorn, Cooper), forage pea (Arvika) and hairy vetch (VNS) could support some levels of SCN reproduction. Cover crops that are non-host to SCN can be incorporated into a crop rotation system for a sustainable management of this pathogen.

8.3.2.3.3 Seed Treatment

A number of seed treatment products aimed at SCN control are being evaluated at NDSU (Mathew et al. 2014). Preliminary results suggest that some chemical products may reduce SCN numbers. Few seed treatment products aimed at SCN management are labeled and marketed as, (1) Avicta®500FS and (2) Avicta® Complete Beans 500 and (3) Poncho Votivo®. The Avicta products are a blend of different proportions of nematicide, insecticide and fungicide, while the Poncho Votivo product contains a *Bacillus firmus* bacterium which creates a living barrier that prevents nematodes from reaching the roots. The performance of these seed treatments is generally unpredictable, depends on specific soil and weather conditions and does not guarantee increased yields.

It is worthy of note that no single management approach provides an adequate control of SCN and hence, an integrated management scheme in which many other strategies including use of resistant varieties, crop rotation, cover crops, tillage practices, phytosanitary practices, chemical seed treatment, etc., are required for a sustainable management of this nematode.

8.3.2.4 Soybean Cyst Nematode Is a Threat to Dry Bean Production in North Dakota

Between 2007 and 2009, the effect of soybean cyst nematode (HG type 0) on dry bean was investigated. The cultivars GTS-900 (pinto bean), Montcalm (kidney bean) and Mayflower (navy bean) were evaluated in eight field experiments at four locations in North Dakota. The soybean cyst nematode reproduced on all three dry bean cultivars with reproduction factors ranging from 6.1 to 1.2. Plant growth and seed yield including pod number (PN), pod weight (PW), seed number (SN) and seed weight (SW), were significantly reduced by SCN (Poromarto and Nelson 2009; Poromarto et al. 2010). Recently, SCN was implicated in irregular patches of stunting and yellowing in a commercial dry bean field in the neighboring State of Minnesota (Yan et al. 2017a). These results indicate that SCN is a potential threat to the large dry bean industry in the North Dakota and Northern Minnesota region (Pormarto et al. 2010). Consequently, SCN resistance sources from plant introductions of *Phaseolus vulgaris* have been identified and SCN resistance is currently being introduced into breeding materials for the NDSU Dry Bean Breeding Program, while at the same time, the genetic basis for SCN resistance or susceptibility in dry bean is also being characterized (Nelson 2017; Shalu et al. 2017).

8.3.3 Sugar Beet Cyst Nematode, Heterodera schachtii

Sugar beet cyst nematode (SBCN) is a major problem for many sugar beet (*Beta vulgaris*) growing regions. The species was first described in 1859 in Germany and is now distributed worldwide. In the United States, SBCN was first reported in Utah in 1895 and is present in all sugar beet producing states except Minnesota and Eastern North Dakota.

The sugar beet cyst nematode was confirmed to be present in the Yellowstone Valley of Western North Dakota in 2011 (Nelson et al. 2012), even though it was first reported, although not confirmed, in the state in 1958 (Caveness 1958). Population densities ranged from 100 to 1,750 eggs/100 cm^3 soil in four fields in the Yellowstone Valley. Plants infected with SBCN show stunting and reduced leaf growth, with older outer leaves turning yellow and wilted during the hot period of the day. The taproot tends to be stunted with fibrous "bearded roots" (Fig. 8.2a). The most important confirmation of SBCN infection is the presence of white to yellow lemon-shaped females attached to feeder roots (Fig. 8.2a) or yellow-brown cysts (dead mature females) in soil (Fig. 8.2b) (Khan et al. 2016). Interestingly, the nematode has not been detected in Eastern North Dakota in the Red River Valley where sugar beet is mainly produced (Porter and Chen 2005).

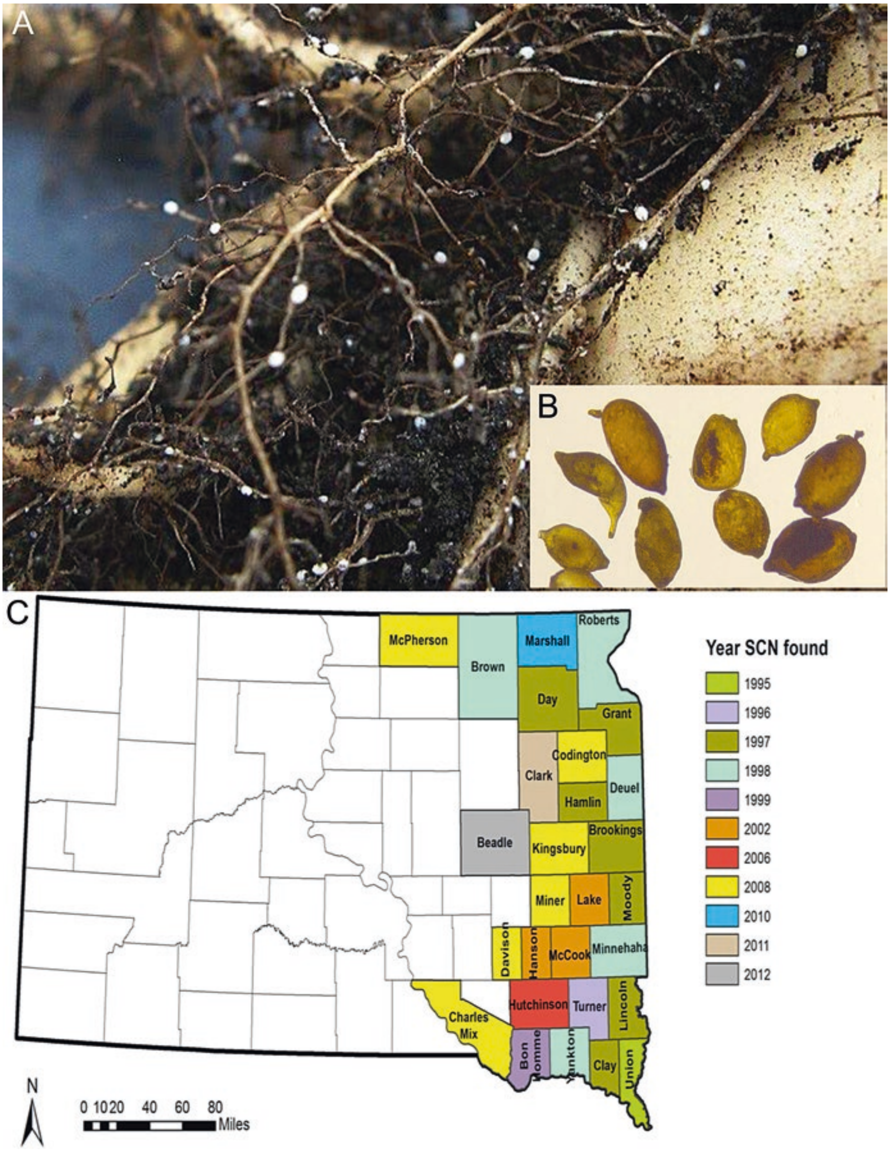

Fig. 8.2 (**a**) White, lemon-shaped females feeding on root hairs of sugar beet. (Photo: courtesy of Steve Poindexter, Michigan State University). (**b**) Yellow-brown female cysts from a sugar beet cyst nematode-infested field in North Dakota. (Photo: courtesy of Guiping Yan, NDSU). (**c**) Detection and distribution of *Heterodera glycines* (SCN) in South Dakota. (Credit: Dr. Emmanuel Byamukama, SDSU)

8.3.3.1 Management of SBCN

The first step in management is sampling soil for the presence of SBCN cysts or juveniles or the presence of white females on root. Field symptoms such as patchy distribution of chlorotic leaves, stunted plants, profuse fibrous roots*, etc.,* may be similar to that caused by other stress factors. If soil sampling shows that SBCN is absent from a field, then prevention of SBCN introduction into the field will be the key strategy. This can be achieved by avoiding movement of machinery and equipment from areas infested with SBCN into non-infested fields, washing thoroughly machineries and equipment after use, especially those coming from nematode-infested regions with known SBCN problems, avoiding or limiting the use of host crops in rotation, good control of weed hosts, and taking proper sanitation measures between infested areas and non-infested areas (Khan et al. 2016; Anonymous 2017).

Various strategies are recommended to reduce cyst nematode populations below the economic threshold: use of tolerant cultivars, rotation with non-host crops, use of trap crops, early planting, weed control, phytosanitation, nematicide treatment, *etc.* Sugar beet cyst nematode-tolerant cultivars should be planted, if available, and rotated with non-host crops, including wheat, soybean, barley, corn, potato and alfalfa. Weeds that are hosts for SBCN such as shepherd's purse, common lambsquarters, chickweed, pigweed, dock, and purslane, must be controlled. Rotations with non-host crops may reduce initial SBCN population by 40–60% annually and a 3 to 4-year rotation is needed in heavily infested fields to reduce population density below damaging levels (Khan et al. 2016). Trap crops attract SBCN but prevent them from developing and reproducing, thus reducing population densities drastically. Some SBCN tolerant cultivars of oilseed radish including Defender, Image, and Colonel, and White mustard, are effective (Khan et al. 2016). Early planting is recommended, when soil temperatures are not favorable for infection and less than 15 °C. Chemical nematicides may be effective, but are typically difficult to apply and may be uneconomical. Biological seed treatment with *Pasteuria nishizawe* may help manage SBCN on tolerant sugar beet cultivars (Khan et al. 2016).

8.3.4 Lesion Nematodes, Pratylenchus *spp.*

Pratylenchus is a major nematode genus frequently found in North Dakota potato fields. These nematodes, apart from the damage they cause through their feeding activities, also interact with other organisms to increase disease incidence and severity. *Pratylenchus* spp. infect potato tubers causing a scabby appearance with sunken lesions or dark, wart-like bumps that turn purple on tubers in storage. Yield losses may be exacerbated by interaction with the fungus *Verticillium dahliae* causing a disease known as Potato Early Dying disease complex (PED) (MacGuidwin and Rouse 1990).

During 2015, 48 out of 54 soil samples collected from potato fields in Sargent County, North Dakota contained root lesion nematodes with population densities ranging from 125 to 1,900/kg of soil. Initial population density of 1,540 root lesion nematodes/kg soil increased to 9,163 specimens/kg soil and 48 specimens/g roots on potato cultivar, 'All Blue' after 10 weeks. In April 2016, the nematode was identified as *P. scribneri* (Huang and Yan 2017; Yan et al. 2016c), and found to be the most prevalent plant parasitic nematode infesting potato fields in Sargent County, North Dakota (Plaisance et al. 2016b). Preliminary greenhouse studies showed that potato and corn were good hosts of *P. scribneri* while wheat and soybeans were poor and intermediate hosts, respectively (Plaisance et al. 2016b).

Similarly, in 2015, soil samples collected from a wheat field in Walsh County, North Dakota were found to have root lesion nematodes from 125 to 1,044/kg soil. This nematode, with an initial density of 500 root lesion nematodes/kg soil, could reproduce on commercial and common wheat cultivars Glenn and Faller to an average of 24 or 20 root lesion nematodes per gram root after 10 weeks. The nematode was identified as *P. neglectus* (Yan et al. 2016d).

Two new, unnamed *Pratylenchus* species have been reported in two different fields in Richland County, North Dakota (Yan et al. 2017d, e). In 2015, two soil samples collected from a soybean field in Walcott, North Dakota contained 125 and 350 root lesion nematodes per kg of soil. In 2016, four soil samples were collected from the same field and all the samples had root lesion nematodes ranging from 300 to 2000. One soil sample with 350 root lesion nematodes per kg soil was planted to a commercial soybean cultivar, Barnes. After 15 weeks of growth in a greenhouse (22 °C, 16 h light), the final population density in soil was 1,518 ± 541 root lesion nematodes per kg soil and 25 ± 20 per g of fresh roots. Reproduction factor of the nematode was 5.02, indicating that this nematode infected and reproduced well on the soybean cultivar (Yan et al. 2017d). Again in 2015 and 2016, 10 of 11 soil samples collected from a soybean field in Hankinson, North Dakota, contained root lesion nematodes ranging from 150 to 875/kg of soil. One soil sample with 300 lesion nematodes/kg was used to inoculate soybean cultivar, Barnes. After 15 weeks of growth in the greenhouse, the population had increased to a final density of 460 ± 181 lesion nematodes/kg in soil and 34 ± 21 lesion nematodes/g of fresh roots. The reproduction factor of the nematode from both roots and soil was 3.76, indicating that this lesion nematode had reproduced well on the commercial soybean cultivar (Yan et al. 2017e).

8.3.5 Stubby Root Nematodes, **Trichodorus** *and* **Paratrichodorus** *spp.*

Stubby root nematodes are a major concern in potato production since they transmit *Tobacco rattle virus* (TRV) which causes the corky ringspot disease. *Paratrichodorus allius* has been identified in soil samples from potato fields in Sargent County, North Dakota (Huang et al. 2017a, b; Yan et al. 2016b, e). Previously, TRV associated with corky ringspot on potato in North Dakota was reported, but stubby root nematodes were not investigated (David et al. 2010). This virus is widespread in North Dakota as well as reported from the neighboring states of Minnesota and Wisconsin (Gudmestad et al. 2008). A research study on the association between the virus, nematode and occurrence of corky ringspot is underway at the North Dakota State University. Many potato processing companies have a zero-tolerance policy for potato tubers with the disease, and an entire shipment can be rejected if a single infected tuber is detected, thereby, making disease incidence a critical qualitative parameter (Plaisance et al. 2016a).

8.3.6 Other Plant Parasitic Nematodes

Other plant parasitic nematodes of concern include *Tylenchorhynchus* spp., *Paratylenchus* spp., *Hoplolaimus* spp., *Helicotylenchus* spp. and *Xiphinema* spp. (Upadhaya et al. 2017; Yan et al. 2015b, 2016a, 2017b, c). Some of these nematode species have been frequently detected at relatively high densities, however, the economic damage they cause in the North and South Dakota's agroecosystem is largely unknown.

8.3.6.1 Stunt Nematodes, *Tylenchorhynchus* spp.

North Dakota and South Dakota are part of the Great Plains region known for supporting extensive cattle ranching and dry farming. Western wheatgrass, *Agropyron smithii*, blue grama, *Bouteloua gracilis*, and warm-season short grass, *Buchloe dactyloides,* are predominant grasses in short and mixed-grass prairies of the Northern Great Plains (Sims et al. 1978; Smolik and Lewis 1982). *Tylenchorhynchus robustus* is reported to be the dominant member of Dolichodoridae in a mixed prairie (Smolik and Lewis 1982) reducing growth, clipping plant weight and root/crown weights (Smolik 1982). Nematicide treatments increased growth of native range grasses 28–59% in Western South Dakota (Smolik 1977a). Recently, an unknown *Tylenchorhynchus* sp. was reported from a soybean field in North Dakota (Yan et al. 2017b). The greenhouse bioassay showed that this new species was capable of infecting soybean plants. However, the impact of this nematode on soybean growth and yield need to be assessed.

8.3.6.2 Pin Nematodes, *Paratylenchus* spp.

Pin nematodes (PN) were found to be the major plant parasitic nematodes in pea fields in North Dakota (Upadhaya et al. 2016). In 2015, 91 soil samples were collected from 31 fields in 9 counties. Pin nematodes were present in 60% of the samples with a highest density of 21,500 per kg of soil, followed by spiral (22%), stunt (21%), dagger (8%), root lesion (2%) and stubby root (1%) nematodes. In a separate survey, a total of 135 soil samples were collected during 2015 and 2016. Pin nematodes were the dominant plant parasitic nematodes, detected in 72% of the soil samples with mean and highest population densities of 3,560 and 35,572 specimens per kg of soil, respectively. Interestingly, in this survey, more than 97% of the PN populations in the fields were fourth stage juveniles (J-4) without a distinct stylet, whereas less than 3% of the populations were stylet-bearing, plant-feeding adults. The nematode was identified as *Paratylenchus nanus* (Upadhaya et al. 2016; Thorne and Smolik 1971). Reproductions of the PN were evaluated at four initial population levels (3,000, 5,000, 6,000, and 13,000 nematodes/kg soil) and it reproduced on different cultivars of pea (Columbian, Aragorn and Cooper), in a greenhouse study. However, those without stylet had lower reproduction factor compared to the stylet-bearing ones. Moreover, the proportion of PN adults with stylet (15–33%) in all the final populations was significantly greater for each cultivar than in the initial populations (<3%). In a separate preliminary greenhouse study, *P. nanus* reduced the plant height of six field pea cultivars by 37% (Arcadia), 36% (Columbian), 29% (Bridger), 22% (Cruiser), 20% (Salamanca) and 19% (Aragorn) after 11 weeks of growth with an initial inoculum of 4,500 nematodes/kg of soil (Upadhaya et al. 2017). This study showed that significant populations of stylet-bearing, plant-feeding pin nematodes could parasitize these pea cultivars.

8.3.6.3 Spiral Nematodes, *Helicotylenchus* spp.

Spiral nematodes are common plant parasitic nematodes in many fields of North Dakota. In June 2015, two soil samples were collected from a soybean field in Richland County, North Dakota. Both samples contained spiral nematodes at 1,500–3,300 per kg of soil. In June and August 2016, ten soil samples were collected from the same field. Nine of the samples had spiral nematodes ranging in numbers from 125 to 3,065 per kg of soil. One soil sample containing *H. microlobus,* with 1,500 nematodes per kg soil, was used to inoculate two soybean cultivars, Sheyenne and Barnes, commercially cultivated in the state. After 15 weeks of growth at 22 °C in a greenhouse, the final population density was 9,300 ± 1,701 *H. microlobus* per kg soil for Sheyenne and 9,451 ± 2,751 for Barnes. The reproduction factor in Sheyenne and Barnes was 6.2 and 6.3, respectively, indicating that this spiral nematode invades and reproduces well on these soybean cultivars. Infected soybean roots had small brown lesions on the surface (Yan et al. 2017c).

8.3.6.4 Lance Nematodes, *Hoplolaimus* spp.

In August 2015, *Hoplolaimus* spp. were collected from a soybean field near Cogswell, Sargent County, North Dakota with density at 210 nematodes per 100 cm^3 of soil. Four soil samples collected in October 2015 from the same field had lance nematodes ranging in numbers from 30 to 100 per 100 cm^3 soil. One soil sample containing *H. stephanus*, with 60 nematodes per 100 cm^3 soil, was used to inoculate soybean cultivar, Lamour, in three replicates. After 12 weeks of growth in a greenhouse (22 °C, 16 h light), mean population numbers of lance nematodes had only increased slightly (68 ± 50 per 100 cm^3 soil). Stunted and shortened lateral roots branching from the main root were observed (Yan et al. 2016a).

8.3.7 *Soybean Cyst Nematode,* Heterodera glycines *in South Dakota*

8.3.7.1 Detection and Distribution

Soybean cyst nematode was first detected in 1995 in Union County in South Dakota (Smolik 1995). By 2007, the nematode was confirmed in 19 counties in South Dakota (Smolik and Draper 2007). From 2003 to 2012, the South Dakota State University (SDSU) received a total of 4,578 soybean soil samples that were voluntarily submitted by soybean growers as well as collected during annual soybean disease surveys from 43 counties in South Dakota by the SDSU Plant Diagnostic Clinic. Subsequently, 33% of soybean fields were found to have SCN. The top four counties with the highest number of positive samples for SCN were Turner, Clay, Union and Lincoln Counties. The years 2005 and 2012 had the highest SCN population densities averaging 3,124 and 2,245 eggs and second stage juveniles per 100 cm^3 of soil, respectively. Turner County had the highest incidence (50%) followed by Clay, Union and Lincoln Counties. Interestingly, as in North Dakota, the counties found to be infested with SCN span the eastern part of South Dakota. This shows the expanded risk of SCN from the south-eastern corner to the north-eastern corner in both states. Currently 28 counties in South Dakota have been found to be infested with SCN (Acharya et al. 2014, 2016) (Fig. 8.2c).

8.3.7.2 *Heterodera glycines* HG Types

HG refers to *Heterodera glycines* and the type indicates seven Plant Introduction lines with various sources of resistance. For example, HG type 2.5.7 refers to a SCN population that is capable of reproducing on the PI line numbers 2, 5, and 7. HG types that are prevalent in South Dakota include HG types 0, 1, 2, 7, 2.7, 5.7, 1.3.6 and 2.5.7, with HG type 7 being the most predominant (36%), followed by HG type 0 (29%) and HG type 2.5.7 (16%) (Acharya et al. 2016). These HG types collectively accounted for 80% of *H. glycines* populations in South Dakota. HG type 7 means, at least 10% female index (FI) on indicator line #7. The diversity of the *H. glycines* populations in HG types varied between and within the counties, with Brookings, Clay, Turner and Union Counties having more diverse SCN populations. HG types with greater than 10% reproduction on indicator lines PI 88788, PI 209332, and PI 548316 were prevalent in the soil samples tested, suggesting that the use of these sources of resistance for developing SCN-resistant cultivars in the state is no longer effective.

8.3.7.3 Management

Any approach to managing soybean cyst nematode in fields is aimed at reducing the nematode population below the level that may result in significant yield losses. Once the nematode is established in a field, there is no practical way to eliminate it. Therefore, early detection of the nematode, rotation with a non-host crop, and use of resistant soybean varieties are the critical components of SCN management in South Dakota (Smolik and Draper 2007). The SDSU Plant Diagnostic Clinic provides SCN diagnostic services to soybean growers in the state. Growers are provided with a Soybean Cyst Nematode Soil Sampling Information Sheet which contains field location, cropping history, grower's address, instructions for collecting the soil samples and other information. This practice has tremendously helped in obtaining the early detection and distribution of the nematode in South Dakota.

8.3.7.3.1 Crop Rotation

Crop rotation with non-host crops to reduce nematode populations is an essential component of SCN management. High SCN population densities (>1,000 eggs/100 cm^3 soil) are best managed by crop rotation with non-host crops such as corn, small grains, sunflowers, flax, canola or alfalfa followed by a SCN-resistant soybean variety. In the absence of locally adapted, SCN-resistant soybean varieties, growers opt for longer rotations with non-host crops between soybean crops. Dry beans are an excellent host for SCN and are not rotated with soybeans.

8.3.7.3.2 Resistant Varieties

Soybean cyst nematode-resistant soybean varieties, in combination with crop rotation, are a very important management tool. Planting SCN-resistant soybean varieties reduces yield loss and SCN population densities. In field plot tests conducted over an 11-year period, yields of SCN-resistant lines were 23–63% higher than those of susceptible lines (Smolik and Draper 2007). It is best to plant a SCN-resistant variety in fields where SCN has been detected, even with population densities as low as 150 eggs per 100 cm^3 soil or less. Fields with fairly high SCN populations (>5,000 eggs per 100 cm^3) are rotated to non-host crops to reduce SCN numbers before planting resistant soybean varieties.

8.3.7.3.3 Cultural Practices

Provision of optimal growing conditions of the crop will reduce plant stress and yield loss due to SCN. Good soil tillage practices and adequate soil fertility improve plant growth and development. Also, management of weeds, diseases and insects reduces plant stress and minimizes SCN damage. Efforts should be made to avoid spreading SCN from infested to un-infested fields by movement of infested soil on farm equipment and tools. Equipment and farm tools should be power-washed after working in infested fields. Tillage practices that reduce wind and water erosion also can slow the spread of SCN.

8.3.7.3.4 Seed Treatment

Use of nematicides for control of SCN has not been popular amongst growers in South Dakota. However, few nematicides or fungicides with nematicidal properties are being marketed. Soybean seeds are treated before planting. Avicta Complete Beans 500® (abamectin + thiomethoxam + mefenoxam + fludioxonil) applied at 6.2 fl oz/cwt (100 lb) seed, targets SCN, as well as, damping off, seedling rots, early-season Phytophthora root rot, *Fusarium* and *Rhizoctonia* root rot diseases. Clariva pn® (*Pasteuria nishizawae*-PN1) is also being labelled for control of SCN. Pocho/Votivo® (*Bacillus firmus* I-1582 + clothianidin) applied at 0.13 mg ai/seed targets SCN.

8.3.8 Lesion Nematodes, **Pratylenchus** *spp., in South Dakota*

Pratylenchus scribneri and *P. hexincisus* are commonly associated with corn in South Dakota (Smolik 1977b, 1978; Draper et al. 2009). Under high nematode population densities, infected plants are stunted with uneven plant height along rows. Infected plants also show yellowing of leaves, root necrosis, stubby roots and eventually, poor ear fill (Draper et al. 2009). Population density of *P. scribneri* at harvest was related to yield loss in irrigated corn in South Dakota (Smolik and Evenson 1987). In the absence of nematicide, the mean number of *P. scribneri* could be as higher as 8,000 nematodes/g dry root at midseason and 6,000 nematodes/g dry root at harvest, resulting in estimated yield losses of 246–361 kg/ha. Similarly, the mean number of *P. hexincisus* could be as high as 3,400/g dry root at midseason and 4,092/g root at harvest, resulting in an estimated yield loss of 599 kg/ha (Smolik and Evenson 1987). This indicates that *P. hexincisus* and *P. scribneri* may have significant impact on corn production in South Dakota.

8.3.9 Dagger Nematodes, **Xiphinema americanum,** *in South Dakota*

The American dagger nematode, *Xiphinema americanum*, is one of the most commonly encountered nematodes in South Dakota soils (Thorne and Malek 1968). Furthermore, it is one of the most common nematode species found in the Great Plains, and feeds ectoparasitically on roots of all kinds of plants, from native grass to cotton trees (Thorne 1974). Apart from the damage caused by direct feeding on plant roots, the nematode is also economically important due to its ability to transmit nepoviruses.

Symptoms of stunting and premature decline and dieback of shelterbelt trees have been associated with *X. americanum* infestation. It has also been suggested that the nematode serves as the primary parasite that makes openings through which fungi and bacteria can enter and join in the destruction of root systems. Generally, in severely infested trees, it is almost impossible to find a single live feeder root (Malek 1969). Thorne (1974) suggested that *X. americanum* caused more damage to crops, orchards and timber than any other single nematode species in the USA. *Xiphinema americanum* was pathogenic to cottonwood and green ash under greenhouse conditions. Experimental demonstrations of pathogenic capabilities have been infrequent and often inconclusive because of difficulties in maintaining *X. americanum* populations in laboratory or greenhouse conditions (Malek 1969).

8.3.10 General Nematode Management Tactics for Vermiform Nematodes

8.3.10.1 Disease Diagnosis

Nematodes from the genera *Pratylenchus, Helicotylenchus, Hoplolaimus*, *Longidorus*, *Trichodorus*, *Paratrichodorus*, *Paratylenchus* and *Tylenchorhynchus* have been reported on field crops including corn, soybean, dry edible peas, barley, potato, wheat, etc., in both North Dakota and South Dakota, but to date, their effects have been inconsequential or not extensively investigated (Smolik 1978; Draper et al. 2009). General nematode management strategies can be used to reduce their impacts, where necessary. In any management strategy, accurate detection and estimation of population density of the nematode species through soil analysis is paramount. Molecular methods have been used for detection, identification and quantification of *Pratylenchus scribneri* and *Paratrichodorus allius* in North Dakota (Huang and Yan 2017; Huang et al. 2017a, b). Practically, no single strategy should suffice, therefore, an integrated, sustainable management approach is recommended, contingent on a number of factors including field situation, cropping sequence, nematode species, nematode density, available resources, crop rotation, cover cropping, trap cropping, fallowing, removal of infested plants, weed control, resistant varieties, soil amendment, fertilization and tillage practices (Heald 1987; McKenry 1987; Young 1992; Westphal et al. 2006, 2009; Xing and Westphal 2009; Westphal 2011; Anonymous 2017).

8.3.10.2 Crop Rotation

Growing crops that are non-hosts or poor-hosts to a particular nematode species in rotation with a primary crop reduces the target nematode population. Thus, in the absence of a suitable host, nematode population density reduces over time. Successful nematode management through crop rotation depends on the species of the nematode present in a field, damage threshold level, host range of the species present, weed host, the expected rate of population decline or increase, the number of nematode species present, crop plants, availability of resistant varieties and time of planting (Anonymous 2017). Nematodes with a narrow host range such as soybean cyst nematode, which only reproduces on soybeans and its closely related legumes, are easily managed by crop rotation, unlike nematodes such as lesion nematodes and dagger nematodes, which have a wider host range. The three *Pratylenchus* species most commonly associated with field crops in North and South Dakota (*P. hexincisus*, *P. scirbneri* and *P. neglectus*) often occur in mixed populations. In a situation where, for instance, soybean cyst nematode with a narrow host range is present together with a nematode with a wide host range such as lesion nematode, a rotation ideal for soybean cyst nematode reduction may favor buildup of lesion nematode (Smolik 1978; Draper et al. 2009; Yan et al. 2016c).

Corn and potato are good hosts for both *Pratylenchus hexincisus* and *P. scribneri* whereas, alfalfa and red clover are non-hosts. *Pratylenchus hexincisus* reproduces more on wheat and rye than *P. scribneri* whereas sorghum, soybean, tomato and white clover are better hosts for *P. scribneri*. Other species of lesion nematodes damage both grasses and broad-leaf plants. The wide host range of lesion nematodes limits their effective management with crop rotation. Again, an important part of a crop rotation strategy is what is grown in the field during the offseason period when a cash crop is not grown. When the field is allowed to fallow, free of weeds and volunteer plants, nematode populations plummet. To minimize the problem of soil erosion during the period of fallow, weeds known to be non-host may be left on the field as barriers to erosion. Alternatively, cover crops which are non-hosts to the target nematode can be grown during the offseason period. Cover crops such as radish, mustards and other Brassicas may have nematicidal properties against the target nematode, if the shoots of these crops are incorporated into the soil (Heald 1987; Westphal et al. 2006; Xing and Westphal 2009).

8.3.10.3 Use of Resistant and Tolerant Varieties

The use of resistant varieties is another practical means of controlling nematodes (Young 1992; Roberts 2002). Crop plants may be described as non-host or immune, resistant, susceptible, tolerant or intolerant to a particular nematode species. Plants may be invaded by nematodes and may show damage, but chemical or physical barriers within the plant will prevent population increases (resistant varieties). However, when plants do not allow nematodes to attack including initial root invasion, these are called non-host or immune. Tolerant hosts allow nematode invasion and reproduction but are able to withstand nematode attack whereas intolerant hosts are more likely to be damaged by nematode attack (Anonymous 2017). Resistant or non-host varieties should be used whenever possible to reduce yield loss. Population development of *P. scribneri* and *P. hexincisus* varies among varieties of corn, soybean and wheat. Currently, there are no resistant varieties available against most vermiform nematodes.

8.3.10.4 Chemical Control

Nematicide application has been frequently used to control lesion nematodes on corn in South Dakota and North Dakota (Bergeson 1978; Draper et al. 2009). Foliar sprays with oxamyl drastically reduced nematode populations on ash seedlings and generally improved seedling growth. Soil fumigation with 1, 3 – dichloropropene and related chlorinated C3 hydrocarbons (1, 3 – D) increased growth of green ash and golden willow over a 4-year period on land infested with initially low populations of dagger nematodes, but did not affect growth of cottonwood, Siberian pea tree or honey locust (Malek and Smolik 1975). In North Dakota, field applications of oxamyl combined with clothianidin showed a potential efficacy against *Paratrichodorus* spp., but did not result in increased yield (Plaisance et al. 2016a).

Owing to environmental and health concerns, most fumigant nematicides have been phased out and are replaced by less toxic, environmentally friendly chemical products. Some of these emerging products include: abamectin or Avid® containing avermectin; Nimitz® containing fluensulfone; Multiguard Protect® containing furfural; and Kontos® or Movento® containing spirotetramat. The specific situation determines whether the expense of chemical application is warranted, however, unless a soil analysis reveals exceptionally high nematode populations, it is not economically viable to use nematicides for the control of nematodes (Draper et al. 2009). For effective management, these chemical products must be applied in conjunction with other long-term sustainable management practices (Westphal 2011).

8.3.11 Nematode Management in Sustainable Agriculture

Management of plant parasitic nematodes in sustainable agriculture aims at optimizing resources, skills and technology to achieve long-term control of nematodes without adverse effect on the environment or humans. Thus, methods of nematode control that curb the threats that nematodes pose to crop production without compromising other life forms and the environment now or in the future, form part of sustainable farming practices. It is in compliance with this background that many fumigant nematicides have been phased out and have been replaced with other innocuous cultural practices and technologies, to ensure sustained levels of control of plant pathogens and returns to growers, while minimizing adverse impacts to immediate and off-farm environments.

Consequently, the use of crop rotation practices, resistant crop cultivars, timing of planting, prevention and exclusion practices, tillage practices, fallowing, organic amendments, cover cropping, trap cropping, green manuring, etc. to mitigate nematode problems, form an integral part of sustainable agriculture. These practices, in addition to providing nematode control, may provide alternative sources of soil nitrogen, reduce soil erosion, improve soil structure, improve water retention and provide ecological niches to soil fauna and flora. They are not harmful to natural systems, farmers, their neighbors or consumers and pose no risk of environmental (water and atmospheric) pollution, yet may provide nematode control and generate the required crop productivity to growers.

References

Acharya, K., Byamukama, E., & Tande, C. (2014). The status of soybean cyst nematode, *Heterodera glycines*, in South Dakota. *Phytopathology, 104*, S3.3. https://doi.org/10.1094/PHYTO-104-11-S3.1.

Acharya, K., Tande, C., & Byamukama, E. (2016). Determination of *Heterodera glycines* virulence phenotypes occurring in South Dakota. *Plant Disease, 100*, 2281–2286.

Acharya, K., Plaisance, A., & Yan, G. P. (2017). Evaluation of cover crops for hosts and population reduction of soybean cyst nematode. *Phytopathology, 107*, S1.1. https://doi.org/10.1094/PHYTO-107-1-S1.1.

Anonymous. (2014). *South Dakota Ag economic contribution study*. South Dakota Department of Agriculture. https://www.google.com/webhp?sourceid=navclientandie=UTF-8andgws_rd=ssl#q=South+Dakota+Ag+Economic+contribution+study.+South+Dakota+Department+of+Agriculture+and*andspf=1

Anonymous. (2016). *North Dakota wheat statistics*. North Dakota Wheat Commission. http://www.ndwheat.com/buyers/default.asp?ID=539

Anonymous. (2017). *Biology and management of plant parasitic nematodes*. Davis: Department of Nematology, University of California http://www.google.com/url?sa=tandrct=jandq=andesrc=sandsource=webandcd=1andcad=rjaanduact=8andved=0ahUKEwjIjruO4q7TAhVMVWMKHVL4DQ0QFggnMAAandurl=http%3A%2F%2Fplpnemweb.ucdavis.edu%2Fnemaplex%2FCourseinfo%2FHandouts%2FWesterdahl.pdfandusg=AFQjCNHcL6YTjld8THFgoTZ1MlyiGbHVzA.

Baidoo, R., Yan, G. P., Nelson, B., Skantar, A. M., & Chen, S. (2017). Use of chemical flocculation and nested PCR for *Heterodera glycines* detection in DNA extracts from field soils with low population densities. *Plant Disease, 101*, 1153–1161.

Bergeson, G. B. (1978). Control of the lesion nematode *Pratylenchus* spp. in corn with carbofuran. *Plant Disease Reporter, 62*, 295–297.

Berghuis, B. (2016). *Increasing soybean cyst nematode awareness in North Dakota through a grower-based sampling program*. 2016 Soybean Cyst Nematode Conference. S1.2. Coral Gables, Florida, FL, December 13–15.

Bradley, C. A., Biller, C. R., & Nelson, B. D. (2004). First report of soybean cyst nematode (*Heterodera glycines*) on soybean in North Dakota. *Plant Disease, 88*, 1287.

Caveness, F. E. (1958). *A study of nematodes associated with sugarbeet production in selected northwest and north central states* (p. 157). Ft. Collins: Sugarbeet Development Foundation.

Chitwood, B. G. (1949). Cyst-forming *Heterodera* encountered in soil sampling. *Plant Disease Reporter, 33*, 130–131.

Chowdhury, I., Yan, G. P., Plaisance, A., Nelson, B., Markell, S., Helms, T. C., & Upadhaya, A. (2016). *Population diversity of soybean cyst nematode in North Dakota Fields*. In Abstracts of 55th annual meeting of the society of nematologists, Montreal Quebec, Canada, July 17–21 (pp. 68–69).

Chowdhury, I. A., Yan, G. P., & Plaisance, A. (2017). Characterizing virulence phenotypes of soybean cyst nematode (*Heterodera glycines*) in infested fields of North Dakota. *Phytopathology, 107*, S1.3. https://doi.org/10.1094/PHYTO-107-1-S1.1.

David, N., Mallik, I., & Gudmestad, N. C. (2010). First report of the *Tobacco rattle virus* associated with Corky Ringspot in potatoes grown in North Dakota. *Plant Disease, 94*, 130. https://doi.org/10.1094/PDIS-94-1-0130B.

Donald, P. A. (1978). *Plant nematodes in and relevant to North Dakota*. M.S. thesis, North Dakota State University, Fargo. p. 70.

Donald, P. A., & Hosford, R. M., Jr. (1980). Plant parasitic nematodes of North Dakota. *Plant Disease, 64*, 45–47.

Draper, M. A., Langham, M. A., Clay, S. A., & Bradley, R. E. (2009). *Best management practices for corn production in South Dakota: Corn diseases in South Dakota*. Extension Circulars. p. 499. http://openprairie.sdstate.edu/extension_circ/499

Golden, A. M., Epps, J. M., Riggs, R. D., Duclos, L. A., Fox, J. A., & Bernard, R. L. (1970). Terminology and identity of infraspecific forms of the soybean cyst nematode (*Heterodera glycines*). *Plant Disease Reporter, 54*, 544–546.

Gudmestad, N. C., Mallik, I., Pasche, J. S., & Crosslin, J. M. (2008). First report of *Tobacco rattle virus* causing corky ringspot in potatoes grown in Minnesota and Wisconsin. *Plant Disease, 92*, 1254. https://doi.org/10.1094/PDIS-92-8-1254C.

Heald, C. M. (1987). Classical nematode management practices. In J. A. Veech & D. W. Dickson (Eds.), *Vistas on nematology* (pp. 100–105). Hyattsville: Society of Nematologists.

Huang, D., & Yan, G. P. (2017). Specific detection of the root lesion nematode *Pratylenchus scribneri* using conventional and real-time PCR. *Plant Disease, 1010*, 359–365.

Huang, D., Yan, G. P., & Skantar, A. M. (2017a). Development of real-time and conventional PCR assays for identifying stubby root nematode *Paratrichodorus allius*. *Plant Disease, 1010*, 964–972.

Huang, D., Yan, G. P., Gudmestad, N., & Skantar, A. (2017b). Quantification of *Paratrichodorus allius* in DNA extracted from soil using TaqMan Probe and SYBR Green real-time PCR assays. *Nematology, 19*, 987–1001.

Khan, M., Arabiat, S., Chanda, A. K., & Yan, G. P. (2016). *Sugar beet cyst nematode* (North Dakota Extension Bulletin, p. 1788). Fargo: North Dakota State University. 2 p. https://www.ag.ndsu.edu/pubs/plantsci/pests/pp1788.pdf

Krupinsky, J. M., Barker, R. E., & Donald, P. A. (1983). Frequency of plant parasitic nematodes associated with blue gama and western wheatgrass in the Western Dakotas. *Plant Disease, 67*, 399–401.

MacGuiwin, A. E., & Rouse, D. I. (1990). Role of *Pratylenchus penetrans* in the potato early disease of Russet Burbank potato. *Phytopathology, 80*, 1077–1082.

Malek, R. B. (1969). Population fluctuations and observations of the life cycle of *Xiphinema americanum* associated with cottonwood (*Populus deltoids*) in South Dakota. *Proceedings of the Helminthological Society of Washington, 36*, 270–274.

Malek, R. B., & Smolik, J. D. (1975). Effects of *Xiphinema americanum* on growth of shelterbelt trees. *Plant Disease Reporter, 59*, 144–148.

Mathew, F., Markell, S., Jantzi, D., Yan, G. P., Nelson, B., & Helms, T. (2014). *Soybean cyst nematode*, *North Dakota Extension Bulletin* (p. 1732). Fargo: North Dakota State Univ, 4 p.

McKenry, M. V. (1987). Control strategies in high-value crops. In R. H. Brown & B. R. Kerry (Eds.), *Principles and practices of nematode control in crops* (pp. 330–349). Sydney: Academic.

Nelson, B. (2017). *The confrontation: Soybean cyst nematode and common bean*. 2017 Soybean cyst nematode conference. S1.7. Coral Gables. Florida. December 13–15.

Nelson, B. D., Bolton, M. D., Lopez-Nicora, H. D., & Niblack, T. L. (2012). First confirmed report of sugarbeet cyst nematode, *Heterodera schachtii*, in North Dakota. *Plant Disease, 96*, 772. https://doi.org/10.1094/PDIS-02-12-0112-PDN.

Niblack, T. L., Arelli, P. R., Noel, G. R., Opperman, C. H., Orf, J. H., Schmitt, D. P., Shannon, J. G., & Tylka, G. L. (2002). A revised classification scheme for genetically diverse populations of *Heterodera glycines*. *Journal of Nematology, 34*, 279–288.

Niblack, T. L., Tylka, G. L., & Riggs, R. D. (2004). Nematode pathogens of soybean. In J. R. Wilcox (Ed.), *Soybeans: Improvement, production, and uses* (3rd ed., pp. 821–851). Madison: American Society of Agronomy.

Pepper, E. H. (1963). Nematodes in North Dakota. *Plant Disease Report, 47*, 102–106.

Pepper, E. H. (1968). *Nematology in the North Central Region 1956–1966*, *NCR publication No. 187. Special Report 58*. Ames: Agric. Home Econ. Exp. Stn, Iowa State Univ. Sci. Tech..

Plaisance, A., & Yan, G. P. (2015). *Comparison of two nematode extraction techniques*. In Abstracts of 54th annual meeting of the society of nematologists, East Lansing, MI, July 19–24 (p. 120).

Plaisance, A., Yan, G. P., Peterson, D., Gudmestad, N. C., Thorsness, K. B. (2016a). *Experimental chemical applications for control of corky ring spot disease of potato vectored by Paratrichodorus allius*. In Abstracts of 55th annual meeting of the society of nematologists, Montreal Quebec, Canada, July 17–21 (p. 159).

Plaisance, A., Yan, G. P., Upadhaya, A. (2016b). *Selected northern-grown crops as hosts of Pratylenchus scribneri*. In Abstracts of 55th annual meeting of the society of nematologists, Montreal Quebec, Canada, July 17–21 (pp. 159–160).

Poromarto, S., & Nelson, B. (2009). Reproduction of soybean cyst nematode on dry bean cultivars adapted to North Dakota and northern Minnesota. *Plant Disease, 93*, 507–511.

Poromarto, S., Nelson, B., & Goswami, R. S. (2010). Effect of soybean cyst nematode on growth of dry bean in the field. *Plant Disease, 94*, 1299–1304.

Poromarto, S. H., Gramig, G. G., Nelson, B. D., Jr., & Jain, S. (2015). Evaluation of weed species from the Northern Great Plains as hosts of soybean cyst nematode. *Plant Health Progress*. https://doi.org/10.1094/PHP-RS-14-0024.

Porter, P. M., & Chen, S. (2005). Sugarbeet cyst nematode not detected in the Red River Valley of Minnesota and North Dakota. *Journal of Sugarbeet Research, 42*, 79–84.

Riggs, R. D. (1988). Races of *Heterodera glycines*. *Nematropica, 18*, 163–170.

Riggs, R. D., & Schmitt, D. P. (1988). Complete characterization of the race scheme for *Heterodera glycines*. *Journal of Nematology, 22*, 392–395.

Roberts, P. A. (2002). Concepts and consequences of resistance. In J. L. Starr, R. Cook, & J. Bridge (Eds.), *Plant resistance to parasitic nematodes* (pp. 23–41). London: CAB International.

Shalu, J., Kishore C., Brueggeman, R., Osorno, J., Richards, J., & Nelson, B. (2017). *Soybean cyst nematode in dry bean (Phaseolus vulgaris): Understanding and managing underground enemies in the era of genomics*. Soybean cyst nematode conference. S1.5. December 13–15. Coral Gables. Florida.

Sims, P. L., Singh, J. S., & Lauenroth, W. K. (1978). The structure and function of ten Western North American grasslands. I. Abiotic and vegetational characteristics. *Journal of Ecology, 66*, 251–258.

Smolik, J. D. (1977a). Effect of nematicide treatment on growth of range grasses in field and glasshouse studies. In J. K. Marshall (Ed.), *Proceedings of below-ground ecosystem symposium* (pp. 257–260). Colorado State University Range Science Series No. 26.

Smolik, J. D. (1977b). Nematodes associated with irrigated corn in South Dakota. *Proceedings of the South Dakota Academy of Science, 56*, 93–99.

Smolik, J. D. (1978). Influence of previous insecticidal use on ability of carbofuran to control nematode populations in corn and effect on corn yield. *Plant Disease Report, 62*, 95–99.

Smolik, J. D. (1982). Effect of *Tylenchorhynchus robustoides* on growth of buffalo grass and western wheatgrass. *Journal of Nematology, 14*, 585–588.

Smolik, J. D. (1995). First report of *Heterodera glycines* on soybean in South Dakota. *Plant Disease, 80*, 224.

Smolik, J. D., & Draper, M. A. (2007). *Soybean cyst nematode*. SDSU Extension Fact Sheets. Paper 81. http://openprairie.sdstate.edu/extension_fact/81

Smolik, J. D., & Evenson, P. D. (1987). Relationship of yields and *Pratylenchus* spp. population densities in dryland and irrigated corn. *Annals of Applied Nematology, 1*, 71–73.

Smolik, J. D., & Lewis, J. K. (1982). Effect of range condition on density and biomass of nematodes in a mixed ecosystem. *Journal of Range Management, 35*, 657–663.

Spears, J. F. (1956). Occurrence of the grass cyst nematode, *Heterodera punctata*, and *Heterodera cacti* group cysts in North Dakota and Minnesota. *Plant Disease Reporter, 40*, 583–584.

Thorne, G. (1974). Nematodes of the Northern Great Plains part II. *Technical Bulletins,* 5. 94 pp.

Thorne, G., & Malek, R. B. (1968). Nematodes of the Northern Great Plains. Part I. Tylenchida. *Technical Bulletin of South Dakota Agricultural Experiment Station, 31*, 1–111.

Thorne, G., & Smolik, J. D. (1971). The identity of *Paratylenchus nanus* Cobb, 1923. *Proceedings of the Helminthological Society of Washington, 38*, 90–92.

Tylka, G. L., & Marett, C. C. (2014). *Distribution of the soybean cyst nematode, Heterodera glycines, in the United States and Canada: 1954 to 2014*. https://doi.org/10.1094/PHP-BR-14-0006.

Upadhaya, A., Yan, G. P., Plaisance, A., Pasche, J. S., & McPhee, K. (2016). *Identification and reproduction of pin nematodes on field pea (Pisum sativum) in North Dakota*. In Abstracts of 55th annual meeting of the society of nematologists, Montreal Quebec, Canada, July 17–21 (pp. 185–186).

Upadhaya, A., Yan, G. P., Plaisance, A., Pasche, J., & McPhee, K. (2017). Pin nematode: a potential threat to pea production in North Dakota. *Proceedings of the North Dakota Academy of Science, 71*, 45.

USDA-NASS. (2015a). *State agriculture overview, South Dakota*. https://www.nass.usda.gov/Statistics_by_State/South_Dakota/

USDA-NASS. (2015b). *State agriculture overview, North Dakota*. https://www.nass.usda.gov/Statistics_by_State/North_Dakota/

USDA-NASS. (2016a). *News release. South Dakota's rank in U.S agriculture*. p. 1. https://www.google.com/webhp?sourceid=navclientandie=UTF8andgws_rd=ssl#q=South+Dakota's+rank+in+US+agricultureand*andspf=107

USDA-NASS. (2016b). News release. North Dakota's rank in U.S agriculture. p. 1. https://www.google.com/webhp?sourceid=navclientandie=UTF8andgws_rd=ssl#q=North+Dakota's+rank+in+US+agricultureand*andspf=1

Westphal, A. (2011). Sustainable approaches to the management of plant parasitic nematodes and disease complexes. *Journal of Nematology, 43*, 122–125.

Westphal, A., Xing, L. J., & Egel, D. S. (2006). *Use of cover crops for management of root knot nematodes in cucurbits*. Annual International Research Conference Methyl Bromide Alternatives Emission Reduction, Orlando, FL, 6–9, 2006 22-1-3.

Westphal, A., Xing, L. J., Pillsbury, R., & Vyn, T. J. (2009). Effects of tillage intensity on population densities of *Heterodera glycines* in intensive soybean production systems. *Field Crops Research, 113*, 218–226.

Winstead, N. N., Skotland, C. B., & Sasser, J. N. (1955). Soybean cyst nematode in North Carolina. *Plant Disease Report, 39*, 9–11.

Xing, L. J., & Westpal, A. (2009). Effects of crop rotation of soybean with corn on severity of sudden death syndrome and population densities of *H. glycines* in naturally infested soil. *Field Crops Research, 112*, 107–117.

Yan, G. P., & Baidoo, R. (2017). Molecular detection of soybean cyst nematode in North Dakota. *Phytopathology, 107*, S1.9. https://doi.org/10.1094/PHYTO-107-1-S1.1.

Yan, G. P., & Plaisance, A. (2016). Vermiform plant parasitic nematodes on soybean in North Dakota and their relationship with soybean cyst nematode. *Phytopathology, 106*, S4.104. https://doi.org/10.1094/PHYTO-106-12-S4.1.

Yan, G. P., Markell, S., Nelson, B. J., Helms, T. C., & Osorno, J. M. (2015a). *The status of soybean cyst nematode occurrence and management in North Dakota*. In Abstracts of 54th annual meeting of the society of nematologists, East Lansing, MI, July 19–24 (pp. 126–127).

Yan, G. P., Plaisance, A., & Ye, W. (2015b). Plant parasitic nematodes on field crops in Southeastern and Northeastern North Dakota. *Phytopathology, 105*(S4), 153.

Yan, G. P., Plaisance, A., Huang, D., & Handoo, Z. A. (2016a). First report of the lance nematode *Hoplolaimus stephanus* from a soybean field in North Dakota. *Plant Disease, 100*, 2536. https://doi.org/10.1094/PDIS-07-16-1012-PDN.

Yan, G. P., Plaisance, A., Huang, D., & Handoo, Z. A. (2016b). First detection of the stubby root nematode *Paratrichodorus allius* on potato in North Dakota and on sugarbeet in Minnesota. (Abstr.). *Phytopathology, 106*, S4.125. https://doi.org/10.1094/PHYTO-106-12-S4.1.

Yan, G. P., Plaisance, A., Huang, D., Gudmestad, N. C., & Handoo, Z. A. (2016c). First report of the root lesion nematode *Pratylenchus scribneri* infecting potato in North Dakota. *Plant Disease, 100*, 1023. https://doi.org/10.1094/PDIS-10-15-1227-PDN.

Yan, G. P., Plaisance, A., Huang, D., Liu, Z., Chapara, V., & Handoo, Z. A. (2016d). First report of the root lesion nematode *Pratylenchus neglectus* on wheat (*Triticum aestivum*) in North Dakota. *Plant Disease, 100*, 1794. https://doi.org/10.1094/PDIS-02-16-0260-PDN.

Yan, G. P., Plaisance, A., Huang, D., Upadhaya, A., Gudmestad, N. C., & Handoo, Z. A. (2016e). First report of the stubby root nematode *Paratrichodorus allius* on potato in North Dakota. *Plant Disease, 100*, 1247. https://doi.org/10.1094/PDIS-11-15-1350-PDN.

Yan, G. P., Plaisance, A., Chowdhury, I., Baidoo, R., Upadhaya, A., Pasche, J., Markell, S., Chen, S., & Nelson, B. (2017a). First report of the soybean cyst nematode *Heterodera glycines* infecting dry bean (*Phaseolus vulgaris* L.) in a commercial field in Minnesota. *Plant Disease, 101*, 391.

Yan, G. P., Plaisance, A., Huang, D., Handoo, Z. A. (2017b). First report of a new stunt nematode *Tylenchorhynchus* sp. from a soybean field in North Dakota. *Plant Disease, 102*, 453. https://doi.org/10.1094/PDIS-05-17-0616-PDN

Yan, G. P., Plaisance, A., Huang, D., & Handoo, Z. A. (2017c). First report of the spiral nematode *Helicotylenchus microlobus* infecting soybean in North Dakota. *Journal of Nematology, 49*, 1.

Yan, G. P., Plaisance, A., Huang, D., Chowdhury, I. A., & Handoo, Z. A. (2017d). First report of the new root lesion nematode *Pratylenchus* sp. on soybean in North Dakota. *Plant Disease, 101*, 1554.

Yan, G. P., Plaisance, A., Huang, D., Handoo, Z. A., & Chitwood, D. J. (2017e). First report of a new, unnamed lesion nematode *Pratylenchus* sp. infecting soybean in North Dakota. *Plant Disease, 101*, 1555.

Young, L. D. (1992). Problems and strategies associated with long-term use of nematode resistant cultivars. *Journal of Nematology, 24*, 228–233.