Chapter 1
Current State of Plant Parasitic Nematodes in Canada

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1.1 Introduction

In Canada, there is a consensus among experienced nematologists that although crop losses related to plant parasitic nematodes (PPN) have not been exactly estimated, they could be in the range of 5–15% (Potter and McKeown 2003). Similar to many countries, the damages caused by PPNs are most often overlooked, mainly because the typical above ground symptoms of yellowing and stunting are often confused with other diseases, environmental factors such as drought and nutrient deficiencies. A relatively small portion of Canada's land is suitable for agriculture, or about 7% (65 million ha). Across the country, the character of agriculture differs from one province to the next, with climates and soil types influencing the commodities produced. Over 80% of arable land in Canada is located in the Western Prairie provinces. Saskatchewan accounts for almost 38% of farmland, with Alberta

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and Manitoba accounting for 31% and 11%, respectively. Ontario accounts for 8% of the land, Quebec 5%, British Columbia 4%, while Nova Scotia, New Brunswick and Prince Edward Island each contain only 1%, and Newfoundland and Labrador account for less than 1% of Canada's total arable land.

The area per farm continues to increase with great variation from one region to another reflecting regional differences in commodities grown according to differences in soil, climate, topography and markets. Larger farms are located in the Canadian Prairies, where the crops produced are mainly grains, cereals with wheat by far the largest crop and pulses, oilseeds, mainly canola, and tame or native pasture for backgrounding of cattle. The average farm size in Saskatchewan is approximately 675 ha, more than twice the national average. In Alberta, the average farm size is about 472 ha, a little over one and a half times the national average. In the other Prairie province, Manitoba, it is 459 ha (Statistics Canada 2014). Compared to farms of the Prairies, the average size of farms is much smaller elsewhere; British Columbia (132 ha), Quebec (113 ha), Ontario (99 ha) and the Atlantic Provinces (ranging from 161 ha in Prince Edward Island to 62 ha in Newfoundland and Labrador) (Statistics Canada 2014). In terms of area, corn and soybean are the major crops in Ontario and Quebec, but specialized crops such as greenhouse, floriculture and nursery trees are also produced. Fruit and vegetable production is concentrated in Ontario, Quebec, British Columbia and the Atlantic Provinces. Canada is 1 of the 20 largest potato-producing countries in the world. In fact, potatoes are the largest vegetable crop in the country (162,515 ha). They are grown in all provinces and are economically important in several provinces. Prince Edward Island is the largest producer (about 39,512 ha), followed by Manitoba (32,630 ha), New Brunswick (24,228 ha) and Alberta (22,160 ha) (Statistics Canada 2014). Alberta is poised to increase its potato production with the establishment of more processing facilities. Thus, the Prairies are set to become the major growing region in Canada.

Canadian agroecosystems have historically been less affected by PPNs when compared to other countries, mainly because Canada has a relatively cool climate. Winters are sufficiently severe in most agricultural areas of Canada to prevent survival of many of the most pathogenic PPN species found in more southern regions of North America. The cool climate also restricts cropping to one annual crop per year in most agricultural areas, which limits population buildup of those PPN species that do persist in Canada. Diverse crop rotations are often used allowing for breaks in susceptible hosts. Thus, the climate directly and indirectly dictates the PPN species and their severity.

The most common and damaging groups are root lesion nematodes (*Pratylenchus* spp.), and cyst nematodes (*Heterodera* spp., and *Globodera* spp.). With the acceleration of climate change, quarantined and invasive alien nematode species pose greater challenges, for example the stem and bulb nematode (*Ditylenchus dipsaci*) has become a serious pest in recent years, illustrating the need for development of nematology programs and extension in Canada. It is likely that the most devastating PPNs in the future will be different from the ones being dealt with at the present.

For the management of PPN, Canada, like other developed countries, has transitioned from the wide use of broad spectrum fumigant nematicides in the 1990s and early 2000s, to the adoption of integrated pest management (IPM) practices such as rotation with non-host crops and resistant varieties, and the use of green manure cover crops and other types of organic amendments.

Canada faces great challenges, as does the rest of the world, in understanding and controlling PPN in order to increase productivity for an ever-increasing human population while minimizing impacts of agriculture on the environment. This chapter attempts to read the past in order to understand the present, with some hints for the future, related to PPN in Canada.

1.2 Root Lesion Nematodes, *Pratylenchus* spp.

Root lesion nematodes are migratory endoparasites, and the most common PPN in Canadian agroecosystems. Twelve species have been recorded: *Pratylenchus alleni, P. crenatus*, *P. fallax*, *P. flakkensis*, *P. hexincisus*, *P. macrostylus*, *P. neglectus*, *P. penetrans*, *P. pratensis*, *P. sensillatus*, *P. thornei*, and *P. zeae*. The most common and destructive species is *P. penetrans* and the highest diversity of species is observed in the province of Ontario, followed by the province of Quebec (Townshend et al. 1978; Yu 2008; Bélair et al. 2013). In Manitoba, *P. neglectus* was found to be the predominant species, and *P. penetrans* was reported decades ago near the USA border but not currently (Mahran et al. 2010a). *P. neglectus* is present in every Prairie Province in about a quarter of commercial crop fields (Tenuta et al. unpublished). Elsewhere, co-infestations by multiple species are common, e.g., *P. neglectus, P. crenatus*, and *P. penetrans* were found in the same potato fields in Ontario (Olthof et al. 1982), while *P. crenatus* and *P. penetrans* were found to be sympatric in Prince Edward Island (Kimpinski 1979). Interestingly *P. neglectus* has never been detected in Prince Edward Island, while this species is found in large populations in Ontario (Olthof 1990). Surveys for PPN in golf courses, in different climate regions within Ontario and Quebec, also revealed that *Pratylenchus* was the most frequently detected genus (Yu et al. 1998; Simard et al. 2008). These nematodes are ubiquitous in all provinces and affect many crops (Potter and McKeown 2003). As an illustration of the ubiquitous nature of this genus, a survey of nematodes associated with highbush blueberry in British Columbia and other areas of the Pacific Northwest reported that 73% of fields were affected by PPN and that *Pratylenchus* was the most common genus (Zasada et al. 2010).

1.2.1 Pratylenchus penetrans

Overall, *Pratylenchus penetrans* is the most serious pest in Canada, attacking most of the high-value horticultural crops (Table 1.1). In addition, *P. penetrans* interacts with pathogenic fungi to cause serious replant disease complexes of tree-fruit crops such as the peach replant disease and the apple replant disease (Patrick 1955;

Table 1.1 The agriculturally important plant parasitic nematodes and their associated hosts in Canada

Nematode	Province[a]	Crop	Reference
Anguina agrostis	NS, NW, ON, SK	Turfgrass	Baker (1955, 1957, 1959)
Ditylenchus destructor	ON, PE	Garlic, potato	Baker (1946) and Yu et al. (2012)
D. dipsaci	AL, BC, MN, ON, PE, QC, SK	Alfalfa, garlic, onion	Mountain (1957), Vrain and Lalik (1983), Vrain (1987), CABI/EPPO (2009), Réseau d'avertissements phytosanitaires (2013), and Hajihassani and Tenuta (2017)
Globodera pallida	NF	Potato	Stone (1977)
G. rostochiensis	BC, NF, QC	Potato	Olsen and Mulvey (1962), Orchard (1965), and Sun et al. (2007)
Heterodera avenae	ON	Corn, oat	Putnam and Chapman (1935) and Fushtey (1965)
H. carotae	ON	Carrot	Yu et al. (2017)
H. fici	ON (greenhouse)	Fig	Sun et al. (2017)
H. glycines	ON, QC	Soybean	Anderson et al. (1988) and Mimee et al. (2014a)
H. schachtii	AL, ON	Sugar beet	Baker (1942) and Lilly et al. (1961)
Longidorus diadecturus	ON	Peach	Eveleigh and Allen (1982)
L. breviannulatus	ON	Apple, cherry, peach, raspberry, turfgrass	Van Driel et al. (1990) and Simard et al. (2009)
L. elongatus	BC, ON	Strawberry, turfgrass	McElroy (1977), Allen and Ebsary (1988), and Pedram et al. (2010)
Meloidogyne hapla	BC, MN, NB, ON, PE, QC	Cabbage, carrot, cauliflower, lettuce, onion, potato, strawberry, tomato	Olthof and Potter (1972), Potter and Townshend (1973), Sayre and Toyama (1964), Vrain et al. (1981), Bélair (1992), and CABI/EPPO (2002)
M. incognita	ON, QC (greenhouse)	Tomato, cucumber	Bird (1969), Johnson and Boekhoven (1969), and Bélair (unpublished)
M. microtyla	ON	Grass	Mulvey et al. (1975)
M. naasi	QC	Turfgrass	Bélair et al. (2006)
Paratrichodorus renifer	BC	Blueberry, potato	Kawchuk et al. (1997), Xu and Nie (2006), and Forge et al. (2009, 2012)
Pratylenchus alleni	QC	Soybean	Bélair et al. (2013)

(continued)

Table 1.1 (continued)

Nematode	Province[a]	Crop	Reference
P. crenatus	BC, ON, PE	Blue berry, potato	Kimpinski (1979), Olthof et al. (1982), and Zasada et al. (2017)
P. fallax	ON	Turfgrass	Yu et al. (1997)
P. neglectus	AL, BC, MN, ON, QC	Potato	Olthof et al. (1982), Mahran et al. (2010a), and Forge et al. (2015a)
P. penetrans	AL, BC, SK, MN, NB, NS, ON, PE, QC	Apple, barley, bluberry, carrot, corn, grapes, oat, onion, pea, peach, pear, plum, potato, raspberry, soybean, strawberry, tabacco, wheat	Baker (1955), Potter and Townshend (1973), Oltholf et al. (1982), Kimpinski (1987), Dauphinais et al. (2005), Yu (2008), Forge et al. (2012), and Bélair et al. (2018)
P. thornei	ON	Wheat	Yu (1997)
Trichodorus primitivus	ON	Turfgrass	Pedram et al. (2010)
Xiphinema americanum	ON, QC	Apple, blueberry, peach	Vrain and Rousselle (1980), Allen et al. (1984), and Ebsary et al. (1984)
X. rivesi	ON	Apple	Ebsary et al. (1984)

[a]Names of the provinces and territories of Canada are represented by two letter. *AL* Alberta, *BC* British Columbia, *MB* Manitoba, *NB* New Brunswick, *NL* Newfoundland and Labrador, *NS* Nova Scotia, *NW* North West Territory, *ON* Ontario, *QC* Quebec, *PE* Prince Edward Island, *SK* Saskatchewan

Wensley 1956; Mountain and Boyce 1958a, b; Ward and Durkee 1956; Mountain and Patrick 1959; Potter and Olthof 1974, 1977; Braun et al. 2010; Forge et al. 2016a). It also interacts with particular fungal pathogens to cause brown root rot of tobacco (Olthof 1967, 1971; Elliot and Marks 1972), and early dying disease on potato (Kimpinski et al. 2001; Bélair et al. 2005; Dauphinais et al. 2005). In Prince Edward Island, *P. penetrans* has been recognized as a widespread constraint on potato production since the 1970s (Kimpinski et al. 1992). In Quebec, severe symptoms of early dying have been observed in potato fields (Bélair unpublished). A similar interaction with *Verticillium dahliae* was also observed in strawberry fields (Bélair et al. 2018). In soybean, *P. penetrans* was found in 42% of the tested fields (78 out of 185) in the province of Quebec and 8% of the fields showed a population density exceeding the theoretical economic threshold (Dauphinais et al. 2018).

1.2.2 Pratylenchus neglectus

In Manitoba, *P. neglectus* was recently found in a third of 31 commercial potato fields examined (Mahran et al. 2010a). However, the dominant potato cultivar 'Russet Burbank' was not a good host for the Manitoba populations of *P. neglectus*, or if the nematode had significant effects on yields (Mahran et al. 2010a). The studies in Manitoba suggested that rotation crops other than potato such as canola and wheat, were likely primary hosts to the nematode, as shown in the U.S.A. (Smiley et al. 2004; Johnson 2007). More recently, a survey of pulse fields across the Prairies found widespread distribution of *P. neglectus* (Tenuta et al. unpublished). In Alberta, high level of *P. neglectus* populations was associated with potato yield losses in a study where short crop rotations, with wheat preceding potato, resulted in the greatest expression of potato early dying disease symptoms and the lowest yields of several alternative rotations (Forge et al. 2015a). It is unclear if the apparent differences between the Manitoba and Alberta studies are due to differences in the inherent pathogenicity of *P. neglectus* populations or the environments (e.g. soil texture, irrigation) and crop rotations. Previous research also suggests that there may be differences in the ability of *P. neglectus* populations to parasitize and damage potato (Olthof 1990; Hafez et al. 1999).

Worldwide, *P. neglectus* is recognized as a significant pest of small grain and oilseed crops (Taylor et al. 1999; Smiley et al. 2004; Johnson 2007). Considering the importance of these crops to agriculture in Western Canada, research on the impacts of *P. neglectus* on small grain and oilseed crops in Western Canada is urgently needed. The species was also recently found north of Quebec City, which lies outside of what was previously known as the northern limit of its distribution (Bélair unpublished).

1.2.3 Other **Pratylenchus** *Species*

Even though *P. penetrans* is still the most common species in Canada, Canadian nematologists should remain vigilant for any outbreaks of other species. *Pratylenchus thornei*, a serious pest on wheat in some countries, was found in wheat in Ontario (Yu 1997). The recent isolation of *P. alleni* in a Quebec soybean field has also raised some concerns about the possible establishment of species that are more aggressive. The yield losses from *P. alleni* in diseased areas ranged from 38% to 54% (Bélair et al. 2013). In USA, the pathogenicity of *P. alleni* in soybean has been established (Acosta and Malek 1981), but the species is also known to affect other crops such as corn and wheat (Wartman and Bernard 1985). Recently, *P. crenatus* was found to be the main species parasitizing highbush blueberry in British Columbia, as well as, in other areas of the Pacific Northwest (Zasada et al. 2017).

1.2.4 Management of **Pratylenchus penetrans**

Given the ubiquitous presence of *Pratylenchus penetrans* in Canadian fruit and vegetable production systems, a major focus of research has been the identification of cultural practices that may minimize impacts of *P. penetrans* on high-value fruit and vegetable crops. Crop rotation is a challenging approach for *P. penetrans* management due to its wide host range, which also includes many weed species (Bélair et al. 2007). In their comprehensive analysis of weed hosts, Bélair et al. (2007) found that the family Brassicaceae was shown to be the best hosts while representatives of the Cyperaceae were the worst. Annual bluegrass crops were shown to be tolerant to *P. penetrans* under controlled conditions (Bélair and Simard 2008). Despite its wide host range, Canadian research has shown that rotation with suppressive cover crops can be a successful approach to managing *P. penetrans* in annual cropping systems. Ball-Coelho et al. (2003) and Bélair et al. (2005) demonstrated that rotating to a specific variety of forage pearl millet, CFPM 101, prior to planting the potato cash crop resulted in lower *P. penetrans* populations at the time of potato planting. As a consequence, they observed increased yields relative to other types of cover crops including other varieties of forage pearl millet. The cultivar CFPM 101 has been shown to be a poor host to *P. penetrans* that does not allow population buildup. It is not clear if it may also stimulate active suppression via toxic metabolites, or perhaps, by stimulating the development of a suppressive soil food web. Mahran et al. (2008a, b), in a laboratory and field study found that volatile fatty acids in pig slurry and acidified pig slurry could kill the nematode. In British Columbia, however, frequent modest applications of dairy manure slurry to tall fescue resulted in greater *P. penetrans* population densities than a corresponding fertilizer treatment or an untreated control, presumably, as a result of enhanced nutritional value of root tissue (Forge et al. 2005). This research indicates that the utility of manure slurries for *P. penetrans* control will depend on the interplay of application rates with growth responses of the crops. Brassica "bio-fumigant" green manures have also been evaluated extensively for control of *P. penetrans* in Canadian vegetable rotations. In related Canadian research, glucosinolate-containing *Brassica* seed meals suppressed *P. penetrans* under greenhouse conditions (Yu et al. 2007a) but not in corn fields (Yu et al. 2007b).

As part of an integrated replant management program for perennial fruit crops, Forge et al. (2015a, b, 2016b) have shown that heavy applications (>50 Mg/ha) of poultry manure or compost can suppress populations of *P. penetrans* through at least two full growing seasons after replanting raspberry (Forge et al. 2016b) or sweet cherry (Forge et al. 2015b; Watson et al. 2017). The authors speculated that the poultry manure could have bio-fumigant effects owing to the relatively high amounts of ammonia released into the soil environment at such high application rates, but the duration of suppression suggests that stimulation of suppressive soil food webs or rhizosphere communities could also be involved. The researchers demonstrated that the reductions in numbers of *P. penetrans* in compost-treated soil was associated with increased colonization of the cherry rhizosphere by bacteria with nematode suppressive activity but speculate that other biological antagonists could also be involved in the suppression (Watson et al. 2017).

Options for cultural management in perennial fruit crops are constrained by the lack of annual tillage to facilitate incorporation of organic amendments, antagonistic cover crops or control agents. The use of paper mulch in an apple orchard reduced *P. penetrans* populations and could explain the increased root growth of the apple trees (Forge et al. 2008). Other types of organic mulches, including, alfalfa hay

(Forge et al. 2003, 2013) seem to give similar results. Concomitant increases in food web structure suggest that organic mulches may increase the presence of nematode antagonists, creating a suppressive food web, thereby decreasing the damage caused by *P. penetrans* (Forge and Kempler 2009).

1.3 Root Knot Nematodes, *Meloidogyne* spp.

Root knot nematodes are sedentary PPN and among the most damaging of soil-borne pests of horticultural and field crops. Most damages are attributed to these four species: *Meloidogyne incognita*, *M. arenaria*, *M. javanica*, and *M. hapla*, with *M. chitwoodi* being a major pest of potato (Nicol et al. 2011). However, because of our temperate climate, the problems associated with root knot nematodes are far less important in Canada; *M. incognita*, *M. arenaria* and *M. javanica* are unable to persist where the soil freezes, and *M. chitwoodi* has not been introduced to Canada. Consequently, the main species of concern for Canadian agriculture is currently the northern root knot nematode (*M. hapla*), which has been reported in British Columbia, Manitoba, Ontario, Quebec and Prince Edward Island parasitizing a range of horticultural crops (Zimmer and Walkof 1968; Potter and Townshend 1973; Willis et al. 1976; Vrain and Dupré 1982; Bélair 2005) and alfalfa (Townshend et al. 1973).

Several other root knot nematode species are potential concerns on limited crops in Canada, or pose a risk of establishment. In a survey nematodes in golf course turf in Quebec, *M. naasi* was isolated from severely damaged annual bluegrass plants (Bélair et al. 2006). Although it is a common species in Europe and in several states in the USA where it causes significant damage, *M. naasi* has rarely been observed in Canada. *Meloidogyne microtyla*, a new species at the time was found on grass in Southwestern Ontario in 1975 (Mulvey et al. 1975).

Southern root knot nematode (*M. incognita*) has, so far, only been found on several vegetable crops in greenhouses in Southwestern Ontario (Mountain and Sayre 1961) and Southern Quebec (Bélair unpublished). This species could take advantage of climate change to move to open fields, or spread from nearby USA states of New York and Pennsylvania (Walters and Barker 1994) to the neighbouring provinces.

The Columbia root knot nematode (*M. chitwoodi*), which is on the quarantine list of the Canadian Food Inspection Agency (CFIA), was first described in the Columbia River basin of Oregon and Washington in 1980 (Santo et al. 1980). This nematode is substantially more damaging to potato than *M. hapla* (Van Der Beek et al. 1998). It also has a very wide host range that covers many crop species, including tomato and cereals (Ferris et al. 1994). Thus, this species is more difficult to control by means of crop rotation than *M. hapla*, which has a narrower host range and does not reproduce on cereals. Considering the proximity of *M. chitwoodi*-infested areas in the US to Canadian potato production areas, Canadian nematologists must continue to be vigilant. Other species of concern include *M. fallax, M. minor, M. enterolobii, M. exigua,* and *M. paranaensis,* because they have only recently been described (Elling 2013).

1.3.1 Management of **Meloidogyne hapla**

Meloidogyne hapla has been reported in the provinces of New Brunswick, Ontario, Prince Edward Island, British Columbia and Quebec (CABI/EPPO 2002). Although the nematode is widespread, the populations are generally low. Many vegetable crops such as cabbage, cauliflower, onion and tomato have been shown to be affected by the nematode (Olthof and Potter 1972; Sayre and Toyama 1964), but it is on carrots cultivated in muck soils that the pest has received most attention. Crop rotation with a non-host crops such as cereals or grasses are used to maintain *M. hapla* densities below damaging levels, which are extremely low for carrots (Bélair 1992; Bélair and Parent 1996). Even at the detectable level of 1 infective juvenile per 100 ml soil, severe forking and stunting of the tap root are induced in carrots, which are rendered unmarketable (Bélair 1992).

Several nematicides were effective in reducing the *M. hapla* populations and increasing yields of marketable carrot (Vrain et al. 1981). In strawberry production, the presence of multiple root pathogens including *M. hapla,* justifies preplant fumigation with chloropicrin and metham sodium to increase vigor and yields over the 2-year production period. In potato production, *M. hapla* is not considered to be a primary problem. However, soil fumigation using chloropicrin, metham sodium, or metham potassium is occasionally performed by some growers to manage other soil-borne pathogens, especially *Verticillium dahliae* and root lesion nematodes which together cause the potato early dying disease complex (Celetti and Al-Mughrabi pers. comm.). The planting of certified seed also contributes to limiting the dispersal and losses caused by PPN in potato production. Occasionally, potato tubers containing *M. hapla* females can be observed causing some necrosis underneath the potato peel during storage, but no direct actions are taken by the growers to manage this disorder in Eastern Canada (Bélair unpublished).

With the withdrawal of dichloropropene from the registered list of nematicides, combined with additional restrictions on the use of chloropicrin and metham sodium in Canada, growers have been forced to consider more sustainable cultural practices to control *M. hapla*. A small number of studies were done in Canada in recent years to find alternative and sustainable methods of controlling *M. hapla*. Seed exudates of *Tagetes* spp. (Riga et al. 2005) and oriental mustard bran (Yu et al. 2007a) demonstrated nematicidal activity on root knot nematodes. The effect of nicotine was also studied and proved to be toxic to several species of nematodes including *M. hapla* (Yu and Potter 2008). Soil amendment with *Streptomyces lydicus* significantly decreased *M. hapla* juveniles in soil (Bélair et al. 2011).

Market garden production of vegetables is increasing rapidly in areas around most major Canadian cities. As *M. hapla* can parasitize many of the popular crops in market garden production, the impact of this nematode on market garden production is likely to increase. At this point in time, however, there is limited awareness of the prevalence of root knot nematodes in small-scale vegetable production in Canada.

1.4 Cyst Nematodes, *Heterodera* spp. and *Globodera* spp.

Heterodera spp., and *Globodera* spp. commonly known as cyst nematodes, are sedentary endoparasites that are well adapted for cold-temperate climate regions such as Canada. They infect the roots of many plants including many important crops grown in Canada such as cereals, corn, soybean and potato. They are very difficult to control because of the ability of eggs in dried cysts to survive in soil for extended periods.

1.4.1 Heterodera *spp.*

Heterodera species of significance in Canada include soybean cyst nematode (*H. glycines*), sugar beet cyst nematode (*H. schachtii*), cereal cyst nematodes (*H. avenae* and *H. filipjevi*) and carrot cyst nematode (*H. carotae*).

The soybean cyst nematode is particularly important as soybean production has been expanding in Canada. The pest was first reported in Southwest Ontario in 1987 (Anderson et al. 1988). Since then it has spread north and northeastwards along the St. Lawrence River and, in 2013, was found in Quebec (Mimee et al. 2014a). It is currently present at low population densities in all areas producing soybean in Quebec (Mimee et al. 2016). It is considered likely that soybean cyst nematode was present and causing soybean yield losses in Southwest Ontario by the 1970s, but had gone undiagnosed (Tenuta pers. comm.). The nematode has expanded northward in North Dakota and Minnesota to the Manitoba border though surveys of soybean conducted in Manitoba between 2013 and 2015 did not find the nematode (Tenuta et al. unpublished). Surveys continue in Manitoba as the area of production has increased from insignificant in the early 2000 and expected to cap at 1.2 million hectares within 30 years. Soybean cyst nematode was a regulated pest in Canada until the fall of 2013 when it was de-regulated (CFIA 2013).

The sugar beet cyst nematode, *H. schachtii,* was a serious pest in Southern Ontario in the early 1950s when the crop was widely cultivated (Baker 1942). It was first found in Alberta in 1961 (Lilly et al. 1961) and has become recognized as a significant pest for the sugar beet industry in Southern Alberta. Currently, the nematode is successfully managed using a 4-year rotation. The Manitoba Sugar Company conducted extensive surveys for *H. schachtii* when sugar beet was grown in the province. The nematode was first reported in 1976 and over several years, found on light soils near the city of Winkler (Zednai 1979). The pest has recently been reported in North Dakota where sugar beet is still grown in the Red River Valley, which is contiguous with Southern Manitoba (Nelson et al. 2012).

The cereal cyst nematode, *H. avenae,* was first reported damaging oat in Ontario in the 1930s (Putnam and Chapman 1935), with further investigation occurring through the 1940s (Baker and Chapman 1946). Later, the nematode was found infesting corn in the same regions (Fushtey 1965; Fushtey and Johnson 1966). *Heterodera avenae* is widespread on wheat in the Northwestern US states of Washington, Idaho and Montana that border British Columbia, Alberta and Saskatchewan (Smiley and Nicol 2009). A closely related species, *H. filipjevi,* is also present in Washington (Smiley and Yan 2015) and recently reported in Montana (Dyer et al. 2015). Neither species appears to have become established in the major Canadian cereal-producing regions of Saskatchewan and Alberta despite the proximity to infestations in nearby Washington, Idaho and Montana. Considering this precarious situation and the long-recognized importance of the nematode in Ontario, surprisingly little research has been directed at this nematode in Canada.

The carrot cyst nematode, *H. carotae,* was recently reported in the Holland Marsh region in the province of Ontario (Madani et al. 2017; Yu et al. 2017). These are the first reports of the pest in Canada. A preliminary survey indicated that the pest is wide spread in the region (Vander Kooi et al. 2017). A diagnostic conventional PCR method was developed based on populations of *H. carotae* from Ontario and Italy using primer sets based on the *coxI* gene sequence in real-time PCR and melt curve analysis (Madani et al. 2017).

1.4.1.1 Management of *Heterodera* spp.

Plant resistance remains the most effective and economically viable strategy to control soybean cyst nematode, but the presence of new virulent populations, or HG types, can reduce the efficacy of this strategy (Niblack et al. 2002). A recent phenotypic characterization of soybean cyst nematode populations in Ontario reported 24 different HG types (Faghihi et al. 2010). This diversity of HG types is a major concern, given that the number of resistance genes available in commercial cultivars is very limited. Fortunately, 73% of the populations did not reproduce well on PI 88788, which is the resistance source used in the vast majority of resistant cultivars. However, the study also demonstrated that 15% of the populations developed well on PI 548402 (cv. Peking), even though that source of resistance is not generally present in commercial cultivars in Ontario. Thus, the development of new cultivars based on novel resistance sources is necessary. Fortunately, future breeding will be facilitated by new technologies such as marker-assisted selection (MAS) and genotyping by sequencing (GBS). These techniques have already been used to identify early maturity genes (Tardivel et al. 2014), another meaningful trait for Canadian productivity, as soybean is grown farther north each year.

Unfortunately, a modelling of the soybean cyst nematode life cycle under current and future (2041–2070) conditions in Quebec predicts that it could survive in all soybean-growing areas (Mimee et al. 2014b). Because the optimal temperature for soybean cyst nematode is warm (27 °C) and the production of cysts is directly influenced by temperature (Da Rocha et al. 2008), it will be interesting to see if this pest will really become problematic in colder regions. If so, these environmental conditions will likely exert a strong selection pressure on the pest, and the resulting HG types may be difficult to predict. New methods for studying the population genetics of cyst nematodes (Mimee et al. 2015a) and current studies to rapidly quantify their abundance in soil using real-time PCR (Tenuta et al. unpublished) will be very useful for monitoring. Another popular management tool in managing the pest is through rotating soybean with non-host crops. We must also remain vigilant on the potential spread of the pest to the new soybean producing provinces of Manitoba and the Atlantic Maritime Provinces.

The cereal cyst nematode has not warranted the development of management strategies in Canada because oats were historically grown mostly for animal feed and the economic impact of the nematode was low. This situation could change as oats are increasingly being grown for human consumption and therefore, considered to be of greater economic value. Wheat is the most important crop to Canada. Although the cereal cyst nematodes have not yet been found infesting wheat in Canada, in recognition of the fact that they are serious pests on the crop in many countries of the world, Canadian researchers must remain vigilant for the possibility that they could one day become serious pests of the most valuable crop for the nation.

1.4.2 **Globodera *spp.***

The genus *Globodera* comprises several species, including golden cyst nematode (*G. rostochiensis*) and pale cyst nematode (*G. pallida*), that are major pests of potato in the world. They are both of high economic importance, and quarantined under strict regulations in Canada by the Canadian Food Inspection Agency (CFIA) as well as in many other countries. In Canada, *G. rostochiensis* has been present on the Saanich Peninsula of Vancouver Island, British Columbia, since 1965 (Orchard 1965), and both *G. rostochiensis* and *G. pallida* have been present on the Island of Newfoundland since 1962 (Olsen and Mulvey 1962; Stone 1977). In 2006, *G. rostochiensis* was reported from potato in the Saint-Amable region, Quebec (Sun et al. 2007), confirmed by morphological and a phylogenetic analysis (Yu et al. 2010c) and later determined to be pathotype Ro1 (Mahran et al. 2010b). Genetic analyses strongly suggest that both species were probably introduced to Canada from Europe, and that multiple introductions of *G. rostochiensis* occurred (Madani et al. 2010; Boucher et al. 2013). In the bioclimatic condition of Quebec, the species was found to do a single life cycle each year, however, a second hatching cohort was observed each year and could soon result in a full second generation in light of climate change (Mimee et al. 2015b). A few G. *rostochiensis* cysts were recovered from a sample from each of two farms out of 2721 samples taken in Alberta in 2007 by CFIA (unpublished). As a result, CFIA and USDA-APHIS instituted a bi-lateral monitoring program and guidelines for declaration of a field containing PCN (CFIA USDA-APHIS 2014).

1.4.2.1 Management of *Globodera* spp. in Canada

The potato cyst nematodes have a narrow host range, and their distribution in Canada remains limited to a few well-defined sites. The management of the pests includes containment and population reduction by using resistant varieties. Immediately after the finding of the pests either in Newfoundland, BC, and Quebec, delimitation surveys were carried out establishing the boundaries of the infestations, followed by strict phytosanitary measures. A minimum measure was a ban on planting susceptible cultivars of potato. Good outcomes have resulted. On the Saanich Peninsula a recent survey did not reveal any positive samples for *G. rostochiensis* with the exception of one field with a history of quarantine infractions (Rott et al. 2010). In Saint-Amable, CFIA has authorized a 1-year production of resistant cultivars followed by a 2-year rotation with a non-host crop (Mahran et al. 2010b). This strategy appears to have been effective, given that population densities quickly dropped below detection levels (Bélair et al. 2016) and very few viable eggs remain 10 years after the establishment of the quarantine area (Mimee et al. 2017). However, the implementation of quarantine measures was shown to modify the biodiversity and abundance of weeds in the regulated fields, resulting in a significant increase of nightshade weed species (*Solanum* spp.) that could support and serve as pest refuges for *G. rostochiensis* (Mimee et al. 2014c). *Globodera rostochiensis* was already known to reproduce on Canadian nightshades, and interestingly, the nematode populations in the different provinces showed dissimilar host preferences for these weeds (Rott et al. 2011).

Detection and precise species-level identification are critical issues in potato cyst nematode management. For this purpose, a multiplex quantitative polymerase chain reaction (qPCR) assay was developed for the simultaneous differentiation of *G. rostochiensis, G. pallida,* and *G. tabacum* (Madani et al. 2008; Mimee et al. 2017). The same team also developed a method based on the heat shock gene *hsp*90 (Madani et al. 2011). It was recently shown that potato cyst nematode pathotypes could be differentiated with specific single-nucleotide polymorphisms (Mimee et al. 2015a). Thus, the next step will be to replace the long and expensive pathotyping assays in greenhouses with rapid and simple allele-specific oligonucleotide PCR assays.

Even though the current Canadian populations have been characterized and strict containment and monitoring is in place, awareness and vigilance is required moving forward. Recently, a new species of potato cyst nematode, *G. ellingtonae*, was described in Oregon (Handoo et al. 2012), and *G. pallida* was found in numerous fields in Idaho (Skantar et al. 2007). These findings serve as reminders that understanding of the phylogenetic and geographic origins of potato cyst nematodes is not complete and additional research is needed. Especially, new strategies effective against all the pathotypes should be explored. For that, the recent publication of the genome sequence of *G. rostochiensis* (Eves-van den Akker et al. 2016) and the transcriptome variation during hatching and survival (Duceppe et al. 2017) will be very useful.

1.5 *Ditylenchus* spp.

1.5.1 Stem and Bulb Nematode, Ditylenchus dipsaci

Stem and bulb nematode is one of the most destructive nematode pests especially in temperate regions. If not controlled, it can cause complete failure of host crops such as onions, garlic, cereals, legumes, strawberries and ornamental plants, especially flower bulbs. It is also an international quarantined nematode pest. In Canada, *Ditylenchus dipsaci* was first reported on onion in one area of Ontario in 1957 (Mountain 1957) and then was found in nearby counties of Ontario in subsequent years (Sayre and Mountain 1962; Johnson and Kayler 1972; Fushtey and Kelly 1975). It was reported in Saskatchewan on creeping thistle in 1979 (Watson and Shorthouse 1979), then in British Columbia on alfalfa in 1983 (Vrain and Lalik 1983), Alberta in 1987 (Vrain 1987), and then in Quebec and Prince Edward Island (CABI/EPPO 2009). The reported finding in Saskatchewan was likely a find of a closely related *D. weischeri*. Although widely distributed, *D. dipsaci* was not considered to be a serious pest in Canada until the recent outbreak on garlic in Ontario. The identity of the nematode in the outbreak was confirmed (Yu et al. 2010b), and a subsequent survey showed that it was widespread in most garlic growing fields in Ontario (Qiao et al. 2013). It has since spread to the neighbouring provinces of Quebec (Réseau d'avertissements phytosanitaires 2013) and Manitoba (Hajihassani and Tenuta 2017) and is an ongoing economic concern in Ontario (Celetti 2011).

One of the main challenges is the precise identification of *D. dipsaci,* which has several races, each of which exhibits a different host preference, and thus managing this nematode is complicated. A recent study showed that two distinct introductions of this parasite into Ontario likely occurred and found genetic differences within a race (Qiao et al. 2013). Sequence analyses of *D. dipsaci* and *D. destructor* (potato rot nematode), initiated by Agriculture and Agri-Food Canada and the CFIA (Yu et al. 2014), should make it easier to develop specific molecular diagnostic tests in the future.

Recently, *Ditylenchus* populations that parasitize creeping thistle in Russia (Chizhov et al. 2010) as well as Manitoba and Saskatchewan (Watson and Shorthouse 1979; Tenuta et al. 2014) were recognized to be *D. weischeri*. This species has a very different host preference than *D. dipsaci* with specialization to creeping thistle and no host compatibility with onion and strawberry (Chizhov et al. 2010), common bean, chickpea, lentil, canola, wheat and garlic (Hajihassani et al. 2016). Yellow pea seems to be a very weak host for *D. weischeri*, with Hajihassani et al. (2016) reporting that the nematode could survive but not reproduce on two of five varieties of yellow pea examined. A follow-up study failed to show development and reproduction of the nematode on yellow pea at 17 and 22 °C but at a very high average temperature of 27 °C (Hajihassani et al. 2017). Further, the nematode did not reproduce or cause yield damage to yellow pea in a field study (Hajihassani et al. 2017). Madani et al. (2015) reported species-specific PCR primers to differentiate *D. dipsaci* and *D. weischeri* to aid screening of export and import commodities for the former. More recently, Madani and Tenuta (2018) provided additional molecular evidence of several genes further substantiating recognition that *D. weischeri* is a distinct species from *D. dipsaci*.

1.5.1.1 Management of the Stem and Bulb Nematode

With cooperation from major seed suppliers, the Ontario Ministry of Agriculture, Food and Rural Affairs (OMFRA) introduced a program producing and distributing garlic seeds free from the stem and bulb nematodes in Ontario (Hughes and Celetti 2011). In 2013, Quebec growers were worried about the introduction of *D. dipsaci*–infected seed pieces, which raised the potential threat of PPN to the garlic industry (Réseau d'avertissements phytosanitaires 2011, 2013). Stem and bulb nematode can also be spread by irrigation and contaminated equipment (Celetti 2009).

Several chemicals have been tested in field trails to control this pest in Ontario, and several have shown promising results (Celetti and Paibomesai 2015). For example, Agri-Mek®, an abamectin-based insecticide, was effective in reducing nematode populations and increasing yields when garlic cloves were soaked in the compound at the labelled rate prior to the planting.

1.5.2 Potato Rot Nematode, **Ditylenchus destructor**

Potato rot nematode is a serious nematode pest in a number of root and tuber crops, primarily in potatoes, and is an internationally quarantined pest. In Canada, this pest was found in Prince Edward Island on potato in 1946 (Baker 1946), and in Ontario on garlic in 2012 (Yu et al. 2012). Fortunately, the species has effectively been contained.

1.6 Virus Vector Nematodes

1.6.1 Dagger Nematodes, **Xiphinema** *spp.*

Ectoparasites, dagger nematodes are known to damage roots and directly affect plant growth. However, dagger nematodes are perhaps most important due to their ability to vector viruses that cause more significant economic losses than the nematodes alone (Van Driell et al. 1990; Brown and Trudgill 1998; Singh et al. 2013). Several species are present, and damage to several crops has been reported in British Columbia, Quebec, and Ontario (The Canadian Phytopathological Society 2005, 2006, 2008, 2009, 2010, 2011, 2012, 2013, 2014). The dominant species in Canada are part of the *Xiphinema americanum sensu lato* complex, and *X. rivesi* (Graham et al. 1988; Robbins 1993; BCMA 2013). In Yu et al. (2010a), the authors formally identified *X. chambersi* for the first time in Canada, in Turkey Point Provincial Park, Ontario. This species is commonly found on ornamental trees but is also known to cause significant damage in strawberry (Perry 1958; Ruehle 1971). The Canadian National Collection of Insects, Arachnids and Nematodes now lists nine species from Canada*: X. americanum, X. bricolensis, X. pacificum, X. chambersi, X. bakeri, X. diversicaudatum, X. occiduum* and *X. rivesi*. Damages caused by dagger nematodes are expected to worsen as climate changes. For example, increased soil temperatures will likely influence population densities, hosts phenology, geographic distribution, and habitats suitable for introduced nematodes (Neilson and Boag 1996; Boag et al. 1997).

In the 1980s, Vrain and Rousselle (1980) confirmed the high occurrence of *X. americanum sensu lato* in Quebec apple orchards. This species is known to be a vector of the *Tobacco ringspot virus* (TRSV) which in apple causes apple union necrosis, a severe girdling of affected apple trees resulting from the disorganisation of tissue at the scion/rootstock interface (Lana et al. 1983). In Southwestern Quebec, near the USA border, numerous apple orchards have been replaced by highbush blueberry fields. Symptoms of ringspot-type virus in some highbush blueberry plantings have been observed but the presence and role of *X. americanum* in those plantings has not being confirmed (Lambert pers. comm.). In the nearby State of New York, Fuchs et al. (2010) successfully isolated both TRSV and *Tomato ringspot virus* (ToRSV), and also recovered *X. americanum* from the soil in diseased highbush blueberry plants in various plantings.

Xiphinema index is the primary vector of *Grapevine fanleaf virus* which is a serious concern for growing wine industries in Ontario and BC. *X. index* has not been found so far in Canada, but preventive measures related to imports are a high priority (CFIA 2009).

1.6.2 Needle Nematodes, Longidorus *spp.*

The Canadian National Collection of Insects, Arachnids and Nematodes currently lists three species of the ectoparasite *Longidorus* from Canada: *L. breviannulatus, L. diadecturus* and *L. elongatus*. These species are widely distributed in Canada and are of economic importance because they parasitize many plants and vector viruses (Eveleigh and Allen 1982; Ebsary et al. 1984; Brown and Trudgill 1998; Simard et al. 2008, 2009). *Longidorus* spp. is frequently found in apple and peach orchards as well as in grape, strawberry, corn, and turfgrass (The Canadian Phytopathological Society 2005 to 2014). *Longidorus diadecturus* was found from peach fields in Ontario and was proven to be a vector for peach rosette mosaic virus (Allen et al. 1982a; Stobbs and Van Schagen 1996). It is listed as an A1 quarantined nematode pest by the European and Mediterranean Plant Protection Organization. In 2009, Simard et al. (2009) confirmed the pathogenicity of *L. breviannulatus* to creeping bentgrass in Quebec. This needle nematode species was already known for transmitting mosaic viruses to peach trees in Ontario (Van Driell et al. 1990). The species *L. elongatus*, known to damage a wide range of crops including beet, barley, potato, and raspberry (Singh et al. 2013), was reported in 2010 in Ontario (Pedram et al. 2010). In various horticultural crops, virus diseases are on the rise across the country. Growers should be aware of nematodes that are potential vectors from infested hosts and/or reservoir weedy plants, so that these pests can be detected early in the field.

1.6.3 Stubby Root Nematodes

Stubby root nematodes (*Paratrichodorus* spp., *Trichodorus* spp. and *Nanidorus* spp.) are other ectoparasites parasiting a wide range of hosts (Riga and Neilson 2005; Davis 2012). *Paratrichodorus renifer*, which was identified for the first time in Canada in 2009 (Forge et al. 2009) and *N. minor*, which is widespread in Canada (Anderson 2008), are responsible for economic losses in turfgrass and berry crops (Zasada et al. 2010; The Canadian Phytopathological Society 2005 to 2014). Recent greenhouse and microplot studies indicate that *P. renifer* can reduce growth and yield of blueberry and could become a greater concern as the relatively young blueberry industry in British Columbia continues to expand and mature (Forge et al. 2012). Stubby root nematodes are also known to be vectors of tobacco rattle *virus* in potato fields in Eastern Canada and a small area of coastal British Columbia (Xu and Nie 2006; Kawchuk et al. 1997). In Ontario, Pedram et al. (2010) identified for the first time *T. primitivus* in the rhizosphere of grasses (*Poa* spp. and *Festuca* spp.). The members of the genus *Trichodorus*, most likely *T. primitivus*, are currently known to cause direct damage to roots and also transmit tobraviruses such as the *Tobacco rattle virus* present in potato fields in British Columbia (Kawchuk et al. 1997; Xu and Nie 2006). Other species listed in the Canadian National Collection of Insects, Arachnids and Nematodes are *P. nanus* and *P. pachydermus*.

1.6.4 Management

Historically, research attention has been focused on plant resistance to nepoviruses rather than the nematode vectors. Grape cultivars and rootstocks have been evaluated for resistance to the *Tomato ringspot virus* (Allen et al. 1982b) and several rootstocks have been found to be resistant to the virus.

Fumigation of soil is recommended when replanting fruit trees in Canada, primarily for management of *P. penetrans* and other components of replant disease complexes. Fumigation is also recommended when *Xiphinema* populations exceed 100/kg soil and/or when nepoviruses were present in the old planting (OMFRA 2017; BCFGA 2017).

1.7 Conclusion and Future Perspectives

Canadian agriculture will undergo numerous changes in the coming decades. The development of sustainable and resilient production systems continues to be a major goal and whole-system approaches to food, feed, and other fiber production that balance environmental impacts, social equity and economic viability are being promoted across the country. Climate change will create some opportunities for Canadian agriculture to grow and diversify, and the adoption of more sustainable practices such as minimum tillage, winter cover cropping and organic production will also grow. However, climate change and corresponding changes in the extent and intensity of cropping systems will also present numerous new challenges, particularly with respect to pests and diseases.

This review has revealed several emerging PPN issues in Canada that will be grafted to these elaborate agricultural challenges. The continual expansion of soybean cyst nematode to Manitoba and Quebec and Maritimes poses a very serious threat to soybean production in Canada. Recent reporting of the golden nematode in Quebec highlights how the potato industry needs to prevent potato cyst nematodes from establishing in other important potato-growing regions of Canada. Improved understanding of the importance of *P. neglectus* in potato, canola, wheat and pulse crops in the Canadian Prairies is required. Similarly, the role of cereal cyst nematodes on wheat in the Canadian Prairies is unexplored. *Ditylenchus* spp. have emerged in recent years as significant concerns in Canada as *D. destructor* has been reported but contained near Ottawa, *D. dipsaci* infestation of garlic farms has spread from Ontario to farms in Manitoba and Quebec, and *D. dipsaci* infestation of garlic has become more prevalent in British Columbia.

Rising temperatures and increasing commercial trade could also bring surprises. Species such as *Pratylenchus alleni* are being discovered, and long-established species could become more problematic. For example, Tenuta (2014) estimated that the within-season potential for population buildup of *P. penetrans* will increase with climate change. Exotic species of significance such as *M. incognita* could become established as average soil temperatures rise, and the impact of climate change on established but unproblematic species is yet to be determined. Indeed, the expected mean annual temperature increases of 2 °C by 2050 and 4–5 °C by 2100 if greenhouse gas emissions are not controlled (Price et al. 2013) could have a major impact on all nematode species in the cool climate of most agricultural areas in Canada (Fig. 1.1).

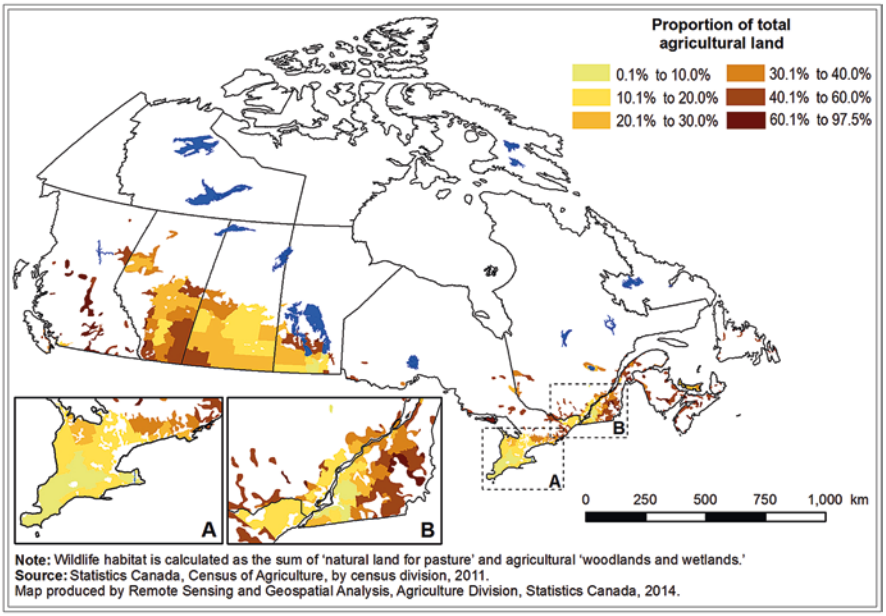

Fig. 1.1 Distribution of agricultural land across Canada (2011)

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