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Abstract

The Pacific Northwest (PNW) of the United States (Idaho, Oregon, and Washington) is a diverse agricultural production area with over 400 different commodities grown in the region. Plant-parasitic nematodes are a constraint to the production of many of these commodities. Soil sample data from 2012 to 2016 were obtained from nematode diagnostic laboratories in the region to assess trends in occurrence, population densities, and distribution of plant-parasitic nematodes in the PNW. A total of 38,022 unique data points were analyzed. The number of plant-parasitic nematode samples processed in the PNW by diagnostic laboratories has significantly increased from 2012 to 2016. Fifteen genera of plant-parasitic nematodes were identified by diagnostic laboratories, with 86% of the samples in the PNW containing at least one plant-parasitic nematode genus. These laboratories provide a valuable service to agriculture in the PNW. Additionally, they serve as a rich source of information on plant-parasitic nematode distribution, occurrence, and abundance that would otherwise be impossible for a research laboratory to interpret individual grower reports and make management recommendations.

Agriculture Production and Plant-Parasitic Nematodes in the Pacific Northwest (PNW)

The PNW of the United States includes the states of Idaho, Oregon, and Washington. In this region over 17 million ha are under agricultural production (USDA NASS 2014). Idaho, Oregon, and Washington rank at the 21st, 20th, and 11th in the United States for crop value, respectively (USDA NASS 2014). Agriculture production in the PNW is diverse because of the range of ecoclimates in the region. The ecoclimates are simplistically considered in relationship to the Cascade Mountain range that runs north-south through Washington and Oregon. West of this mountain range receives abundant rainfall (>900 mm) and has a maritime climate with a narrow temperature range. East of this mountain range rainfall is more limited (230 mm) and the region is semiarid. Agricultural crops that are commonly grown west of the Cascade Mountains include small fruits (blueberry, cranberry, grape), grass seed (bluegrass, fescue), hazelnut, mint, vegetables (corn, beans, peas, cucurbits), spring wheat, and pears. East of the Cascade Mountains irrigation is required, and crops grown in this area of the region include small fruits (grape, blueberry), hops, wheat (spring and winter, either irrigated or nonirrigated), tree fruits (cherry, apple, pear, peach, apricot), potato, hay (grass, alfalfa), mint, vegetables (corn, bean, carrot, peas, asparagus, sugarbeet), and other grain crops (oats, barley). Of these crops, hay, wheat, and potato dominate agriculture production in the region, with these commodities grown on approximately 2.3 million ha (USDA NASS 2014).

Because of the diversity of commodities grown in the PNW, the plant-parasitic nematodes found in the region would also be expected to be diverse. At least 20 genera encompassing 51 species have been reported in the PNW (Zasada et al. in press). The most economically important genera present in the region are *Meloidogyne* and *Pratylenchus* (Jones et al. 2013). Surveys of plant-parasitic nematodes in the region have been conducted on specific commodities including wine and juice grapes (Pinkerton et al. 1999; Zasada et al. 2012), potato (Nyczepir et al. 1982), turfgrass (Chastagner and McElroy 1984; McClure et al. 2012), grass seed (Alderman 1991; Alderman et al. 2005), blueberry (Converse and Ramsdell 1982; Zasada et al. 2010), and raspberry (Gigot et al. 2013). Broader surveys have also been conducted to consider the crops grown in rotation in the semiarid regions of the PNW (Hafez et al. 1992; Smiley et al. 2004). To date, only one paper has presented plant-parasitic nematode data from diagnostic lab samples processed in the PNW (Hafez et al. 2010).

Nematode diagnostic laboratory samples provide a rich source of information on plant-parasitic nematode distribution, occurrence, and abundance that would otherwise be impossible for a research laboratory to collect. To our knowledge, growers and crop consultants in the PNW utilize at least six laboratories for plant-parasitic

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*The e-Xtra logo stands for “electronic extra” and indicates that four supplementary tables are published online.

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nematode diagnostics. We obtained data from five of these diagnostic laboratories spanning a 5-year period from 2012 to 2016. The goal of this effort was to summarize these data to highlight regional trends in the occurrence, distribution, and population densities of plant-parasitic nematodes in the PNW.

Compilation of Data from PNW Nematode Diagnostic Laboratories

Data from 2012 to 2016 were requested from all of the nematode diagnostic laboratories that were assumed to process the majority of the nematode samples in the PNW. From this request, data were obtained from five laboratories; a requirement for receiving these data was that the laboratories would not be identified. From three of these laboratories all of the available data were provided. From two of the laboratories only a portion of the data were made available, owing either to time constraints or to the desire of a client to keep the information private. Only data from soil extractions were included in this study. All of the laboratories extract nematodes by wet sieving followed by sugar centrifugation (Ingham 1994). Three of the laboratories extract nematodes from 250 cm³ of soil, while the remaining two laboratories extract nematodes from 100 and 500 cm³ of soil. The price per sample for the extraction and quantification of plant-parasitic nematodes from soil ranges from US$25 to US$60. Some laboratories include species identification of *Meloidogyne*, *Pratylenchus*, and *Xiphinema* spp. in this cost, whereas other laboratories charge extra for species identification.

Data were obtained from the nematode diagnostic laboratories either electronically or on paper. Data were entered into an Excel spreadsheet (Microsoft, Bellevue, WA) and converted when necessary so that all population densities were expressed as number of nematodes/250 cm³ of soil. Additional analyses and graphics were conducted using JMP 13 (SAS, Cary, NC) and R (R Core Team 2017). The entire dataset was composed of 38,022 samples. Data were sorted to achieve various summaries and analyses. Number of nematode diagnostic samples over time and across the calendar year were considered. For plant-parasitic nematode family/genera, percentage occurrence, maximum population density, and mean population density when present in a sample were calculated for each year and all years combined for the entire PNW and each individual state (shown in the tables and supplementary tables). To evaluate species composition of the genera *Meloidogyne* and *Pratylenchus*, only those samples in which species identification was conducted were considered. The percentage occurrence for each species of *Meloidogyne* (*M. chitwoodi*, *M. hapla*, and *M. naasi*; *n* = 9,383) and *Pratylenchus* (*P. penetrans*, *P. neglectus*, *P. thornei*, and *P. crenatus*; *n* = 1,587) was calculated for the entire PNW and for each state. For some diagnostic samples (*n* = 29,302), additional data on location were provided (city or county). These data were grouped into six to seven regions within each state (Idaho, Oregon, and Washington) (https://www.oregon.gov/ODA/shared/Documents/Publications/Administration/ORGrowingRegions.pdf, https://idfg.idaho.gov/files/trapping-regionsjpg, https://www.dnr.wa.gov/about/dnr-regions-and-districts). Sample number count data for the entire region as well as percentage occurrence of the top five plant-parasitic nematode genera were mapped using R software and the ggmap package (Kahle and Wickham 2013; R Core Team 2017).

For each nematode family/genera and species of *Meloidogyne* and *Pratylenchus*, the presence or absence (percentage occurrence) was calculated, and these data were then analyzed by the *χ²* test for independence for effects of location (PNW, Idaho, Oregon, and Washington). The number of samples processed by the diagnostic laboratories was also analyzed by the *χ²* test for effects of year and month. Population densities of plant-parasitic nematodes were analyzed using Mann–Whitney and Kruskal–Wallis tests for effects of location (PNW, Idaho, Oregon, and Washington) (Sokal and Rohlf 1995). These methods are nonparametric approaches for comparing independent groups of sampled data and are used for data that do not meet normal distribution and equal variance assumptions.

Trends in Number of Plant-Parasitic Nematode Diagnostic Samples in the PNW

There was a trend for the majority of the samples in the PNW, regardless of year, being processed in September and October (Fig. 1A). This was supported by the *χ²* analysis, with the most samples processed in September (*n* = 7,611) followed by October (*n* = 6,882) (*P* < 0.0001); the fewest number of samples were processed in January (*n* = 214). This trend in sample processing during a calendar year was similar to what is described in the annual reports from the Oregon State University Testing Service (Corvallis, OR) spanning from 2003 to 2008 (http://plant-clinic.bpp.oregonstate.edu/nematodes-resources/). In 2008, twice as many samples were processed in September and October than in any other month. Nematode population densities fluctuate throughout the year, with the dogma that population densities are the highest in the fall. In peppermint in Oregon, population densities of *P. penetrans*, *Paratylenchus* sp., and *Mesocriocenema xenoplax* were the highest in April and decreased to August (Merrifield and Ingham 1996). In a 2-year study in raspberry, there was a numeric trend for higher population densities of *P. penetrans* in soil in the summer/fall (Forge et al. 1998). Data collected for a degree day model for *M. chitwoodi* demonstrated that population densities of this nematode peaked at potato harvest in September and declined during the winter, with population densities being the lowest in summer (Pinkerton et al. 1991). Although a single sampling time does not exist to encompass peak population densities of all of the plant-parasitic nematodes in all the crops found in the PNW, previous research does demonstrate that population densities of several of the most economically important nematodes in the region are at their highest in the fall. The upward spike in samples processed in September and October may be explained in the context of fumigation, with growers and crop consultants submitting samples to diagnostic laboratories to decide if fumigation is necessary or to determine if fumigation was effective. There are several crops in the PNW that rely heavily on preplant fumigation to manage nematodes including potato, vegetables, small fruits, and tree crops (Ingham et al. 2000; King and Tabenera 2013; Walters et al. 2016; Westerdahl et al. 2003).

The number of nematode samples processed in the PNW significantly increased over the years considered (*P* < 0.0001; Fig. 1B). There were more samples processed in 2016 than any other year, and the fewest samples were processed in 2012. What is driving this increase in submitted samples over time is unclear. Hafez et al. (2010) reported on diagnostic samples processed at the University of Idaho (Parma, ID) from 2000 to 2006. Over this period 1,628 samples were considered in the analysis; the number of samples received in a given year was not reported. The annual reports from the Oregon State University Testing Service (http://plant-clinic.bpp.oregonstate.edu/nematodes-resources/) state that on average, 936 samples were processed per year between 1993 and 2008, with the maximum number of samples, 1,547, processed in 2002.

Plant-Parasitic Nematodes Found in the PNW

Fifteen plant-parasitic nematode genera were identified in diagnostic samples in the PNW. All of the diagnostic laboratories identified all plant-parasitic nematodes encountered in a sample to at least family/genus. At least 20 genera and 51 species of plant-parasitic
nematodes have been previously reported in the PNW (Zasada et al. in press). We only considered the diagnostic data from soil samples; therefore, this report does not provide a robust assessment of the presence of the foliar nematodes *Aphelenchoides*, stem and bulb nematodes *Ditylenchus*, and seed gall nematodes *Anguina* in the region. Additionally, data from extraction methods used to isolate cysts of *Heterodera avenae* and *H. filipjevi* from soil (USDA cyst extractor, Fenwick Can, etc.; Ingham 1994), both important parasites of wheat in the region (Smiley 2016), were not included. Juveniles of *Heterodera* spp. were detected in only 0.3% of samples in the PNW. *H. avenae* is more widespread in the PNW, with *H. filipjevi* having a more limited distribution, with reports from Washington and Oregon (Smiley 2016). Combined, *Hoplolaimus, Rotylenchus, Gracilacus, Longidorus*, and *Hemicycliophora* were found in 0.7% of samples in the PNW (data not shown). The eight plant-parasitic nematode genera with greater than 2% occurrence in the PNW are considered further (see below).

**Trends in Plant-Parasitic Nematode Occurrence and Population Densities in the PNW**

The most commonly encountered plant-parasitic nematode genus in the PNW was *Pratylenchus* (*P < 0.0001; Table 1). *Pratylenchus* was found in 30% more diagnostic samples than the next most commonly encountered genus, *Tylenchorhynchus*. The next most commonly encountered genera were *Meloidogyne* and *Paratrichodorus*, followed by *Paratylenchus*. Less commonly encountered family/genera, occurring in 2 to 6% of samples, were *Helicotylenchus, Criconematidae*, and *Xiphinema*. In general, this same trend was also observed in the individual states (Tables 2 and 3).

*Paratylenchus* had highest mean population density of any of the plant-parasitic nematodes detected in the PNW (*P < 0.0001; Table 1). *Paratrichodorus, Tylenchorhynchus*, and *Xiphinema* had the lowest mean population densities (*P < 0.0001; Table 1). When detected, *Paratylenchus* also occurred at the highest maximum population density of the nematode genera in the PNW (Table 1). The maximum population density of *Paratylenchus* was 2.5 times higher than the maximum population density of *Meloidogyne*. The lowest maximum population density was for *Xiphinema*, which was 1.3 times lower than the next lowest population density, *Paratrichodorus*. Data for each year, 2012 to 2016, for the region and for individual states are presented in Supplementary Tables S1, S2, S3, and S4. Trends in specific nematode family/genera/species are described below.

*Pratylenchus*. The percentage occurrence of the migratory endoparasitic root-lesion nematode was at least 20% greater in samples from Idaho compared with samples from across the region or from Oregon and Washington (*P < 0.0001; Table 3). Mean population densities of this nematode were also much higher in Idaho, at least 1.8 times, than in the entire PNW or in the other two states (*P < 0.0001*). Conversely, mean population densities of *Pratylenchus* were the lowest in Washington, with population densities 56% lower than the PNW mean. Species identified by diagnostic laboratories in the PNW included *P. penetrans, P. neglectus, P. thornei*, and *P. crenatus*. The mean (and maximum) population densities for these nematodes were 82 (2,763), 98 (2,225), 403 (2,970), and 35 (198) nematodes/
250 cm³ of soil for *P. penetrans*, *P. neglectus*, *P. thornei*, and *P. crenatus*, respectively.

*P. penetrans* parasiizes over 400 hosts, and in the PNW it has been reported on alfalfa, raspberry, mint, legumes, potato, Easter lily, apple, cherry, peach, pear, strawberry, potato, and wheat (Gigot et al. 2013; Hafez 1998a; Hafez et al. 1992, 2010; Ingham et al. 2005; Jensen 1961). This nematode has been demonstrated to reduce yield of tree fruits, raspberry, mint, and Easter lily in the PNW (McElroy 1992; Merrifield and Ingham 1996; Santo and Wilson 1990; Westerdahl et al. 2003; Zasada et al. 2015). Both *P. neglectus* and *P. thornei* are important parasites of wheat in the PNW (Smiley et al. 2005a, b). In addition to wheat, hosts for these nematodes include alfalfa, apple, crested wheat grass, legumes, onion, beet, sugarbeet, brassicas, barley, hops, apple, peppermint, spearmint, bean, Kentucky bluegrass, pear, potato, corn, and turnip (Hafez et al. 1992, 2010; Riga et al. 2008; Smiley et al. 2005a, b). *P. crenatus* has only been reported to parasitize a limited number of crops in the PNW including blueberry, bluegrass, apple, alfalfa, and wheat (Chastagner and McElroy 1984; Hafez et al. 1992, 2010; Zasada et al. 2017). At least eight other species of *Pratylenchus* have been reported in the PNW (Hafez et al. 1992, 2010; Jensen 1961; Riga et al. 2008).

**Meloidogyne.** There was a higher percentage occurrence of root-knot nematodes in Washington than in Idaho and Oregon (*P < 0.0001; Table 3). Both Idaho and Oregon had a lower percentage occurrence of *Meloidogyne* spp. than the regional occurrence. The mean population density of *Meloidogyne* species when present was also higher in Washington than the regional mean (*P < 0.0001; Table 3). Species identified by diagnostic laboratories in the PNW included *M. hapla*, *M. chitwoodi*, and *M. naasi* (*n = 9,383; Fig. 2). *M. chitwoodi* was at least twice as likely to be identified in samples as *M. hapla* in the PNW (*P < 0.0001; Fig. 2). In samples in which *M. chitwoodi* was present, mean (and maximum) population densities were 185 (21,760) second-stage juveniles (J2)/250 cm³ of soil. Population densities of *M. chitwoodi* in the region have been reported in field experiments to range from 129 to 231 J2/250 g of dry soil prior to treatment application (Ingham et al. 2000, 2007a). *M. chitwoodi* has a relatively narrow host range in the PNW and is a parasite of alfalfa, sugarbeet, and potato (Hafez 1998a, b; Hafez et al. 2010; Jensen 1961; Santo et al. 1980). *M. chitwoodi* is a major concern to the US$1.8 billion potato industry in the PNW, because there is zero tolerance for the type of damage that the nematode causes to the tubers. In potato, because *M. chitwoodi* reproduces rapidly during warm seasons (Pinkerton et al. 1991), crop rejection may occur even with low population levels, and generally fields with any *M. chitwoodi* must be treated with a preplant fumigant, nonfumigant nematicides, or both (Ingham et al. 2007a).

*M. hapla* was the second most commonly found *Meloidogyne* spp. in the PNW and individual states (Fig. 2). There was a higher percentage occurrence of *M. hapla* in Oregon than across the region (*P < 0.0001). When present, mean (and maximum) population densities of *M. hapla* in the PNW were 164 (8,040) J2/250 cm³ of soil. *M. hapla* parasitizes a range of crops in the PNW including alfalfa, sugarbeet, peppermint, strawberry, potato, grape, carrot, and

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**TABLE 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meloidogyne</th>
<th>Pratylenchus</th>
<th>Paratrichodorus</th>
<th>Tylenchorhynchus</th>
<th>Paratylenchus</th>
<th>Helicotylenchus</th>
<th>Criconematidae</th>
<th>Xiphinema</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurrence (%)</td>
<td>28 c,y</td>
<td>69 a</td>
<td>22 c</td>
<td>39 b</td>
<td>17 d</td>
<td>6 e</td>
<td>3 f</td>
<td>2 f</td>
</tr>
<tr>
<td>Maximum</td>
<td>21,760 18,155 1,205 5,520 55,363 11,215 7,505 910</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>240 c,a</td>
<td>256 b</td>
<td>29 f</td>
<td>98 d</td>
<td>462 a</td>
<td>171 ac</td>
<td>163 ac</td>
<td>73 c</td>
</tr>
</tbody>
</table>

w Number of samples included in analysis was 38,022.

x Included as *Mesocriconema* and *Criconema*.

y Percentage occurrence data were analyzed for effects using χ² analysis. Values followed by the same letter are not significantly different from each other (*P < 0.05*).

z Mean values followed by the same letter are not significantly different (*P < 0.05*) according to Kruskal–Wallis and Mann–Whitney nonparametric statistical tests.

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**TABLE 2**

<table>
<thead>
<tr>
<th>Region/state</th>
<th>Paratrichodorus</th>
<th>Xiphinema</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>PNW</td>
<td>22 c, a 1,205 29 b, 39 b 5,520 98 b 17 55,363 462 a 6 b 11,215 171 a 3 a 7,505 163 ab 2 b 910 73 a</td>
<td></td>
</tr>
<tr>
<td>Idaho</td>
<td>29 a 1,205 44 a 79 a 5,520 139 a 16 10,640 235 c 19 a 11,215 175 a 3 a 7,505 125 b 1 c 355 24 b</td>
<td></td>
</tr>
<tr>
<td>Oregon</td>
<td>25 b 801 21 c 19 d 875 26 d 19 55,363 1,205 b 1 c 785 143 a 1 b 685 113 ab 1 c 578 56 ab</td>
<td></td>
</tr>
<tr>
<td>Washington</td>
<td>23 c 600 25 c 26 c 3,500 44 c 16 17,660 246 c 1 c 3,040 119 b 3 a 6,315 188 a 4 a 910 83 a</td>
<td></td>
</tr>
</tbody>
</table>

w Number of samples included in analysis was 38,022 (PNW), 10,810 (Idaho), 7,429 (Oregon), and 19,783 (Washington).

x Included as *Mesocriconema* and *Criconema*.

y Percentage occurrence data were analyzed for effects using χ² analysis. Values followed by the same letter are not significantly different from each other (*P < 0.05*).

z Mean values followed by the same letter are not significantly different (*P < 0.05*) according to Kruskal–Wallis and Mann–Whitney nonparametric statistical tests.
other various vegetables (Hafez 1998a; Jensen 1961; Pinkerton et al. 1999; Zasada et al. 2012). Despite the widespread occurrence of *M. hapla* and diversity of crops that it parasitizes, little information is available on the economic impact of this plant-parasitic nematode in the PNW. The only other *Meloidogyne* species reported by the diagnostic labs was *M. naasi*. In samples in which *M. naasi* was detected the mean (and maximum) population density was 93 (1,750) J2/250 cm$^3$ of soil in the PNW. *M. naasi* has been reported from turfgrass in the PNW (McCure et al. 2012) and also parasitizes cereals and weeds (Mitchell et al. 1973; Roberts et al. 1982). *M. chitwoodi* and *M. hapla* did occur as mixed populations in the PNW (Fig. 2). Mixed populations of all three species or combinations of *M. chitwoodi* or *M. hapla* with *M. naasi* were also found but were not common (≤1.3%).

Both *M. chitwoodi* and *M. hapla* have a relatively high tolerance for cooler temperatures compared with other *Meloidogyne* spp. (Nyczepir et al. 1982), so their widespread occurrence in the PNW is expected. The higher incidence of *M. chitwoodi* in the PNW may be owing to two factors. First, *M. chitwoodi* is able to reproduce on potato at lower temperatures than *M. hapla*, therefore having more generations per growing season (O’Bannon and Sant’oro 1984; Pinkerton et al. 1991). Second, the deployment of crops with resistance to *M. hapla* has increased over time, especially in Idaho, resulting in a lower incidence of this nematode compared with *M. chitwoodi*. Currently, potato varieties commonly grown in the PNW lack resistance to *M. chitwoodi*.

**Paratrichodorus.** Stubby-root nematodes were found in 23 to 29% of diagnostic samples in Idaho, Oregon, and Washington (Table 2). Five species of *Paratrichodorus* have been reported in the PNW (Forge et al. 2009; Hafez 1998b; Hafez et al. 1992, 2010; Riga and Neilson 2005); however, the most significant species are *P. allius* and *P. teres* because of their ability to transmit tobacco rattle virus (TRV) causing corky ringspot in potato (Jensen et al. 1974). *P. allius* has a wide host range (Mojtahedi and Sant’oro 1999); however, this nematode is only of economic concern in onion and potato. Across the region, mean population densities of *Paratrichodorus* ranged from 21 to 44 nematodes/250 cm$^3$ of soil (Table 2). Research on the management of *P. allius* in onion demonstrated that there may be economic benefit from managing this nematode when populations are as low as 4 *P. allius*/250 g of soil (Ingham et al. 1999). This nematode can reduce yield of storage onions and those grown for dehydration. In potato, *P. allius* rarely reaches densities that are damaging; however, in some fields *P. allius* and *P. teres* can vector TRV. TRV can cause necrotic areas or rings to form on tubers, resulting in a quality defect that can cause rejection of the product. This type of damage can occur at population densities of *P. allius* as low as 3 nematodes/250 g of soil when the virus is present (Ingham et al. 2007b).

**Tylenchorhynchus.** This nematode was at least twice as likely to be found in Idaho as across the region or in Oregon and Washington (*P < 0.0001; Table 2). As a migratory ectoparasite, *Tylenchorhynchus* has not been demonstrated to be economically damaging to any commodity grown in the region. This nematode has been reported in onion, beet, brassica, apple, alfalfa, potato, wheat, hay, peppermint, spearmint, pea, corn, grape, barley, corn, hop, and bluegrass in the region (Chastagner and McElroy 1984; Hafez et al. 1992, 2010; Jensen 1961; Zasada et al. 2012). The species of *Tylenchorhynchus* present in the PNW has not been reported.

**Paratylenchus.** Pin nematodes are a migratory ectoparasite primarily of woody perennials (apple, blueberry, grape, pear) but also of barley, bluegrass, onion, bean, potato, spearmint, wheat, peppermint, sugarbeet, alfalfa, bean, pea, legumes, corn, hops, and hay in the PNW (Hafez et al. 1992, 2010; Jensen 1961; Pinkerton et al. 1999; Zasada et al. 2010, 2012). The percentage occurrence of this nematode across the states in the PNW was consistent, ranging from 16 to 19% (Table 2). The highest mean population densities of this nematode were observed in Oregon with mint as the host (*P < 0.0001; Table 2). This density was three to five times higher than *Paratylenchus* population densities reported from Idaho and Washington. *Paratylenchus* has been reported to occur at high population densities on many plants, but it causes significant damage to only a few hosts (Raski and Radewald 1958). In a 1996 study in Oregon, *Paratylenchus* sp. reached peak population densities ranging from approximately 3,000 to 5,000 nematodes/250 g of soil in mint (Merrifield and Ingham 1996). Conversely, surveys of wine grape vineyards in the PNW reported population densities <250 nematodes/250 g of soil (Pinkerton et al. 1999; Zasada et al. 2012). The only species of *Paratylenchus* reported in the PNW were *P. nanus*, which damages bluegrass (Chastagner and McElroy 1984), and *P. hamatus* on legumes (Riga et al. 2008).

**Helicotylenchus.** The percentage occurrence of the migratory ectoparasite *Helicotylenchus* was variable, with this nematode found in approximately 20% of samples in Idaho and rarely in samples from Oregon and Washington (*P < 0.0001; Table 2). Mean population densities of this nematode were relatively consistent across the states, with the highest maximum and mean densities found in Idaho (*P < 0.0001). The only species that has been reported in the PNW is *H. pseudorobustus* in bluegrass (Chastagner and McElroy 1984). The economic impact of this nematode has not been documented in the region.

**Criconematidae.** The occurrence of ring nematodes within the individual states was consistent with the regional percentage occurrence (Table 2). The lowest mean population density of this nematode was found in Oregon, which was significantly lower than the highest population density found in Washington (*P < 0.0013; Table 2). The identification in this group of nematodes varied among diagnostic laboratories, with the genus reported as *Mesocriconema (= Criconemella), Criconemoides*, or simply as “ring” nematode. *Criconema mutabile, Mesocriconema curvatum, M. ornatum, and M. rusticum* have been reported in the PNW (Chastagner and McElroy 1984; Hafez et al. 1992, 2010), and *M. xenoplax* is likely the species present on grape and tree fruits.

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**TABLE 3**

<table>
<thead>
<tr>
<th>Region/state</th>
<th>Meloidogyne</th>
<th>Pratylenchus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>Max</td>
</tr>
<tr>
<td>PNW</td>
<td>28</td>
<td>21,760</td>
</tr>
<tr>
<td>Idaho</td>
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<tr>
<td>Oregon</td>
<td>17 d</td>
<td>7,070</td>
</tr>
<tr>
<td>Washington</td>
<td>36 a</td>
<td>10,000</td>
</tr>
</tbody>
</table>

x Number of samples included in the analysis was 38,022 (PNW), 10,812 (Idaho), 7,431 (Oregon), and 19,785 (Washington).

y Percentage occurrence data were analyzed for effects using $\chi^2$ analysis. Values followed by the same letter are not significantly different from each other ($P < 0.05$).

z Mean values followed by the same letter are not significantly different ($P < 0.05$) according to Kruskal–Wallis and Mann–Whitney nonparametric statistical tests.
Xiphinema. Dagger nematodes were more commonly found in Washington than in Idaho or Oregon (\( P < 0.0001 \); Table 2). These migratory ectoparasites are primarily parasites of perennial crops in the PNW including apple, blueberry, cherry, grape, and raspberry (Hafez et al. 1992, 2010; Pinkerton et al. 1999; Zasada et al. 2010, 2012). Washington’s tree fruit industry, including apples and cherries, is the largest in the PNW, potentially explaining the higher incidence of Xiphinema species in the state. In diagnostic samples, Xiphinema was occasionally identified to species including X. bakeri, X. rivesi, X. pachtaicum, and X. americanum sensu lato (in the broad sense). X. bakeri is only reported to occur on raspberry and can cause reduced vigor of raspberry (McElroy 1970). The other Xiphinema species all belong to the X. americanum species complex, which includes at least 32 species in North America (Robbins 1993). Alone, these nematodes are only damaging to plants when present at high population densities. The bigger threat from this group of nematodes is their ability to vector viruses (MacFarlane et al. 2016). X. rivesi is a vector of cherry rasp leaf virus, tomato ringspot virus, and tobacco ringspot virus, all viruses reported to be present in the PNW (Converse and Ramsdell 1982). X. pachtaicum has not been demonstrated to be a vector for these viruses. The true diversity of Xiphinema species present in the PNW, and their ability to vector viruses, requires further study.

Ditylenchus. The bulb and stem nematode was found in <2% of soil samples processed in the PNW; however, it was found in 7% of samples processed in Idaho (data not shown). Population densities of this nematode, when present, were consistent across the states, with approximately 25 nematodes/250 cm\(^3\) of soil. Ditylenchus destructor and D. dipsaci have been reported in the PNW (Blodgett 1945; Hafez 1998a; Hafez et al. 1992, 2010; Jensen 1961). D. dipsaci is cosmopolitan and has a wide host range of more than 500 plant species. In the PNW, principal hosts include alfalfa and onion (Hafez 1998a; Hafez et al. 1992, 2010). It is the most serious yield-limiting nematode pest of alfalfa in Idaho. This nematode is a cool-season nematode and in alfalfa is most damaging to the first cutting. In onion, the nematode becomes active in cool, moist conditions and subsequently causes plants to be stunted and yellow. Infected plants produce a high incidence of cracked bulbs and culls (Hafez and Sundararaj 2016). D. destructor is an economically important parasite of potato and has been reported in Idaho (Hafez et al. 2010), but it is not widespread in the PNW.

### Diagnostic Samples and Plant-Parasitic Nematode Occurrences in Idaho, Oregon, and Washington

A graphical representation of the number of samples processed and percentage occurrences of plant-parasitic nematodes in defined regions of each Idaho, Oregon, and Washington helped to visualize additional regionwide trends (Fig. 3; https://www.}

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**FIGURE 2**

Percentage distribution of *Meloidogyne* species (\( \text{Mc} = \text{M. chitwoodi}; \text{Mh} = \text{M. hapla}; \text{and Mn} = \text{M. naasi} \)) in samples in which *Meloidogyne* were present and the nematodes were identified to species (\( n = 9,383 \)) in the Pacific Northwest (PNW) and in individual states (Idaho, Oregon, and Washington).
The Columbia Basin of Washington and Oregon is where a large number of samples were collected for nematode diagnostics. This entire area is agriculturally productive and diverse. Other areas where nematodes were sampled extensively include the Willamette Valley in Oregon and the Snake River region of Idaho. Mapping the percentage occurrence of the top five occurring plant-parasitic nematodes in the PNW highlighted a few obvious trends that further support the statistical analyses presented in this paper (Tables 1, 2, and 3). First, the higher percentage occurrence of *Pratylenchus* compared with other plant-parasitic nematodes appears to be relatively consistent across the regions within the PNW states (Fig. 3). *Meloidogyne* is more commonly found in areas of each state where potato production is common, including the Columbia Basin of Oregon and Washington, the Klamath Basin of Oregon, and the Snake River region of Idaho. Although *Paratrichodorus* had a higher percentage occurrence in Idaho compared with Oregon and Washington (Table 2), it appears that there is “hot spot” of this nematode in the Klamath Basin in Oregon as well (Fig. 3). The map also clearly supports a higher percentage

![Map showing nematode occurrence](image)

**FIGURE 3**

*A*, Number of nematode diagnostic samples processed from 2012 to 2016 in different regions of the Pacific Northwest (Idaho, Oregon, and Washington; n = 29,301). **B–F**, Percentage occurrence of plant-parasitic nematode genera from 2012 to 2016 in different regions of the Pacific Northwest.
occurrence of *Tylenchlorhynchus* in Idaho compared with Oregon and Washington.

**Conclusions**

Plant-parasitic nematodes are commonly encountered in diagnostic samples processed by laboratories in the PNW. There are eight genera of plant-parasitic nematodes that occur in >2% of diagnostic samples, of which *Meloidogyne* and *Pratylenchus* are the most economically important. By summarizing regional trends in plant-parasitic nematode occurrence, distribution, and population densities, diagnostic laboratory and extension personnel now have an empirical basis upon which to compare individual grower reports. Although it is relatively easy to quantify plant-parasitic nematode population densities in soil samples, understanding the impact of plant-parasitic nematodes on crop productivity in the PNW for many crops still remains unknown.

**Acknowledgments**

The authors thank the diagnostic laboratories that generously provided data for this effort.

**Literature Cited**


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