Impact of *Pratylenchus penetrans* on Established Red Raspberry Productivity

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Abstract

Han, Z., Walters, T. W., and Zasada, I. A. 2014. Impact of *Pratylenchus penetrans* on established red raspberry productivity. Plant Dis. 98:1514-1520.

The plant-parasitic nematode *Pratylenchus penetrans* is a major constraint to the production of red raspberry. To determine whether several popular raspberry cultivars in Washington State differ in susceptibility to *P. penetrans* and whether post-plant nematicides treatments are warranted, five independent, multiyear trials were conducted. Trials in existing plantings of 'Cascade Bounty', 'Chemainus', 'Meeker' (two trials), and 'Saanich' raspberry were established in northwest Washington. Treated plots were protected from *P. penetrans* by applying nematicides over a 3-year period, while nontreated plots received no nematicides. *P. penetrans* population densities in soil and root samples were assessed spring and fall of each year. In addition, impact of *P. penetrans* on raspberry yield, fruit composition, cane production, and root biomass was measured several times in each cultivar during the 3-year study. *P. penetrans* root population densities in nematicide-treated plots were consistently lower than those in nontreated plots at all the samplings. There were few consistent treatment differences in fine root biomass, the preferred feeding sites for *P. penetrans*. However, a complete root system sampling of one of the cultivars did show greater fine root biomass in treated plants compared with nontreated plants. When differences were observed aboveground, treated plants yielded less than corresponding nontreated plants, indicating that the nematicides may have been phytotoxic to some of the cultivars. This study suggests that post-plant nematicide applications are of limited benefit because, at least during the 3-year time period of this study, there were few observable benefits of protecting these raspberry cultivars from *P. penetrans*.

Washington State is the largest producer of processed red raspberry (*Rubus idaeus* L.) in the United States, with an annual crop value of approximately $50 million (22). The plant-parasitic nematode *Pratylenchus penetrans* (Cobb, 1917) Filip. & Stek. 1941 is a major constraint to red raspberry production in this region, along with other pathogens and pests (17). *Pratylenchus* spp. have been shown to reduce nutrient and water uptake in perennial plants (14,24). Consequently, the reduction in nutrient and water uptake can reduce plant vigor and shorten the productive lifespan of a planting (3,33). Feeding and migration of this nematode in raspberry roots causes necrotic lesions that can kill roots over time. Several studies have reported on the impact of *P. penetrans* on red raspberry establishment (1,16). When red raspberry was planted in *P. penetrans*-infested soil, mortality was greater and plant growth was reduced compared with plants grown in areas free of nematodes (16).

Red raspberry production, like strawberry and other high-value crop systems, relies significantly on preplant soil fumigation for the control of plant-parasitic nematodes (3,30). Soil fumigation can protect young plants and significantly increase plant growth and yield in the following years. However, the improvement of plant growth and yield using soil fumigation disappears after a few years, and high densities of *P. penetrans* can be found in both soil and red raspberry roots within 4 years of fumigation (1). For decades, raspberry growers were able to mitigate the impact of *P. penetrans* after establishment by applying the contact nematicide fenamiphos. When mature raspberry plants are infested with *P. penetrans*, nematicide applications can increase plant growth and yield (27). Very similar results have been found in other perennial crops infested with *P. penetrans* (6,18). The registration for fenamiphos was cancelled in the United States (23), creating a void in ways by which raspberry growers can manage *P. penetrans* after establishment of the crop. The Washington raspberry industry has actively pursued finding post-plant management options for *P. penetrans*; however, there are no other U.S.-registered, post-plant nematicide treatments that effectively control *P. penetrans* in bearing red raspberry.

Most of the previous research on the impact of *P. penetrans* on red raspberry establishment and productivity was conducted on the 'Willamette' raspberry; however, Willamette is no longer commonly grown in northwest Washington. Presently, the floricane-bearing 'Meeker', 'Chemainus', 'Saanich', and 'Cascade Bounty' are most commonly planted in Washington because of the commercial traits and disease resistances of these cultivars. These four cultivars made up approximately 80% of plant sales from 2006 to 2010 in Washington State (29). The goals of this study were to determine how *P. penetrans* affects red raspberry growth at the post-plant stage by using post-plant nematicide applications to protect the plant from *P. penetrans*, and whether the impact differs among red raspberry cultivars most commonly grown in Washington. This information will guide growers in cultivar selection, and will address whether post-plant nematicide applications can improve the productivity of red raspberry grown in northwest Washington.

Materials and Methods

Experimental design and treatments. Experiments were established in spring 2011 in five commercial raspberry fields in northwest Washington. Established raspberry fields were identified with relatively uniform population densities of *P. penetrans* and without a history of root rot caused by *Phytophthora rubi* (T. W. Walters and I. A. Zasada, *unpublished data*), representing different regional climates, raspberry cultivars, and soil types in Whatcom and Skagit Counties (Table 1). The identity of the *Pratylenchus* sp. at each field was confirmed as *Pratylenchus penetrans* based upon morphological characteristics and the presence of males (2). Each trial was an independent experiment (Table 1) and, although raspberry cultivar varied among locations, the same experimental design was implemented at each location. In each trial, a one-way completely randomized experimental design with five or six replications was established. Each experimental unit (plot) was one row wide (1.2

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Accepted for publication 21 April 2014.

http://dx.doi.org/10.1094/PDIS-12-13-1235-RE

m), one post length long (9 m), and comprised of 9 to 12 plants, with an identical plant number in each plot within a location. Within locations, an equal number of plots (replications) were either treated with nematicides or not. In the treated plots, the nematicides fosthiazate (EC 900; Syngenta Crop Protection) and oxamyl (Vydate L; DuPont) were applied in June 2011, in April and May 2012, and in April 2013. Vydate L was applied at 1,532 ml/ha (oxamyl at 367 g/ha), and EC 900 was applied at 919 ml/ha (fosthiazate at 5,044 g/ha) at each application. Oxamyl and fosthiazate were applied together with a CO_2-powered backpack sprayer in a volume of 1 liter/plot using a single-nozzle boom (8006 nozzle; Teejet) sprayed directly on the soil in a 1.2-m-wide band centered on the row. Rates were calculated on the basis of the field acreage but were concentrated in the band, as described previously (28). Each application was followed by rainfall or overhead water application of at least 1 cm. Nontreated plots received no nematicide and no additional overhead water application. Fertility, irrigation, and pest management practices were handled by the cooperating growers and followed recommended practices for the region (11).

***P. penetrans* dynamics in roots and soil.** *P. penetrans* population densities were determined in the spring and fall of all years. From each plot at each collection date, 12 soil cores (2.5 cm in diameter by 25 cm deep) were collected and combined. At the same time, two root cores (15 by 15 by 15 cm) within the bed of each plot were collected using a square-blade shovel; roots were picked manually from the cores and saved. Both soil and roots collected from the same plot were placed in a polyethylene bag and stored at 5°C until processed. For extraction of *P. penetrans* from soil, 100 g of soil from each sample was placed on a Baermann funnel and collected after 5 days (7). A subsample of 50 g of soil from each plot was placed in an oven set at 70°C for 7 days, and then weighed to determine dry weight. To determine *P. penetrans* population densities in roots, collected roots were washed free of soil, and fine roots (diameter ≤2 mm) were preferentially collected for extraction. Nematodes were extracted from roots by intermittent mist, and *P. penetrans* collected after 7 days (7). After extraction, root samples were dried in an oven set at 70°C for 7 days to determine dry weights. Population densities of *P. penetrans* in soil and roots were determined using a stereomicroscope at ×40 magnification, and expressed as number of *P. penetrans* per 100 g of dry soil or *P. penetrans* per gram of dry root.

Assessment of yield and fruit quality. Fruit was machine-harvested at all locations using the growers' harvesters. During all years, harvesting machines were driven down the raspberry rows to the end of each plot until all the berries from the plot were collected. The exception was Meeker trial 2, where yield data were not collected in 2013 due to logistical issues. Berries were collected in flats and weighed immediately after harvest. Berries were collected at least once a week during the peak harvest season to determine yield (12 July to 3 August 2011, 7 July to 28 July 2012, and 5 July to 31 July 2013). In all trials, 25 and 50 berries in July 2012 and 2013, respectively, were sampled randomly by hand from each plot, placed in a polyethylene bag, crushed manually, and weighed. The juice was collected to measure percentage soluble solids (°Brix) using a refractometer (Model PA202; MISCO) at room temperature (25); juice from each bag was measured two times and the values were averaged. Measurements of soluble solids of the berries were repeated from each plot in August 2012 and July 2013.

Primocane and root biomass measurements. In June 2012 and 2013, two plants were chosen randomly from each plot, and primocane (shoots germinated from roots and crowns in the first year; the same canes become floricanes in the second year) number was counted. In addition, two plants, each with 10 primocanes (5), were chosen randomly and primocane height was measured.

To collect fine roots from each trial (cultivar), two cores were collected within the root zone in each plot using a modified soil cutter (8 cm in diameter by 20 cm deep), combined, and passed through a 4-mm pore-diameter sieve in September 2012 and August 2013. Roots retained on the sieve were placed in a polyethylene bag and stored at 5°C until processed. For processing, the entire root sample was placed in a bucket and covered with approximately 10 liters of water. This slurry was agitated and then poured over a 2-mm-diameter sieve two times; roots retained on the sieve were collected and placed in water. Roots were then partitioned into woody (diameter >2 mm) and fine roots (diameter ≤2 mm). *P. penetrans* was extracted from the fine roots and enumerated as described above. Dry weights of woody and fine roots were determined after nematode extraction, as described above.

Whole-plant destructive sampling. A destructive sampling was conducted only at Meeker trial 2 in December 2011 and 2012. Starting 1.2 m (2011) and 2.7 m (2012) from the south end of each plot, two plants were removed from a 1.5-m area. A shovel was used to excavate the area to a depth of 0.5 m, and the whole plant (roots, primocanes, and floricanes) was removed; roots were collected by hand to ensure that most of the plant material was collected. Whole plants were bagged and transported to the laboratory for further processing. Primocanes and floricanes were cut, separated from roots, and counted, and fresh weights determined. Roots were washed free of soil and sorted by diameter into smaller roots (diameter ≤5 mm) and larger roots (diameter >5 mm), and root fresh weights were measured. Approximately 20 g of fresh fine roots (diameter ≤2 mm) were sampled, and *P. penetrans* extracted from the roots and quantified as described above. All plant parts (primocanes, floricanes, and smaller and larger roots) were dried at 38°C for 7 days before dry weights were measured.

Other pest assessments. In May 2012, to determine the presence and density of aphids, a timed observation was conducted in all trials. Each plot was observed for 2 min by counting the aphids on the underside of raspberry leaves at heights of 0.5 to 1.7 m on the west side of the raspberry row (10). The counts began at one end of each plot and continued until the end was reached or time ran out. To determine the presence and population of root weevils in May 2012, one soil core was collected from the bed of each plot in each trial using a standard golf tee cutter (8 cm in diameter by 16 cm deep), and the soil was passed through a 2-mm-diameter sieve to recover root weevils, which were counted. Trials were scouted each year for characteristic root rot symptoms cause by *Phytophthora rubi* (collapsing floricanes, wilting primocanes, and premature yellowing of older leaves).

Statistical analyses. Nematode population density data were transformed prior to analysis to meet normality or equal variance assumptions of the model; nontransformed, raw data are presented in tables and figures. In the Chemainus trial, *Pratylenchus penetrans* soil population density data were $\arcsin\sqrt{x/12000}$ transformed and, in the Meeker trial 1, soil population density data were $\arcsin\sqrt{x/14000}$ transformed, where x = *P. penetrans* population densities. *P. penetrans* soil population density data in the Saanich trial and both soil and root population data in the Cascade Bounty trial were $\ln(x + 1)$ transformed, where x = *P. penetrans* population densities. In Meeker trial 2, *P. penetrans* soil and root population density data were $\sqrt{x}$ transformed, where x = *P. penetrans*

Table 1. Cultivar, location, and age of five red raspberry (*Rubus idaeus*) fields included in experiments in northwest Washington designed to determine the impact of *Pratylenchus penetrans* on established raspberry productivity

Cultivar[y]	Location	Age of crop in 2012 (years)
Chemainus	Lynden	4
Saanich	Lynden	4
Meeker 1	Lynden	4
Meeker 2	Burlington[z]	7
Cascade Bounty	Everson	3

[y] Each trial (cultivar) was assessed as an individual experiment. Meeker raspberry was evaluated in two locations designated Meeker 1 and Meeker 2.

[z] The only trial located in Skagit County, WA; all other trials were located in Whatcom County, WA.

population densities. The remaining *P. penetrans* population density data were rank transformed using PROC RANK in SAS 9.2 (SAS Institute). PROC MIXED was used for repeated measures analysis to compare results among sample times. Covariance structures were chosen according to the experimental design and the default information criteria, Akaike's information criteria and Bayesian information criteria (9). Means separations were performed using the LSMEANS statement to adjust all pairwise differences by default in PROC MIXED, with the macro program "Pdmix800.sas" (19) used to generated means separations. Yield, berry soluble solids content, berry weight, primocane number, and height data from all trials were analyzed using PROC TTEST separated by year. Data from the destructive Meeker trial 2 sampling were analyzed using PROC MIXED as a one-factor (treatment) completely randomized design separated by year. Smaller root (diameter ≤5 mm) dry weight data were ln(x) transformed, where x = small root dry weight, to meet the assumption of normality. Data from the primocane and root biomass measurements were analyzed using PROC TTEST separated by year.

Results

***P. penetrans* dynamics in roots and soil.** Across all trials (cultivars) except Cascade Bounty, *P. penetrans* initial population densities were 45 to 327 nematodes per 100 g of dry soil and 304 to 1,408 nematodes per gram of dry roots (Fig. 1B–E). For Cascade Bounty, there were 7 nematodes per 100 g of dry soil and 239 nematodes per gram of dry root, on average, at the beginning of the study (Fig. 1). The population dynamics of *P. penetrans* followed similar trends across trials, with a few minor differences. In most trials, applications of oxamyl and fosthiazate successfully reduced *P. penetrans* population densities in both soil and roots during the 3-year study compared with the initial sampling date (Fig. 1A–E). The exception was at Meeker trial 2, where *P. penetrans* population densities in treated soil and roots were 35 to 156 nematodes per 100 g of dry soil and 55 to 806 nematodes per gram of dry root over the course of the study. In fact, in April 2013, *P. penetrans* population densities in treated and nontreated root samples were similar at this site (Fig. 1D). At all of the sites except the Cascade

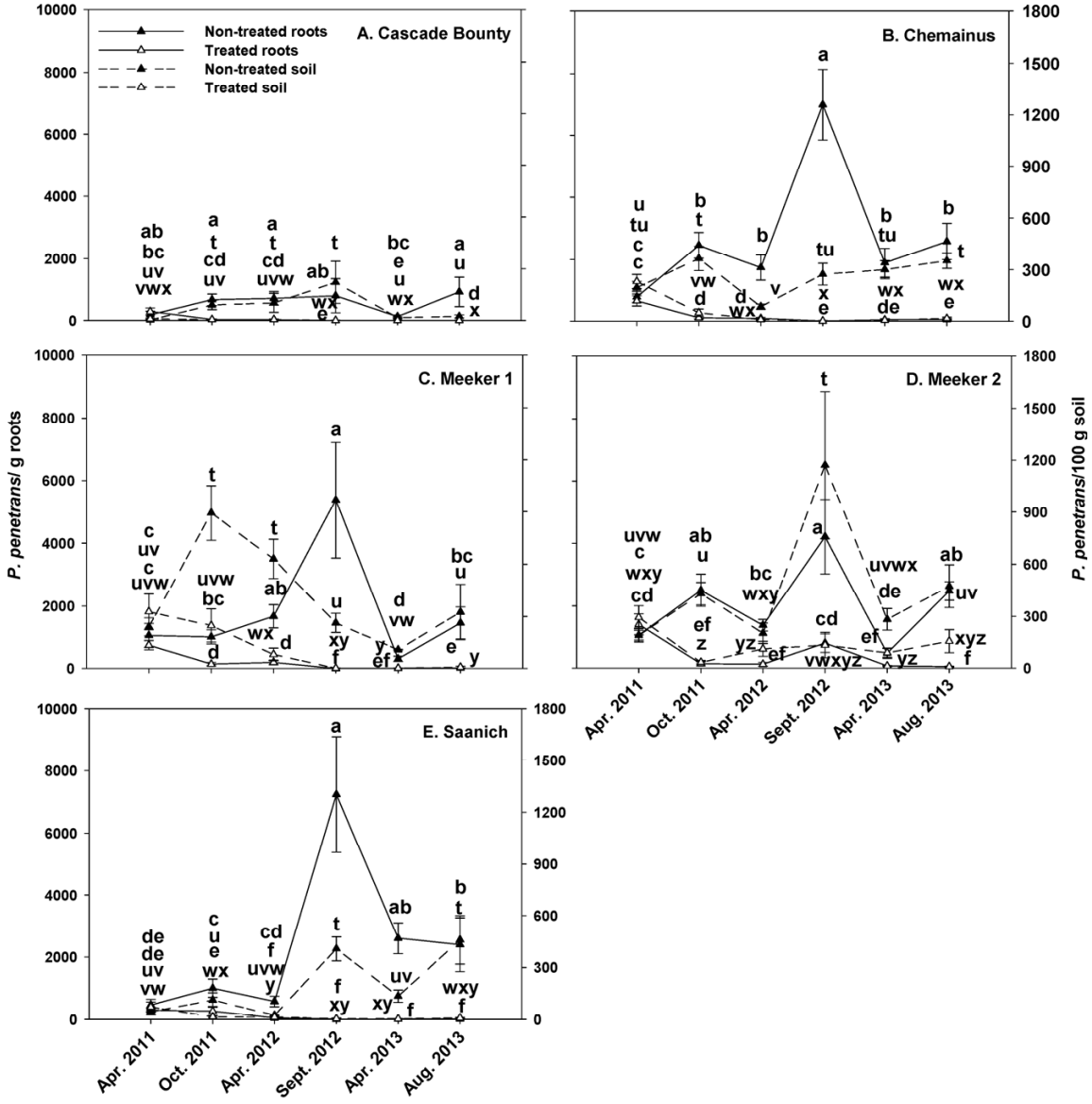

Fig. 1. *Pratylenchus penetrans* population densities on red raspberry (*Rubus idaeus*) cultivars **A,** Cascade Bounty; **B,** Chemainus; **C,** Meeker trial 1; **D,** Meeker trial 2; and **E,** Saanich either treated or not treated with oxamyl (Vydate L) at 1,532 ml/ha (367 g/ha) and fosthiazate at 919 ml/ha (5,044 g/ha) at each application. Nematicide applications were made in spring of each year. Nontransformed data are shown and each value is the mean ± standard error of six replicated plots. Means separation for populations in soil and roots was based on transformed data, with the type of transformation depending upon the trial. Lowercase letters a to e are used for means separation of root populations, while the letters t to z are used for means separation of soil populations. Within root or soil populations, means sharing the same letter are not significantly different based on a repeated measures analysis ($P \leq 0.05$).

Bounty trial, there was a trend for higher *P. penetrans* population densities in roots in the fall of each year compared with the spring; however this trend was not always significant. Also, in these cultivars, there was a spike in *P. penetrans* populations in roots in September 2012 (Fig. 1B–E).

Impact of *P. penetrans* on yield and fruit quality. For the partial harvest data from 2011, there were no significant differences in yield of Chemainus, Saanich, Meeker trial 1, or Meeker trial 2 between treated and nontreated plants (Fig. 2A). However, for Cascade Bounty, treated plants had a 21% reduction in yield compared with the yield of nontreated plants. For the partial harvest data of 2012, yields of treated plants in both Chemainus and Meeker trial 1 were reduced by 19% compared with corresponding nontreated plants (Fig. 2B). No significant differences were observed in partial harvest data of 2013 (Fig. 2C). There were few consistent trends in soluble solid content (measured as °Brix) and fruit weight between the treatments at any of the trials (*data not shown*). In July 2012, treated Meeker trial 2 had reduced soluble solid content ($P < 0.0346$) than nontreated plants (10.9 and 11.2, respectively); however, this difference was not observed at the second assessment of fruit quality in August. Treated plants of Meeker trial 1 had greater fruit weight (76.0 g) than nontreated plants (69.4 g) in July 2012 ($P < 0.0391$); this trend was not observed in August 2012. At the latter sampling date in 2012, both treated Chemainus and Cascade Bounty had significantly lower soluble solids ($P < 0.001$) than corresponding nontreated plants; there were no differences in fruit weights between nematicide-treated and nontreated cultivars in any of the trials at this sampling date. In 2013, fruit from nontreated Chemainus had higher (10.9) soluble solids content than treated Chemainus (10.1) at the July assessment ($P = 0.0438$). Later in the season in 2013, differences in soluble solid content were only observed in Cascade Bounty, with higher content in nontreated (9.4) versus treated (8.9) fruit ($P = 0.0457$).

Impact of *P. penetrans* on primocane growth and root biomass. There were generally no differences in the vigor (primocane height and number) of treated and nontreated plants (*data not shown*). However, in 2012, nematicide-treated Chemainus had greater primocane height (131 cm) and number (21 primocanes) compared with nontreated Chemainus (116 cm and 18 primocanes) ($P \leq 0.05$). In 2013, nematicide-treated Cascade Bounty had greater primocane height (154 cm) compared with nontreated plants (140 cm) ($P \leq 0.05$). There were no significant differences in aboveground plant growth parameters between treatments in any of the other cultivars.

Treated Chemainus and Meeker trial 1 had more fine roots in 2012 compared with nontreated plants whereas, in Cascade Bounty, the nematicide-treated plants had lower fine root biomass (Table 2). There was no treatment effect on the dry weight of roots >2 mm in any cultivar. In 2013, there was no significant difference observed in root biomass in any cultivar. Similar to observations in the *P. penetrans* population dynamics over time dataset (Fig. 1), *P. penetrans* root population densities were significantly greater in nontreated cultivars compared with treated cultivars in all trials in 2012 and 2013 (Table 2).

Impact of *P. penetrans* on whole plant biomass. There was no significant difference in primocane number, primocane dry weight, floricane number, floricane dry weight, or large root dry weight between treated and nontreated plants in Meeker trial 2 in 2011 (Table 3). However, the dry weight of fine roots in treated plants was 51% greater than in nontreated plants. Limited fine roots were observed in nontreated plants, and fine roots that were present were typically brown, dead or dying, and bunched (witches' broom; 10) in the larger roots. In 2012, similar trends were observed with few significant aboveground impacts of the nematicide treatment on plant performance (Table 3). In 2012, there were more primocanes in treated plants compared with nontreated plants; however, there was no significant difference in primocane dry weight between the treatments. Belowground, there continued to be significant differences in fine root biomass between the treatments (Table 3); treated plants had 65% more fine roots than nontreated plants.

Presence of other pests. No damaging levels of other insect pests were found in the trials. A few large raspberry aphids (*Amphorophora agathonica*; 10) were detected in all the trials (*data not shown*). Although the damage threshold of large raspberry aphids on raspberry is not known, this aphid damages raspberry plants only at extremely high populations (20). In addition, no weevils (*Otiorhynchus* spp.) were detected (*data not shown*). No evidence of root rot caused by *Phytophthora rubi* was observed during yearly scouting events.

Discussion

Repeated applications of oxamyl and fosthiazate successfully reduced *Pratylenchus penetrans* population densities in both soil and roots in all five red raspberry trials. The effectiveness of these nematicides for the suppression of *P. penetrans* was consistent with the findings of Zasada et al. (31), as well as effectiveness previously demonstrated for Meeker, Willamette, and 'Nootka' (28). The successful *P. penetrans* control was reflected in 51 to 65% greater fine root biomass in treated plots in Meeker trial 2 compared with nontreated plots. However, in this study, despite protection of raspberry cultivars from *P. penetrans* for over 2 years, consistent differences in plant and fruit productivity were not observed.

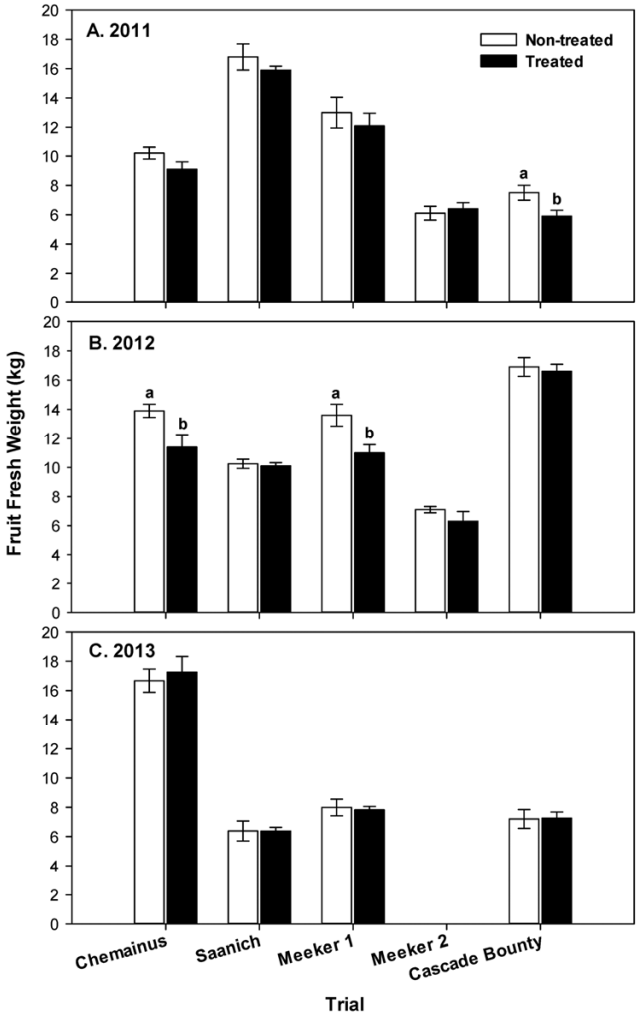

Fig. 2. Fruit weight of raspberry (*Rubus idaeus)* cultivars harvested in **A,** 2011; **B,** 2012; and **C,** 2013 from plots either treated or not treated with oxamyl (Vydate L) at 1,532 ml/ha (367 g/ha) and fosthiazate at 919 ml/ha (5,044 g/ha) at each application to control *Pratylenchus penetrans*. Nematicide applications were made in spring of each year. Nontransformed data are shown and each bar represents the mean ± standard error of five or six replicate plots. Each cultivar was evaluated in a separate trial as an independent experiment; within a cultivar, bars without letters are not significantly different according to Student's *t* test using $P \leq 0.05$.

Belowground, it was surprising that few consistent differences in fine root biomass were observed over the course of this research. Fine root biomass is an important parameter with which to assess *P. penetrans* damage. It is well known that fine roots are the preferred feeding site of *P. penetrans* and that the nematode reduces fine root biomass by penetrating the roots, migrating within the roots, and feeding on the root cells (3). Apple and cherry trees grown in *P. penetrans*-infested soil had a greater percentage of bunched, dark, and dead or dying fine roots, whereas apple and cherry trees grown in a nematicide-treated soil had extensive root systems with healthy fine roots (12,13). Coffee infested with *P. coffeae* had less fine root biomass compared with nematode-free plants (24). *P. coffeae* also reduced carbon fixation in coffee seedlings (15).

Our inability to consistently detect differences in fine root biomass between treated and nontreated plants may have been due to the methodology used across the trials. This is exemplified in the Meeker trial 2, where both root sampling methods, core and destructive sampling, were used. The destructive sampling protocol consistently demonstrated that nontreated plants had lower fine root biomass and a greater percentage of dead or dying roots, while treated roots were asymptomatic. An increase in fine root biomass in treated plants was not observed in this same trial when using the core method. This indirectly demonstrated that assessing root systems using cores collected from only a few locations within the root zone may have had less differentiating power than destructive, whole-plant sampling.

Vrain et al. (26) showed that *P. penetrans* populations in both soil and roots did not follow any seasonal patterns. In our study, in general, *P. penetrans* population densities in nontreated soil increased during the summer and decreased during the winter. However, due to variation in population densities within trials, significant differences were not always observed. Winter conditions appeared to be associated with greater mortality of *P. penetrans* (8), but mortality was greater in the top 15 cm of soil than deeper in the soil profile. In this study, soil samples were collected 30 cm deep, which may be the reason that a significant decline of populations in soil after winter was not always observed. In addition, population densities of *P. penetrans* in soil should not be considered a reliable indicator to predict potential damage of this nematode to established red raspberry. Fluctuations of *P. penetrans* population densities in soil can be misleading and may result in underestimation of the actual population densities of this nematode parasitizing the roots.

The inability to measure differences in aboveground growth and yield of raspberry plants even after protecting the plants from *P. penetrans* for more than 2 years with post-plant nematicide applications is likely due to the complex growth dynamics of these perennial plants. Roots, as a carbon sink in raspberry, can compensate for carbon resources available to aboveground portions of the plants (4,5). More importantly, aboveground biomass does not respond immediately to root damage caused by root-feeding nematodes because of the complexity of compensation mechanisms in perennial plants. Grapevines infested by ring nematode (*Mesocriconema xenoplax*), even under extreme stress (15% sunlight), did not show a reduction in shoot biomass until the second year of exposure to *M. xenoplax* (21). In addition, due to this complex source-sink relationship, the response of aboveground plant por-

Table 2. Root biomass and *Pratylenchus penetrans* population densities in roots of raspberry (*Rubus idaeus*) cultivars either treated or not treated with post-plant nematicides[y]

	Dry weight (g) of roots ≤2 mm diameter			Dry weight (g) of roots >2 mm diameter			*P. penetrans*/g of dry roots		
Trial[z]	Nontreated	Treated	*P* value	Nontreated	Treated	*P* value	Nontreated	Treated	*P* value
2012									
Chemainus	0.6 b	1.3 a	0.0185	7.2	9.1	0.4271	3,712 a	39 b	0.0008
Saanich	0.9	1.3	0.2945	8.9	8.1	0.7419	3,362 a	46 b	0.0258
Meeker trial 1	1.1 b	1.8 a	0.0235	3.8	3.3	0.5583	2,272 a	31 b	0.0027
Meeker trial 2	1.5	2.0	0.2153	5.8	5.3	0.7892	3,473 a	354 b	0.0011
Cascade Bounty	1.2 a	0.9 b	0.0110	2.6	1.7	0.1207	2,262 a	14 b	0.0143
2013									
Chemainus	0.6	0.5	0.5897	2.2	2.4	0.8567	9,184 a	72 b	0.0106
Saanich	0.6	0.6	0.9796	4.3	1.9	0.2378	8,105 a	53 b	0.0024
Meeker trial 1	0.8	1.0	0.2585	0.5	1.1	0.1864	6,434 a	29 b	0.0003
Meeker trial 2	0.5	1.0	0.1539	1.9	1.4	0.6392	12,564 a	101 b	0.0057
Cascade Bounty	0.4	0.4	0.9245	2.0	1.7	0.8430	6,625 a	0 b	0.0001

[y] Plants were either treated or not treated with oxamyl (Vydate L) at 1,532 ml/ha (367 g/ha) and fosthiazate at 919 ml/ha (5044 g/ha) at each application. Nematicide applications were carried out in spring of each year. Root biomass and *P. penetrans* population were detected in fall 2012 and 2013. *P* value = probability of no significant difference between treated and nontreated plots based on an analysis of variance.

[z] Nontransformed data are shown. Each trial was assessed as an individual experiment. Each value is the mean of five or six replicate plots; within each trial, means followed by different letters are significantly different between columns according to Student's *t* test ($P \leq 0.05$).

Table 3. Aboveground and belowground biomass of established Meeker red raspberry (*Rubus idaeus*) plants in Burlington, WA (Meeker trial 2) that were either treated or not treated with post-plant nematicides to control *Pratylenchus penetrans*[y]

Treatment[z]	Primocane number/plant	Primocane dry weight (g)	Floricane number	Floricane dry weight (g)	Fine root (diameter <5 mm) dry weight (g)	Course root (diameter >5 mm) dry weight (g)	Total root dry weight (g)
2011							
Treated	32.2	1,098.7	28.3	858.8	225.3 b	1,447.5	1,672.8
Nontreated	27.7	962.8	25.8	843.2	149.5 a	1,374.8	1,524.3
P value	0.3935	0.5228	0.6166	0.9231	0.0229	0.6350	0.3732
2012							
Treated	46.0 a	892.8	22.7	624.7	212.4 b	1,087.8	1,300.2
Nontreated	35.8 b	766.6	32.8	755.8	128.0 a	1,033.6	1,161.6
P value	0.0410	0.4396	0.0542	0.3385	0.0028	0.6333	0.2448

[y] Plants were either treated or not treated with oxamyl (Vydate L) at 1,532 ml/ha (367 g/ha) and fosthiazate at 919 ml/ha (5,044 g/ha) at each application. Nematicide applications were carried out in spring of each year.

[z] Nontransformed data are shown. Each value is the mean of six replicate plots; means not followed by a letter within the same column are not significantly different according to Student's *t* test ($P \leq 0.05$). *P* value = probability of no significant difference between treated and nontreated plots based on an analysis of variance.

tions to improved root health may also be delayed. Due to root loss, it can take 3 years to increase yield after improvements of root and cane growth in the first and second year, respectively (17). Vrain and Keng (27) documented that the yield of 7-year-old Willamette raspberry infested with *P. penetrans* increased 15 months after applications of fenamiphos or carbofuran compared with nontreated plants. Similar results were obtained in apple trees severely infested by *P. penetrans*, with yield increases not observed until 3 years after applications of fenamiphos in spring and fall compared with nontreated control plots (18). In this study, similar results were not observed.

Another potential reason for not observing increases in yields or plant productivity of nematicide-treated plants may have been phytotoxicity. The combined application of oxamyl and fosthiazate is not registered for use on raspberry in the United States This treatment was chosen because both of these nematicides have been shown to reduce population densities of *P. penetrans* in raspberry (28,31), and the desired goal was to reduce *P. penetrans* population densities as much as possible to increase chances of measuring whether *P. penetrans* affects plant growth and fruit yields. Treated Cascade Bounty plants had lower yields than those observed in nontreated plants 3 months after the initial nematicide application. Although yield reduction was not observed in the following years, there was less fine root biomass that year in treated versus nontreated plants. These results lead to the conclusion that the nematicides used in the study may have been phytotoxic to Cascade Bounty. This conclusion is further supported by lack of insect damage or root rot caused by *Phytophthora rubi* at this location. Phytotoxicity of post-plant nematicide applications to raspberry has been reported. The yield of Nootka raspberry was reduced after treatment with oxamyl (28). Similarly, Willamette raspberry treated with fenamiphos at 16 kg a.i./ha had reduced cumulative floricane diameter compared with plants treated with fenamiphos at 8 kg a.i./ha (27).

In addition to few observable differences in aboveground growth and yield, consistent differences in fruit quality were not detected between the treatments. Although significant differences were observed in soluble solids between treated and nontreated plants in three trials, the differences observed in the first sampling did not persist to the second year of sampling. Therefore, it was not evident that the nematicide treatments affected fruit quality in a positive manner. In fact, treated plots of Chemainus and Cascade Bounty had lower soluble solids than nontreated plots at some sampling dates, again suggesting a phytotoxic effect. No studies have documented that *Pratylenchus* spp. or, for that matter, any plant-parasitic nematodes affect the quality of red raspberry or other perennial fruit crops.

In the Pacific Northwest, recommendations indicate that when *Pratylenchus penetrans* populations reach 1,000 to 4,000 *P. penetrans* per 500 cm^3 soil in established raspberry fields, which is equivalent to 140 to 550 *P. penetrans* per 100 g of dry soil, plant growth will decrease and post-plant nematicide treatments will be required (17). Our study does not support this recommendation. Soil populations in nontreated plots in all trials reached or exceeded 140 to 550 *P. penetrans* per 100 g of dry soil. Although nematicide treatments decreased root and soil *P. penetrans* population densities, there were no corresponding increases in yield. Also, there were only a few significant differences in other above- and belowground attributes between treated and nontreated raspberry. Our overall failure to document benefits of nematicide could be a result of the raspberry production systems used on these farms. The fine roots favored by *P. penetrans* and protected by nematicide treatments provide essential water and nutrients to the plant. However, Washington raspberry growers typically supply water and nutrients through a drip irrigation system several times a week. Raspberry plants with reduced fine roots may be more dramatically affected under less luxuriant conditions.

Based on the current cropping system in Washington, in which growers replant raspberry plants every 6 to 8 years, this study suggests that post-plant nematicide applications are of limited benefit because, at least during a 3-year time period after application, there may be little economic benefits to the grower. Whether the nematicide applications may have longer-term benefits, such as extending plant life or improving plant growth, remains to be determined.

Acknowledgments

This research was partially funded by a grant from the Northwest Center for Small Fruit Research and Washington Specialty Crop Block Grant K514. We thank J. N. Pinkerton and D. Wallace for technical assistance.

Literature Cited

1. Bélair, G. 1991. Effects of preplant soil fumigation on nematode population densities and on growth and yield of raspberry. Phytoprotection 72:21-25.
2. Castillo, P., and Vovlas, N. 2007. *Pratylenchus*, Nematoda, Pratylenchidae: diagnosis, biology, pathogenicity and management. Nematol. Monogr. Perspect. 6:1-530.
3. Davis, E. L., and MacGuidwin, A. E. 2005. Lesion nematode disease. The Plant Health Instructor. Online publication. doi:10.1094/PHI-I-2000-1030-02. http://www.apsnet.org/edcenter/intropp/lessons/Nematodes/Pages/LesionNematode.aspx
4. Fernandez, G. E., and Pritts, M. P. 1993. Growth and source-sink relationship in 'Titan' red raspberry. Acta Hortic. 352:151-157.
5. Fernandez, G. E., and Pritts, M. P. 1996. Carbon supply reduction has a minimal influence on current year's red raspberry (*Rubus idaeus* L.) fruit production. J. Am. Soc. Hortic. Sci. 121:473-477.
6. Hasey, J. K., Westerdahl, B. B., and Lampinen, B. 2004. Long-term performance of own-rooted 'Chandler' walnut compared to 'Chandler' walnuts on Paradox rootstock. Acta Hortic. 636:83-87.
7. Ingham, R. E. 1994. Nematodes. Pages 459-490 in: Methods of Soil Analysis Part 2—Microbiological and Biochemical Properties. S. H. Michelson, ed. Soil Science Society of America, Inc., Madison, WI.
8. Kimpinski, J., and Dunn, R. A. Effect of low temperatures in the field and laboratory on survival of *Pratylenchus penetrans*. Plant Dis. 69:526-527.
9. Kincaid, C. 2005. Guidelines for selecting the covariance structure in mixed model analysis. SUGI 30 Proceedings: Paper 198-30. http://www2.sas.com/proceedings/sugi30/198-30.pdf
10. Lightle, D., and Lee, J. 2013. Large raspberry aphid *Amphorophora agathonica*. Pac. Northwest Ext. Publ. PNW 648. Oregon State University, Corvallis.
11. Lower Mainland Horticulture Improvement Association. 2005. Berry Production Guide. Lower Mainland Horticulture Improvement Association, Vancouver, British Columbia, Canada.
12. Mai, W. F., and Abawi, G. S. 1981. Controlling replant diseases of pome and stone fruits in northeastern United States by preplant fumigation. Plant Dis. 65:859-864.
13. Mai, W. F., Parker, K. G., and Hickey, K. D.1970. Root disease of fruit trees in New York State. II. Populations of *Pratylenchus penetrans* and growth of apple in response to soil treatment with nematicides. Plant Dis. Rep. 54:792-795.
14. Malakeberhan, H., Bird, G. W., and Gore, R. 1997. Impact of *Pratylenchus penetrans* infection on *Prunus avium* rootstocks. J. Nematol. 29:381-388.
15. Mazzafera, P., Kubo, R. K., and Inomoto, M. M. 2004. Carbon fixation and partitioning in coffee seedlings infested with *Pratylenchus coffeae*. Eur. J. Plant Pathol. 110:861-865.
16. McElroy, F. D. 1977. Effect of two nematode species on establishment, growth, and yield of raspberry. Plant Dis. Rep. 61:277-279.
17. McElroy, F. D. 1992. A plant health care program for brambles in the Pacific Northwest. J. Nematol. 24:457-462.
18. Santo G. S., and Wilson, J. H. 1990. Effects of fenamiphos on *Pratylenchus penetrans* and growth of apple. Suppl. J. Nematol. 22:779-792.
19. Saxton, A. M. 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. Pages 1243-1246 in: Proc. 23rd SAS Users Group Int. SAS Institute, Cary, NC.
20. Schaefers, G. A., and Gordon, S. C. 1991. Raspberry aphids. Pages 71-72 in: Compendium of Raspberry and Blackberry Disease and Insects. M. A. Ellis, R. H. Converse, R. N. Williams, and B. Williamson, eds. American Phytopathological Society, St. Paul, MN.
21. Schreiner, R. P., Pinkerton, J. N., and Zasada, I. A. 2012. Delayed response to ring nematode (*Mesocriconema xenoplax*) feeding on grape roots linked to vine carbohydrate reserves and nematode feeding pressure. Soil Biol. Biochem. 45:89-97.
22. United States Department of Agriculture. 2012. Noncitrus Fruits and Nuts 2011 Summary. http://usda01.library.cornell.edu/usda/nass/NoncFruiNu//2010s/2012/NoncFruiNu-07-06-2012.pdf
23. United States Environmental Protection Agency. 2008. Fenamiphos Facts. http://www.epa.gov/oppsrrd1/REDs/factsheets/fenamiphos_ired_fs.htm
24. Vaast, P., Caswell-Chen, E. P., and Zasoski, R. J. 1998. Effects of two endoparasitic nematodes (*Pratylenchus coffeae*) and (*Meloidogyne konaensis*) on ammonium and nitrate by Arabica coffee (*Coffea arabica* L.). Appl. Soil Ecol. 10:171-178.
25. Vanden Heuvel, J. E., Sullivan, J. A., and Proctor, J. T. A. 2000. Trellising system and cane density affect yield and fruit quality of red raspberry.

HortScience 35:1215-1219.
26. Vrain, T. C., Forge, T. A., and DeYoung, R. 1997. Population dynamics of *Pratylenchus penetrans* parasitizing raspberry. Fundam. Appl. Nematol. 20:29-36.
27. Vrain, T. C., and Keng, J. C. W. 1986. Application of nonvolatile nematicides through a trickle irrigation system to control *Pratylenchus penetrans* in raspberries. Can. J. Plant Pathol. 8:97-101.
28. Walters, T. W., Pinkerton, J. N., Riga, E., Zasada, I. A., Partika, M., Yoshida, H. A., and Ishida, C. 2009. Managing plant-parasitic nematodes in established red raspberry fields. HortTechnology 19:762-768.
29. Washington Red Raspberry Commission. 2010. U.S. Red Raspberry Council. http://www.red-raspberry.org/worldNews.asp
30. Zasada, I. A., Halbrendt, J. M., Kokalis-Burelle, N., LaMondia, J., McKenry, M. V., and Noling, J. W. 2010. Managing nematodes without methyl bromide. Annu. Rev. Phytopathol. 48:311-328.
31. Zasada, I. A., Walters, T. W., and Pinkerton, J. N. 2010. Post-plant nematicides for the control of root lesion nematode in red raspberry. HortTechnology 20:856-861.