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Annual and Perennial Alleyway Cover Crops Vary in Their Effects on *Pratylenchus penetrans* in Pacific Northwest Red Raspberry (*Rubus idaeus*)

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Abstract: Cover crops can provide many benefits to agroecosystems, such as lessening soil erosion and increasing water infiltration. However, cover crop use is not common in established red raspberry (*Rubus idaeus*) fields in the Pacific Northwest. Raspberry growers are concerned about resource competition between the cover crop and raspberry crop, as well as increasing population densities of the plant-parasitic nematode *Pratylenchus penetrans*, which has a wide host range and has been shown to reduce raspberry plant vigor and yield. A 2-yr study was conducted in an established 'Meeker' raspberry field in northwest Washington to evaluate the effects of nine alleyway cover crops, mowed weed cover, and the industry standard of bare cultivated soil on *P. penetrans* population dynamics, raspberry yield, and fruit quality. The host status for *P. penetrans* of cover crops included in the field experiment, as well as *Brassica juncea* 'Pacific Gold' and *Sinapis alba* 'Ida Gold', was also evaluated in greenhouse experiments. In the field experiment, *P. penetrans* population densities did not increase in alleyway cover crop roots over time or in alleyway soil surrounding cover crop roots (means range from 0 to 116 *P. penetrans*/100 g of soil) compared with the bare cultivated control (means range from 2 to 55 *P. penetrans*/100 g of soil). *Pratylenchus penetrans* populations did not increase over time in raspberry grown adjacent to alleyways with cover crops (means range from 1,081 to 6,120 *P. penetrans*/g of root) compared with those grown adjacent to bare cultivated soil alleyways (means range from 2,391 to 5,536 *P. penetrans*/g of root). Raspberry grown adjacent to bare cultivated soil did not have significantly higher yield or fruit quality than raspberry grown adjacent to cover crops in either year of the experiment. In the greenhouse assays, 'Norwest 553' wheat and a perennial ryegrass mix were poor hosts for *P. penetrans*, whereas 'Nora' and 'TAM 606' oat and 'Pacific Gold' and 'Ida Gold' mustard were good hosts. These results support the idea that the potential benefits of alleyway cover crops outweigh the potential risk of increasing *P. penetrans* population densities and do not compromise raspberry yield or fruit quality.
Key words: cultivation, ground cover, host suitability, management, root lesion nematode.

In Pacific Northwest (PNW) red raspberry (*R. idaeus*) production, alleyway soil surfaces are kept bare by repeated shallow cultivation and herbicide application (Pacific Northwest Extension, 2007; Walters et al., 2011). Tractors, cultivators, sprayers, and mechanical harvesters pass through the alleyways dozens of times each year, which can lead to soil compaction and negatively affect soil quality. The spring season in the PNW is typically wet from months of rain, which often causes standing water where soil is bare. This can delay field work because workers and equipment cannot enter the alleyways and can also put the crop at risk if growers are unable to perform time-sensitive pesticide and nutrient applications. During the summer, dust from loose, dry soil can accumulate on fruit which can promote spidermite (*Tetranychus* spp., *Eotetranychus* sp., *Panonychus* sp.) infestations or decrease fruit quality (Tangioshi et al., 2003; Pacific Northwest Extension, 2007). With over 3,700 ha of red raspberry harvested in Washington alone (USDA-NASS, 2017), there is a great deal of bare soil being impacted by field work in this production system.

An alternative to continuous bare soil cultivation of the alleyways between raspberry rows is to establish annual or perennial cover crops in this area. Annual and perennial cover crops are used around the world in various perennial production systems and can provide many benefits to soils and cash crops within these production systems. Potential benefits include increased soil organic matter, weed suppression, decreased soil erosion, increased water infiltration, improved soil structure, improved nutrient cycling and management, promotion of beneficial soil microorganisms, and pest and pathogen suppression (Freyman, 1989; Zebarth et al., 1993; Forge et al., 2000; Mazzola and Gu, 2002; Pacific Northwest Extension, 2007; Sarrantonio, 2007; Magdoff and Van Es, 2009). Cover crops can be grown simultaneously with a cash crop, before planting a cash crop, or after cash crop termination. In perennial systems such as raspberry, cover crops can be grown in the alleyways that are maintained between raspberry rows. Despite all of the reported benefits of cover crops, commercial raspberry growers in the PNW cite concerns regarding potential resource competition between the alleyway cover crop and raspberry crop, as well as cover crops being hosts for plant-parasitic nematodes and other soilborne pathogens as reasons for not using alleyway cover crops. These concerns need to be addressed before growers consider adoption of alleyway cover cropping.

Indeed, certain cover crops may be hosts for plant-parasitic nematodes and could serve to increase populations rather than suppress them which could negatively affect the cash crop (Widmer and Abawi, 1998). *Pratylenchus penetrans* (Cobb, 1917) Filipjev and Schuurmans Stekhoven is commonly found in PNW soils. It is one of the most important pests to red raspberry and is thought to be a major contributor to crop decline in the region (McElroy, 1977; Pinkerton et al.,

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2009; Zasada et al., 2015). *Pratylenchus penetrans* is a migratory endoparasite that moves between soil and plant roots and feeds on plant roots. This feeding causes a reduced ability by the plant to uptake water and nutrients. Because *P. penetrans* has a host range of more than 350 plants (Castillo and Vovlas, 2007), an alleyway cover crop should be selected carefully to not increase population densities of *P. penetrans* and subsequently reduce the productivity of the cash crop.

Several cover crop species are hosts for *P. penetrans.* The cover crops 'NK-200' perennial ryegrass (*Lolium perenne* L.), cereal rye (*Secale cereale* L.), 'Marshall' wheat (*Triticum aestivum* L.), 'Robust' barley (*Hordeum vulgare* L.), 'Ladino' white clover (*Trifolium repens* L.), 'Starter' oat (*Avena sativa* L.), and several other commonly used cover crops were determined to be suitable hosts for *P. penetrans* in greenhouse and field studies (Thies et al., 1995). 'Saia' oat (*Avena strigosa* Schreb.), 'Galt' barley, 'New Zealand Dwarf' white clover, 'Canada #1' red top (*Agrostis alba* L.), and 'Roland 21' creeping red fescue (*Festuca rubra* L.) were grown as alleyway cover crops in red raspberry and all were determined to be suitable hosts for *P. penetrans* (Vrain et al., 1996). Although the host suitability of the cover crops differed, the degree of suitability did not significantly affect the growth and productivity of the adjacent raspberry plants. The host suitability of 'Saia' oat, along with 'Wheeler' rye, 'Trudan 8' sudangrass (*Sorghum sudanense* (Piper) Stapf.), 'SS 222' sudangrass × sorghum hybrid, and 'Humus' oilseed rape (*Brassica napus* L.) have been examined (Forge et al., 2000). All of the cover crops supported populations of *P. penetrans* in the field, but 'Wheeler' rye consistently supported the lowest *P. penetrans* density per gram of root, and the final population density was lower than the initial density. However, this difference did not translate into significantly lower *P. penetrans* densities in the roots of the strawberry (*Fragaria* × *ananassa* Duchesne) crop that was planted following the termination and incorporation of all the cover crops.

The objective of this study was to evaluate the effects of eight annual cover crops and one perennial cover crop grown in the alleyway between raspberry beds and the industry standard bare cultivated soil alleyway on *P. penetrans* population dynamics in roots and surrounding soil of the cover crops and adjacent raspberry plants. Raspberry yield and fruit quality were also evaluated to determine any potential resource competition between the cover crops and the raspberry crop. Cover crops evaluated in the field were also evaluated for *P. penetrans* host suitability in the greenhouse.

Materials and Methods

Evaluation of alleyway cover crops in an established raspberry field: The experiment was conducted from the Fall of 2014 to the Fall of 2016 (24 mon) in an established commercial 'Meeker' red raspberry field in Lynden, WA. The entire experimental area was 0.35 ha and comprised 17 rows of raised beds (approximately 25 cm tall, 45 cm wide) with 3 m of spacing between beds (alleyways). Before establishing this experiment, alleyways had been routinely cultivated throughout the year to control weeds, and no ground cover had been planted in the alleyways. The soil in this field is a Lynden sandy loam, with a pH of 6.4, 3.94% organic matter, a cation exchange capacity of 10 meq/100 g, 89.4 ppm of nitrate, 200.9 mg/kg of phosphorus, and 227.1 mg/kg of potassium (Brookside Laboratories, Inc., New Bremen, OH). The mean *P. penetrans* population density in raspberry roots in this field was 4,320 ± 798 *P. penetrans*/g of root. The raspberry crop was managed by the commercial grower, including irrigation and fertilization, throughout the duration of this experiment and recommended conventional practices for the region were followed (Pacific Northwest Extension, 2007).

Experimental treatments were arranged in a completely randomized design and replicated four times. Each treatment plot consisted of 9.1 m of raised bed with 1.2 m of alleyway on each side of a raised bed; the total area of each plot was approximately 28 m^2. A buffer area 9 m long was established between each treatment plot in the same row. Untreated beds and alleyways were adjacent to each treatment plot to avoid any undesired interaction between treatments.

Eight cover crop species were planted in the alleyways during the fall of each year (Table 1). Cover crops included in the study were selected because seeds are readily available to growers in the region and because they are suitable for the environment. Each year, a weedy mow control (Mow) and a cultivated, bare soil control (Till) were also established in the alleyways. These treatments were first planted in the Fall of 2014 and replanted in the same plots in the Fall of 2015. The exception was the perennial ryegrass mix of 51.25% *Lolium hybridum* 'Tetralite' and 48.24% *L. perenne* 'Kentaur' (grass mix 1) which was seeded only once at the beginning of the experiment and was maintained over the duration of the study.

For cover crop establishment in year 1, immediately before seeding, all alleyways were cultivated to a depth of 15 cm. Cover crop treatments were seeded on 1 October 2014 using a compact drill (3P500V; Land Pride, Salina, KS). All plots were seeded with approximately a 15 cm wide band left unseeded adjacent to the raised raspberry beds on either side. This area is where the tires of machinery and equipment pass throughout the season. Both ryegrass mixes were seeded at 28 kg/ha, per the supplier's instructions. The remaining cover crop treatments were seeded at 112 kg/ha. Cover crop establishment, stand, and coverage were visually monitored throughout the experiment.

All of the cover crop treatments, perennial and annual, and the Mow treatment were mowed for the first

TABLE 1. Crop type, species name, and cultivar for alleyway cover crops included in the Washington raspberry (*Rubus idaeus*) field study and *Pratylenchus penetrans* greenhouse host assays.

Crop	Cultivar
Hard, red winter wheat (*Triticum aestivum*)[a]	Norwest 553
Soft, white winter wheat (*T. aestivum*)[a]	Rosalyn
Winter-hardy oat (*Avena sativa*)[b]	Nora
Winter-hardy oat (*A. sativa*)[b]	TAM 606
Intermediate and tetraploid perennial ryegrass mix (*Lolium hybridum, Lolium perenne*)[c]	51.25% Tetralite, 48.24% Kentaur
Perennial ryegrass mix (*L. perenne*)[c]	43.93% Esquire, 31.44% TopHat 2, 22.49% Tetragreen
Triticale (*Triticosecale* sp.)[d]	Trical 103BB
Triticale (*Triticosecale* sp.)[d]	TriMark 099
Cereal rye (*Secale cereale*)[c]	Common

[a] Sourced from WSU Northwest Research and Extension Center Plant Breeding Program, Mount Vernon, WA.
[b] Sourced from Justin Seed Co., Justin, TX.
[c] Sourced from Bailey Seed Co., Salem, OR.
[d] Sourced from ProGene Plant Research, Othello, OR.

time on 27 April 2015. Till plots were cultivated twice in the first year of the experiment, on 9 June and 17 August 2015. On 22 September 2015, the annual cover crop treatments and the Mow and Till treatments were terminated and alleyways were subsoiled and cultivated by the grower. The perennial treatment, grass mix 1, was left intact for the second year of the experiment. The raspberry floricanes were pruned and the canes were flail-mowed and then incorporated into the alleyways by the grower on 5 October 2015. In year 2, cover crops were seeded at the same rates as in year 1 on 8 October 2015 using a custom-made double-disc planter with a cone seeder that seeded seven rows with 15 cm spacing. The cover crop and Mow treatments were mowed once in year 2 on 13 May 2016. Till plots were cultivated on 20 May 2016 and again on 27 July. Treatments were not irrigated or fertilized throughout the duration of the experiment. The experiment was terminated on 15 August 2016.

Population densities of *P. penetrans* in alleyway treatments and adjacent raspberry beds were determined in the Spring and Fall of 2015 (year 1) and 2016 (year 2). To determine *P. penetrans* population densities in the soil, four cores, 2.5 cm diam. and 20 cm deep, were collected and combined from each side of the bed within 15 cm of the raspberry crown and from both alleyways adjacent to the bed; soil cores from the bed were kept separate from alleyway soil cores. To determine *P. penetrans* population densities in roots, roots from the raspberry crop were collected from three randomly selected raspberry plants in the beds, and roots from the cover crop treatments were collected from four locations in the alleyways using a square-blade shovel (15 cm^3 core). All samples were placed in a cooler and transported to the laboratory for *P. penetrans* extraction and quantification. Mixed stages of *P. penetrans* were extracted from a 50 g subsample of soil using the Baermann funnel extraction method (Ayoub, 1980). *Pratylenchus penetrans* were collected after 5 d. For *P. penetrans* extraction from roots, roots ≤2 mm in diameter were preferentially selected, rinsed free of soil, and placed under intermittent mist for 5 d (Ayoub, 1980). Extracted roots were oven-dried for 1 wk at 70°C and then weighed. *Pratylenchus penetrans* collected from soil and roots were identified and counted using a stereoscope at ×40 magnification. The nematodes were identified as *P. penetrans* based on morphology as well as the presence of males, a diagnostic trait for this species (Castillo and Vovlas, 2007). Population densities are expressed as number of *P. penetrans*/100 g of soil or number of *P. penetrans*/g of root.

Fruit was mechanically harvested from late June to mid-July in 2015 and early June to early July in 2016 by the grower. To estimate yield, a modified version of the yield estimation methodology developed by Daubeny (1986) was conducted on the raspberry crop in June of each year. Three raspberry plants per treatment plot were randomly selected and the total cane number from each plant were counted and averaged. The number of laterals on two canes from each of the selected plants were counted and averaged. Then, the fruit, including buds, flowers, and green fruit on two laterals in five different fruiting zones in the raspberry canopy were counted and averaged. These means were multiplied along with the number of plants/ha, average berry weight (described below), and a yield loss correction factor which took into account potential yield loss due to mechanical harvesting. Early-, mid-, and late-season ripe raspberry fruit collection occurred on 26 June, 7 July, and 16 July in year 1 and on 14 June, 21 June, and 5 July 2016 in year 2, respectively. At each sampling date, 30 fruit were randomly selected from each treatment plot, weighed, and frozen for future total soluble solids (TSS) analysis. To perform TSS analysis, the fruit from each treatment plot and time point was crushed in a sample mesh bag (Agdia®, Inc., Elkhart, IN) and the juice was strained out into a test tube. Three drops of juice were placed on a digital refractometer (Palm Abbe digital refractometer, Model #PA201; MISCO, Solon, OH) for each measurement. Juice from each treatment plot and time point was analyzed three times, the value of each was recorded, and the mean of the three values was calculated.

All data were subjected to statistical analysis using Statistical Analysis System software (Version 9.3; SAS Institute Inc., Cary, NC). Alpha was set at 0.05 for all data. All raspberry root and soil data were subjected to a Dunnett's t-test, comparing all other treatments to Till. Raspberry root and soil data were compared across all four sampling dates. The cover crop soil data within each sampling date were analyzed using a Dunnett's t-test. The cover crop root data were analyzed using an analysis of variance with Tukey as the post hoc test, instead of a Dunnett's t-test, because there was no root data for the Till control (no roots were present). Annual cover crops were only compared within year (spring and fall sampling dates). The perennial treatments, Till and grass mix 1, were compared across all four sampling dates. To compare across sampling dates, repeated measures were used for both raspberry plant and cover crop data. Much of the nematode data had unequal variance. When this occurred, means were transformed by log $(x + 10)$ and reanalyzed. All data are presented with original means, even when transformations were performed.

Greenhouse evaluation of cover crops as hosts for P. penetrans*:* Host assay experiments were conducted at the WSU-NWREC, Mount Vernon, WA, to determine the host suitability of the cover crops used in the field trial (Table 1) as well as *B. juncea* 'Pacific Gold' and *S. alba* 'Ida Gold' for *P. penetrans*. 'Meeker' raspberry was included in the experiments as a positive control. The assays were conducted in a greenhouse and treatments were arranged in a completely randomized design on a bench; treatments were replicated six times. Lynnwood sandy loam soil, collected from a raspberry field in Lynden, WA, was used for all assays. The soil was sieved through a 4-mm mesh sieve and homogenized using a cement mixer. Six subsamples of 50 g of soil were collected and *P. penetrans* population densities determined as described earlier; no *P. penetrans* were found in the soil. Two pots sizes were used in the assays; 656 ml (6.4 cm diam. and 25.4 cm height; D40H, Stuewe & Sons, Inc., Tangent, OR) and 2.6 liter (14 × 14 × 15 cm; McConkey & Co., Sumner, WA) pots.

In the first experiment (host assays 1 and 2), all the cover crop species used in the field trial and the two mustard cover crops were seeded into the 656 ml pots (Table 1). The cover crops were overseeded and then thinned to one plant before inoculation. A single tissue culture 'Meeker' raspberry (Northwest Plant Co., Ferndale, WA) was planted per pot. In host assay 1, plants were inoculated 14 d after seeding. To obtain inoculum, raspberry roots were collected from the field trial as described earlier and *P. penetrans* were collected under intermittent mist for 5 d as described earlier. In host assay 1, the 656 ml pots were inoculated with 626 *P. penetrans* in 3.5 ml of water, corresponding to approximately 2 *P. penetrans*/g of soil. Two holes, 5-cm deep, were made on either side of the plant and the *P. penetrans*-water suspension was added to the root zone. The pots were kept in the greenhouse for the duration of the assay at 21 to 24°C with supplemental lighting to provide a 16-hr photoperiod. Pots were watered once daily and fertilized once weekly with 20N–20P–20K dissolvable fertilizer (Jack's Classic All Purpose; JR Peters Inc., Allentown, PA). The mustards were terminated 59 d after inoculation because of bolting. The remaining plants were terminated 72 d after inoculation. At assay termination, shoots were cut at soil level and discarded. The remaining contents of the pots were then separated into roots and soil for *P. penetrans* extraction as described earlier. Host assay 2 was conducted using the same methods as described for host assay 1. Inoculation of cover crops occurred 22 d after seeding. Pots were inoculated with 918 *P. penetrans* in 3.5 ml of water. This inoculation density corresponded to 2 *P. penetrans*/g of soil. The 'Ida Gold' and 'Pacific Gold' mustards were terminated 24 d after inoculation because of bolting. The rest of the plants were terminated 69 d after inoculation. Data collection for assay 2 was as described for assay 1.

In the second experiment (host assays 3 and 4), the grass mixes 1 and 2 were seeded at a rate of 1 g of seed/pot in the 2.6 liter pots and were not thinned. A single tissue culture 'Meeker' raspberry was planted per pot. In host assay 3, the soil in the pots was inoculated with 1,969 *P. penetrans* in 11 ml of water per pot, corresponding to 1 *P. penetrans*/g of soil 14 d after seeding. Four holes were made in the soil around the plant and the *P. penetrans*-water suspension was added to the root zone. Plants were terminated 72 d after inoculation. Host assay 4 was similar to host assay 3 with a few exceptions. Inoculation of cover crops occurred 22 d after seeding with 3,231 *P. penetrans* in 12.4 ml per pot. This inoculation density corresponded to 2 *P. penetrans*/g of soil. The plants were terminated 69 d after inoculation. Greenhouse conditions, plant maintenance, and data collection for host assays 3 and 4 was as described for host assay 1.

The reproductive factor (RF) value was calculated for each pot by dividing the final population of *P. penetrans* recovered from roots and soil by the initial inoculation population of *P. penetrans* (Oostenbrink, 1966). The results from the host assays were different, therefore, they were analyzed separately. All data were subjected to statistical analysis using statistical analysis system. Alpha was set at 0.05 for all data. Data were initially subjected to analysis of variance with Tukey as the post hoc test. Much of the data had unequal variance. When this occurred, means were transformed using log $(x + 10)$ and reanalyzed. Certain data that did not meet all the assumptions of analysis of variance were analyzed using a Kruskal–Wallis nonparametric test. All data are presented with original means, even when transformations were performed.

Results

Evaluation of alleyway cover crops in an established raspberry field: In both years of the study, cover crops germinated and emerged by 1 November. Stand and alleyway coverage were consistent and persisted into the spring. Annual cover crops began to senesce in late July, whereas grass mixes 1 and 2 remained green and continued to grow. In the first year of evaluating the cover crops in the field, although there was obvious numeric variability among the treatments, there were no significant differences for *P. penetrans* per gram of cover crop root (Table 2) in the Spring of 2015, the first spring after seeding. The 'Norwest' wheat and cereal rye treatments had *P. penetrans* densities 20 times greater than 'Rosalyn' wheat, which was the annual treatment with the lowest density. No *P. penetrans* were found in grass mix 1 roots; it was the only alleyway treatment to not have *P. penetrans* recovered from its roots. In the alleyways, the 'Nora' oat treatment had the highest density of *P. penetrans* per 100 g of soil. Population densities of *P. penetrans* in 'Nora' oat (116 ± 40 *P. penetrans*/100 g of soil) were significantly different than in Till (2 ± 2 *P. penetrans*/100 g of soil) at this sampling date and approximately twice as high as the treatment with the next highest density, grass mix 2 (61 ± 40 *P. penetrans*/100 g of soil). In the Fall of 2015, almost 1 yr after seeding, while there were no statistically significant differences among treatments, grass mix 1 continued to support low *P. penetrans* per gram of root, with only grass mix 2 having fewer *P. penetrans* per gram of root (Table 2). There were also no significant differences in *P. penetrans* population densities in alleyway soil comparing all other treatments to Till. There were 0 *P. penetrans*/100 g soil in grass mix 1, 'Trical 103BB' triticale, and 'TriMark 099' triticale alleyway soil samples. The Till treatment had the fourth highest average density of *P. penetrans* in soil (16 ± 6 *P. penetrans*/100 g of soil), 1 yr after treatment establishment.

In the second year of evaluating the annual cover crops in the field, in the Spring of 2016 (the first spring after the second seeding), 'Trical 103BB' triticale, 'TAM 606' oat, and 'Rosalyn' wheat supported low *P. penetrans* densities per gram of root (Table 2). During this year, grass mix 1 was considered a perennial cover crop treatment because it was maintained (no tillage) throughout the duration of the experiment. In year 2, grass mix 1 continued to support low densities of *P. penetrans* in roots, and the mean density was not significantly different from the annual cover crops or industry standard Till (Table 2). In the corresponding alleyway soil samples from this sampling date, there were no significant differences between Till (5 ± 1 *P. penetrans*/100 g of soil) and all other treatments (0 to 14 *P. penetrans*/100 g of soil); *P. penetrans* population densities were low in all treatments (data not shown). In the Fall of 2016, 1 yr after the second seeding, cereal rye had the highest *P. penetrans* density per gram of root and was nearly twice the density of the treatment with the next largest density, 'TAM 606' oat (Table 2). The grass mix 1 treatment had the lowest *P. penetrans* population density. Population densities of *P. penetrans* in alleyway soil were not significantly different between Till (55 ± 55 *P. penetrans*/100 g of soil) and all other treatments (3 to 88 *P. penetrans*/100 g of soil). The perennial cover crop, grass mix 1, was the only treatment that consistently supported extremely low densities of

Table 2. *Pratylenchus penetrans* population densities over a 2-yr period from cover crops roots in alleyways adjacent to raised beds of raspberry (*Rubus idaeus*) in Lynden, WA.

	P. penetrans/g of cover crop root							
Treatment[a]	Spring 2015		Fall 2015		Spring 2016		Fall 2016	
Till (industry standard)	-		-		-		-	
Mow	-		-		-		-	
Cereal rye	292 ± 280[b]		325 ± 286		220 ± 383		830 ± 554	
Oat 'Nora'	31 ± 31		253 ± 202		325 ± 251		378 ± 246	
Oat 'TAM 606'	187 ± 187		503 ± 498		84 ± 131		439 ± 263	
Triticale 'Trical 103BB'	68 ± 49		447 ± 443		12 ± 20		340 ± 335	
Triticale 'TriMark 099'	39 ± 39		39 ± 22		352 ± 632		77 ± 53	
Wheat 'Norwest 553'	297 ± 256		336 ± 329		371 ± 434		282 ± 195	
Wheat 'Rosalyn'	14 ± 14	B[c]	81 ± 38	A	94 ± 54		228 ± 90	
Grass mix 1 (perennial)	0	B	5 ± 3	B	44 ± 43	A	8 ± 5	B
Grass mix 2 (annual)	88 ± 81		1 ± 1		341 ± 666		52 ± 50	
Overall mean[d]	108		221		205		293	

[a] Treatment abbreviations: Till = control bare cultivated soil, Mow = control weedy mow, Grass mix 1 = intermediate and tetraploid perennial ryegrass mix, Grass mix 2 = perennial ryegrass mix.

[b] Values are the mean of 4 replications ± SE.

[c] Values followed by the same uppercase letter in the same row are not significantly different from one another at $P \leq 0.05$. Annual treatment means were compared within year; perennial treatment means were compared across all four sampling dates.

[d] The overall mean is an average of all the *P. penetrans* population densities in all cover crops in each season.

P. penetrans in its roots and surrounding soil throughout the 2 yr of the study.

There was a treatment by season interaction for *P. penetrans* population densities per gram of root for 'Rosalyn' wheat in the first year of the study (Table 2), with significantly higher *P. penetrans* densities in the fall compared with the spring; those differences did not persist into the second year. In the alleyway soil, 'Nora' oat had significantly higher densities of *P. penetrans* (116 ± 40 *P. penetrans*/100 g of soil) in the Spring of 2015 compared with all other seasons (3 to 42 *P. penetrans*/100 g of soil). The 'TriMark 099' triticale treatment had significantly higher *P. penetrans* densities in the Fall of 2016 (9 ± 5 *P. penetrans*/100 g of soil) compared with all other sampling dates (0 *P. penetrans*/100 g of soil). Across sampling dates in the perennial cover crop grass mix 1, the *P. penetrans* population density in roots was significantly higher in the Spring of 2016 compared with all other sampling dates (Table 2).

In the Spring of 2015, raspberry plants grown in raised beds adjacent to alleyways seeded with cover crops or residential weeds (Mow) did not have significantly higher *P. penetrans* population densities compared with raspberry plants grown adjacent to cultivated, bare soil (Till; Table 3). There were also no significant differences between Till and all other treatments for *P. penetrans* population densities in bed soil surrounding roots (2 to 203 *P. penetrans*/100 g of soil). This trend continued in both raspberry roots and soil for the duration of the study; there were no significant differences between Till and all other treatments at any sampling date (Table 3).

There was also a treatment by season interaction in the *P. penetrans* population densities of raspberry roots growing adjacent to Mow, cereal rye, grass mix 1, 'TAM 606' oat, 'Trical 103BB' triticale, and 'Rosalyn' wheat alleyways (Table 3). In general, population densities in the Fall of 2015 were significantly higher compared to *P. penetrans* population densities in the other seasons for all of the previously mentioned treatments. In addition, there was a trend across treatments that the *P. penetrans* population densities in raspberry roots in all treatments were lower at the end of year 2 (Fall 2016) than at the end of year 1 (Fall 2015). A treatment by season interaction was also observed in raised bed soil adjacent to cereal rye, 'Nora' oat, 'TAM 606' oat, and 'TriMark 099' triticale alleyways. Similar to observations for root *P. penetrans* populations, *P. penetrans* soil population densities in the raised beds generally declined over the course of the experiment with densities being the highest in the Fall of 2015 (128 to 355 *P. penetrans*/100 g of soil) and lowest in the Fall of 2016 (14 to 438 *P. penetrans*/100 g of soil). The exception to this was Till and 'Norwest 553' wheat. Densities of *P. penetrans* for both treatments were higher in the Fall of 2016 (438 ± 320 and 270 ± 95 *P. penetrans*/100 g of soil, respectively) than the Fall of 2015 (273 ± 23 and 165 ± 60 *P. penetrans*/100 g of soil, respectively), but differences were not significant.

There were no significant differences in estimated fruit yield in either year between Till and all other treatments (data not shown). Yield from raspberry plants growing adjacent to industry standard Till alleyways did not have the highest mean yield in either year (23.6 ± 3.0 t/ha in 2015, 19.5 ± 4.4 t/ha in 2016). Raspberry grown adjacent to 'Rosalyn' wheat alleyways had the highest mean yield in 2015 (23.7 ± 1.9 t/ha), whereas raspberry in 'TAM 606' oat plots had the highest mean yield in 2016 (23.4 ± 1.5 t/ha). There were also no significant differences in measured TSS in either summer of the study (data not shown). In 2015, fruit collected from raspberry adjacent to 'TriMark 099'

Table 3. *Pratylenchus penetrans* population densities over a 2-yr period from raspberry (*Rubus idaeus*) roots adjacent to alleyways with annual and perennial cover crops in Lynden, WA.

	P. penetrans/g of raspberry root							
Treatment[a]	Spring 2015		Fall 2015		Spring 2016		Fall 2016	
Till (industry standard)	4,847 ± 1,639[b]		5,536 ± 1,185		3,286 ± 424		2,391 ± 566	
Mow	2,319 ± 1,254	B[c]	6,120 ± 986	A	2,277 ± 397	B	1,861 ± 178	B
Cereal rye	3,915 ± 1,257	AB	5,616 ± 744	A	1,799 ± 431	B	1,976 ± 432	B
Oat 'Nora'	2,372 ± 571		3,255 ± 1,850		2,211 ± 701		2,931 ± 689	
Oat 'Tam 606'	3,020 ± 863	B	5,750 ± 870	A	2,546 ± 521	B	4,462 ± 603	AB
Triticale 'Trical 103BB'	2,294 ± 780	AB	4,175 ± 862	A	4,037 ± 742	A	1,331 ± 568	B
Triticale 'TriMark 099'	5,005 ± 765		4,309 ± 1,137		2,703 ± 1,004		3,084 ± 595	
Wheat 'Norwest 553'	2,884 ± 555		4,879 ± 1,796		1,677 ± 580		2,516 ± 817	
Wheat 'Rosalyn'	2,596 ± 354	AB	4,320 ± 703	A	1,081 ± 217	B	2,919 ± 1,009	AB
Grass mix 1 (perennial)	5,112 ± 853	A	5,205 ± 1,126	A	2,192 ± 334	B	3,857 ± 846	AB
Grass mix 2 (annual)	3,176 ± 1,180		5,192 ± 1,796		4,298 ± 384		3,166 ± 1,658	
Overall mean[d]	3,432	B	4,941	A	2,555	C	2,796	BC

[a] Treatment abbreviations: Till = control bare cultivated soil, Mow = control weedy mow, Grass mix 1 = intermediate and tetraploid perennial ryegrass mix, Grass mix 2 = perennial ryegrass mix.
[b] Values are the mean of 4 replications ± SE.
[c] Values followed by the same uppercase letter in the same row are not significantly different from one another at $P \leq 0.05$.
[d] Overall mean is the average of all the *P. penetrans* population densities in cover crop roots within each season.

triticale alleyways had the highest TSS (11.1 ± 0.2 °Brix). Fruit collected from raspberry adjacent to grass mix 1 alleyways had the highest TSS in 2016 (12.0 ± 0.2 °Brix). The TSS in 2016 was significantly higher across all treatments compared with 2015 (data not shown).

Greenhouse evaluation of cover crops as hosts for P. penetrans*:* Data from the host assay experiments are presented separately. In host assay 1, 'Pacific Gold' mustard had the highest *P. penetrans* per gram of root and also the highest RF value (Table 4). However, the number of *P. penetrans* per gram of root for 'Pacific Gold' mustard was not significantly greater than that of 'Ida Gold' mustard or either oat cultivar. The RF value for 'Pacific Gold' mustard was significantly higher than all other treatments with the exception of cereal rye and 'Nora' oat. The cover crops 'TriMark 099' triticale and 'Norwest' wheat had RF values less than 1.0, but were not significantly different than those of 'TAM 606' oat, 'Trical 103BB' triticale, 'Rosalyn' wheat, and the raspberry control. The cover crops 'Nora' oat, 'TAM 606' oat, 'Pacific Gold' mustard, and 'Ida Gold' mustard all had significantly higher *P. penetrans* densities per gram of root compared with the raspberry control and cereal rye. 'Nora' oat and 'Pacific Gold' mustard had significantly higher RF values than the raspberry control.

In host assay 2, all treatments performed similarly to host assay 1 when comparing their host suitability relative to each other, with the exception of 'TriMark 099' triticale. The 'TriMark 099' triticale cover crop had the lowest mean *P. penetrans* per gram of root in host assay 1, but had the 5th highest *P. penetrans* density in host assay 2. The RF value for 'TriMark 099' triticale also reflected this change. In host assay 1, it had the lowest RF value, but in host assay 2 it had the 4th highest RF value. Similar to host assay 1, 'Norwest' wheat had a low mean *P. penetrans* per gram of root (Table 4) in host assay 2, but it was only significantly lower than 'Nora' oat, 'TAM 606' oat, and 'Ida Gold' mustard. The 'Norwest' wheat cover crop was the only cover crop to have a RF value less than 1.0 in host assay 2 (Table 4), and the RF value was significantly lower than that of cereal rye, 'Nora' oat, and 'TAM 606' oat. The only cover crops to have significantly higher densities of *P. penetrans* per gram of root than the raspberry control were 'Nora' and 'TAM 606' oats, whereas the cereal rye and 'TAM 606' oat cover crops were the only cover crops to have significantly higher RF values compared with the raspberry control.

In host assay 3, grass mix 1 and 2 had significantly lower densities of *P. penetrans*/g of root and RF values compared with the raspberry control. Both of these cover crops had RF values < 1.0 (Table 5). In host assay 4, grass mix 2 performed similarly to host assay 3, with the lowest mean *P. penetrans* per gram of root and RF value (Table 5) and was significantly lower than that of grass mix 1 and the raspberry control. The grass mix 2 was the only species to have an RF value less than 1.0.

The cover crop mean root weights rankings relative to each other were consistent across the assays. In general, the root weights were larger in host assay 2 than in host assay 1 (Table 4). The 'Pacific Gold' and 'Ida Gold' mustards had the smallest root weights in both assays. The 'Nora' and 'TAM 606' oat cover crops had the 7th and 8th, respectively, largest root systems in host assay 1 and were tied for 7th in host assay 2. Raspberry, 'Norwest' wheat, and 'Rosalyn' wheat were ranked in the middle in both assays. The cover crops cereal rye and 'TriMark 099' triticale had heavy root weights in both assays. The only exception was 'Trical 103BB' triticale which was ranked 2nd for the largest root system in host assay 1, but had a much smaller root weight in host assay 2.

Discussion

The current industry practice in PNW raspberry production is to maintain bare, cultivated soil in the

Table 4. Host status of cover crops for *Pratylenchus penetrans* in greenhouse host assays conducted in Mount Vernon, WA.

	Host assay 1						Host assay 2					
Treatment	*P. penetrans*/g of root		Root weight (g)		RF[a]		*P. penetrans*/g of root		Root weight (g)		RF	
Cereal rye	743 ± 196	bc[b]	1.26 ± 0.09	ab	2.04	ab	1,070 ± 359	ab	2.00 ± 0.11	a	2.59	a
Oat 'Nora'	1,936 ± 678	ab	0.51 ± 0.12	cd	1.99	ab	2,392 ± 184	ab	0.75 ± 0.06	efg	2.30	ab
Oat 'TAM 606'	3,226 ± 1,093	ab	0.36 ± 0.10	d	1.37	bc	3,393 ± 991	a	0.75 ± 0.12	def	2.39	a
Triticale 'Trical 103BB'	1,424 ± 702	bc	1.27 ± 0.36	ab	1.70	ab	718 ± 168	b	0.95 ± 0.08	cde	0.79	c
Triticale 'TriMark 099'	276 ± 50	c	1.47 ± 0.07	a	0.66	b	1,113 ± 339	ab	1.86 ± 0.21	ab	2.07	ab
Wheat 'Norwest 553'	656 ± 231	bc	0.78 ± 0.17	bcd	0.70	b	417 ± 236	b	1.29 ± 0.25	bcde	0.46	c
Wheat 'Rosalyn'	1,338 ± 491	bc	0.62 ± 0.12	bcd	1.10	ab	874 ± 340	b	1.37 ± 0.23	abcd	1.02	c
Mustard 'Pacific Gold'	5,212 ± 768	a	0.20 ± 0.01	d	2.84	a	1,705 ± 841	ab	0.30 ± 0.04	gf	1.03	c
Mustard 'Ida Gold'	2,832 ± 884	ab	0.18 ± 0.02	d	1.78	ab	2,060 ± 771	ab	0.20 ± 0.04	g	1.09	c
Raspberry 'Meeker'	627 ± 150	bc	1.17 ± 0.05	abc	1.53	ab	744 ± 189	b	1.44 ± 0.06	abc	1.33	bc

[a] RF = Reproductive factor (final population density/initial inoculum). In host assay, 1, 656 ml pots were inoculated with 626 *P. penetrans*/pot. In host assay 2, 656 ml pots were inoculated with 918 *P. penetrans*/pot.

[b] Values are the mean of 6 replications ± SE. Values followed by the same lowercase letter in the same column are not significantly different from one another at $P \leq 0.05$.

TABLE 5. Host status of cover crops for *Pratylenchus penetrans* in greenhouse host assays conducted in Mount Vernon, WA.

Treatment[a]	Host assay 3						Host assay 4					
	P. penetrans/g of root		Root weight (g)		RF[b]		*P. penetrans*/g of root		Root weight (g)		RF	
Grass mix 1	108 ± 17	b[c]	8.19 ± 0.35	a	0.57	b	263 ± 50	b	10.60 ± 0.92	a	1.10	b
Grass mix 2	62 ± 10	c	8.39 ± 0.33	a	0.50	b	123 ± 28	c	10.95 ± 0.43	a	0.50	c
Raspberry 'Meeker'	910 ± 165	a	2.08 ± 0.19	b	1.51	a	1,402 ± 309	a	2.31 ± 0.30	b	1.97	a

[a] Treatment abbreviations: Grass mix 1 = 51.25% 'Tetralite', 48.24% 'Kentaur', an intermediate and tetraploid perennial ryegrass mix (*Lolium hybridum, Lolium perenne*); Grass mix 2 = 3.93% 'Esquire', 31.44% 'TopHat 2', 22.49% 'Tetragreen', a perennial ryegrass mix (*L. perenne*).
[b] RF = reproductive factor (final population density/initial inoculum). In host assay 3, 2.6 liter pots were inoculated with 1,969 *P. penetrans*/pot. In host assay 4, 2.6 liter pots were inoculated with 3,231 *P. penetrans*/pot.
[c] Values are the mean of six replications ± SE. Values followed by the same lowercase letter in the same column are not significantly different from one another at $P \leq 0.05$.

alleyways between raspberry beds. This practice, referred to as Till in this study, did not perform better than any of the cover crop treatments. The presence of annual and perennial alleyway cover crops did not increase *P. penetrans* population densities in the alleyways or in adjacent raspberry plants compared with the industry standard. This was evident when comparing population densities of *P. penetrans* in raspberry roots (2,555 to 4,941 *P. penetrans*/g root when averaged across treatments) with those in cover crop roots (108 to 293 *P. penetrans*/g root when averaged across cover crops). These results are similar to what was previously observed by Vrain et al. (1996). In this study, cover crops that were poor hosts for *P. penetrans* did not affect *P. penetrans* population densities in adjacent 'Willamette' raspberry roots and soil, positively or negatively. The lack of significant results in our study confirms this as well in 'Meeker' raspberry, which is one of the most widely planted raspberry cultivars in the PNW (Moore and Daubeny, 1993; Pacific Northwest Extension, 2007). Low population densities of *P. penetrans* in alleyway soil were also observed, both in soil with cover crops growing (9 to 26 *P. penetrans*/100 g of soil) and bare cultivated soil (2 to 55 *P. penetrans*/100 g of soil). Similar population densities in soil were observed in a study comparing broadcast fumigation with bed fumigation in the raspberry production system (Walters et al., 2017); population densities of *P. penetrans* ranged from 3 to 174 *P. penetrans*/100 g of soil at three different field sites.

Raspberry was a superior host relative to the alleyway cover crops in the field environment, whereas in the greenhouse host assays many of the cover crops were better hosts for *P. penetrans* than raspberry. This difference may be attributed to the fact that except for grass mixes 1 and 2, all of the cover crops are annuals and naturally senesced during the summer. However, even in the spring, well before senescence, none of the cover crops were particularly good hosts for *P. penetrans* in the field, especially when population densities were compared with those on raspberry. Under controlled conditions in the greenhouse, cereal rye, 'Nora' oat, and 'TAM 606' oat were consistently good hosts (RF > 1), 'Norwest' wheat and grass mix 2 were consistently poor hosts (RF < 1), and 'Rosalyn' wheat and 'Trical 103BB' triticale were maintenance hosts (RF = 1). Differences in observed host suitability of cover crops for *P. penetrans* in the field and greenhouse assays may be attributed to the harsh environment in the alleyways of raspberry fields. This area of the raspberry field does not receive supplemental irrigation, only rainfall. In northern WA, whereas the winter is very wet, the summer can be dry with average rainfall from June to August of approximately 90 mm. However, the rainfall in the 3 yr during which this study was conducted was far less than the average. The total rainfall from 1 June to 31 August in 2014, 2015, and 2016 was 50.3, 31.24, and 68.33 mm, respectively (WSU AgWeatherNet, 2017a, 2017b, 2017c). In addition to lack of moisture, the alleyway can become very compacted because of repeated movement of equipment to apply pesticides and conduct mechanical harvest. In fact, the 15-cm area closest to the raspberry beds is so compacted and experiences so much tire traffic that resident weeds do not grow there. This was the case in the field where our study was conducted. These factors combined may make alleyways between raised raspberry beds an unsuitable environment for *P. penetrans* to survive and reproduce and may explain the lack of impact the cover crops had on the raspberry crop.

To our knowledge, this is the first time that many of these cover crop cultivars have been tested as suitable hosts for *P. penetrans*. Whether suitable or poor hosts, this is important information to have when planting cover crops in soil with a history of *P. penetrans*. The results of our greenhouse host assays were consistent with the results observed by Thies et al. (1995) in a controlled environment. Several forage grasses were evaluated in the greenhouse for 6 wk, including 'Starter' oat, 'Marshall' wheat, 'NK-200' perennial ryegrass, and generic cereal rye for their host suitability for *P. penetrans*. Based on the presented data, oat and cereal rye were extremely good hosts with RF values of 3.5 and 5.4, respectively. Wheat and perennial ryegrass were poor hosts with RF values less than 1.0. In two greenhouse studies, Forge et al. (2000) evaluated the host suitability of winter cover crops, including 'Wheeler' rye, 'Saia' oat, and 'Amity' oat for *P. penetrans*. After growing for 10 wk, 'Wheeler' rye and 'Saia' oat were maintenance hosts for *P. penetrans*, with RF values at 0.97 and 0.96, respectively. The RF value for 'Amity' oat was slightly less, 0.90, making it a less suitable host. The same study was performed again, but cover crops were left to grow for 20 wk. After 20 wk, 'Wheeler' rye and 'Amity' oat were very good hosts with RF values of 4.4 and 2.5, respectively. 'Saia' oat was still only a maintenance host with an RF value of 1.2. However, 'Saia' oat is not an equal comparison to 'Nora' and 'TAM 606' oats in our study because it is a different species, *A. strigosa* not *A. sativa* (Dial, 2014). In addition, 'Saia' oat was determined to be a suitable host in a field study (Vrain et al., 1996). In another greenhouse study, the host suitability of 'Aubade' perennial ryegrass, 'Musketeer' rye, and 'Ultima' oats for *P. penetrans* was evaluated (Bélair et al., 2002). All three cover crops were confirmed as very good hosts with RF values of 8.4, 9.0, and 5.7, respectively. All these greenhouse studies confirm that different cultivars within the same crop species may vary in their host suitability for *P. penetrans*. The duration of an experiment and the inoculum size are important factors in crop response. In general, however, the results of the previous studies support our findings; oat and cereal rye are good hosts for *P. penetrans*, wheat can either be a poor host or maintenance host, and perennial ryegrass is a poor host.

Although host suitability is an important factor for growers to consider, the effect a cover crop has on the cash crop yield is their primary concern. In our study, cover crop treatments did not negatively affect yield or fruit quality in either year of our study. In raspberry, alleyway management comparing bare soil, oats, and timothy grass (*Phleum pretense* L.) did not significantly affect raspberry fruit weight or cane diameter (Sanderson and Cutliffe, 1988), although raspberry cane diameter was numerically lowest in the timothy grass plots. Over the 4 yr of the study, the same yield trends were observed across treatments; yield was highest in the second year and lowest in the fourth year. Throughout the 4 yr, overall yield of raspberry adjacent to timothy grass was significantly lower than bare soil and oats. The yield of raspberry adjacent to oats was the highest throughout the study, but was not significantly higher than the bare soil treatment. An opposing trend was observed in 'Willamette' raspberry grown adjacent to alleyways with bare soil or perennial ryegrass over 5 yr (Bowen and Freyman, 1995). Fruit yield, cane height, and cane diameter over 5 yr between bare soil alleyways and alleyways planted to perennial ryegrass were significantly higher in raspberry adjacent to bare soil than raspberry adjacent to perennial ryegrass.

In a 2-yr study of raspberry in two locations, 'Willamette' raspberry was again grown adjacent to bare soil or perennial ryegrass alleyways (Freyman, 1989). In location 1, perennial ryegrass was established in a newly established raspberry planting, and reduction in cane diameter in the first year and cane diameter and height over the second year were observed in plants grown in areas with perennial ryegrass compared with bare soil. In the first year of the study at location 1, there were no significant differences in yield. However, in the 2nd year, raspberry adjacent to the bare soil control had significantly higher mean yield than that of perennial ryegrass. In location 2, however, the treatments were established in a 4-yr-old raspberry planting and perennial ryegrass did not reduce cane diameter compared with bare soil. In both years at location 2, raspberry adjacent to the bare soil alleyway had higher yields than raspberry growing adjacent to perennial ryegrass. Vrain et al. (1996) did not report fruit yield or fruit quality, but instead fruiting cane count, biomass, height, and diameter of 'Willamette' raspberry grown adjacent to a bare soil control or various cover crops, including 'Saia' oats. Plants adjacent to the bare soil control had higher fruiting cane mass, height, and diameter, but not fruiting cane count or total mass per plot than 'Saia' oat. Because of the differing ways in which the data were collected and reported in previous studies, it is difficult to make an equivalent comparison to the results in our study. With the exception of Vrain et al. (1996), none of the previous studies comparing alleyway cover crop effects on raspberry yield also included a *P. penetrans* component. All of these studies took place in British Columbia where *P. penetrans* is also extremely common in raspberry (McElroy, 1972; Vrain et al., 1996). British Columbia is often considered part of the PNW in terms of climate, soil type, and crop production. There could have been a *P. penetrans* effect that was not taken into account in many of these studies.

There are also other benefits than just yield which growers may consider when deciding to implement alleyway cover crops. In various production systems, the maintenance of cover crops has been shown to be more economical as compared to repeated tillage (Archer et al., 2007; Sánchez-Girón et al., 2007; Bernstein et al., 2011), especially over the long term. There is also the benefit of decreased soil erosion and increased soil organic matter (Milgroom et al., 2005), which can improve soil quality. In addition, growers may find that mowing the alleyways is simply easier than cultivating from both an equipment and logistics perspective; smaller, cheaper equipment that can maneuver more quickly through the alleyways could reduce cost, time, and labor compared with tillage (Reberg-Horton et al., 2011). Alleyway cover crops can improve soil drainage which may help mitigate standing water in the alleyways, thus allowing growers to enter their fields with machinery earlier in the spring.

The biggest limitation of this study was that it was a 2-yr experiment with a perennial crop that can be in production for at least 5 yr. This study also began during the third year of production. Results may have been different if cover crops had been seeded during the first year of establishment or if the study had been continued for additional years, as in the case of the study conducted by Freyman (1989). However, implementing alleyway cover crops once the raspberry crop has been established may have eliminated the resource competition aspect and may have been responsible for the lack of differences in yield among the treatments. This may be a strategy that growers wish to use—seeding cover crops 1 yr after planting a new raspberry crop.

This study supports the implementation of alleyway cover crops in red raspberry production in the PNW. The potential physical and chemical soil quality benefits in addition to the potential economic and labor advantages outweigh the perceived risks. Our results demonstrate that alleyway cover crops did not affect yield, fruit quality, or *P. penetrans* population densities in raspberry roots and soil, compared with the current industry-standard practice of repeatedly cultivated bare soil alleyways. The use of alleyway cover crops did not increase alleyway *P. penetrans* population densities either. Alleyways do not appear to be a hospitable environment for *P. penetrans* reproduction possibly because of soil compaction and lack of irrigation and fertilization of cover crops. Results varied from season to season within and across the treatments, but the bare cultivated soil control (Till) was consistently not superior to the cover crop treatments. Future studies should examine the effects of cover crops in raspberry alleyways over a longer period of time and also the effects when planted adjacent to other raspberry cultivars of different maturities.

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