Post-Plant Nematicides for the Control of Root Lesion Nematode in Red Raspberry

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Summary. To identify a post-plant nematicide to control root lesion nematode [RLN (*Pratylenchus penetrans*)] in red raspberry (*Rubus idaeus*), a number of nematicides was tested in soil-only and plant-based experiments. In soil-only experiments, soil naturally infested with RLN was drenched with the nematicides and nematode survival was assessed 7 and 14 days after treatment. Fosthiazate and oxamyl reduced RLN recovery 92% and 52% across trials and sampling times, respectively, compared with the nontreated control. Other nematicides that resulted in moderate, and sometimes inconsistent, control of RLN were soapbark (*Quillaja saponaria*) saponins, 1,3-dichloropropene, and methomyl. In plant-based experiments, 'Meeker' red raspberry was established in pots with RLN-infested soil mixed with greenhouse soil and the nematicides were applied as soil drenches or as a foliar application. Nematode recovery and cane and root weights were quantified as measurements of nematicide toxicity and phytotoxicity, respectively. Similar to soil-only experiments, fosthiazate and oxamyl were the most effective nematicides tested in reducing RLN population densities in established red raspberry. Fosthiazate and oxamyl significantly reduced RLN per gram dry root population densities by 97% and 87%, respectively, compared with the infested, nontreated control. None of the other nematicides reduced RLN population densities compared with the infested, nontreated controls. There was no phytotoxicity to red raspberry associated with any of the nematicides.

Plant-parasitic nematodes are major pests of red raspberry, reducing yield and cane growth, and leading to economic losses in many production regions (Bélair, 1991; McElroy, 1991; Szczygiel and Rebandel, 1988; Trudgill, 1986). Plant-parasitic nematodes were first reported in *Rubus* species in North America in the 1930s, when root lesion nematodes were associated with declining red raspberries (McElroy, 1992). Growers have been able to manage plant-parasitic nematodes in raspberry crops by pre-plant fumigation with methyl bromide and other soil fumigants and/or post-plant treatment with fenamiphos. However, in recent years, many of the most effective nematode management tools are no longer available, with fenamiphos being removed from the U.S. market in 2007, and the phasing-out of methyl bromide use in all U.S. commodities in 1995. In addition, new U.S. Environmental Protection Agency (USEPA) reregistration eligibility requirements (REDs) for common soil fumigants will put restrictions on their use (USEPA, 2009). Therefore, the red raspberry industry is at a time when long-term, economically viable plant-parasitic nematode management strategies must be developed.

The root lesion nematode (RLN) is a migratory endoparasite that moves between soil and roots, but feeds on and migrates in root cortical cells. Feeding by the nematode kills tissues in the root cortex, which appear as necrotic lesions or spots on roots. On raspberry, RLN feeding on feeder roots can reduce the capacity of the plant to uptake nutrients and water. The RLN was shown to cause 24% mortality of red raspberry plants after 2 years (McElroy, 1975). The rate of raspberry decline depends upon the nematode population density but usually occurs over a 3- to 4-year period (McElroy, 1992). The rate of decline will also depend upon the variety and environment in which a plant is grown, but clearly, when this nematode is left unchecked and population densities increase in established raspberry plantings, significant yield loss can occur.

Currently, there are few post-plant nematicides labeled for use in red raspberry. For example, a recent search of the Crop Data Management Systems Inc. (CDMS) pesticide label database identified only two commercially available products, Nema-Q (saponins of soapbark; Monterey AgResources, Fresno, CA) and Ecozin (growth regulator containing azadirachtin; AMVAC Chemical Corp., Los Angeles), labeled in Washington State (CDMS, 2009), neither of which has been tested for managing RLN in raspberry crops. However, there are other insecticides/nematicides labeled for use in the United States that could potentially be used to control plant-parasitic nematodes in red raspberry.

Traditional nematicides that are registered for use in the United States include fosthiazate, oxamyl, and 1,3-dichloropropene (1,3-D). Fosthiazate has been shown to effectively control plant-parasitic nematodes in a diversity of crops, including potato [*Solanum tuberosum* (Ingham et al., 2000)] and strawberry [*Fragaria*

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The mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the United States Department of Agriculture.

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
65.1985	fl oz/lb	mL·kg^{-1}	0.0153
9.3540	gal/acre	L·ha^{-1}	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
6.4516	inch^2	cm^2	0.1550
16.3871	inch^3	cm^3	0.0610
1.1209	lb/acre	kg·ha^{-1}	0.8922
28.3495	oz	g	0.0353
1	ppm	mg·L^{-1}	1
1.1692	pt/acre	L·ha^{-1}	0.8553
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

×*ananassa* (Gilreath et al., 2008)]. Oxamyl is labeled for use in perennial crops such as apple (*Malus* spp.), banana (*Musa* spp.), citrus (*Citrus* spp.), and pear (*Pyrus* spp.), and is labeled for use on raspberry in Canada. While 1,3-D is known to be a very effective nematicide when applied as a soil fumigant (Gilreath et al., 2008; Schneider et al., 2008), it is also marketed for application by drip irrigation. A relatively new nematicide that belongs to the fluoralkenyl group is MCW-2 [5-chloro-2-(3,4,4-trifluorobut-3-enylsulfonyl)-1,3-thiazole; Makhteshim Agan, Airport City, Israel]. This compound has a far lower mammalian toxicity than organophosphate or carbamate nematicides, exhibits low leaching potential in soil, and has a relatively short half-life in soil (Oka et al., 2008a).

Another grouping of nematicides includes plant-based products, including furfural (2-furancarboxaldehyde), saponins of soapbark, and extracts of walnut (*Juglans regia*). Furfural is a liquid found in many essential oils from plants, and is present in fruit juices, alcoholic beverages, and bread (Rodríguez-Kábana et al., 1993). The mode of action of furfural against nematodes has been described as the destruction of the nematode cuticle (Burger, 2005). A product based on the saponins of soapbark is labeled for use on red raspberry and is approved for use in organically managed cropping systems. Plants in the family Juglandaceae (including walnut) produce juglone, which is known to be active against a range of organisms, including weeds (Shrestha, 2009) and nematodes (McKenry and Anwar, 2003).

Two insecticides that have received attention as potential nematicides are methomyl and spirotetramat. Methomyl, a carbamate, was effective as a nematicide against the cereal cyst nematode (*Heterodera avenae*) applied to wheat (*Triticum* sp.) as a broadcast application (Brown, 1973). Spirotetramat is systemic in the plant and is registered for use in several perennial cropping systems, including grape (*Vitis* spp.), cherry (*Prunus* spp.), and citrus for the control of insects, including aphids (Aphidoidea), phylloxera (*Viteus vitifoliae*), and thrips (Thysanoptera). Recently, spirotetramat has shown the potential to control plant-parasitic nematodes in perennial crops (M. McKenry, personal communication). There are also products that are not marketed as nematicides per se, but as plant performance products based upon the use of plant hormones, supporting nutrients, and other hormone cofactors designed to ensure optimum hormone balance and activity to withstand stress, including plant-parasitic nematodes.

The goal of our research program is to identify nematicides and management practices that can be labeled and used to minimize the impact of plant-parasitic nematodes on red raspberry crops. The specific objectives of this research were to identify nematicides that are directly toxic to RLN in soil, to identify nematicides that suppress RLN population densities in established red raspberry plants, and to determine if there are any phytotoxic effects of the nematicides on raspberry plants.

Materials and methods

Nematodes and soil used in studies. The RLN population used in all studies was obtained from a red raspberry field in Lynden, WA. Soil, a Kickerville silt loam (Isotic, Mesic Typic Haplorthods), was collected from the root zone of established plants. Initially, soil was passed through a 4-mm sieve on which roots were retained; the root material collected on the 4-mm sieve was cut into small pieces and stored in a sealed bag at 4 °C. The sieved soil was then placed on a greenhouse bench to partially dry for 1 to 2 d to allow for the application of nematicides in a volume of water to wet the soil without drainage from the container. Dried soil was crushed by rolling and was passed through a 2-mm sieve with material retained on the sieve being discarded. At this time, stored roots were added back into the sieved, dried soil. Soil and roots were homogenized by hand and stored at 4 °C until used in experiments.

Evaluation of nematicides in soil against RLN. Deepots™ (2 × 7 inch cells; Stuewe and Sons, Keiser, OR) were loaded with 250 g of RLN-infested soil (≈700 RLN per Deepot™). All nematicides were applied as drenches in 37.5 mL of water. In trial 1, nematicide application was based upon the volume of soil (250 cm^3) being treated. In trials 2 and 3, nematicide applications were calculated based upon an area basis, with the surface area of soil in the Deepot™ being 3 $inch^2$. The nematicides screened, and the rates used, are listed in Table 1. A nontreated control (water only) was also included. All nematicide rate combinations, and the nontreated control, were replicated six times and the experiment was conducted three times.

Deepots™ with treated soil were left for 7 or 14 d in a greenhouse with 24/18 °C day/night temperatures. At

Table 1. Nematicides and rates tested against root lesion nematode.

Nematicide	Rate[z]
Bioforge[y]	5 gal/acre[x]
1,3-dichloropropene	12[w], 36[w], and 72 lb/acre
Fenamiphos	7.5 lb/acre
Fosthiazate	11.3 lb/acre
Furfural	118.5 lb/acre
Walnut extract	10,000 ppm[x]
MCW-2[v]	8.9 lb/acre
Methomyl	1.1 lb/acre
Oxamyl	2 lb/acre
Soapbark saponins	3[w] and 6 lb/acre
Root Power[y]	1 pt/acre[x]
Spirotetramat[u]	0.2 lb/acre
Stimulate Plus[y,t]	1 pt/acre[x]

[z]Rates are expressed as pounds a.i. per acre unless otherwise noted; 1 gal/acre = 9.3540 $L \cdot ha^{-1}$, 1 lb/acre = 1.1209 $kg \cdot ha^{-1}$, 1 ppm = 1 $mg \cdot L^{-1}$, 1 pt/acre = 1.1692 $L \cdot ha^{-1}$.
[y]In greenhouse experiments, these products (Stoller USA, Houston, TX) were applied on a weekly basis for the duration of the experiments.
[x]These nematicides do not contain a specific a.i.
[w]Rates tested in soil only studies.
[v]Makhteshim Agan, Airport City, Israel.
[u]Evaluated in plant-based experiments only. Two types of adjuvants [R-11 (Wilber-Ellis, San Francisco) or Dyne-Amic (Helena Chemical Co., Collierville, TN)] at 0.025% were mixed with the chemical.
[t]Evaluated in plant-based experiments only.

these times, all of the soil was removed from the cells and was homogenized. A 75-g aliquot of soil was placed directly on a Baerman funnel (Ingham, 1998), and RLN was extracted from soil for 7 d. Extracted nematodes were collected and the number of nematodes was determined using a dissecting microscope at 40× magnification.

Evaluation of nematicides in established raspberry plants against RLN. 'Meeker' red raspberry was propagated from certified roots (Norcal Nursery, Burlington, WA). Roots were placed into 14 × 14-inch flats containing perlite (Sun Grow Horticulture, Bellevue, WA) and shoots were allowed to sprout from roots. Rooted shoots were excised and transferred to 14 × 14-inch flats containing perlite where the plants established root systems under intermittent mist. After ≈2 to 3 weeks, these plants were transplanted into 1-gal pots containing a steam pasteurized soil mix (1:2 by volume, washed sand and Willamette loam). Plants were fertilized with 20N–8.8P–16.6K (J.R. Peters, Allentown, PA) weekly and were grown in a greenhouse under long-day conditions (16-h photoperiod) with 26/18 °C day/night temperatures for ≈1 month before inoculation.

For inoculation with RLN, the plants were removed from the pots and adhering soil mix was gently removed from the roots. This soil, as well as the soil remaining in the pots, was saved in a container. About 1200 g of the soil mix was removed from the container and was replaced with field soil (see above) containing (mean ± SD) 1788 ± 338 mixed-stage RLN. The nematode-infested soil was combined with the soil mix and returned to the pots along with the raspberry plant. Noninfested controls were included; for this treatment, plants were removed from pots as above, and then replaced using original soil. Infested and noninfested control plants were grown for 1 and 2 months in trials 1 and 2, respectively. All pots were watered with drip irrigation in a greenhouse under long-day conditions (16-h photoperiod) with 26/18 °C day/night temperatures, and were fertilized weekly with 20N–8.8P–16.6K.

The nematicides and rates that were applied to the established raspberry plants infested with RLN are listed in Table 1. Plants were not watered the day before nematicide applications to allow the soil to dry slightly before applying nematicides. All nematicides, except spirotetramat, were applied as soil drenches, and rates were calculated based upon a soil surface area of 27 inch². The products Bioforge, Root Power, and Stimulate Plus (Stoller USA, Houston, TX) were applied on a weekly basis at the rates listed in Table 1. Spirotetramat was applied as a foliar application and was mixed with the adjuvant R-11 (Wilber-Ellis, San Francisco) or Dyne-Amic (Helena Chemical Co., Collierville, TN) at 0.025% and was delivered to the surface area of leaves until runoff in ≈200 mL of water. A nontreated, nematode-infested control and a nontreated, nematode-noninfested control were included in the study. The experiment was arranged in a completely randomized design and was maintained under the same greenhouse conditions as stated above. All treatments were replicated eight times and the experiment was conducted twice. The experimental duration was ≈3 months from initial nematicide treatment, during which time the plants were pruned and staked to manage growth and fertilized with 20N–8.8P–16.6K weekly.

At termination, the aboveground portion of the plant was removed, air-dried, and then placed in a 70 °C oven overnight before determining dry weight. The contents of the pot were emptied onto a tray where the roots were shaken free of soil and a 50-g soil sample was collected. The 50-g soil sample was placed on a Baermann funnel and nematodes were extracted for 5 d. Roots were washed free of soil and RLN were extracted by intermittent mist for 1 week (Ingham, 1998). The roots were then placed in a 70 °C oven for 1 week before determining dry weight. The RLN were enumerated using a dissecting microscope at 40× magnification and were expressed as number of RLN per gram dry root or total number (soil plus root) of RLN recovered per pot.

Statistical analyses. Trials from soil-only and plant-based experiments were analyzed separately because there was a significant interaction between treatments and experiments ($P < 0.001$). Nematode data were log transformed before analysis. Model variance components were estimated for each experiment using analysis of variance (ANOVA) procedures and means were separated by Fisher's protected least significant difference (LSD) test (Statgraphics Plus Version 3; Manugistics, Rockville, MD)

Results

Evaluation of nematicides in soil against RLN. In trial 1, where rates were calculated based upon soil volume and were therefore lower than rates in trials 2 and 3, nematode recovery was significantly ($P < 0.001$) lower 7 d after treatment in soil treated with oxamyl, methomyl, fosthiazate, and fenamiphos compared with the nontreated control (Table 2). After 14 d, the only nematicide that resulted in lower nematode recovery compared with the nontreated control was fosthizate. In trial 2, fenamiphos, fosthiazate, and oxamyl reduced nematode recovery from treated soil compared with the nontreated control at both sampling times, 7 and 14 d. The nematicides MCW-2, Root Power, soapbark saponins (6 lb/acre), and furfural reduced nematode recovery at one, but not both, sampling dates compared with the nontreated control. The same application basis, surface area, was used in trial 3 as in trial 2, and again in trial 3, oxamyl and fosthizate reduced nematode recovery compared with the nontreated control at both sampling times. The higher rate of soapbark saponins continued to demonstrate activity against RLN, with reduced recovery compared with the nontreated control at both sampling times, instead of only the first sampling time as in trials 1 and 2. The lower rate of soapbark saponins (3 lb/acre) also reduced nematode recovery compared with the nontreated control, but only at the latter sampling time. Methomyl and fenamiphos reduced RLN recovery compared with the nontreated control at the 14-d sampling time, but not the 7-d sampling time. Trial 3 was the only trial where 1,3-D was tested at the 72-lb/acre rate, and it reduced RLN recovery compared with the nontreated control at both sampling times. In this trial, the intermediate 1,3-D rate, 36 lb/acre, also reduced nematode recovery compared with nontreated control, but only at the 14-d sampling time.

Evaluation of nematicides in established raspberry against RLN. None of the nematicide treatments, regardless of trial, reduced the total number of RLN per pot nor

Table 2. Population densities of root lesion nematode in soil following treatment with nematicides.[z]

Nematicide	Trial 1[y]		Trial 2[x]		Trial 3[x]	
	Root lesion nematodes [no./250 g (8.82 oz) soil][w]					
	7 d	14 d	7 d	14 d	7 d	14 d
Nontreated control	104 de[v]	113 cd	115 f	169 e	121 ef	159 f
Bioforge[u]	76 bcd	89 bc	68 ef	134 de	122 ef	83 def
Walnut extract	79 bcd	73 bc	80 ef	114 cde	125 ef	95 def
1,3 dichloropropene (12 lb/acre)[t]	NT	NT	80 ef	143 de	NT	NT
1,3 dichloropropene (36 lb/acre)	NT	NT	95 f	139 de	116 def	53 cde
1,3 dichloropropene (72 lb/acre)	NT	NT	NT	NT	37 b	37 bc
Fenamiphos	46 ab	57 ab	31 ab	70 bc	50 bc	99 def
Fosthiazate	14 a	6 a	11 a	6 a	11 a	11 a
Furfural	132 e	173 d	66 def	78 bcd	189 f	160 f
Methomyl	41 ab	116 c	108 f	98 cde	97 cdef	42 bcd
MCW-2[s]	87 cd	125 cd	47 abcd	105 cde	68 bcde	98 def
Soapbark saponins (3 lb/acre)	101 de	121 cd	70 def	103 cde	85 cde	111 e
Soapbark saponins (6 lb/acre)	69 bcd	81 bc	67 def	58 b	60 bcd	36 ab
Oxamyl	53 bc	94 bc	37 abc	72 bc	59 bcd	53 cde
Root Power[u]	99 de	123 cd	82 cde	138 de	82 cde	156 ef

[z]The soil was a Kickerville silt loam collected from a red raspberry field in Lynden, WA. Rates are listed in Table 1.
[y]The application of nematicides was based upon the volume of soil being treated.
[x]The application of nematicides was based upon the surface area of soil being treated.
[w]1 nematode/250 g = 0.1134 nematode/oz.
[v]Means within a trial and sampling time (7 and 14 d) followed by the same letter are not significantly different according to Fisher's protected least significant difference at $P < 0.001$ (n = 6).
[u]Stoller USA, Houston, TX.
[t]1 lb/acre = 1.1209 $kg \cdot ha^{-1}$.
[s]Makhteshim Agan, Airport City, Israel.
NT = not tested.

RLN per gram dry root to levels found in the noninfested, nontreated controls (Table 3). In both trials, only fosthizate and oxyamyl reduced total number of RLN per pot and RLN per gram dry root compared with the infested, nontreated control. Fosthizate was the most effective nematicide tested. The number of RLN per gram dry root was lower in oxamyl-treated soils compared with all treatments except fosthiazate and the noninfested, nontreated control. In trial 2, 1,3-D and fenamiphos applications to soil resulted in lower total RLN per pot compared with the infested, nontreated control; however, this difference was not detected for RLN per gram dry root.

No one treatment stood out as promoting plant growth or causing phytotoxicity (Table 3). In trial 1, the infested, nontreated control and nearly all of the nematicide treatments had greater root weights than the noninfested, nontreated control. Bioforge- and fosthiazate-treated plants had lower root weights than infested, nontreated controls. There was no consistent trend observed for cane weights. Bioforge and furfural treatments reduced cane weights in trial 1. In trial 2, over half of the treatments produced root weights that were statistically similar to each other. Bioforge- and fosthiazate-treated plants again had lower root weights than infested, nontreated controls, as did fenamiphos-treated plants. The same was true for cane weight, with 10 of the 16 treatments having similar cane weights ranging from 20.1 to 24.5 g. Fenamiphos reduced cane weight in trial 2.

Discussion

Fosthiazate and oxamyl were the most effective nematicides tested for the control of RLN in soil and in red raspberry plants. It is interesting to note that both of these nematicides were more effective than fenamiphos, the red raspberry industry standard for post-plant RLN control before the discontinuation of this product. While not as consistent, soapbark saponins, 1,3-D, and methomyl appeared to be directly toxic to RLN with a reduction in recovery of the nematode from soils treated with nematicides, but inconsistent results in plant-based experiments.

Our previous research efforts demonstrated that spring applications of oxamyl and fosthiazate reduced RLN population densities for up to 2 years (Walters et al., 2009). In the same studies, oxamyl application rate determined the duration of nematode suppression. While both of these nematicides would be a good fit for raspberry production systems, the prospect of adding red raspberry to existing fosthiazate and oxamyl labels in the United States is uncertain. Fosthiazate is currently only labeled for use on tomato in the United States.

Another conventional nematicide tested was 1,3-D, which was moderately and inconsistently effective against RLN. 1,3-D is most commonly used as a pre-plant soil fumigant, and is applied alone or in combination with chloropicrin. Rates of 1,3-D used for soil fumigation (typically 277 lb/acre) are much higher than rates used in this study. The sting nematode (*Belonolaimus longicaudatus*) was controlled for 2 months by slit injections of 1,3-D at 46.8 $L \cdot ha^{-1}$ into established bermudagrass (*Cynodon* spp.) compared with untreated plots (Crow et al., 2003). The formulation applied in these experiments (Cordon; Dow Agrosciences, Indianapolis) is 93.6% 1,3-D, and is marketed for application by drip irrigation. We tested this 1,3-D formulation in previous studies, but not at the rate of 72 lb/acre (Walters et al., 2009). A fall application of 8.4 lb/acre 1,3-D applied through the drip line did not reduce

Table 3. Effects of nematicides on the recovery of root lesion nematode and on the growth of 'Meeker' red raspberry.[z]

Nematicide	Root lesion nematodes [no./250 g (8.82 oz) soil][y]	Root lesion nematodes [no./g (0.0353 oz) dry root][x]	Root wt (g)[w]	Cane wt (g)
		Trial 1		
Noninfested, nontreated control	109 a[v]	33 a	3.3 ab	30.0 cde
Infested, nontreated control	26,347 d	4,530 de	5.7 d	31.0 cde
Bioforge[u]	23,418 d	3,393 de	4.7 c	27.1 ab
Walnut extract	44,319 d	15,473 f	4.8 cd	30.7 cde
1,3-dichloropropene (72 lb/acre)[t]	23,697 d	4,709 de	5.2 cd	27.4 abc
Fenamiphos	35,154 d	6,303 de	5.2 cd	29.2 cde
Fosthiazate	875 b	168 b	4.7 c	31.8 de
Furfural	30,879 d	6,887 e	4.3 bc	23.6 b
MCW-2[s]	16,628 d	6,196 de	5.1 cd	28.7 cde
Methomyl	31,475 d	6,456 de	4.9 cd	29.0 cde
Soapbark saponins (6 lb/acre)	41,174 d	8,742 ef	5.0 cd	30.6 cde
Oxamyl	3,784 c	699 c	5.4 cd	32.5 e
Root Power[u]	33,103 d	6,535 de	4.8 cd	27.6 abd
Stimulate Plus[u]	40,859 d	8,318 ef	4.8 cd	29.0 cde
		Trial 2		
Noninfested, nontreated control	0 a	0 a	4.8 abcd	26.6 cd
Infested, nontreated control	75,143 efg	5,521 de	6.6 de	24.5 bcd
Bioforge	103,623 g	3,045 de	4.6 abc	21.0 abc
Walnut extract	52,966 de	5,015 de	5.9 bcde	23.1 abc
1,3-dichloropropene (72 lb/acre)	32,208 c	2,854 d	6.1 cde	24.5 abcd
Fenamiphos	45,962 d	5,625 de	4.2 ab	20.1 a
Fosthiazate	1,023 b	129 b	4.0 a	20.8 ab
Furfural	59,056 defg	4,526 de	6.4 cde	23.0 abc
MCW-2	72,953 efg	4,534 de	7.3 e	22.5 abc
Methomyl	64,537 efg	4,294 de	6.0 bcde	26.6 cd
Spirotetremat + R-11[r]	55,317 def	5,977 de	5.8 abcde	23.5 abc
Spirotetremat + Dyne-Amic[r]	90,105 fg	9,893 e	4.9 abcd	23.1 abc
Soapbark saponins (6 lb/acre)	67,434 efg	5,509 de	6.2 cde	24.1 abc
Oxamyl	6,927 c	588 c	6.5 cde	29.5 d
Root Power	61,222 efg	6,552 de	6.5 cde	23.7 abc
Stimulate Plus	60,528 defg	4,045 de	7.3 e	25.6 bcd

[z]The soil was a Kickerville silt loam collected from a red raspberry field in Lynden, WA. Rates and application methods are listed in Table 1.
[y]1 nematode/250 g = 0.1134 nematode/oz.
[x]1 nematode/g = 28.3495 nematodes/oz.
[w]1 g = 0.0353 oz.
[v]Means within a trial followed by the same letter are not significantly different according to Fisher's protected least significant difference at $P < 0.001$ (n = 8).
[u]Stoller USA, Houston, TX.
[t]1 lb/acre = 1.1209 kg·ha^{-1}.
[s]Makhteshim Agan, Airport City, Israel.
[r]The adjuvant R-11 (Wilber-Ellis, San Francisco, CA) or Dyne-Amic (Helena Chemical Co., Collierville, TN) at 0.025% was mixed with the chemical.

RLN population densities compared with the nontreated control.

The relatively new nematicide, MCW-2, was not effective in our studies for the control of RLN. This compound showed irreversible nematicidal activity against juveniles of the root-knot nematode (*Meloidogyne javanica*) in water-based assays (Oka et al., 2008b). When applied to soil, MCW-2 controlled the root-knot nematode similarly to or better than fenamiphos or cadusafos.

Two products were evaluated that are marketed as insecticides, methomyl and spirotetramat. Methomyl had some activity against RLN in soil only experiments, but was not effective in plant-based experiments. Methomyl was not as effective as aldicarb when drilled into soil or applied as a seed treatment. More recently, methomyl was tested as a seed treatment to control the root-knot nematode [*Meloidogyne incognita* (Desaeger et al., 2007)]. Of the seed treatments tested, including oxyamyl and abamectin, methomyl was the least effective in controlling the root-knot nematode on cucumber (*Cucumis sativus*) and cotton (*Gossypium* sp.). High rates of methomyl applied to seed gave nematode control similar to abamectin-treated seeds, however, nematode infection increased with time after application. Spirotetramat is foliar applied and requires the use of an adjuvant for leaf penetration. In our plant-based experiments spirotetramat, applied with two different adjuvants, did not control RLN.

We tested three plant-based products in our experiments, soapbark saponins, a walnut extract, and furfural. While soapbark saponins showed some direct contact activity against RLN in our soil tests, none of these plant-based products suppressed RLN when it was established on red raspberry. Whole extracts of soapbark resulted in the reduction of several plant-parasitic nematodes, including the RLN *Pratylenchus thornei*, when exposed to 100 ppm water extracts

(Martín and Magunacelaya, 2005). When the plant extract was applied to table grapes, plant-parasitic nematode reproductive indices were lower than the nontreated control and were similar to conventional nematicides (Martín and Magunacelaya, 2005). In another study, a 35% extract of soapbark, applied as a split application of 41 L·ha^{-1}, initially followed by 9.35 L·ha^{-1} applications every 4 weeks, was not effective in suppressing plant-parasitic nematodes damaging turf (Crow, 2005).

Water extracts from wood of walnut caused 100% mortality of *M. incognita*, and provided nematode control in grape vines equal to fenamiphos over a 2-year period (McKenry and Anwar, 2003). When RLN was exposed to the walnut extract product NatureCur (Redox Chemical, Burley, CA), RLN was immobilized initially, but mobility was restored by subsequent incubation in water (Pinkerton and Kitner, 2006). NatureCur was also evaluated for the control of RLN in strawberry. At a rate of 4800 mg·L^{-1}, it resulted in a modest reduction in RLN, which was different from the infested control, but not different from fenamiphos (Pinkerton and Kitner, 2006).

While furfural was not effective against RLN in these studies, it was efficacious in other studies. Furfural applied pre-plant at 0.1 to 1.0 mL·kg^{-1} soil suppressed population densities of the root-knot nematode *Meloidogyne arenaria* and the RLN *Pratylenchus brachyurus* (Rodríguez-Kábana et al., 1993). The number of nematodes recovered from roots was inversely related to the rate of furfural applied to soil. When furfural was applied pre- and post-plant to tomato (*Solanum lycopersicum*) and bell pepper (*Capsicum annuum*) for the control of the root-knot nematode *M. incognita*, results were variable (Kokalis-Burelle, 2007).

The plant performance products tested in these studies (Bioforge, Root Feed, and Stimulate Plus) did not reduce population densities of RLN, nor had growth effects on the treated plants that were significantly different from the other treatments. These products ranged from being an antioxidant comprised primarily of N,N'-diformyl urea, a solution guaranteed to contain boron and zinc, and a combination of cytokinin, gibberellic acid, and indole-3-butyric acid.

These experiments may not have fully evaluated the potential of each compound to manage RLN. For example, the plant performance products may have required longer durations of application to elicit a change in plant physiology that would alter nematode populations. It is also possible that some of the products that were applied only once will require multiple applications to control RLN. In tomato and bell pepper, furfural was applied twice, as a pre- and post-plant application, to control *M. incognita* (Kokalis-Burelle, 2007). An initial application followed by sequential applications at lower rates is recommended for soapbark saponins. Timing of application may also be an important factor for some of these compounds. In California, research is under way to determine the best time to apply spirotetramat for the control of plant-parasitic nematodes (M. McKenry, personal communication)

The RLN is a particularly difficult nematode to control. Our experiments did demonstrate that some of the nematicides tested were directly toxic to RLN, but for these same compounds, RLN control was not achieved in plant-based experiments. RLN are active in the soil and root throughout the year, with ≈40% of the population residing in the roots (Vrain et al., 1997). It is possible that at the time of nematicide drench application in plant-based experiments, a significant proportion of the population resided in the roots, protected from exposure to the nematicides. More frequent applications and/or higher concentrations of nematicides may be required to manage RLN which moves between the soil and roots (Pinkerton and Kitner, 2006).

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