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Drip Chemigation with Imidacloprid and Nematodes for Control of Scarab Larvae in Nursery Crops[1]

Michael E. Reding[2], Heping Zhu[3], and Richard Derksen[4]
USDA-Agricultural Research Service, Application Technology Research Unit
1680 Madison Avenue, Wooster, OH

Abstract

Larvae of scarabs, also known as white grubs, are subterranean insects that damage ornamental nursery crops when they feed on roots. Management is generally based on application of chemical insecticides to the soil surface, followed by supplemental water to leach the toxicants into the soil. Drip irrigation systems have the potential to deliver insecticides and insect pathogens to the root zones of crops to control subterranean insects. From 2004 through 2006, we tested the efficacy of imidacloprid (2004–2006), clothianidin (2006), or entomopathogenic nematodes (EPN) + imidacloprid (2005) applied through drip irrigation to control white grubs in an ornamental nursery. Insecticides (imidacloprid or clothianidin) or EPN + imidacloprid were injected into drip irrigation lines at the upstream end of rows in a commercial nursery. EPN + imidacloprid was also injected into the root zone of trees or applied as a surface drench. In 2004 and 2005, imidacloprid applied at a preventive timing through drip irrigation lines significantly reduced the numbers of white grubs in the root zones of Kousa dogwood (*Cornus kousa* Hance) trees. In 2006, variation in the data resulted in no significant differences at the $P = 0.05$ level, although, the percentage reductions of grubs by imidacloprid and clothianidin applied through drip irrigation were similar to trials in 2004 and 2005. EPN + imidacloprid applied through drip irrigation, injected into the soil, and surface drenched at a curative timing all significantly reduced the numbers of grubs compared to untreated trees. These data indicate drip irrigation is a viable delivery system for controls of white grubs in nursery crops.

Index words: ornamental trees, white grubs, oriental beetle, *Cornus*, crabapple.

Chemicals used in this study: imidacloprid (Marathon II), clothianidin (Celero 16WSG).

Significance to the Nursery Industry

White grubs are serious pests of nursery crops in many eastern and Midwestern states. Control of white grubs is usually done by applying insecticides to the soil surface, followed by supplemental water to leach the materials into the soil. Drip irrigation systems have the potential to deliver insecticides and insect pathogens to the root zones of crops to control insects below ground. Drip chemigation is the application of nutrients or pesticides through a drip irrigation system. Some of the benefits of drip chemigation for application of pesticides are reduced costs for labor and fuel, less drift, and reductions in worker exposure to pesticides compared to standard surface sprays. In the following study, drip chemigation was tested for control of white grubs in field-grown nursery crops. Insecticides and entomopathogenic nematodes applied through drip irrigation successfully reduced numbers of white grubs in field-grown Kousa dogwoods and crabapples. During three years of testing, drip chemigation with imidacloprid reduced numbers of grubs from 62 to 83%. Clothianidin was tested during one year, and it reduced the numbers of grubs by 65%. Our data indicates that drip chemigation is a viable application technique for control of white grubs in nursery crops. Drip chemigation has not been used in nursery crops for control of white grubs or other subterranean pests. The presented research was conducted in a field production nursery, but the drip chemigation technique used should also be appropriate for control of white grubs in container grown crops irrigated by drip systems.

Introduction

In recent years, the larvae of exotic scarabs (*Coleoptera: Scarabaeidae*) have been found stunting and killing field-grown nursery crops in northern Ohio (14). The larvae of scarab beetles, also known as white grubs, injure or kill plants by feeding on the roots. Plants damaged or killed by grubs are generally devoid of fibrous roots (14). Young plants appear more vulnerable to feeding injury by grubs than older and more established plants. In a survey of ornamental nurseries in northern Ohio, Reding and Klein (13) found that oriental beetle (*Anomala orientalis* Waterhouse) and European chafer (*Rhizotrogus majalis* Razoumowsky) were the most common species of white grubs. Both species have been found damaging plants in ornamental nurseries in the mid-western and northeastern sections of the United States (10, 11, 14, 18).

Preventive treatments of insecticides such as imidacloprid, are generally sprayed or broadcast on the soil surface to control white grubs in turf and field-grown nursery crops (9). Mannion et al. (9) reduced the numbers of Japanese beetle (*Popillia japonica* Newman) grubs in field-grown nursery crops with preventive timed surface treatments of granular and sprayable formulations of imidacloprid. Nielsen and Cowles (10) reduced the numbers of Japanese beetle and oriental beetle grubs in container-grown nursery crops with drench treatments of imidacloprid. Efficacy of imidacloprid

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[2]Research Entomologist, USDA-ARS Application Technology Research Unit, Horticultural Insects Research Group <mike.reding@ars.usda.gov>.

[3]Agricultural Engineer, USDA-ARS Application Technology Research Unit, Agricultural Engineering Group <heping.zhu@ars.usda.gov>.

[4]Agricultural Engineer, USDA-ARS Application Technology Research Unit, Agricultural Engineering Group <rich.derksen@ars.usda.gov>.

treatments is usually dependent on applications of sufficient amounts of water to facilitate movement of the chemical into the root zone. This procedure is recommended on the Marathon II and Marathon 60 WP (imidacloprid, OHP Inc., Mainland, PA) labels for control of white grubs in nurseries. Nursery crops such as trees and shrubs have relatively deep root systems, as a result, ensuring movement of insecticides into the soil is usually critical for effective grub control in nursery crops. However, Mannion et al. (9) reduced numbers of grubs in nursery trees with treatments of imidacloprid where no supplemental water was applied. In commercial nurseries, water is usually applied through overhead sprinkler irrigation to facilitate movement of insecticides into the soil. This technique is not practical for growers that use drip irrigation because the amounts of water applied and surface area of soil covered are less than typical overhead irrigation. Applying insecticide through the drip line may alleviate this problem by concentrating the insecticide in the tree-line more directly over the root zone, instead of spreading it across a comparatively large surface area. In addition, this application method would reduce worker exposure during application, drift, and the amount of labor required compared to spray or broadcast applications.

Entomopathogenic nematodes (EPN) have shown potential as natural controls for scarab grubs in turf (4, 7) and woody ornamental crops (18). Wright et al. (18) achieved control of Japanese beetle grubs equivalent to insecticide treatments and reduced numbers of European chafer grubs in container-grown Taxus with surface-drenches of various species of EPN. There appears to be a synergism between EPN and certain neonicotinoid insecticides, including imidacloprid (6, 8). This synergism makes it possible to use lower rates of insecticide when combined with EPN than if the insecticide was used alone (8). In addition, these combination treatments were effective at curative timings, which is in contrast to neonicotinoids being most effective at preventive timings when used alone (6, 8, 12). Use of curative treatments makes monitoring to make decisions on the need to treat for grubs a viable management technique instead of relying only on prophylactic treatments. One of the issues related to acceptance of using EPN for control of scarab grubs by growers has been a practical method of application on a commercial scale. Wennemann et al. (17) successfully delivered four different species of EPN through drip irrigation lines with pressure compensating emitters in vineyards. If applying EPN through drip irrigation provides effective control of scarab grubs, use of EPN may become a more acceptable alternative for growers.

The objective of this research was to test the efficacy of white grub controls applied through drip irrigation in ornamental nursery crops. Application of pesticides or nutrients through drip irrigation systems is called drip chemigation.

Materials and Methods

Study sites and general experimental design. All trials were conducted in a commercial nursery in northern Ohio that produces balled and burlapped ornamental trees. The rows used in this research were 110 to 168 m (360 to 550 ft) long with 66 to 140 trees in the rows. Spacing between trees within rows was approximately 1 to 1.5 m (3.3 to 5 ft), depending on the cultivar and size of tree at planting. The experiments were arranged in completely randomized designs. Only a proportion of the trees in each row were as-

Table 1. Application timing, rate determination and rates of insecticides and nematodes for all trials 2004–2006.

Year	Timing	Treatment[z]	Insecticide or nematodes applied per tree	Label recommendation and calculation
2004	Preventive: July 1	Drip imidacloprid	0.67 ml Marathon II	Rate based on an estimated root zone equal to a 26 L container: per tree rate for 75 trees
2005	Preventive (trial-1): July 11	Drip imidacloprid	0.42 ml Marathon II	Rate based on an estimated root zone equal to a 19 L container: per tree rate for 110 trees
		Surface spray imidacloprid	0.21 ml Marathon II	Uniform band 15 cm wider than root ball: total band width 75 cm
	Curative (trial-2) August 16	Drip imidacloprid + EPN Subsurface imidacloprid + EPN Surface imidacloprid + EPN	0.11 ml Marathon II + 23,000 EPN Rates were the same for all application methods	1/4 trial-1 drip rate EPN: *H. bacteriophora*
2006	Preventive: July 16	Standard Drip imidacloprid External emitter imidacloprid Standard Drip clothianidin	0.37 ml Marathon II 0.37 ml Marathon II 0.13 g Celero 16 WSG	Rate based on an estimated root zone equal to a 19 L container: per tree rate for 135 trees

[z]EPN = entomopathogenic nematodes, *Heterorhabditis bacteriophora* strain GPS11.

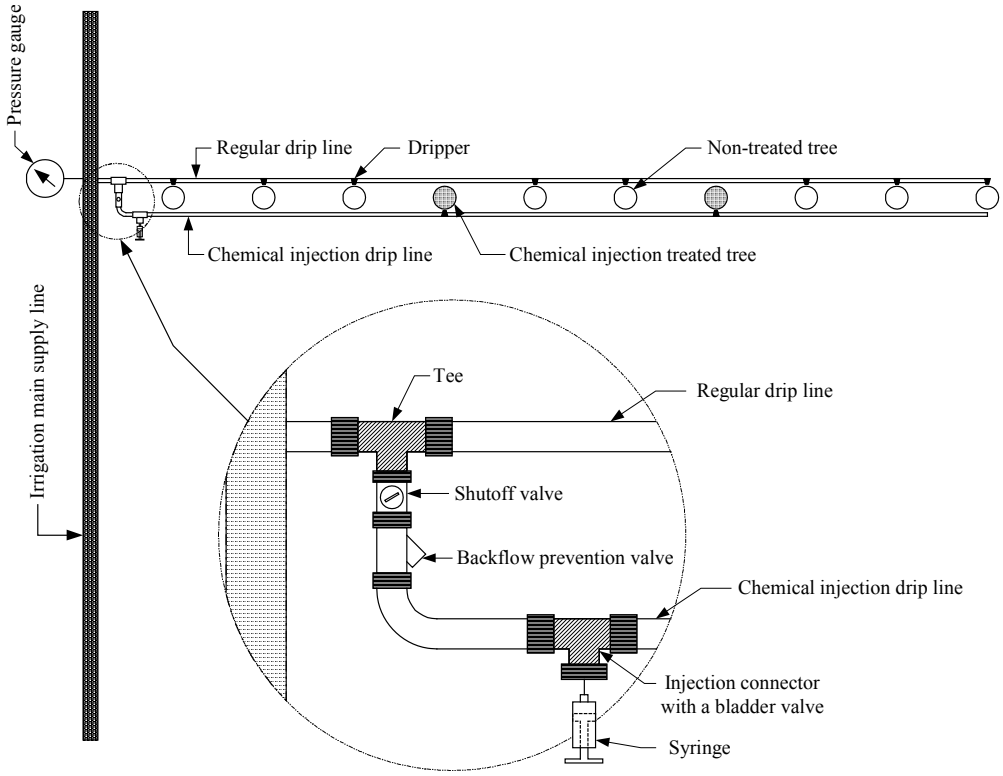

Fig. 1. Schematic diagram of a double drip irrigation line for 2004 and 2005 trials for trees in the same row receiving either irrigation water only or drip applied insecticide plus water. The regular drip line supplied water only and the chemical injection drip line supplied water and imidacloprid to trees.

signed treatments with the remainder unused, even when the entire length of the row was included in the trial. All trees were planted during spring of the year in which the trial was conducted. Trees used in the 2004, 2005, and 2006 trials were planted in spring 2004, 2005, and 2006, respectively. Trials were evaluated by digging trees in the fall and carefully searching the extracted roots and soil for grubs. All grubs were identified to species and instar. The treatments applied through the drip line were injected into the line at the upstream end of the row through a novel valve system described below. Rates of the insecticides and nematodes applied are listed in Table 1.

Chemigation system. A chemical injection system was designed and built, then installed at the beginning edge (upstream end) of each insecticide treatment drip line (as seen in the detailed schematic of Fig. 1). This system included an injection valve assembled with a 1.27 cm (0.5 in) thread PVC tee (Lasco Fittings, Inc., Brownsville, TN), a 1.27 cm (0.5 in) NPT electric wire connector (Kleinhuis North America, Inc., Worthington, OH), and a bladder valve removed from a 40 cm (16 in) diameter plastic toy ball (item# 3314903313, Ball, Bounce, and Sport Inc. Ashland, OH). In addition, a backflow prevention valve (Model T-413, Nibco Inc., Elkhart, IN) was installed in the insecticide line upstream of the injection valve, to prevent insecticide flowing upstream to the regular drip line or main irrigation supply line. A 50 ml (1.7 oz) Pro-Pistol™ pistol grip syringe (Model 1005, Neogen Corporation, Lexington, KY) with a 0.9 mm (0.35 in) inside diameter needle was used to inject insecticide or insecticide + entomopathogenic nematodes into the drip line through the injection valve. In 2004 and 2005, the first emitter in the insecticide injection line was at least 6.1 m (20 ft) downstream from the injection connectors so the insecticide had enough time to mix uniformly with water inside the drip line before reaching the emitters. In 2006, because part of the test was to treat the entire row, the injection valve was much closer [≤ 1 m (3.3 ft)] to the first treated tree and thus there may have been less uniform mixing of the insecticide and water than in 2004 and 2005.

In 2004 and 2005, two drip lines were installed on the soil surface and close to the middle line of each tree row, one line for injection of insecticide, and the other to supply irrigation to the remaining trees, including the untreated controls (Fig. 1). The drip lines were polyethylene tubing with a 1.75 cm (0.69 in) outside diameter (OD) and 1.24 cm (0.5 in) inside diameter (ID), and were connected to the main irrigation supply line. External pressure compensating emitters (Part Number 01WPC2, Netafim Irrigation, Inc., Fresno, CA) with a nominal flow rate of 1.9 LPH (0.5 gal/hr) per emitter were used to trickle water to trees. Emitters were installed in the two drip lines in such a manner that each tree received irrigation water from only one emitter. The insecticide treated trees received irrigation from the chemical injection drip lines, and the control trees received water from the other drip irrigation lines. Consequently, all of the trees were supposed to receive the same amount of water every time irrigation was applied. Water was run through the lines for at least 20 minutes before application of the insecticide and remained on during the application. The total irrigation period during application was approximately two hours. The irrigation regimen in this nursery was to turn on water for two hours

a day, on the condition there was insufficient rainfall to wet the soil during that day.

In 2006, only one line was used per row because rows were either treated or untreated. The irrigation lines for the standard and control treatments had integral (internal) pressure-compensated emitters with a nominal flow rate of 2.3 LPH (0.6 gal/hr) per emitter and emitter spacing at 60 cm (24 in) intervals (UniRam RC 16012, Netafim Irrigation, Inc., Fresno, CA). These lines were polyethylene tubing with a 1.61 cm (0.6 in) outside diameter (OD) and 1.37 cm (0.54 in) inside diameter (ID), and were connected to the main irrigation supply line.

Soil samples were taken from the drip applied and untreated control treatments each year to determine the presence of the applied insecticides in the soil. A separate soil corer [2 cm (0.78 in) diam. × 45 cm (18 in) long] was used for treated and untreated trees. Soil samples were placed in glass jars and transported to the lab. In the lab, the samples were stored at –40C (–40F) until analysis. Methanol was used to extract imidacloprid from the soil samples (2) and ELISA kits for imidacloprid (Envirologix, Inc., Portland, ME) were used to determine the amount of imidacloprid in the soil (1). Acetonitrile was used to extract clothianidin from the soil samples and Liquid Chromatography/Mass-Spectrometry was used for analysis (5).

2004 Trial. Three rows of field-grown Kousa dogwood (*Cornus kousa* Hance) cultivar 'Heart Throb' were used in this trial, with approximately 35 m (115 ft) of the upstream end of each row used for the experiment (each row was approximately 109 m (358 ft) long). This trial had 2 treatments, drip applied imidacloprid (Marathon II® Olympic Horticultural Products, Inc., Mainland, PA) and an untreated control (water only) (see Table 1 for rates), with a total of 18 single-tree replications per treatment and 6 replications of each treatment per row. The insecticide was applied on July 1, 2004, at a preventive timing. Initially, 10 ml (0.34 oz) of undiluted Marathon II was put into the syringe, which was sufficient insecticide to treat two rows at 4 ml (0.14 oz) per row. The syringe operated as a ratcheted mechanism that could be set to deliver 1 ml (0.03 oz) of solution with each squeeze of the trigger. However, we were not certain whether we could effectively dispense such a small volume. The undiluted Marathon II was injected into rows one and two. During this application there was leakage in both rows from the needle at the valve and a complete dose of the insecticide did not get into the lines. We concluded that the leakage was caused by a combination of back-pressure from the irrigation line, applying a low amount of compressible liquid formulation, and not emptying the syringe into each drip line. Consequently, before injection into the third row, the formulated insecticide [4 ml (0.14 oz)] was mixed with water for a total volume of 40 ml (1.4 oz), then all of this mixture was put into the syringe. The entire volume was then dispensed into the drip line, where no apparent leakage occurred at the injection point. On July 14, soil cores were taken from the treated and untreated trees nearest and farthest from the injection points in each row. Two sets of cores were taken from each sampled tree and pooled for the respective trees. These soil samples were taken next to emitters at depths of 5, 10, and 20 cm (2, 4, and 8 in) and at locations 15 and 30 cm (6 and 12 in) away from the same emitters at a depth of 5 cm (2 in). Trees were dug for evaluation September 21, 2004.

2005 Trials. Two trials were conducted in 2005 (Table 1). Three rows of field-grown Kousa dogwoods (*C. kousa*) cultivars 'Wolf Eyes' (trial-1) and 'Satomi' (trial-2) were used in each trial. Trial-1 had 3 treatments: 1) drip applied imidacloprid (Marathon II), 2) surface spray of imidacloprid (Marathon II), and 3) untreated control (irrigation water only) (see Table 1 for rates) with 30 single-tree replications and 10 trees of each treatment per row. The entire length of each row was used with only a proportion of the trees assigned treatments. The insecticide treatments were applied at a preventive timing on July 11, 2005. In the drip applied treatment, Marathon II was mixed with water for a total volume of 45 ml (1.5 oz) for each row. Then, each volume was injected into a drip line so the entire 45 ml (1.5 oz) was dispensed into the line. On July 28, two soil cores were taken from the drip applied imidacloprid and untreated trees closest to the injection point, midway down the row, and at the far end of the row. These samples were taken next to emitters at depths of 5, 10, and 20 cm (2, 4, and 8 in). The trees at the far end of the row were about 110 m (360 ft) from the injection point. The trees were dug for evaluation September 20 and 21, 2005.

Trial-2 had 4 treatments: 1) drip applied entomopathogenic nematodes (EPN) + imidacloprid (Marathon II), 2) subsurface applied EPN + imidacloprid (Marathon II), 3) a surface drench of EPN + imidacloprid (Marathon II), and 4) untreated control (water only) (see Table 1 for rates), with 12 single-tree replications per treatment. The EPN species used was *Heterorhabditis bacteriophora* (Poinar) strain GPS11 and were reared from infected *Galleria mellonella* L. The EPN and formulated insecticide were mixed together in water before application to the trees. The drip applied treatment was injected into the drip line using the same technique as in trial-1. The subsurface treatment was applied by a portable CO_2 sprayer operated at 345 kpa (50 psi) using a spray wand with a pointed nozzle that was inserted about 5 cm (2 in) into the soil. This treatment was applied at two locations for each tree on opposite sides of a tree to emit a total of 400 ml (13.5 oz) of solution. The surface treatment was applied as a surface-drench in 400 ml (13.5 oz) of solution per tree. The rates were adjusted to deliver the same dose of insecticide and nematodes per tree in each treatment. The treatments in this trial were applied at a curative timing on August 16, 2005. To determine whether EPN were present in the treatments, post-treatment soil samples (cores) were taken from each trial-tree on August 24. Samples were taken approximately 15 cm (6 in) from each tree and to a depth of 15 cm (6 in), then placed in plastic containers and transported to the lab. In the lab, three *G. mellonella* larvae were placed on the soil in each container and incubated at room temperature [ca. 23C (73F)] for up to 2 wk or until the *G. mellonella* changed color indicating an infection, whichever came first. At least one infected *G. mellonella* in a container was considered a positive test for the presence of EPN in a sample. The trees were dug to evaluate the numbers of white grubs on October 4, 2005.

2006 Trial. In 2006, the trial was conducted in two adjacent blocks of crabapple trees (*Malus* Mill.) of various cultivars with 5 rows used in one block and 7 in the other. There were 4 treatments: 1) imidacloprid (Marathon II) applied through drip line with internal compensating emitters spaced at 60 cm (24 in) intervals (the nursery's standard drip line); 2) imidacloprid (Marathon II) applied through drip line with

Table 2. Mean (±SD) numbers of white grubs in the preventive timed drip chemigation trials 2004 through 2006.

Year	Treatment	Mean (±SD) grubs per tree[z]	% reduction of grubs versus untreated
2004	Untreated	9.4 (5.8)a	
	Drip applied imidacloprid	3.6 (3.8)b	62.4
2005	Untreated	4.0 (3.2)a	
	Drip applied imidacloprid	0.7 (1.0)b	83.3
	Spray applied imidacloprid	0.6 (0.9)b	85.0
2006[y]	Untreated	19.9 (18.2)a	
	Standard drip clothianidin	7.0 (2.7)a	64.8
	Standard drip imidacloprid	4.7 (4.2)a	76.4
	External emitter imidacloprid	0.04 (0.1)a	99.8

[z]Means within columns and years followed by the same letter are not significantly different, ANOVA, $P \leq 0.05$ (multiple comparison of means, Tukey's HSD, $\alpha = 0.05$). In 2004 and 2005, there were 18 and 30 single-tree replications per treatment, respectively. In 2006, each row was a replication with 8 trees per replication for a total of 24 trees per treatment.

[y]Data were transformed before analysis [sqrt (x + 0.5)] and the untransformed means (±SD) are presented in the table.

external emitters at each tree (for comparison with previous years); 3) clothianidin (Celero 16 WSG, Arysta, Cary, NC) applied through standard drip line; 4) untreated (irrigation water only); with 3 replications. The insecticides were applied on July 14, 2006, with one treatment assigned per row and each row a replication. The entire length of each row was treated, but only 8 trees from each row were sampled for grubs. Because we wanted to include the entire length of the row in our evaluation, the trees to be sampled were assigned by dividing a row into 8 sections, then randomly assigning one tree within each section (for example, a row of 80 trees was divided into 8 sections of 10 trees, then one of the 10 trees in each section was randomly assigned as a tree to be sampled). There was approximately 1 m (3.3 ft) of irrigation line between the injection valve and the first emitter, in contrast to 2004 and 2005 when there was at least 6 m (20 ft) between the injection valve and the first emitter. On July 26, two soil cores were taken next to trees at both ends and the center of each row at depths of 5 cm (2 in) and 20 cm (8 in). Samples were not taken relative to the proximity of emitters. The external emitters were next to trees, but in general the internal emitters were not. Trees were dug for evaluation on September 26 and 27, and October 5, 2006.

Data analysis. Efficacy data were analyzed by analysis of variance with multiple comparison of means done by Tukey's 'Honestly Significant Difference' test (Tukey's HSD, 15). Each trial was examined for homogeneity of variances before analysis. Variances of grub counts were heterogeneous in both 2005 trials and the 2006 trial so the data were transformed [sqrt (x + 0.5)] before analysis (19). This transformation corrected the heterogeneity in these trials and the untransformed means (±SD) are presented. In 2005 trial-1, data on distribution of grubs within rows and comparison of efficacy relative to the injector location were analyzed by ANOVA (15). For this analysis, each row was divided into three sections (the injection valve end of the row, mid-row, and the far end of the row) and the data within rows and sections were treated as sub-samples and averaged by section. In 2005, there were 3 trees in the injector end section and the far end section of each row, and 4 trees in the center section of each row. In 2006, there was so much variation between rows within treatments because of the differences in grub numbers between the two trial blocks that distribution of grubs within rows was not analyzed.

Results and Discussion

2004 Efficacy. In 2004, drip applied imidacloprid significantly reduced the numbers of scarab grubs compared to the untreated trees ($F = 12.93$; df = 1, 34; $P = 0.001$) (Table 2). There were some problems injecting the imidacloprid into the drip lines in rows 1 and 2, which negatively affected grub control in those rows (grub numbers were reduced 31 and 49%, respectively). However, in row 3 the problem was corrected and the number of grubs was reduced by 90% and the untreated trees in that row had a mean of 12 grubs/tree.

Table 3. Mean (±SD) numbers of white grubs found in Trial-2 2005 where nematodes + imidacloprid (Marathon II) were applied by various methods.

Treatment	Mean (±SD) numbers of grubs per tree[z]	% reduction of grubs versus untreated trees	% samples where EPN recovered[y]
Untreated	5.1 (2.8)a	NA	0.0%
Drip applied	2.3 (0.6)b	54.9%	25.0%
Subsurface	1.2 (1.0)b	77.0%	83.0%
Surface drench	0.8 (1.7)b	85.2%	75.0%

[z]Means within columns followed by the same letter are not significantly different, ANOVA, $P \leq 0.05$ (multiple comparison of means, Tukey's HSD, $\alpha = 0.05$). There were 12 single-tree replications per treatment. The data was transformed [sqrt (x + 0.5] before analysis and the untransformed means (±SD) are presented in the table.

[y]EPN = entomopathogenic nematodes, *Heterorhabditis bacteriophora* strain GPS11.

Table 4. The species of scarab grubs found in each trial presented as a proportion of the total number of grubs found in each treatment.

Year		Treatment	Proportion of all grubs found[z]				Total grubs
			OB	AGB	EC	JB	
2004		Untreated	0.84	0.12	0.05	0.00	170
		Drip	0.88	0.05	0.05	0.02	64
2005	Trial-1	Untreated	0.92	0.05	0.02	0.01	119
		Drip	0.84	0.11	0.00	0.05	19
		Spray	0.94	0.06	0.00	0.00	17
	Trial-2	Untreated	0.87	0.13	0.00	0.00	61
		Drip	0.78	0.22	0.00	0.00	28
		Subsurface	0.92	0.08	0.00	0.00	14
		Surface drench	1.00	0.00	0.00	0.00	9
2006		Untreated	0.99	0.00	0.01	0.00	477
		Stan-drip cloth.[y]	0.95	0.00	0.04	0.01	169
		Stan-drip imid.[y]	0.97	0.03	0.00	0.00	112
		Ext-drip imid.[y]	1.00	0.00	0.00	0.00	1

[z]OB = oriental beetle, AGB = Asiatic garden beetle, EC = European chafer, JB = Japanese beetle.

[y]Stan-drip cloth. = Standard drip line clothianidin, Stan-drip imid. = Standard drip line imidacloprid, Ext-drip-imid. = External drip-emitter imidacloprid.

2005 Efficacy. In 2005 trial-1, all of the imidacloprid treatments reduced numbers of grubs compared to the untreated trees ($F = 31.22$; df = 2, 87; $P < 0.001$) (Table 2). Numerically, grubs were not distributed evenly along the length of the rows, although there was no statistical difference among mean numbers of grubs in the untreated trees from the injector section (1.9 grubs per tree, 9 trees), center section (5.8 grubs per tree, 12 trees), and far end section (3.9 grubs per tree, 9 trees) of the rows ($F = 4.15$; df = 2, 6; $P = 0.074$). Percentage reduction in the number of grubs were similar among the three sections of the rows within the drip applied treatment (78, 92, and 74% in the injector end section, center section, and far end section of the rows, respectively; $F = 0.97$; df 2, 6; $P = 0.43$).

In trial-2, all of the EPN + imidacloprid treatments significantly reduced the numbers of grubs compared to the untreated control ($F = 12.12$; df = 3, 44; $P < 0.001$) (Table 3). There were no significant differences among the EPN + imidacloprid treatments (application methods). Recovery of EPN in soil samples was highest in the subsurface and surface drench treatments with EPN detected in 83, 75, 25, and 0% of the soil samples from the subsurface, surface drench, drip, and untreated control treatments, respectively (Table 3). During injection of EPN + imidacloprid into the drip lines, the needle detached from the syringe resulting in leakage at each injection. Consequently, that treatment did not receive the intended dose, which may explain the relatively poor efficacy in reducing numbers of grubs and the low recovery of nematodes in the soil samples compared to the subsurface and surface drench treatments. In addition, a percentage of the EPN may have remained in the drip line, although, Wenneman et al. (17) successfully delivered EPN through drip irrigation lines with pressure compensating emitters in vineyards.

2006 Efficacy. In 2006, there were no significant differences among treatments ($F = 3.48$, df = 3, 8, $P = 0.07$). The imidacloprid external emitter, standard drip, and clothianidin treatments reduced the numbers of grubs by 99.8, 76.4, and 64.8%, respectively (Table 2). The lack of statistical significance may be due to the low number of replications. An additional confounding factor was the low numbers of grubs found in the northern-most block (2.5 grubs per tree in the northern block untreated versus 28.6 in the southern block), which contained one untreated replication, all three external emitter replications, one standard drip imidacloprid replication, and no clothianidin replications. This resulted in a lot of variation within treatments even though each replication had 8 sub-samples. When the clothianidin and imidacloprid standard drip replications in the southern block (3 and 2 southern block reps, respectively) were compared with untreated replications from the southern block (2 reps), the numbers of grubs were reduced by 75.3 and 75.5%, respectively. The high numbers of grubs (28.6 per untreated tree in the southern block) in newly planted trees was unexpected. This nursery leaves fields fallow for a year before replanting with new trees. Therefore, the infestations in these fields probably came from mated females migrating from outside the trial blocks and the high population was a new invasion.

Oriental beetle (OB) was the most common scarab in all trials (Table 4). During the three years of this study, at least 84% of the grubs found in each treatment were OB, with the exception of one treatment (drip applied EPN + imidacloprid in 2005). The next most common species was Asiatic garden beetle (*Maladera castanea* Arrow). European chafer (EC) and Japanese beetle (JB) were present in 2004, trial-1 2005, and 2006, but not in trial-2 2005 and were generally uncommon.

Soil analysis. In 2004, imidacloprid was detected in all soil samples. Low levels of imidacloprid were found in samples taken from untreated trees with similar levels found at all three depths next to emitters and 15 cm (6 in) away from emitters (Table 5). The highest level in the untreated trees was detected 30 cm (12 in) from emitters with a mean level of 6.3 µg/kg (ppb) of soil. There was a wide range of variation in the samples taken next to the emitter from treated

Table 5. Concentrations of drip applied insecticides found in soil samples from the chemigation trials.

Year	Treatment (ai)	Depth (cm)	Mean (±SD) active ingredient µg/kg of soil					
			Proximity to injector[z]			Mean for depth	Distance from emitter	
			Near	Mid-row	Far end		15 cm	30 cm
2004	Marathon (Imidacloprid)	5	886 (110)	na	648 (821)	767 (540)	203 (337)	40 (45)
		10	1570 (431)	na	1018 (1295)	1294 (915)	na	na
		20	706 (678)	na	1750 (1963)	1228 (1432)	na	na
	Untreated (Imidacloprid)	5	2.0 (0.5)	na	1.0 (0.5)	1.5 (0.7)	2.3 (2.1)	6.3 (9.3)
		10	2.2 (1.9)	na	1.0 (0.6)	1.6 (1.4)	na	na
		20	2.0 (1.3)	na	1.4 (1.1)	1.7 (1.1)	na	na
2005	Marathon drip (Imidacloprid)	5	536 (667)	222 (127)	1507 (2198)	755 (1288)	na	na
		10	192 (201)	360 (105)	427 (95)	326 (162)	na	na
		20	86 (76)	154 (36)	197 (120)	146 (88)	na	na
	Untreated (Imidacloprid)	5	0.2 (0.0)	0.2 (0.0)	0.5 (0.3)	0.3 (0.2)	na	na
		10	0.2 (0.0)	0.2 (0.1)	0.2 (0.0)	0.2 (0.04)	na	na
		20	1.5 (1.8)	0.2 (0.1)	0.2 (0.0)	0.5 (0.9)	na	na
2006	Marathon internal emitter (Imidacloprid)	5	90 (144)	5 (4)	23 (25)	39 (44)	na	na
		20	8 (5)	4 (6)	10 (6)	7 (3)	na	na
	Marathon external emitter (Imidacloprid)	5	24 (29)	24 (40)	86 (136)	45 (55)	na	na
		20	22 (6)	91 (147)	12 (8)	42 (53)	na	na
	Untreated (Imidacloprid)	5	0.4 (0.5)	0.4 (0.1)	0.2 (0.2)	0.3 (0.2)	na	na
		20	0.1 (0.2)	0.2 (0.2)	0.0	0.1 (0.1)	na	na
	Celero (Clothianidin)	5	642 (789)	90 (55)	1987 (1733)	906 (326)	na	na
		20	213 (181)	833 (1371)	706 (761)	584 (336)	na	na
	Untreated (Clothianidin)	5	0.0	0.0	0.0	0.0	na	na
		20	0.0	0.0	0.0	0.0	na	na

[z]In 2004 and 2005, the samples were taken within 2 cm of an emitter. In 2006, the samples were taken next to trees not in relation to emitter location.

trees with similar levels found at the 10 and 20 cm (4 and 8 in) depths (Table 5). There were generally higher levels at 10 and 20 cm (4 and 8 in) compared to 5 cm (2 in). There was a trend toward higher levels of imidacloprid in samples taken next to emitters of treated trees in row 3 compared to rows 1 and 2 (mean µg/kg (ppb) of 1299 versus 444 and 559, respectively).

In 2005, mean levels of imidacloprid in samples from untreated trees were 0.2 µg/kg (ppb) of soil (the minimum level of detection) in 67% of the samples with only one sample over 1 µg/kg (ppb) [1.5 µg/kg (ppb)] (Table 5). In the treated trees, there was more variation in the concentrations of imidacloprid at the 5 cm (2 in) depth [79 to 4041 µg/kg (ppb)] than at 10 cm (4 in) [53 to 491 µg/kg (ppb)] and 20 cm (8 in) [38 to 328 µg/kg (ppb)]. There was a trend toward increasing levels of imidacloprid as the distance from the injection site increased so that highest mean levels were found at the far end of the rows at each depth (Table 5).

In 2006, mean levels of imidacloprid in samples from untreated trees were ≤ 0.4 µg/kg (ppb) of soil at the 5 cm (2 in) depth and ≤ 0.2 µg/kg (ppb) at 20 cm (8 in) (Table 5). No clothianidin (Celero) was detected in the samples from untreated rows (Table 5). The concentrations of imidacloprid in the Marathon II treated rows had similar overall means at the 5 cm (2 in) depth in the internal and external emitter rows (Table 5). At the 20 cm (8 in) depth, concentrations of imidacloprid were generally higher in the external emitter rows than those with internal emitters. There was no trend related to location within the rows at either depth. There was a lot of variation in levels of clothianidin found in the Celero treated rows with a trend toward higher levels at 5 cm (2 in) depth than at 20 cm (8 in) (Table 5).

In 2004 and 2005, numbers of grubs were significantly reduced in field-grown nursery crops by applying imidacloprid (Marathon II) through drip irrigation. In 2006, the reduction in the number of grubs was not significant, but the percentage reduction compared to the untreated trees was similar to 2004 and 2005. We were also able to significantly reduce grub populations with treatments of nematodes (EPN) + imidacloprid applied by three different methods. There were problems injecting the EPN + imidacloprid into the drip line (trial-2 2005), which may have reduced the efficacy of the drip application treatment. Although, this treatment still reduced the numbers of grubs by 54%. The low percentage of soil samples from the drip treatment where EPN were detected may be related to EPN staying in the drip line. The level of control achieved may have resulted primarily from the imidacloprid, although, imidacloprid alone is considered a poor curative material (12), and this treatment was applied at only 1/4 of the rate used for the preventive treatments, in 2005.

Oriental beetle was the most common scarab found in all three trials, which suggests that the roots of woody plants are favored hosts for this species. Oriental beetle is one of the most serious pests of nursery crops in New Jersey (11). In contrast, the Japanese beetle was uncommon (Table 4). During the three years of this project, we dug 270 trees and collected a total of four JB grubs.

The data from ELISA analysis of soil samples showed an interesting and consistent trend in 2005. Levels of imidacloprid at the 10 and 20 cm (4 and 8 in) depths, increased as the distance from the injection site increased. The highest imidacloprid levels were found at the far end of the rows at all three depths in 2005. The overall means of imidacloprid concentrations were similar in 2004 and 2005 at the 5 cm (2 in) depth, but much higher in 2004 than 2005 at the 10 and 20 cm (4 and 8 in) depths. The levels of imidacloprid in 2006 were much lower than in 2004 and 2005. However, in 2006

soil samples were taken next to trees not next to emitters as in 2004 and 2005. The overall means at the 5 cm (2 in) depth for both external and internal emitter rows in 2006, were similar to levels found in the 2004 samples taken at the same depth 30 cm (12 in) from the emitters. There were very low levels of imidacloprid and no clothianidin in the samples from the untreated trees, indicating that insecticides in the samples from the treated trees were the result of our treatments.

This research was conducted under relatively ideal conditions. We used newly planted trees which generally have smaller root zones than more established trees of the same species. Adequate coverage of relatively small root zones should be more likely than with larger root zones. In addition, the system we used in 2004 and 2005 had drip emitters at each tree only, and thus, none of the insecticide was dispensed between trees. In contrast, the type of drip line most commonly used by the growers in this area has emitters at 60 cm (24 in) intervals. A similar starting dose of insecticide applied through this type of line would be spread over a larger area and not concentrated only at the trees. The 2006 trial included standard drip lines where emitters were spaced at 60 cm (24 in) intervals and did not necessarily line up with the trees. Based on percentage control compared to untreated trees, the level of control in the imidacloprid and clothianidin treatments applied through drip lines with internal emitters in 2006 were comparable to the 2004 and 2005 results with external emitters. This research shows that drip irrigation systems can be used to effectively apply insecticides for control of scarab grubs in field-grown nursery crops. Furthermore, while more testing is needed on efficacy of EPN + imidacloprid applied through drip irrigation as a grub control in nursery crops, the treatments were effective when applied as surface drenches or injected into the soil.

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