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SEASON-LONG INSECTICIDE EFFICACY FOR HEMLOCK WOOLLY ADELGID, *ADELGES TSUGAE* (HEMIPTERA: ADELGIDAE), MANAGEMENT IN NURSERIES

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ABSTRACT

Nursery growers and extension personnel have to rely on efficacy data from forest and landscape systems to manage hemlock woolly adelgid in nurseries. Considerable differences in tree size and culture and application logistics could make such data unsuitable. We evaluated 12 different insecticide formulations for short and long-term control of hemlock woolly adelgid in container grown Eastern hemlocks, *Tsuga canadensis*. All products provided control of first generation hemlock woolly adelgids, though efficacy of foliar applications of neonicotinoids dinotefuran, imidacloprid (Marathon® II), and acetamiprid and foliar or drench applications of spirotetramat acted the most quickly. Foliar and soil applications of neonicotinoids and spirotetramat also prevented reinfestation of second generation crawlers. In contrast, second generation hemlock woolly adelgids successfully colonized trees treated with the contact insecticides, horticultural oil and bifenthrin. Systemic insecticides provided season-long control of hemlock woolly adelgid when applied to foliage, which is the preferred method of application of nursery growers.

Key Words: insecticide efficacy, foliar application, drench, neonicotinoids, nursery, spirotetramat, soilless substrates, container-grown nursery trees

RESUMEN

Los productores de plantas en viveros y personal de extensión tienen que confiar en los datos de eficacia de los sistemas forestales y del campo para manejar el adélgido lanoso del abeto en los viveros. Diferencias considerables en el tamaño del árbol, y su cultura y su aplicación logística podrían hacer estos datos inadecuados. Se evaluaron 12 diferentes formulaciones de insecticidas para el control a corto y largo plazo de adélgido lanoso del abeto en recipientes con plantas de Falso Abeto del Canada, *Tsuga canadensis*. Todos los productos controlaron la primera generación del adélgido lanoso del abeto, aunque la eficacia de las aplicaciones foliares de dinotefuran neonicotinoides, imidacloprid (Maratón® II) acetamiprid y aplicaciones foliares o de empapar de spirotetramat actuaron más rápidamente. Aplicaciones foliares y de suelo de los neonicotinoides y spirotetramat también impidió la reinfestación de los rastreadores (1 estadio de la ninfa) de la segunda generación. Por el contrario, la segunda generación del adélgido lanoso del abeto, colonizaron los árboles tratados con los insecticidas de contacto, el aceite de la horticultura y la bifentrina. Insecticidas sistémicos provieron el control del adélgido lanoso del abeto por toda la temporada cuando fueron aplicados al follaje, que es el método preferido de aplicación de los productores de plantas en viveros.

Hemlock woolly adelgid, *Adelges tsugae* (Anand), has devastated stands of Eastern hemlock, *Tsuga canadensis* L., and Carolina hemlock, *T. caroliniana* Engelman, in 18 states from Maine to Georgia (USFS 2011a). Hemlock woolly adelgid has also become a major pest of hemlocks in ornamental landscapes and urban forests where hemlocks are planted as hedges, shrubs, and shade trees (McClure 1987; Quimby 1996; Raupp et al. 2008). Hemlock woolly adelgid feeding depletes trees of carbohydrates and other resources and rapidly reduces the health and aesthetic value of trees (McClure et al. 2001). Trees lose their char-

acteristic dark green color that is valued in ornamental landscapes and instead become gray, pale-green, or yellow (McClure 1987). Infestation also causes bud mortality, needle loss, reduction of new growth, branch dieback, and tree death (McClure 1987; McClure et al. 2001).

Nurseries that produce hemlocks for ornamental landscapes are typically within the native range of hemlock forests. These hemlock trees are subject to a constant influx of hemlock woolly adelgid crawlers carried by wind or animals (McClure 1990). Growers from locations with active hemlock woolly adelgid infestations are prohibited from

selling plants to many states that have established quarantine laws (USFS 2011b). Even shipments within quarantine areas must be adelgid free to prevent rejection by customers or agriculture inspectors. Importantly, transportation of nursery stock is a primary mechanism of long-distance transport of hemlock woolly adelgid (USFS 2005).

Nursery growers and extension personnel rely on efficacy data derived from forest or ornamental landscapes in order to manage hemlock woolly adelgid in nurseries. For example, nursery growers primarily use horticultural oil, bifenthrin, acephate, and imidacloprid applied to tree foliage, which effectively control the hemlock woolly adelgid in forest and landscape trees (McClure 1987; Stewart & Horner 1994; Rhea 1996; McClure et al. 2001; Raupp et al. 2008). However, landscape and forest systems differ from nurseries in many ways. Landscape and forest trees are typically larger than trees in nurseries, which could affect insecticide coverage and distribution of systemic insecticides (Byrne et al. 2010). Nursery trees are grown in soilless substrates rather than mineral soil and receive consistent water and nutrients via irrigation that are not available to landscape or forest trees. Soil moisture and organic matter can affect systemic insecticide uptake and transport and thus efficacy (Rouchaud et al. 1996; Diaz and McLeod 2005; Lui et al. 2006). Therefore, differences in plant habit and culture could result in better or worse efficacy on container-grown nursery trees than would be predicted by research in landscapes or forests. Knowing the relative efficacy of foliar and soil insecticide applications will allow nursery growers to manage hemlock woolly adelgid in the most effective and economical way.

The objective of this study was to provide growers with necessary information to achieve optimal control of hemlock woolly adelgid with a single insecticide application. To achieve this we

evaluated the efficacy of 6 different insecticides using foliar, drench, soil-applied granular, and tablet formulations for control of the first hemlock woolly adelgid generation in spring. We then evaluated whether the insecticides can prevent re-infestation by the second generation of hemlock woolly adelgid in summer. Finally we evaluated how treatments and hemlock woolly adelgid infestation affect plant growth. To date there are no published evaluations of insecticide efficacy for hemlock woolly adelgid in container nurseries.

MATERIALS AND METHODS

This study was conducted at the North Carolina State University, Mountain Horticultural Crops Research & Extension Center (MHCREC) in Mills River, North Carolina. We purchased Eastern hemlock trees that were 134.5 ± 2 cm tall in #7 (26.5 L) containers from a local grower. The trees were free of hemlock woolly adelgids and had never received insecticide applications. For our study, trees were grown under 30% shade cloth on a gravel pad with drip irrigation. Trees were potted in 7 pine bark: 1 sand substrate amended with 2 lbs dolomitic limestone per cubic yard of substrate and 1 lb per cubic yard micronutrients (Micromax® Scott-Sierra Horticultural Products Co., Marysville, Ohio). Plants were top dressed with a controlled release fertilizer to receive 21g nitrogen per container (Osmocote®, 18-6-12, Scott-Sierra Horticultural Products Co., Marysville, Ohio). Insecticides employed in this study are displayed in Table 1.

Efficacy of insecticides targeting first generation hemlock woolly adelgids

On Apr 12 and Apr 20, 2010, we infested plants by cutting infested Eastern hemlock branches

TABLE 1. INSECTICIDE TREATMENTS (ALPHABETICAL BY ACTIVE INGREDIENT) APPLIED TO HEMLOCK TREES IN 7 GALLON CONTAINERS TO CONTROL THE HEMLOCK WOOLLY ADELGID.

Trade Name	Active Ingredient	Application Method	Rate	Manufacturer
Untreated Control	—	—	—	—
TriStar® 30SG	acetamiprid	foliar	8 oz/100 gal.	Cleary Chem. Corp
Talstar® F	bifenthrin	foliar	0.22 oz/ gal.	FMC Corp.
Safari® 2G	dinotefuran	granular	2.6 g/gal. of pot	Valent USA Corp.
Safari® 20 SG	dinotefuran	foliar	8 oz/100 gal.	Valent USA Corp.
Marathon® 1%G	imidacloprid	granular	5 g/gal. of pot	Bayer
CoreTect™	imidacloprid	tablet	5 tablets/pot	Bayer
Marathon® II	imidacloprid	foliar	1.7 oz/ 00 gal.	Bayer
Horticultural Oil	paraffinic oil	foliar		
Kontos™	spirotetramat	foliar	1.7 oz/100 gal.	Bayer
Kontos™	spirotetramat	foliar	3.4 oz/100 gal.	Bayer
Kontos™	spirotetramat	drench	0.05 ml/l of pot	Bayer
Kontos™	spirotetramat	drench	0.1 ml/l of pot	Bayer
Horticultural oil		foliar	44 ml/gal.	Southern Agric. Insecticides

from trees in nearby natural areas when ovisacs and crawlers were present (Montgomery et al. 2009). We secured the infested branches to experimental plants with zip ties for 1 week each time. On Apr 28, 2010 we collected 1 branch tip from each cardinal direction of each tree and counted the number of crawlers on the terminal 4cm. We assigned trees to 1 of 5 blocks based on initial crawler density. Within each block trees were randomly assigned to 1 of 13 treatments (Table 1).

We applied insecticides on Apr 29, 2010. Foliar treatments were applied using a CO₂ powered backpack sprayer fitted with a single Spraying Systems D2-33 full-cone nozzle at 60 psi delivering 12.5 gpa. All foliar applications, except horticultural oil, included an adjuvant, Dyne-Amic (23.6ml/gal.; Helena Chemical Company, Collierville, Tennessee). We applied drench formulations by mixing product with 1 liter of water and pouring the solution evenly over the substrate. Granular applications were spread evenly on surface of substrate. CoreTect™ (20% imidacloprid and 80% 12-9-4 fertilizer) tablets were inserted approximately 10cm below the substrate surface. Hemlock woolly adelgids were counted as described 1, 7, 14, 28, and 42 d after treatment.

Residual efficacy to prevent re-infestation by second generation hemlock woolly adelgid

In Jun 2010, ovisacs and second generation crawlers were present on natural hemlock stands near MHCREC. On Jun 23 and 31, 2010, we re-infested the experimental trees as described previously. At this time we also infested a second set of untreated, previously uninfested trees to mea-

sure the success of second generation infestation in the absence of insecticides. Hemlock woolly adelgids were counted as described on Jul 8 (70 DAT) and Jul 22 (84 DAT) then again on Oct 8 (154 DAT), 2010.

Effect of insecticides and hemlock woolly adelgid on plant growth

As a measure of overall plant growth, the height of each plant and 2 perpendicular width measurements were recorded before the trial on Apr 28 (0 DAT) and on Oct 8, 2010 (154 DAT). To evaluate plant growth more specifically, the length of current year's growth was measured on 5 randomly selected branch tips per plant (Montgomery et al. 2009).

Statistical analysis of first generation and second generation hemlock woolly adelgid abundance and plant growth was conducted with ANOVA using initial abundance as a blocking factor (Proc Mixed, SAS 9.1 2002). If the ANOVA was significant ($P < 0.05$) means were compared using Fisher's protected LSD (Proc Mixed, SAS 9.1 2002).

RESULTS

Efficacy of insecticides targeting first generation hemlock woolly adelgids

All insecticides significantly reduced the abundance of first generation crawlers compared to untreated controls by 2 wk after treatment (Table 2). In general, foliar products reduced hemlock woolly adelgid abundance more quickly

TABLE 2. MEAN (±SE) HEMLOCK WOOLLY ADELGID ABUNDANCE (IN ORDER OF ABUNDANCE) ON 4 4-CM HEMLOCK BRANCH TIPS COLLECTED 0, 1, 7, 14, 28, AND 42 DAYS AFTER TREATMENT (DAT) WITH INSECTICIDES.

Treatment	App. Method	Mean (±SE) ¹ hemlock woolly adelgid abundance					
		0 DAT	1 DAT	7 DAT	14 DAT	28 DAT	42 DAT
Untreated Control	—	7.9 ± 3.4	4.9±1.2 ab	5.7 ± 1.8	4.2 ± 1.7 a	4.8 ± 1.2 a	6.1 ± 2.4 a
Marathon 1%G	granular	6.4 ± 1.7	5.8 ± 1.8 a	0.8 ± 0.4	0.1 ± 0.1 b	0.3 ± 0.3 c	0.0 ± 0.0 b
Safari 2G	granular	6.0 ± 1.7	3.9 ± 1.3 abc	0.5 ± 0.5	0.2 ± 0.2 b	0.0 ± 0.0 c	0.0 ± 0.0 b
Hort. Oil	foliar	7.7 ± 2.5	3.6 ± 1.3 bc	1.2 ± 0.8	0.4 ± 0.2 b	0.0 ± 0.0 c	0.0 ± 0.0 b
CoreTect	tablet	6.1 ± 1.8	2.6 ± 0.8 cd	1.8 ± 1.4	0.8 ± 0.7 b	0.8 ± 0.4 bc	0.1 ± 0.1 b
Talstar	foliar	7.3 ± 2.2	0.7 ± 0.5 de	0.5 ± 0.4	0.3 ± 0.2 b	0.0 ± 0.0 c	0.2 ± 0.2 b
TriStar 30SG	foliar	6.1 ± 1.5	0.4 ± 0.1 e	2.1 ± 1.7	0.7 ± 0.7 b	2.6 ± 1.8 b	0.0 ± 0.0 b
Kontos (high rate)	drench	7.5 ± 2.7	0.3 ± 0.3 e	2.6 ± 1.1	1.7 ± 1.0 b	0.1 ± 0.1 c	0.0 ± 0.0 b
Marathon II	foliar	6.8 ± 2.0	0.2 ± 0.2 e	0.9 ± 0.6	0.3 ± 0.3 b	0.0 ± 0.0 c	0.3 ± 0.2 b
Kontos (low rate)	foliar	7.4 ± 2.6	0.1 ± 0.1 e	4.7 ± 2.7	1.4 ± 0.5 b	0.1 ± 0.1 c	0.1 ± 0.1 b
Kontos (low rate)	drench	8.4 ± 3.4	0.0 ± 0.0 e	2.0 ± 1.1	0.9 ± 0.3 b	1.7 ± 0.9 b	0.2 ± 0.1 b
Kontos (high rate)	foliar	7.8 ± 2.5	0.0 ± 0.0 e	2.1 ± 0.7	1.0 ± 0.4 b	0.3 ± 0.1 c	0.0 ± 0.0 b
Safari 20 SG	foliar	6.2 ± 1.6	0.0 ± 0.0 e	2.8 ± 1.7	1.2 ± 0.8 b	0.0 ± 0.0 c	0.0 ± 0.0 b
$F_{12,48}^2 P$		1.28; 0.259	8.95; <0.001	1.38; 0.209	2.58; 0.010	7.39; <0.001	9.37; <0.001

¹Numbers followed by the same letter within a column are not significant at $P < 0.05$.

than drench, granular or tablet formulations. The exception to this was Kontos, which at high and low rate drench applications, reduced hemlock woolly adelgid abundance to levels similar to foliar applications by 24h after treatment (Table 2).

Residual efficacy to prevent re-infestation by second generation hemlock woolly adelgid

The second generation of hemlock woolly adelgids did not become as abundant on control trees as the first generation (Table 3). Two wk after reinfestation, hemlock woolly adelgid abundance was significantly greater on control trees than in all insecticide treatments except horticultural oil (Table 3). Hemlock woolly adelgid abundance decreased over the next 12 wk on all treatments. After summer aestivation, 14 wk after reinfestation and 22 wk after insecticide applications, only the control, horticultural oil, and Talstar treatments had hemlock woolly adelgid in our samples (Table 3).

Effect of insecticides and hemlock woolly adelgid on plant growth

There was no effect of any treatment on plant growth as measured by change in plant height ($F_{12,48} = 0.57$; $P = 0.856$), change in plant width ($F_{12,48} = 0.52$; $P = 0.888$), or tip growth ($F_{12,48} = 0.74$; $P = 0.702$) (data not shown).

DISCUSSION

Our research is the first published account of the speed and duration of insecticide efficacy for

managing hemlock woolly adelgid in container-grown hemlock trees. In particular, we demonstrated that Kontos is a promising new insecticide for managing hemlock woolly adelgid in nursery stock that provides rapid, season-long efficacy. Our research also confirms the efficacy of imidacloprid and dinotefuran formulations that have been relied upon for hemlock woolly adelgid management in forest and landscape trees (Stewart & Horner 1994; Rhea 1996; McClure et al. 2001; Raupp et al. 2008).

Pyrethroid and organophosphate insecticides, such as bifenthrin and acephate, are among the insecticides most frequently used to manage hemlock woolly adelgid in nurseries (S. Frank, personal observation). Growers apply these products at least 2 times during the growing season to prevent hemlock woolly adelgid infestation of nursery stock that would otherwise make trees unsalable. These broad-spectrum insecticides kill natural enemies and other non-target organisms on contact and leave a toxic residual that lasts for weeks after application (Raupp et al. 2001). As a consequence, pyrethroid and organophosphate insecticide use can result in secondary outbreaks of mites (Hardman et al. 1988; Prischmann et al. 2005), scale (McClure 1977; Raupp et al. 2001), and other pests (DeBach and Rose 1977; Hardman et al. 1988). Imidacloprid is the other most commonly used insecticide to manage hemlock woolly adelgid in nurseries and other systems (S. Frank, personal observation). Although imidacloprid is less toxic to natural enemies it can still promote spider mite outbreaks (Raupp et al. 2004).

TABLE 3. MEAN ($\pm$ SE) HEMLOCK WOOLLY ADELGID ABUNDANCE ON 4 4CM HEMLOCK BRANCH TIPS 14, 28, AND 98 DAYS AFTER REINFESTATION (DARI) WITH SECOND GENERATION CRAWLERS.

Treatment	App. Method	Mean ($\pm$ SE) ¹ hemlock woolly adelgid abundance		
		14 DARI (70 DAT)	28 DARI (84 DAT)	98 DARI (154 DAT)
Untreated control	—	2.0 $\pm$ 0.8 a	0.4 $\pm$ 0.2	0.2 $\pm$ 0.1
Kontos TM (high rate)	foliar	1.0 $\pm$ 0.4 ab	0.4 $\pm$ 0.4	0.0 $\pm$ 0.0
Horticultural Oil	foliar	0.8 $\pm$ 0.3 b	0.3 $\pm$ 0.2	0.8 $\pm$ 0.3
CoreTect	tablet	0.6 $\pm$ 0.2 bc	0.5 $\pm$ 0.3	0.0 $\pm$ 0.0
Kontos TM (high rate)	drench	0.6 $\pm$ 0.3 bc	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
Kontos TM (low rate)	foliar	0.6 $\pm$ 0.2 bc	0.5 $\pm$ 0.3	0.0 $\pm$ 0.0
Kontos (low rate)	drench	0.5 $\pm$ 0.4 bc	0.1 $\pm$ 0.1	0.0 $\pm$ 0.0
Marathon® 1%G	granular	0.4 $\pm$ 0.3 bc	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
Talstar® F	foliar	0.4 $\pm$ 0.1 bc	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1
TriStar® 30SG	foliar	0.3 $\pm$ 0.1 bc	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
Marathon® II	foliar	0.3 $\pm$ 0.2 bc	0.2 $\pm$ 0.1	0.0 $\pm$ 0.0
Safari® G	granular	0.1 $\pm$ 0.1 c	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
Safari® 20 SG	foliar	0.1 $\pm$ 0.1 c	0.3 $\pm$ 0.2	0.0 $\pm$ 0.0
		$F_{12,50} = 2.37$; $P = 0.017$	$\chi^2_{12} = 19.06$ $P = 0.0884$	$\chi^2_{12} = 32.3$ $P < 0.001$

¹Numbers followed by the same letter within a column are not significant at $P < 0.05$.

Spider mites and soft and armored scale are also important pests of hemlocks in nurseries. Our research indicates that Kontos, Safari, TriStar, and horticultural oil are effective alternatives to pyrethroids, organophosphates, and imidacloprid in nursery production. Products such as Safari and TriStar effectively control many armored scales and could be used when elongate hemlock scale or other armored scales need to be managed in combination with hemlock woolly adelgid. Kontos and Horticultural oil are alternatives to neonicotinoids that growers could use particularly if mite outbreaks are common.

Growers prefer to make foliar rather than drench insecticide applications because they can make foliar applications rapidly with air-blast or other spray equipment. As expected the granular, drench, and tablet formulations of imidacloprid and dinotefuran took longer to achieve control because they must move into the soil then be taken up by the plant before insects ingest them. Despite a brief delay of about 2 wk, granular and drench formulations reduced hemlock woolly adelgid abundance to near zero in the first generation and prevented reinfestation by the second generation. Surprisingly, drench applications of Kontos reduced hemlock woolly adelgid abundance 1 day after treatment to levels comparable to foliar applications.

In our experiment, manual reinfestation of trees with second generation crawlers simulated the natural reinfestation that trees would experience if grown in a nursery near natural hemlock woolly adelgid infestations because crawlers can be carried to new trees by wind or birds. Our infestation method did not achieve as high a population in the second generation as in the first but the new untreated trees were infested with 2 hemlock woolly adelgid per 4cm of branch. All insecticide treatments reduced second generation abundance even though they had been applied 12 weeks earlier. The trend 4 wk after reinfestation was for lowest hemlock woolly adelgid abundance on trees that received granular and drench formulations though Tristar also had no hemlock woolly adelgid at this time. Hemlock woolly adelgid abundance in all treatments declined by Oct when the insects came out of aestivation and began feeding again. At this time, the only treatments with hemlock woolly adelgids present were the control trees and trees treated with the contact insecticides, horticultural oil and Talstar, as opposed to systemic insecticides. This indicates systemic insecticides - neonicotinoids and Kontos - provide season-long control of hemlock woolly adelgid even if they are applied to foliage which is the most rapid and preferred method of growers.

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