INCIDENCE, ABUNDANCE, AND SEVERITY OF MITES ON HEMLOCKS FOLLOWING APPLICATIONS OF IMIDACLOPRID

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Abstract. Hemlock woolly adelgid (*Adelges tsugae*), is one the most serious and damaging insect pest of hemlocks (*Tsuga* spp.) in the eastern United States. The systemic insecticide imidacloprid has gained widespread acceptance and use by arborists to control hemlock woolly adelgid. In a residential landscape, we found populations of spruce spider mites and hemlock rust mites; their injury was found to be greater on hemlocks treated with imidacloprid than on untreated trees. A survey of hemlocks in gardens, parks, and residential landscapes revealed that hemlocks treated with imidacloprid were more likely to be infested with spider mites but not rust mites. Moreover, terminals on imidacloprid-treated hemlocks were approximately nine times more likely to have severe needle damage than untreated trees. Arborists and landscape managers applying imidacloprid to hemlocks should carefully monitor mite populations on treated trees and be prepared to intervene should mite populations increase. This study serves as an example of how a pesticide application for a primary pest, hemlock woolly adelgid, may contribute to the development of a secondary pest—in this case, mites.

Key Words. Secondary pest outbreak; imidacloprid; spruce spider mite; hemlock rust mite; hemlock woolly adelgid.

Systemic insecticides have gained widespread use in the landscape maintenance industry during recent years (Mullins 1993; Sclar and Cranshaw 1996; Gill et al. 1999). Many systemic insecticides, including oxydemeton-methyl, dimethoate, disulfoton, dicrotophos, acephate, and imidacloprid, are applied to the soil where they are absorbed through the roots and distributed throughout the canopy of the plant. These materials have distinct advantages over insecticides applied as sprays to the canopy. First, they provide thorough distribution of insecticide within the plant. Coverage can be difficult with foliar applications when trees are large or obstructed by buildings, water, or property boundaries (Gill et al. 1999). Second, problems associated with drift, such as residues on buildings and vehicles, exposure of workers and nontarget organisms, and the visual apprehension engendered by aerial spray, can be largely avoided when insecticides are administered through the bark or soil as systemics (Sclar and Cranshaw 1996; Gill et al. 1999).

Canadian hemlock *(Tsuga canadensis)* and Carolina hemlock *(T. caroliniana)* are important components of the urban forest in the eastern United States. The hemlock woolly adelgid *(Adelges tsugae)* is an extremely important insect pest of these two species in both natural and managed settings due to its ability to kill infested trees (McClure et al. 2001). Many insecticides can control adelgids on hemlocks. Early studies demonstrated that foliar applications of insecticides—including insecticidal soap and oil, as well as numerous petrochemical insecticides—provided good to excellent control of the hemlock woolly adelgid (McClure 1987, 1988). Thorough coverage was the key to effective control. More recently, McClure (1992) provided convincing evidence that several systemic insecticides, including oxydemeton-methyl, bidrin, and acephate, provided excellent levels of control when injected or implanted through the bark of the tree. Steward and Horner (1994) demonstrated that imidacloprid applied as a soil injection provided excellent control of hemlock woolly adelgid on established eastern hemlocks in a formal public garden. Webb et al. (2003) found that hemlocks treated with imidacloprid remained free of the pest for more than 27 months following a soil application and recovered dramatically after adelgid populations were reduced.

Imidacloprid is one of the most commonly used materials in landscapes owing to its range of activity against key pests including leaf beetles (Sclar and Cranshaw 1996), lace bugs (Gill et al. 1999), aphids (Sclar and Cranshaw 1996), scales (Sclar and Cranshaw 1996; Gill and Reeser 1999), adelgids (Steward and Horner 1994), psyllids (Young 2002), leafminers (d'Eustachio and Raupp 2001), and flatheaded borers (Herms 2003). However, several anecdotal reports and one empirical study (Sclar et al. 1998) indicated that spider mite populations and attendant plant injury may increase following the application of imidacloprid to woody landscape plants such as elm and honeylocust (Sclar et al. 1998). These reports parallel similar observations in agricultural crops in which imidacloprid applications have been implicated in increased mite populations in bedding plants and hops (Sclar et al. 1998; James et al. 2001).

By the end of the 1990s, scientists at the University of Maryland (Raupp), Beltsville Agricultural Research Center (Webb), and Bartlett Tree Experts (Booth) received reports from commercial arborists and landscape managers that mites and injury caused by mites seemed to be more common on hemlocks treated with imidacloprid. Due to the widespread use of imidacloprid for control of hemlock woolly adelgid and growing concerns about increased mite problems following the application of imidacloprid, two independent studies were conducted. The first by Webb and Raupp examined the effects of imidacloprid on the abundance of spruce spider mite *(Oligonychus ununguis)* and hemlock rust mite *(Nalepella tsugifolia)* and their damage on Canadian hemlocks *(T. canadensis)* in a residential landscape. The second by Raupp, Szczepaniec, Booth, and Ahern compared hemlock rust mite abundance and spruce spider mite injury on treated and untreated Canadian hemlocks in parks, gardens, and residential landscapes in the Washington–Baltimore, U.S., metropolitan area. The objectives of the studies were twofold. First, we wanted to know if mites were more abundant or less abundant on imidacloprid-treated trees compared to untreated ones. Second, we wanted to know if mite injury was greater or less on trees treated with imidacloprid compared to untreated controls.

MATERIALS AND METHODS

Study 1: Treated Hemlocks in a Residential Landscape

Hemlocks used in this study were established *T. canadensis* growing in a residential landscape in Frederick County, Maryland. They were infested with the hemlock woolly adelgid for several years and had little or no new growth but lacked dieback or needle loss. Eight hemlock trees 5 to 20 m (16 to 66 ft) in height were randomly assigned to one of two treatments. Four were treated with imidacloprid and four were untreated.

Imidacloprid treatment consisted of a soil-drench application of Merit® 75 WP, 2 g/2.5 cm (0.07 oz/1 in.) dbh, according to the label directions (Bayer 1998). The application was made on 31 March 1999. The soil at the site was moist and did not require supplemental irrigation at the time of application. No supplemental irrigation was supplied during the course of the study.

The effect of imidacloprid on populations of mites and their injury was evaluated in the following way: On 12 October 2001, a pole pruner was used to remove terminals from five branches evenly spaced around the circumference of each tree. Terminals were returned to the laboratory and examined under a microscope. Two species of mites were common—the spruce spider mite and the hemlock rust mite. Mite abundance was estimated by observing the number of mites and mite eggs on the distal 2.5 cm (1 in.) of each terminal. Each terminal was classified using the following abundance rating: 0 = no mites or mite eggs, 1 = 1 to 3 mites or mite eggs, 2 = 4 to 10 mites or mite eggs, 3 = 11 to 25 mites or mite eggs, 4 = 26 or more mites or mite eggs.

Mite injury appeared as fine stippling, usually at the base of older needles, caused by spider mites, or as russetting, usually of entire needles, caused by rust mites (Johnson and Lyon 1988). Needles of hemlock heavily infested with spider mites turn white, usually at the base first, and appear bleached (Johnson and Lyon 1988; Lehman 2002). Terminals were rated for the amount of injury they had sustained and were classified using the following injury rating: 0 = no damage; 1 = stipples or russetting on 1 or 2 needles; 2 = stipples or russetting on several needles; 3 = 10% of needles with stippling or russetting; 4 = 25% of needles with stippling or russetting; 5 = more than 50% of needles with stippling or russetting; 6 = 100% of needles with some stippling and russetting; 7 = 100% of needles injured, some needles white; 8 = 100% of needles injured, 50% of needles white; 9 = 100% of needles injured, more than 50% of needles white; 10 = dead needles.

Statistical methods were as follows: Prior to the analysis, data were examined for normality and homogeneity of variance and transformed, if necessary, to meet the assumptions for the analysis of variance. Data were analyzed as a completely randomized design using an analysis of variance (PROC MIXED, SAS Institute 1999).

Study 2: Survey of Hemlocks in Managed Landscapes

Discussions with arborists and landscape managers in the Washington–Baltimore metropolitan area quickly established that hundreds of hemlock trees had been treated with imidacloprid in a variety of locations since the mid-1990s. Study sites included in the survey had to meet two criteria. First, all study sites were populated with both treated and untreated *T. canadensis* of similar size and age growing in proximity under similar environmental conditions. Second, pesticide applications to treated trees were made by one of four certified pesticide applicators using known rates, methods, and dates of applications.

Four study sites in the Washington–Baltimore metropolitan region met the criteria for inclusion in the study. All four sites were within a 70 km (42 mi) radius of College Park, Maryland. Location 1 was a large, private garden and adjacent public park populated by more than 200 mature hemlocks. Trees were distributed around the garden and park as specimens, components of landscape beds, and along a forest edge. Hemlocks at this location were treated on 16 October 1997 with soil injections of imidacloprid [Merit 75 WP, 2 g/2.5 cm (0.07 oz/1 in.) dbh]. Of more than 200 trees that were treated, 10 randomly selected trees were included in the survey. Untreated trees at Location 1 were part of the same hemlock population occupying a park immediately adjacent to and separated from the garden by a fence. Ten untreated trees were randomly selected for inclusion in the study. Hemlocks ranged in height from 3 to 18 m (10 to 60 ft).

Location 2 was a public research garden populated by more than 100 mature hemlocks in formal and informal landscape beds. Hemlocks at this location were treated on 29 August 2000 with soil injections of imidacloprid [Merit 75 WP, 2 g/2.5 cm (0.07 oz/1 in.) dbh]. Of several dozen trees that had been treated, five were randomly selected for the survey. Five untreated trees at Location 2 were part of an informal landscape bed planted approximately 1,000 m (3,300 ft) from the treated trees. Trees ranged in height from 2 to 5 m (7 to 16 ft).

Location 3 was a privately owned retirement community. All hemlocks included in the survey were specimen plants distributed in landscape beds in an 80 ha (200 ac) managed landscape. Nine hemlocks at this site were treated on 20 April 2001 with soil injections of imidacloprid [Merit 75 WP, 2 g/2.5 cm (0.07 oz/1 in.) dbh]. Ten untreated hemlocks were sampled at this location. Trees ranged in height from 3 to 6 m (10 to 20 ft).

Location 4 was a residential neighborhood where hemlocks had been planted as specimens along property boundaries. Five trees at this site were treated on 16 June 1999 with imidacloprid [Merit 75 WP, 2 g/2.5 cm (0.07 oz/1 in.) dbh]. Approximately 120 m (400 ft) away, on another property boundary, five untreated trees were surveyed. Hemlocks ranged in height from 2 to 8 m (7 to 26 ft).

Hemlocks included in the survey were sampled in the following way: Terminals of five randomly selected branches were removed at evenly spaced intervals around the perimeter of each tree with pole or hand pruners between 27 April and 6 May 2003. Twenty needles on each terminal were examined with a 10× hand lens, and the number of hemlock rust mite nymphs and adults was counted. At the time trees were sampled, spider mites were extremely rare or absent on all trees. However, injury from infestations in previous years was clearly evident. We used the presence of severe chlorosis indicated by bleaching of several or all needles on the previous two seasons' growth to be indicative of high levels of spider mite activity (Johnson and Lyon 1988; Lehman 2002). The percentage of terminals with injured (bleached) needles in a sample of five was recorded for each tree.

Statistical methods included the following: The frequency with which treated and untreated hemlocks were infested with rust mites or injured by spider mites was compared with a log-likelihood test for contingency tables (G-test, Zar 1999). The abundance of rust mites and percentage of branches injured by spider mites were compared for treated and untreated plants using analysis of variance for a randomized complete block. Prior to the analysis, data were examined for normality and homogeneity of variance and transformed, if necessary, to meet the assumptions for the analysis of variance. Individual trees were treated as subsamples, and locations were treated as replicates using an analysis of variance (PROC MIXED, SAS Institute 1999).

RESULTS

Study 1: Treated Hemlocks in a Residential Landscape

Abundance ratings for hemlock rust mites differed significantly between treated and untreated trees at the residential landscape ($F = 17.02$; $df = 1, 6$; $P < 0.0062$) (Figure 1). Rust mites were more abundant on hemlocks treated with imidacloprid. The same result was true for abundance ratings for spider mites ($F = 16.88$; $df = 1, 6$; $P < 0.0063$) (Figure 1). Spider mites were more abundant on treated hemlocks. The injury caused by mites was also greater on trees treated with imidacloprid ($F = 16.30$; $df = 1, 6$; $P < 0.0068$) (Figure 1).

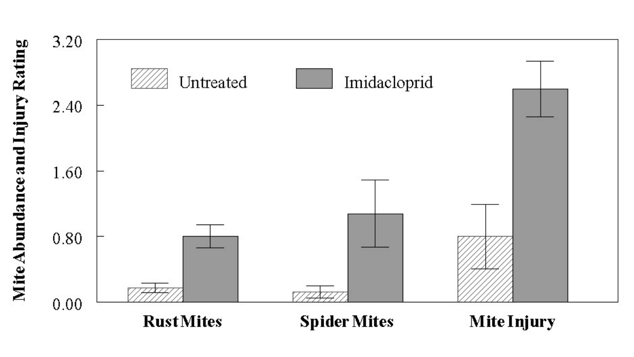

Figure 1. Rust and spider mite abundance and injury ratings on imidacloprid-treated and untreated hemlocks in a residential landscape in Maryland. Abundance rating: 0 = no mites or mite eggs, 1 = 1 to 3 mites or mite eggs, 2 = 4 to 10 mites or mite eggs, 3 = 11 to 25 mites or mite eggs, 4 = 26 or more mites or mite eggs. Injury rating: 0 = no damage; 1 = stipples or russetting on 1 or 2 needles; 2 = stipples or russetting on several needles; 3 = 10% of needles with stippling or russetting; 4 = 25% of needles with stippling or russetting; 5 = more than 50% of needles with stippling or russetting; 6 = 100% of needles with some stippling and russetting; 7 = 100% of needles injured, some needles white; 8 = 100% of needles injured, 50% of needles white; 9 = 100% of needles injured, more than 50% white; 10 = dead needles. Bars represent means, and vertical lines represent standard errors.

Study 2: Survey of Hemlocks in Managed Landscapes

Rust mites were ubiquitous. They were found at each location and on 47 of the 59 trees examined (80% of the tree population). The frequency with which rust mites infested treated and untreated hemlocks was 79% and 80%, respectively. These percentages did not differ. The number of rust mites on each terminal also did not differ between treated and untreated trees (F = 1.36; df = 1, 3; P < 0.327) (Figure2).

The injury caused by spider mites was less common than that of rust mites. Overall, only about 31% of the hemlocks surveyed had spider mite injury on any terminals. However, hemlocks treated with imidacloprid were significantly more likely to have spider mite injury than untreated trees (χ = 11.704, df = 1, P < 0.001). Fifty percent of the trees treated with imidacloprid (15 of 30) had severe spider mite damage on one or more terminals, whereas only 10% (3 of 29) of untreated trees had bleached needles. In addition, a significantly greater percentage of terminals sustained spider mite injury on treated compared to untreated trees (F = 23.47; df = 1, 2; P < 0.039) (Figure2).

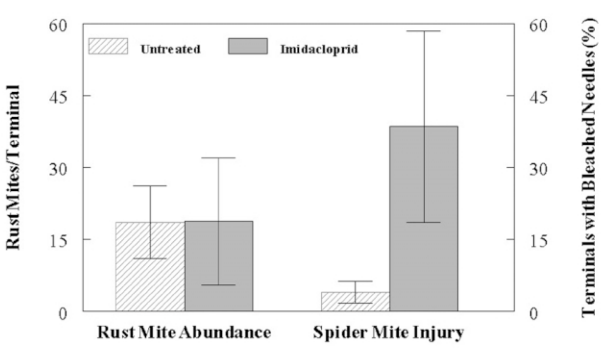

Figure 2. Abundance of hemlock rust mite and spruce spider mite injury on imidacloprid-treated and untreated hemlocks in landscapes in the greater Washington–Baltimore area. Bars represent means, and vertical lines represent standard errors.

DISCUSSION

The two studies were consistent in that they revealed greater levels of mite injury to hemlocks treated with imidacloprid. However, in the residential landscape study, injury was relatively low even on imidacloprid-treated trees. Injury on treated trees was observed on 10% or fewer of the needles. The survey of hemlocks in the second study revealed treated trees with an average of 39% of terminals with bleached needles. This result was contrasted to an average of 4% of terminals injured on untreated trees nearby. These results are in agreement with those of Sclar et al. (1998) and James et al. (2001), who reported greater spider mite injury on bedding plants and hops treated with imidacloprid.

The abundance of spruce spider mites was also greater on imidacloprid-treated hemlocks in the residential landscape. This result was in agreement with the finding that spider mites were more abundant on honeylocust trees treated with imidacloprid (Sclar et al. 1998).

Responses of rust mites to imidacloprid were less consistent between studies. In the residential landscape study, rust mite abundance ratings were about four times greater on treated trees compared to untreated ones. In the survey conducted in spring 2003, rust mites were abundant, averaging more than 18 mites per terminal, with many terminals bearing in excess of 500 mites. However, rust mite abundance did not differ between treated and untreated trees.

Three hypotheses have been suggested to explain greater mite abundance on plants treated with imidacloprid. One hypothesis suggests that sub-lethal doses of imidacloprid may stimulate the reproduction of pests. This phenomenon is known as hormoligosis (Luckey 1968). Hormoligosis has been implicated in increased reproduction in several species of sucking arthropod pests including green peach aphids, citrus thrips, and twospotted spider mite (Dittrich et al. 1974; Lowery and Sears 1986; Morse and Zareh 1991; James and Price 2002). To date, two studies have examined the sub-lethal effect of imidacloprid on the fecundity of spider mites. Sclar et al. (1998) examined the performance of two spotted spider mites feeding on imidacloprid-treated marigolds and found no evidence for hormoligosis. James and Price (2002) found twospotted spider mite fecundity to be increased by direct exposure to imidacloprid sprays or indirectly through exposure to imidacloprid-treated bean leaves.

A second mechanism to explain increased mite abundance on imidacloprid-treated plants is the elimination of natural enemies or suppression of their activities. Mullins (1993) warned that some natural enemies could be killed by foliar applications of imidacloprid but suggested that lethal effects should be negligible when imidacloprid was delivered systemically through seed, soil, or trunk applications. We know now that imidacloprid can be lethal to several types of predatory insects including lady beetles, minute pirate bugs, big-eyed bugs, and other predatory bugs when applied to the insect or as residues on plants or in plants following soil applications (Mizell and Sconyers 1992; Boyd and Boethel 1998; Sclar et al. 1998; Smith and Krischik 1999; Studebaker and Kring 2000; James and Vogele 2001; James and Coyle 2001). Sub-lethal effects of imidacloprid on predators include reduction in prey consumption rates and disruption of locomotion (Smith and Krischik 1999; Vincent et al. 2000; Elzen 2001). Sclar et al. (1998) suggested that suppression of natural enemies such as minute pirate bugs might be a factor contributing to greater levels of spider mites and their injury on honeylocust trees treated with imidacloprid.

A third hypothesis for increased mite populations on imidacloprid-treated plants has been proposed by researchers at the Bayer Corporation (Royalty 2003). This hypothesis suggests that imidacloprid alters the physiology of the plant in a way beneficial to phytophagous mites. Improved nutritional quality of leaves may result in enhanced mite performance, such as increased fecundity.

High levels of nitrogen fertilization have been implicated in outbreaks of several kinds of arthropod pests, including mites (Herms 2002). However, none of the landscape beds used in this study received supplemental fertilization. Adjacent lawn areas either received the same fertilization regime between treatments or received no fertilization. Therefore, elevated mite populations on trees treated with imidacloprid are unlikely to be related to differences in fertilization in this study.

Results of our studies confirm anecdotal reports of elevated mite abundance and attendant damage on trees treated with imidacloprid. They also agree with earlier findings of elevated mite abundance and injury on imidacloprid-treated landscape trees with a history of mite infestations (Sclar et al. 1998). It is noteworthy that imidacloprid applications do not result in elevated mite injury in all cases. This is good news. Only half of the hemlocks treated with imidacloprid had noticeable spider mite injury to their needles. Arborists and landscape managers should be aware that mites and their injury sometimes increase on hemlocks treated with imidacloprid. They should carefully and regularly monitor hemlocks treated with imidacloprid and be prepared to intervene, if necessary.

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Résumé. Le puceron lanigère de la pruche, *Adelges tsugae*, est l'un des insectes les plus sérieux et les plus dommageables des pruches, *Tsuga* spp., dans l'Est des États-Unis. L'imidacloprid, un insecticide systémique, est de plus en plus retenu et utilisé par les arboriculteurs pour le contrôle de ce puceron. En aménagement résidentiel, nous avons observé des populations de tétranyques de l'épinette et d'acariens de la pruche qui causaient des dommages plus importants sur les pruches traités avec l'imidacloprid que celles non traitées. Un inventaire des pruches dans les jardins, les parcs et sur les propriétés résidentielles a révélé que les pruches traitées avec l'imidacloprid tendaient à être plus infestées par les tétranyques mais pas par les acariens de la pruche. De plus, les pousses terminales des pruches traitées avec l'imidacloprid étaient environ neuf fois plus susceptibles d'avoir des dommages sévères sur les aiguilles que les arbres non traitées. Les arboriculteurs et les gestionnaires d'espaces verts qui appliquent de l'imidacloprid sur les pruches devraient suivre attentivement les populations d'acariens en général sur les arbres traités et être prêts à intervenir si ces populations s'accroissent. Cette étude constitue un bon exemple sur comment l'application d'un pesticide sur un insecte primaire, le puceron lanigère de la pruche, peut contribuer à permettre le développement d'insectes secondaires, dans ce cas-ci les acariens.

Zusammenfassung. Die Schierlingstannen-Wollschildlaus ist eine der ernsten Schadinsekten für *Tsuga* spp. in den östlichen Vereinigten Staaten. Das systemische Insektizid Imidacloprid hat unter den Arboristen bei der Kontrolle der Wollschildlaus weit verbreitete Annahme und Verwendung gefunden. In einer bebauten Landschaft fanden wir Populationen von Spinnmilben, Rostmilben und ihren Schäden mehr auf mit Imidacloprid behandelten Bäumen als auf unbehandelten. Eine Untersuchung von Schierlingstannen in Gärten, Parkanlagen und bewohnten Landschaften enthüllte, dass behandelte Tannen mit größerer Wahrscheinlichkeit von Spinnmilben, aber nicht von Rostmilben befallen werden. Überdies zeigten Terminaltriebe behandelter Tannen einen 9mal größeren Nadelschaden als unbehandelte Bäume. Arboristen und Landschaftsmanager, die Imidacloprid anwenden, sollten die Milbenpopulationen genau überwachen, um eventuell bei steigender Population eingreifen zu können. Diese Studie dient als Beispiel, wie ein Pestizid den primären Schädling, die Wollschildlaus, zwar bekämpft, aber den Befall durch sekundäre Schädlinge, wie die Milben, begünstigt.

Resumen. El aldégido del abeto americano, *Adelges tsugae*, es uno de los insectos más dañinos en el este de los Estados Unidos. El insecticida sistémico imidacloprid ha ganado amplia aceptación y uso por los arboristas para el control del aldégido. En un área residencial se encontraron poblaciones de arañas rojas de abetos y ácaros de piceas, y su daño era mayor en los abetos tratados con imidacloprid que en los no tratados. Un estudio de los abetos en jardines, parques y áreas residenciales reveló que los abetos tratados con imidacloprid eran más propensos a ser atacados por las arañas rojas que por los ácaros. Sin embargo, las ramas terminales en los abetos tratados con imidacloprid tenían nueve veces más daño en sus agujas que los no tratados. Los arboristas y los paisajistas que apliquen imidacloprid a los abetos deben monitorear cuidadosamente las poblaciones de ácaros en los árboles tratados y estar preparados para intervenir si sus poblaciones aumentan. Este estudio sirve como ejemplo de cómo la aplicación insecticida para una plaga primaria, el aldégido del abeto, puede contribuir al desarrollo de una plaga secundaria, en este caso los ácaros.