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# Assessing relationships between tree diameter and long-term persistence of imidacloprid and olefin to optimize imidacloprid treatments on eastern hemlock

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ABSTRACT

Hemlock woolly adelgid (HWA), *Adelges tsugae* (Annand), has caused widespread eastern hemlock mortality in the eastern U.S. HWA was first documented in Great Smoky Mountains National Park (GRSM) in 2002. Once documented, GRSM implemented an aggressive integrated pest management (IPM) program. As a part of this IPM strategy, systemic imidacloprid treatments have been widely used to preserve the Park's hemlock resources. A retrospective study was conducted in cooperation with GRSM to examine the long-term effectiveness of imidacloprid treatments on different size hemlock trees. Of particular interest is olefin, a metabolite of imidacloprid, which is greater than 15 times more toxic to HWA than imidacloprid. The concentrations of imidacloprid and olefin were assessed in hemlock branchlets four to seven years post-imidacloprid treatment. Samples were collected from three strata of the canopy from each of four size classes (30, 45, 61, and 76 cm DBH).

Imidacloprid and olefin were present in all size classes four to seven years after a single imidacloprid treatment. Hemlocks from the 61 and 76 cm size classes exhibited higher imidacloprid and olefin concentrations than the 45 cm hemlocks when larger hemlocks were given high-dose treatments. When all hemlocks were given low-dose treatments, 61 cm hemlocks had lower concentrations of olefin, but no significant differences in imidacloprid concentrations among size classes were detected. Olefin concentrations were higher in high-dose compared to low-dose treatments in 76 cm hemlocks. A significant linear relationship exists between the concentration of imidacloprid and olefin in individual branchlets.

A model was developed to optimize the dose of imidacloprid based on the diameter of hemlock trees. Use of this model will result in smaller (<30 cm) and larger (>63 cm) hemlocks receiving lower doses of imidacloprid with expected HWA suppression numerous years after treatment. Information obtained from this study can assist resource managers in developing and modifying HWA suppression programs to maintain low HWA populations while reducing the amount of imidacloprid applied to individual hemlocks. Optimal pesticide applications based on specific hemlock diameters may result in more environmentally and economically sustainable hemlock management programs.



## 1. Introduction

Natural habitats are threatened by exotic and invasive pest species (Vitousek et al., 1996, 1997; Mack et al., 2000). The encroachment of exotic species in a habitat can cause structural and functional changes to occur in natural systems (Castello et al., 1995; Liebhold et al., 1995; Ellison et al., 2005). This phenomenon is both an ecological and economic process (Liebhold et al., 1995). Every year in the United States exotic species in forests cause more than 2 billion dollars in economic impact due to control expenses and product losses (Pimentel et al., 2000). In the last 100 years, many tree species in eastern forests of the United States have been negatively affected by feeding activity or pathogen transmission by nonnative insect pests. Some species that have either been lost or have suffered massive declines in abundance include: American beech (*Fagus grandifolia* Ehrh.), American chestnut (*Castanea*

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*dentata* [Marsh.] Borkh.), eastern hemlock (*Tsuga canadensis* [L.] Carriére), Carolina hemlock (*Tsuga caroliniana* Engelm.), elm (*Ulmus* spp.), and oak (*Quercus* spp.) (Liebhold et al., 1995).

Eastern hemlock populations have declined due to hemlock woolly adelgid, *Adelges tsugae* (Annand) (HWA) (Hemiptera: Adelgidae). The range of eastern hemlock spans much of the eastern United States, from New England south to Georgia and the Atlantic coast west to Wisconsin (USDA Forest Service, 1990). Eastern hemlock has a profound influence on the structure and function of its surrounding ecosystem and is an important foundation species in southern Appalachian forests (Ellison et al., 2005). It is a slow-growing species that inhabits a distinctive ecological niche and thereby plays a vital role in the southern Appalachians (Orwig and Foster, 1998; Ward et al., 2004). As a low-growing evergreen, hemlock provides foliage as food for deer in the winter (Lapin, 1994) and canopy as a habitat for many bird species throughout the year (Tingley et al., 2002), as well as diverse arthropod communities, with greater than 400 insect species associated with hemlock (Wallace and Hain, 2000; Buck et al., 2005; Lynch et al., 2006; Dilling et al., 2007, 2009; Coots et al., 2012). Dense shade provided by hemlocks regulates stream water temperatures. In addition, streams associated with hemlock have higher aquatic macroinvertebrate species richness compared to streams in hardwood-dominated watersheds (Snyder et al., 2002; Webster et al., 2012). Many terrestrial and aquatic species depend on eastern hemlock and are being negatively impacted by the loss of this foundation species.

Hemlock woolly adelgid, which is currently present in 19 states (USDA Forest Service, 2015), has caused a drastic reduction in the hemlock population. Depletion of carbohydrates, reduction of photosynthetic ability, reduction in growth, and initiation of a hypersensitive response occurs in hemlocks due to HWA feeding (Young et al., 1995; Radville et al., 2011; Gonda-King et al., 2014; Nelson et al., 2014), eventually leading to hemlock mortality. Tens of millions of dollars have been invested in programs to suppress HWA and preserve hemlock resources (Aukema et al., 2011).

Eastern hemlock is less resistant to HWA than many other hemlock species (Lagalante and Montgomery, 2003), and native predator communities do not cause sufficient HWA population suppression (McClure, 1987; Wallace and Hain, 2000). As a result, insecticides, especially imidacloprid, are a key component of many HWA management programs. Imidacloprid is a neonicotinoid insecticide that affects the central nervous system of insects to cause eventual termination of nerve signals (Nauen and Bretschneider, 2002). Some of the metabolites of imidacloprid also have insecticidal properties (Nauen et al., 1998). Of particular importance in HWA control is the insecticidal metabolite imidacloprid-olefin, hereafter referred to as olefin (Coots, 2012; Coots et al., 2013; Mayfield et al., 2015; Benton et al., 2015). Olefin is over 15 times more toxic to HWA than imidacloprid based on laboratory dose–response assays (Coots, 2012). The persistence of imidacloprid and olefin in hemlocks can provide long-term presence of insecticidal compounds in hemlock foliage for the suppression of HWA (Cook, 2008; Coots, 2012; Coots et al., 2013; Benton et al., 2015).

The goal of this study is to provide comprehensive information regarding the persistence of imidacloprid and olefin in different size classes of hemlocks (measured as the diameter at breast height [DBH]) for use in forest health management decisions. The current study, which is part of a larger retrospective analysis conducted in collaboration with Great Smoky Mountains National Park (GRSM, also hereafter referred to as the Park), assessed differences in the concentrations of imidacloprid and olefin among hemlocks of different DBH size classes and the distribution of imidacloprid and olefin in the lower, middle, and upper strata of their canopies. In addition, this study explores the variation in imidacloprid and olefin concentrations following only low-dose imidacloprid treatments among different size hemlocks and both low and high-dose imidacloprid treatments in large (76 cm DBH) hemlocks. It is anticipated that the treatment guidelines developed from this information will help to optimize imidacloprid treatments for the suppression of HWA in mixed size hemlock stands.

## 2. Materials and methods

### 2.1. Site/Tree selection

Study sites were selected based on information provided by Park personnel, the GRSM hemlock treatment database, and site visits. Geographic location, forest composition (hemlock dominant or co-dominant), and imidacloprid treatment history were also considered. Study sites were chosen based on hemlock forest composition, similarity of treatment histories, and presence of sufficient number of hemlocks in the specified size classes to meet the study parameters. Imidacloprid basal drench treatments were applied to hemlocks at all selected sites prior to a drought that occurred in the southern Appalachians in the summer of 2007, thus all hemlocks experienced similar water stress conditions.

Eastern hemlocks ($n = 137$) were selected at three sites (Anthony Creek [35°35.682N, 83°45.845W], Hesse Creek [35°40.190N, 83°52.126W]), and Roostertown Road [35°46.676N, 83°14.219W]) on the western side of the Park and one site on private land (Mountain Homes, Inc. [35°40.574N, 83°52.144W]) located adjacent to the western border of the Park (Table 1, Fig. 1). Hemlocks at Anthony Creek, Hesse Creek, and Mountain Homes were sampled during the winters of 2011/2012 and 2012/2013. However, Roostertown Road was only sampled during the winter of 2011/2012.

Hemlocks from Mountain Homes ($n = 33$ trees, 17 ha, elevation: 350 m) received imidacloprid treatments in December 2007, 4 yr before sampling was initiated (Table 1). Imidacloprid treatments were applied to hemlocks at Hesse Creek ($n = 35$ trees, 6 ha, elevation: 311 m) and Roostertown Road ($n = 35$ trees, 1.6 ha, elevation: 548 m) in late 2006 and early 2007, respectively, 5 yr before the first samples were collected. Hemlocks at Anthony Creek ($n = 34$ trees, 21 ha, elevation: 671 m) were treated in late 2006, approximately 6 yr before samples were collected. Hemlocks, depending on the site and the year samples were collected, were treated with imidacloprid four to seven years prior to sample collection. For example, Anthony Creek was six years post-treatment when samples were collected in 2012 and seven years post-treatment in 2013.

The height and DBH of hemlocks ranged from 18.3–36.6 m and 28–79 cm, respectively. Hemlocks were divided into four DBH size classes, 30.4, 45.7, 61.0, 76.2 cm DBH (hereafter referred to as 30, 45, 61, and 76 cm). When the diameter of a hemlock was within 2.5 cm of each DBH size class value, it was placed within that size class, i.e. hemlocks between 58.5 and 63.5 cm DBH were included in the 61 cm size class. Each site contained 10 hemlocks from each of the 30, 45, and 61 cm size classes. However, the availability of trees in the 76 cm size class was limited. As a result only three to five hemlocks at each site from the 76 cm size class were available for sampling. Metal identification tags with tree labels indicating size class and flagging tape were used to identify study trees.

### 2.2. Insecticide application

All hemlocks received a basal drench imidacloprid treatment, which entails an imidacloprid suspension being poured into the soil within 0.6 m of the base of each hemlock trunk. Hemlocks in all size classes at Anthony Creek were given a low-dose imidacloprid