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Assessing an integrated biological and chemical control strategy for managing hemlock woolly adelgid in southern Appalachian forests

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ABSTRACT

In the eastern United States, hemlock woolly adelgid (HWA), *Adelges tsugae* Annand (Hemiptera: Adelgidae) is considered an invasive pest of eastern hemlocks; an ecologically foundational tree species. Current management of HWA focuses on chemical and biological controls, with recent research suggesting that these two tactics could be integrated successfully. The approach is to protect a subset of hemlocks with systemic insecticides while releasing predatory insects onto adjacent, unprotected trees. The goal of this study was to assess the effects of chemical and biological control tactics, alone and in combination, on hemlock health and HWA densities at three southern Appalachian sites (KY, WV, and TN) from 2010 to 2016. Although insecticide applications were effective at protecting individual trees, none of the overall treatments (chemical, biological, or combined) had a significant effect on tree health or HWA population index values relative to untreated plots. Tree health generally declined at all sites over time. HWA populations were highly variable over time and were likely more strongly influenced by extremely low, winter temperatures than by the treatments. Cross-correlation analysis of tree health and HWA population indicated a time-lag effect. At two of the three sites, recovery of tree health lagged 0 – 3 years behind decline in HWA population, and decline in HWA populations lagged approximately 0 – 1 years behind decline in tree health. The predatory beetle, *Laricobius nigrinus*, was recovered two-years, post-release at the KY and WV sites in 2012 and 2013, but was not recovered from the TN site. The lack of sustained recovery of *L. nigrinus* may be attributable to the occurrence of extremely low, winter temperatures in 2014 and 2015, which produced subsequent crashes in the HWA populations. In TN, the *L. nigrinus* population may have been unrecoverable due to a decline in the HWA population shortly after initial release.

1. Introduction

The hemlock woolly adelgid (HWA), *Adelges tsugae* Annand (Hemiptera: Adeglidae), is found on hemlock species (*Tsuga* spp.) worldwide (Havill and Foottit, 2007). HWA is an obligate herbivore of hemlock trees, which it uses as a secondary host, and spruce species (*Picea* spp.), which are its primary hosts (Havill and Foottit, 2007). In its native ranges, HWA rarely reaches population levels that are injurious to hemlocks because it is kept suppressed through a combination of evolved host resistance and a complex of native predators (Havill et al., 2006; Havill and Foottit, 2007). The insect was discovered in the eastern United States (U.S.) in the early 1950 s near Richmond, VA, and this population has been traced back to its origin in the southern region of the Japanese island of Honshu, near the city of Osaka (Havill et al., 2006; Havill et al., 2014). Since then, HWA has become a serious pest on eastern (*T. canadensis* Carriére) hemlock (Wallace and Hain, 2000; Havill and Foottit, 2007), and is established throughout the eastern U.S. from Maine to Georgia and as far west as Michigan (USFS., 2015).

HWA spreads to trees primarily by wind-blown dispersal, incidental transport by birds and other animals, and via the shipment of infested nursery stock (McClure, 1989b, 1990, Russo et al., 2016). Upon arriving at a hemlock tree, HWA settle and feed at the base of needles. First instars, known as “crawlers”, have the capacity to disperse on a host tree and can travel to unoccupied needles (Havill and Foottit, 2007). HWA are bivoltine with a spring generation (progrediens) and a winter generation (sistens). The sistens differ in that they undergo aestival diapause from July through October (Ward et al., 2004; Havill et al., 2014). HWA damages its host by inserting its stylet into the xylem ray parenchyma cells where it feeds (Young et al., 1995). This results in

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carbohydrate depletion, foliar desiccation, and reduction of new growth (Miller-Pierce et al., 2010; Gonda-King et al., 2012; Oten et al., 2012; Domec et al., 2013; Gonda-King et al., 2014). The health of infested hemlock stands is largely dependent upon the density of the HWA (McClure, 1991). Initially, the HWA population causes a decline in tree health. As the trees experience dieback, the HWA population declines due to poor host quality and a lack of new needles on which to settle. This decrease in the HWA population may allow trees to recover and resume new shoot growth. However, new shoots will often be re-infested by HWA and the cycle of decline will continue (McClure, 1991; Orwig et al., 2002). The rate at which this process occurs is not constant. Abiotic factors such as fluctuations in temperature can kill HWA, which can prolong stand survival and slow the range expansion of HWA (Parker et al., 1998, 1999; Skinner et al., 2003; Paradis et al., 2008; McAvoy et al., 2017; Mech et al., 2017).

Eastern hemlock is a long-lived, shade-tolerant, coniferous tree that defines unique ecosystems in eastern North America (Ward et al., 2004), and thus it is considered a foundational species by ecologists (Ellison et al., 2005b, Orwig et al., 2012; Ellison et al., 2016). In areas where hemlock is in decline, major changes have been shown to take place (Ellison et al., 2005a). Stands can transition from hemlock to deciduous hardwoods, and soil-chemical properties can change; namely increased soil-nitrogen content and elevated pH levels (Ellison et al., 2005b). Soil ectomycorrhizal fungi have also been shown to be suppressed in stands experiencing HWA infestation. This can limit future forest regeneration (Lewis et al., 2008). Several avian species have been shown to be closely associated with hemlocks (Tingley et al., 2002). Furthermore, in areas lacking hemlock canopy cover, assemblages of fish and aquatic macroinvertebrates have been shown to be less rich (Evans, 2002).

Management tactics for HWA include chemical and biological controls, precise silvicultural practices, gene conservation, and improvement of host resistance (Vose et al., 2013). A commonly used neonicotinoid insecticide, imidacloprid (Silcox, 2002) is highly effective against HWA (Cowles and Cheah, 2002; Webb et al., 2003; Cowles et al., 2005; Benton et al., 2015). Treatments can be applied in a variety of ways including soil drenches, stem injections, foliar sprays and soil injections (Steward et al., 1998). There are, however, several notable limitations to chemical control programs. First, it is necessary to treat trees individually. Considering the size of a forest, only a small proportion of the trees can reasonably receive treatment. Additionally, the availability of manpower and supplies limits the scale of a chemical treatment program. Finally, the widespread use of insecticides is not desirable because of the potential harmful non-target effects on other insects (Dilling et al., 2009).

Classical biological control programs involve the importation of organisms that possess characteristics that make them able to survive in the targeted environment, unlikely to damage non-target species, and voracious enough to impact the population of the invasive pest. One of the benefits of a biological control program is that the control agent is capable of reproducing and self-dispersing (Van Lenteren et al., 2003). This alleviates a chief limitation of chemical-only controls. Furthermore, a biological control program limits the use of potentially harmful insecticides (Dilling et al., 2009). One of the biological controls for HWA is *Laricobius nigrinus* Fender (Coleoptera: Derodontidae). It is a specialist predator of HWA and can only complete its life cycle on HWA (Zilahi-Balogh et al., 2003b; Zilahi-Balogh et al., 2003a). *L. nigrinus* was cleared for release in 2000 and open releases began in 2003 (Mausel et al., 2010). Since then, > 380,000 individuals have been released in the eastern U.S. with evidence of establishment at many sites (Mausel et al., 2010; Roberts et al., 2011; Davis et al., 2012). *L.* nigrinus has shown the ability to cause significant impact to the winter sistens generation of HWA within four years of release (Mausel et al., 2008; Mayfield et al., 2015). While they can be effective, biological control programs are expensive in terms of the time necessary to identify a potential control agent, perform adequate host-range testing, and establish a field population (Paine et al., 2015). Trees may die before populations of biological control (like *L. nigrinus*) can establish.

The goal of this study was to evaluate an integrated pest management strategy for HWA that combines chemical and biological controls in the same forest stands. Previous research suggests that a combined approach to managing HWA could be effective (Eisenback et al., 2010; Joseph et al., 2011; Mayfield et al., 2015). Under this strategy, chemical treatments could be used to provide initial, temporary protection for a subset of hemlocks in the same forest stand while the *L. nigrinus* population establishes and increases on unprotected trees. After the chemically treated trees lose protection and become re-infested, the *L. nigrinus* population would move onto those trees to provide long-term suppression of HWA. In this study, we attempted to implement this integrated strategy at three sites in the southern Appalachian Mountains. Hemlock tree health, HWA population, and establishment of *L. nigrinus* were monitored over a 5 – 7 year period. We also explored potential correlative relationships between tree health and HWA populations.

2. Methods

2.1. Study sites

The study was conducted at three sites in the southern Appalachian Mountains containing mixed hemlock/deciduous forest. The mean annual minimum winter temperatures were developed from the Plant Hardiness Zones map provided by the United States Department of Agriculture (USDA ARS, 2016). The first site (KY) was established in 2010 at Kentucky Ridge State Forest (36.7196°N, −83.7505°W), with mean annual minimum winter temperatures of −20.6 to −17.8 °C. The second site (WV) was established in 2011 at Twin Falls State Park in West Virginia (37.6221°N, −81.4529°W), with mean annual minimum winter temperatures of −23.3 to −20.6 °C. The third site (TN) was established in 2012 near Oak Ridge, Tennessee (36.0486°N, −84.3879°W) with mean annual minimum winter temperatures of −17.8 to −15.0 °C. Sites were selected based on the widespread abundance of eastern hemlock, presence of HWA throughout the forest, and healthy hemlock crowns at the start of the study. Due to the limited number of *L. nigrinus* beetles that could be acquired for use in any given year, it was necessary to initiate the study at each site sequentially (KY in 2010, WV in 2011, and TN in 2012) rather than simultaneously.

2.2. Assessment of tree health, HWA populations and predator establishment

Tree crown health was evaluated annually every spring using visual estimates of five variables; live crown ratio, live branches, foliage density, new growth and live branch tips. These measurements were rated on a percent scale (0 – 100) by a single observer standing roughly 10 m from the base of each tree. A score closer to 100 represented a healthier tree. The average of these five variables was then used to establish an overall tree crown health index (Jones et al., 2016).

HWA abundance was estimated annually in the spring by randomly sampling the terminal 30 cm of 10 branches from around the entire circumference of the tree. Woolly ovisacs of the current-year sistens were counted on the most recent flush of shoot growth (McClure, 1989a), up to a limit of 20 ovisacs per branch section. One ovisac was considered equivalent to one HWA. The total number of HWA from these branches was then divided by two to arrive at a density index of 0 – 100 (adapted from Cowles et al., 2006). A score closer to 100 represented a more heavily infested tree. This rating method was used because it permits rapid field-assessment and reduces skew from a few number of branches with potentially high population of HWA. Assessment of HWA populations were conducted in the first year of study for each site in order to establish a baseline starting-point for each treatment. The initial HWA index in KY was approximately 30 across all