MAINTENANCE OF EASTERN HEMLOCK FORESTS: FACTORS ASSOCIATED WITH HEMLOCK VULNERABILITY TO HEMLOCK WOOLLY ADELGID

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Abstract.—Eastern hemlock (*Tsuga canadensis* [L.]) is the most shade-tolerant and long-lived tree species in eastern North America. The hemlock woolly adelgid (*Adelges tsugae*) (HWA), is a nonnative invasive insect that feeds on eastern hemlock and Carolina hemlock (*Tsuga caroliniana* Engelm.). HWA currently is established in 17 eastern states and is causing tree decline and wide-ranging tree mortality. Our data from West Virginia and Pennsylvania suggest that hemlock crown vigor (a ranking of amount of live crown) relates to a predictable pattern of hemlock vulnerability at light and moderate levels of HWA infestation. We found that crown variables, such as live crown ratio and crown density and transparency, are accurate predictors of hemlock decline; more vigorous trees appear to be less vulnerable to HWA. Thus, silvicultural thinning treatments may be a means for reducing stand densities and increasing crown vigor in colder areas where climate may slow HWA spread.

INTRODUCTION

The hemlock woolly adelgid (HWA; *Adelges tsugae* Annand) is native to Asia and to western North America, where it has rarely exhibited outbreak dynamics on western hemlock species. HWA was first observed in eastern Virginia in 1951, and has since rapidly expanded its range. It is now found in 17 eastern states from southern Maine to northern Georgia, coinciding with the range of eastern hemlock (*Tsuga canadensis* [L.] Carr.) (Souto et al. 1996), its primary host, and Carolina hemlock (*T. caroliniana* Engelm.). Variations in the rates and direction of expansion are primarily influenced by landscape features and climate. Unlike most insects, HWA feeds, grows, and reproduces during the winter. Hence, periods of low winter temperatures can cause high HWA mortality and hinder population establishment, growth (Parker et al. 1999, Shields and Cheah 2005), and spread rates (Evans and Gregoire 2007). Likewise, the cold temperatures in the high elevations along the Appalachian Mountain Range have helped slow the rate of spread and establishment. HWA appears to spread more slowly in areas with mean minimum temperatures of -15 ºF (plant hardiness zone 5B). Regionally, HWA is spreading to new areas at a rate of 15.6 km/year south of Pennsylvania and 8.13 km/year (or less) in the northern portion of the hemlock's range (Evans and Gregoire 2007). Hemlock mortality associated with HWA establishment can range from almost none to nearly 100 percent (Orwig and Foster 1998, Bair 2002, Mayer et al. 2002). Mortality can occur quickly and uniformly throughout a stand or can occur slowly and in patches over more than a decade. Indirect ecosystem effects of HWA include changes in vegetation structure and composition, changes in wildlife communities, altered nutrient cycling rates, and changes in aquatic communities. Because widespread chemical control is economically unfeasible and biocontrols are still being tested, scientists and managers are investigating strategies to increase hemlock survival.

In the central and southern Appalachian Mountains, hemlock is most frequently found at elevations of 610 to 1,520 m, where it overlaps with red spruce starting at 1,370 m. Most commonly, hemlock is found on north- and east-facing slopes, and in moist coves and valleys. In the northeastern and northern portions of hemlock's range, it

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grows from sea level to about 730 m. On the Allegheny Plateau most of the hemlock grows between 300 and 910 m (Godman and Lancaster 1990). Because of hemlock's high tolerance to shade, it is typically found throughout all canopy layers and can continue to grow slowly for hundreds of years at high stand densities (Godman and Lancaster 1990). Hemlock's slow growth in these crowded conditions can provide a unique habitat for wildlife and aesthetic appeal to landowners.

Results from some studies in the northern portion of its range have suggested that hemlocks growing on sites with adequate and consistent moisture generally survive HWA infestation longer than trees growing on droughty sites and southern aspects, or waterlogged sites (Sivaramakrishnan and Berlyn 2000, Mayer et al. 2002, Orwig 2002, Pontius et al. 2004). However, other studies either failed to find a correlation with site factors (Orwig and Foster 1998, Eschtruth et al. 2006), or had high variability in their results (Royle and Lathrop 2000, Rentch et al. 2009).

Tree crown size and vigor appear to have the strongest relationship to hemlock vulnerability to HWA. Hemlocks in dominant and codominant overstory crown class positions appear to survive HWA longer than intermediate and overtopped crown class trees (Orwig and Foster 1998, Eschtruth et al. 2006) because in the early stages of infestation, intermediate crown class trees showed a higher likelihood of decline than overtopped trees (Rentch et al. 2009). A study conducted in HWA-infested stands located in Delaware Water Gap National Recreation Area, PA, predicted the odds of hemlock radial growth decline based on the relationship between crown condition and HWA infestation. Tree-ring chronologies from increment cores were used to develop a binomial decline index based on 3 consecutive years of below-average growth. Hemlock decline was modeled as a function of an extensive array of tree crown and site variables that were collected during the first 11 years of HWA infestation. Crown variables such as live crown ratio (LCR, ratio of live crown height to total height), crown density (an ocular estimate of the fullness of the crown, based on the amount of skylight blocked by leaves, branches, bole, and fruits), crown dieback (percent of branches with newly dead twigs in the live crown), and foliage transparency (relative amount of light that passes through the live crown) had the most explanatory power in the model, and were relatively accurate predictors of hemlock decline (Rentch et al. 2009). Consequently, silvicultural thinning treatments are being tested as a means for reducing stand densities and increasing crown vigor in colder areas where climate may slow HWA spread (Fajvan 2008).

The objective of this paper is to examine crown vigor data from HWA-infested stands in two different study areas and at different years post-infestation to determine whether patterns in tree decline are correlated with crown characteristics as predicted by the model developed by Rentch and others (2009). Stands located in West Virginia have been infested for only 4 years and HWA populations are still building. Stands in Pennsylvania have been infested for up to 16 years and are considered heavily infested. Some of these stands were sampled in 2003 to develop the aforementioned prediction model (Rentch et al. 2009). Additionally for the West Virginia data, we relate crown vigor data to songbird richness because changes in bird communities often reflect changes in stand structure. Finally, we discuss silvicultural objectives for improving the vigor of stands threatened by HWA.

METHODS

Study Area Descriptions and Sampling Methods

Delaware Water Gap National Recreation Area (DEWA) occupies approximately 27,800 ha along the Delaware River in northeastern Pennsylvania and northwestern New Jersey. Forest stands are primarily dominated by eastern deciduous species with pure hemlock stands occupying about 5 percent of the landscape (Eschtruth et al. 2006). In the mixed stands, hemlock can occupy 30-70 percent of the basal area (Mahan et al. 2004). HWA infestations were first detected in the park in 1989 (Evans 1995) and declines in hemlock health were evident in 1992. From 1993-1995 a system of 81 permanent plots was established in five hemlock stands where no HWA had been previously detected (Rentch et al.

2009). Each plot consisted of 10 permanently tagged hemlocks. A sub-sample of these trees was monitored annually and the following observations were recorded: LCR, crown density, crown dieback, and foliage transparency. All crown ratings were assessed to the nearest 5 percent compared to an ideal, healthy tree, consistent with Forest Health Monitoring Visual Crown Rating methodologies (Schomaker et al. 2007). All sample trees were assigned a vigor rating category (Table 1) at each measurement year. For this paper, we used data collected in 2007 and 2008.

On the New River Gorge National River (NERI) and Gauley River National Recreation Area (GARI) in southeastern West Virginia, a long-term hemlock ecosystem monitoring project was established in 1998 prior to HWA infestation (Wood et al. 2008). Study plots (n = 36) cover an extensive area spanning approximately 97 km from north to south and range in elevation from 427-853 m. Three moisture levels—hydric, mesic, and xeric—were each replicated 12 times. Each plot was 400 m^2 (0.04 ha) in size, with dimensions similar to other HWA stand-level monitoring studies (Mahan et al. 1998, Orwig and Foster 1998). Depending on site conditions, plots were placed either within a hemlock stand or within an isolated patch of hemlock trees and were square (20 m x 20 m) or rectangular (10 m x 40 m). On sites where hemlock was a co-dominant rather than a dominant tree species, plot-centers were deliberately placed where there was a visible amount of hemlock canopy cover. Centers and corners of each plot were permanently marked. We initiated baseline surveys of adelgid presence and hemlock tree vigor, live crown ratio, and diameter in fall/winter 1998 (Wood 1999a, 1999b). These data were collected each fall/winter (except during 1999 and 2005) to coincide with the November-April period in which the current season's HWA population typically exhibits woolly characteristics (Onken et al. 1994). Adelgid presence was determined by scanning the canopy of each hemlock tree with binoculars in search of the woolly form. HWA was first detected on eight plots in 2004. All hemlock trees ≥ 8 cm diameter at breast height (d.b.h.) that were rooted within or intersecting the outside perimeter of each 400 m^2 plot were tallied and d.b.h. was measured. Each tree was given a crown-vigor class rating, which was an index of the health of the live crown based on Onken and others (1994). The entire crown was inspected using binoculars and ranked as 1-5 (Table 1). Additionally, the live crown ratio was visually estimated as the percentage of the total tree height with live foliage.

Plots were placed at least 250 m apart when possible to accommodate avian surveys. Eight pairs of points were <250 m apart; none were <100 m apart. Generally, 250 m between point count stations is considered sufficient for independence between avian sampling stations (Ralph et al. 1993), although some studies have used distances of 100 m (Pendleton 1995). Avian point count surveys were completed each breeding season (late May-end June) from 1999-2008 using standard sampling protocols (Ralph et al. 1993).

Analysis

In the earlier study at DEWA, variables that provided the best fit in the logistic regression model developed for predicting the probability of hemlock decline were: LCR, crown density, d.b.h., foliar transparency and dieback, and plot-level percent HWA infestation (Rentch et al. 2009). We could not test the model directly with the new Pennsylvania (DEWA) and West Virginia (NERI, GARI) data because not all of these variables were measured. For the 2007-08 DEWA measurements (15+ years post-infestation), a value for HWA infestation was not available for those trees, but we did have data for crown density, dieback, transparency, and live crown ratio collected from 682 live trees. For 119 live hemlock trees on the eight West Virginia plots first infested in 2004, the only crown feature that could be compared with the model was LCR. We calculated mean LCR for each crown vigor class in 2004 (first year of infestation), 2006 (2 years post-infestation), and 2008 (4 years post-infestation). For both sites, the individual tree crown features were summarized for each vigor class assigned in the field and compared with the average crown features of trees that were used to develop the previous model (Rentch et al. 2009). Because trees that were categorized as being "in decline" were experiencing reduced diameter growth (Rentch et al. 2009), we plotted these same crown features relative to averages predicted by the model to estimate growth decline.

Table 1.—Definitions for crown vigor classes for each study area.

Pennsylvania		West Virginia	
Vigor class	Definition	Vigor class	Definition
Healthy	tree appears healthy with <10% branch or twig mortality or foliage discoloration	1	>95% healthy crown
Light decline	branch or twig mortality, or foliage discoloration on 10-25% of crown	2	>75-95% healthy crown
Moderate decline	branch or twig mortality or foliage discoloration on 26-50% of crown	3	>50-75% healthy crown
Severe decline	branch or twig mortality or foliage discoloration on more than 50% of crown	4	>25-50% healthy crown
Dead	no live foliage	5	>0-25% healthy crown

Additionally for all 36 West Virginia plots, we related mean LCR and mean crown vigor rank to songbird species richness with Pearson product-moment correlation. Richness was the number of different songbird species detected on each plot in each year. This analysis allowed us to evaluate whether a change in vegetation structure might affect songbird richness.

RESULTS AND DISCUSSION

Annual declines in tree vigor were evident during the first 4 years of infestation in West Virginia. The number of healthy trees decreased as trees categorized with lower crown vigor increased (Fig.1). Mean LCRs for hemlocks ranked as vigor 1 or 2 were higher than the mean of 55.6 percent predicted by the model (Fig. 2). Very few trees, however, were ranked as vigor 1 after the first measurement year (Fig. 1). Trees with crowns ranked 3 or 4 had live crown ratios similar to or less than 55.6 percent (Fig. 2).

At DEWA, healthier trees, those in the light decline category, had LCRs equal to or greater than the mean (Fig. 3), but the number of trees in the light decline category was only 26. The mean LCR for trees classified as in moderate decline (N = 591 trees) was similar to the model mean of 55.6 percent. Trees in severe decline (N = 65 trees) tended to have LCRs below the model mean (Fig. 3), indicating a possible correlation between crown vigor and vulnerability to HWA at this time. After 15 years of infestation at DEWA, no trees were classified as healthy in the data examined (Fig. 3).

Similar trends were found for model comparisons of mean crown density (model = 35.8 percent), dieback (model = 21.1 percent), and transparency (model = 33.8 percent) with DEWA hemlocks (Fig. 3). Trees in light decline had crown features similar to the model mean values, and trees in severe decline had lower vigor crowns than the model predictions. Regardless of time since infestation, crown features of hemlocks that were classified as being healthy, in light decline, or in severe decline are consistent with the model.

After 15-16 years of infestation, however, crown features varied more for DEWA trees classified as being in moderate decline. A more in-depth look indicated that 58 percent had crown density values that were lower than the model mean, and 42 percent had densities greater than the model mean. Dieback values followed a similar trend with 60 percent of the trees having more dieback than the model mean. Crown transparency measurements for trees classified as in moderate decline were the most consistent with the model. Most (88 percent) of the crown transparency values for those trees were greater than the model mean.

Based on the estimates for crown density and dieback, about 40 percent of the trees classified as moderate in the 2007-08 measurement may not yet be showing diameter growth

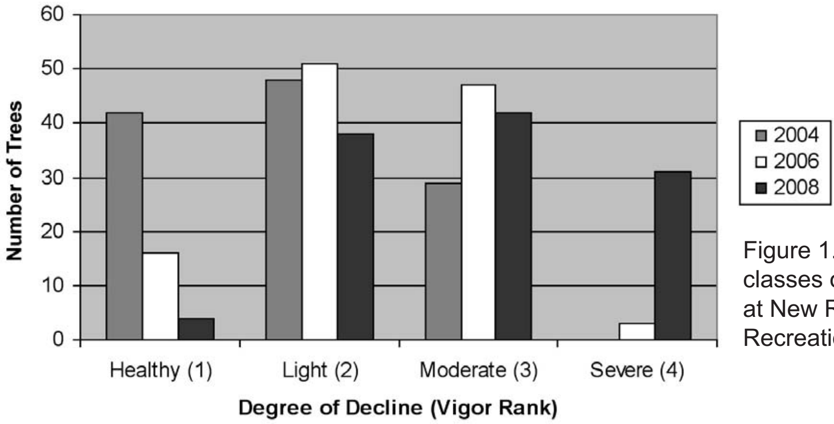

Figure 1.—Number of hemlock trees in four crown vigor classes on 8 plots infested by hemlock woolly adelgid in 2004 at New River Gorge National River and Gauley River National Recreation Area, WV.

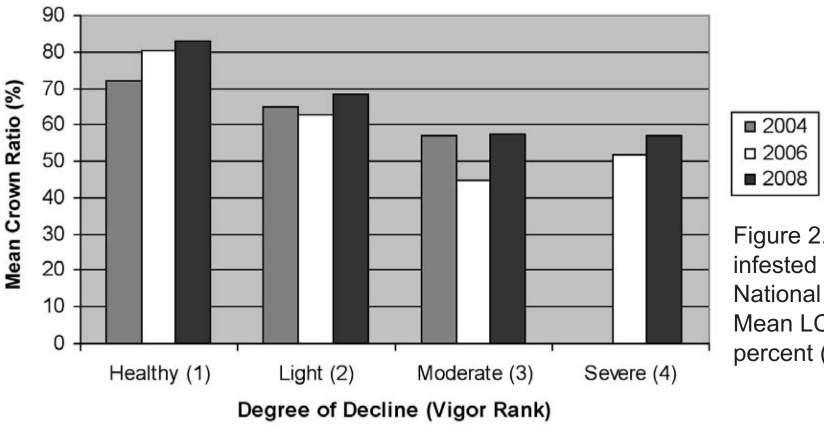

Figure 2.—Hemlock LCR in four crown vigor classes on 8 plots infested by hemlock woolly adelgid in 2004 at New River Gorge National River and Gauley River National Recreation Area, WV. Mean LCR predicted by the model for trees in decline was 55.6 percent (Rentch et al. 2009).

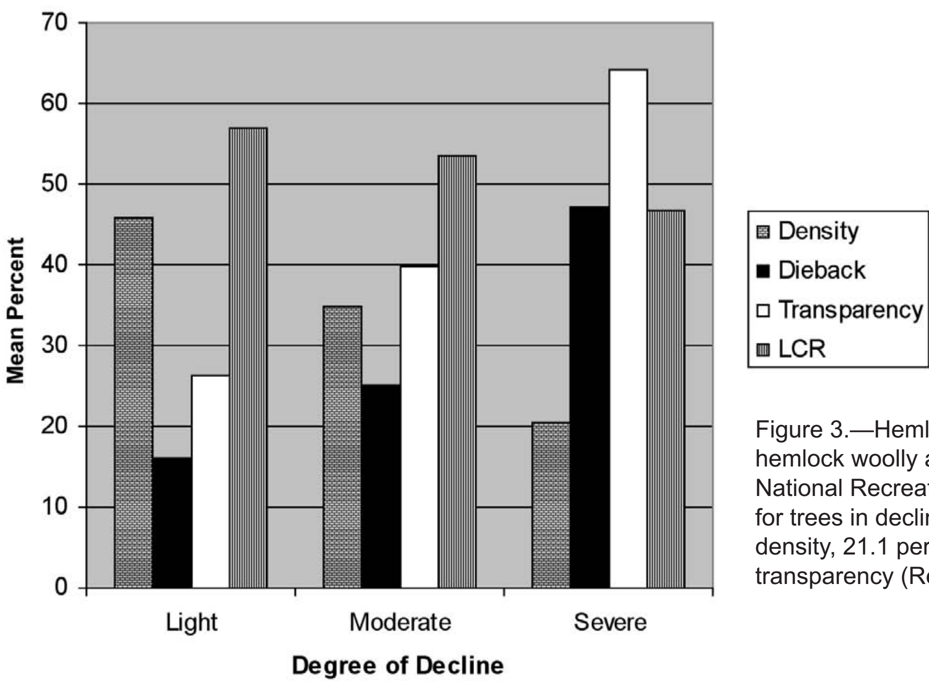

Figure 3.—Hemlock crown characteristics after 15+ years of hemlock woolly adelgid infestation at Delaware Water Gap National Recreation Area. Mean predicted values by the model for trees in decline was 55.6 percent for LCR, 35.8 percent for density, 21.1 percent for dieback, and 33.8 percent for transparency (Rentch et al. 2009).

decline. Trees in the moderate decline category are demonstrating crown vigor changes that are in transition between healthy and severe. Perhaps a temporal evaluation of the data would indicate whether hemlocks with lower vigor than the model values had been infested longer than those with crown features higher than the model mean.

Crown condition has been linked to tree survival and mortality (Dobbertin 2005). LCR is a measurement that is consistently repeatable among annual observers and is dependent only on foliage presence. Low to moderate HWA populations early in an outbreak have the least impact on LCR (Rentch et al. 2009), a relationship supported by our West Virginia data. After 4 years of infestation, all vigor categories still had mean LCRs at or above the model prediction (Fig. 2). In contrast, after 16 years at DEWA, 46 percent of the trees in moderate decline and 34 percent of those rated severe had LCRs above the model mean, which may be a factor in their continued survival. All of the 65 trees rated severe had transparency values above the model mean.

For all 36 sampling plots in West Virginia, songbird richness per plot was not correlated with vigor class ($P = 0.50$) or with LCR ($P = 0.47$). However, mean annual songbird richness increased slightly over time with 8.8 species/plot in 2004, 9.1 in 2006, and 9.5 in 2008. Mean vigor rank was 1.9 in 2004 and 2006 and 2.2 in 2008, while mean LCR was 70 percent in 2004 and 67 percent in 2006 and 2008. Although changes were slight, richness increased over time while LCR decreased, suggesting that some reduction in canopy cover benefitted songbird richness. Canopy reduction through silvicultural thinning might have a similar effect but needs to be investigated before drawing firm conclusions.

Both study areas are located in the northern climatic range for HWA, where cold winters are believed to cause slower spread rates and may help explain the longer survival of infested hemlocks (Evans and Gregoire 2007) compared to areas further south. In the northern region, silvicultural thinnings are also being tested as a means to increase hemlock vigor in overstocked stands prior to HWA infestation (Fajvan 2008). Current management guidelines recommend that thinning operations remove at least 20 percent of the basal area; however, if stands are very dense (> 46 m^2/ha), basal area removal should not exceed more than one-third of the total in any given operation (Lancaster 1985). While healthy hemlocks are no less susceptible to attack, our findings support longer survivability during infestation. Increased survivorship may improve hemlock's chances for recovery, especially if HWA populations crash and/or effective biocontrols are developed.

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