# Hemlock Woolly Adelgid and Elongate Hemlock Scale: Partners in Crime?

James A. Danoff-Burg[1] and Simon Bird [2]

[1]Department of Ecology, Evolution, and Environmental Sciences, Columbia University
1200 Amsterdam Ave., MC 5557, New York, NY 10027

[2]CEH, Bangor, University of Wales, Bangor
Deiniol Road, Bangor Gwynedd LL61 5UP, Wales, UK

## Abstract

The increased mortality of the eastern hemlock in North America has been primarily attributed to the invasion of the hemlock woolly adelgid (HWA). However, in parts of the range of eastern hemlock, the elongate hemlock scale (EHS), another introduced Asian insect, also infests stands and weakens trees. An important step towards achieving the goal of reducing eastern hemlock mortality is to understand how these two exotic insects impact hemlock stands. To address this question, we estimated levels of infestation of HWA and EHS found on 153 trees along the length of an eastern hemlock stand in the Black Rock Forest, Orange County, New York. We also estimated the relative abundance of each of these insects and the levels of needle loss and new growth on these hemlock trees. Using these data, we then determined that both HWA and EHS abundance was significantly correlated with the early stages of hemlock decline, as indicated by the suppression of new growth in infested trees. However, an advanced stage of hemlock health decline, as indicated by needle loss, was significantly correlated with EHS abundance but not HWA abundance. We suggest that HWA and EHS at least contribute equally to the decline of hemlocks at our field site, but that damaging outbreaks of EHS may be enabled by HWA feeding. Therefore, in areas where both HWA and EHS are abundant, forest managers interested in sustaining their eastern hemlock stands should strongly attempt to control both of these introduced pest species.

## Keywords:

Hemlock woolly adelgid, elongate hemlock scale, two-species interactions, hemlock mortality.

## Introduction

Natural populations of eastern hemlock (*Tsuga canadensis* (L.) Carriere) have recently been in rapid decline throughout much of their eastern United States range. The increased mortality of this tree has been primarily attributed to the invasion of the hemlock woolly adelgid (HWA), *Adelges* *tsugae* Annand, an introduced Asian insect (McClure 1980a, 1991; Souto et al. 1996; Royle and Lathrop 1997).

Eastern hemlock has been a component of the forests in the northeastern United States since the Holocene (Fuller 1998). The tree is a late successional species that provides unique habitat for forest biota and tends to create microclimatic and edaphic conditions that are more stable in the short term than the surrounding forest (Finzi et al. 1998; Fuller 1998; Orwig and Foster 1998). Several species of birds, fish, and plants are found preferentially in stands of eastern hemlock (McClure et al. 2001; Mitchell 1999). Eastern hemlock stands also have significant aesthetic qualities that help to stimulate tourism in state and national forest parks. The potential widespread mortality of eastern hemlock therefore has significant ecological and socioeconomic implications (Royle and Lathrop 1997).

The adelgid was first recorded in New York State in the 1990s, by which time it was present in ten other eastern states, from North Carolina to Massachusetts (Onken et al. 1995; Souto et al. 1996). In its native Japan, its natural enemies likely maintain populations of HWA at low, innocuous densities on hemlock trees. In contrast, U.S. populations of HWA reach pest proportions on eastern hemlock due to the lack of natural predators, competitors, parasites, and minimal chemical host resistance (McClure 1995, 1996; McClure and Cheah 1999). Eastern hemlock trees and whole stands have been reported to decline rapidly following HWA infestation (McClure 1990, 1991).

The damage and mortality HWA causes in eastern hemlock forests varies spatially, both at stand and landscape scales, and across a range of tree age and size classes (Orwig and Foster 1996). There is preliminary evidence that environmental conditions, such as elevation, terrain shape, and distance from streams, either control HWA infestation or make some stands differentially sensitive (Young et al. 1999). Although HWA exhibits higher mortality in areas with low minimum temperatures, a small percentage of individuals may be cold tolerant (Parker et al. 1998). This cold tolerance, coupled with the ability of HWA to become airborne or attach to tree bark, birds, small mammals, or deer for transport and to survive several days without feeding (McClure 1987, 1990) indicates that HWA could quickly invade most of the remaining range of the eastern hemlock.

In parts of the range of eastern hemlock, another introduced Asian insect also infests stands and weakens trees. The elongate hemlock scale (*Fiorinia externa* Ferris) was accidentally imported into New York City on infested timber from Japan around 1910 (Ferris 1936). The scale feeds on the underside of eastern hemlock needles causing discoloration and premature needle drop. A feedback mechanism exists between tree host status and scale infestation where the survival, development rate, and fecundity of *F. externa* is related to the nutrient quality of its host, which in turn is influenced by scale density and the edaphic conditions of the hemlock site (McClure 1980a, 1981, 1983). Sustained and heavy attacks of the elongate hemlock scale (EHS) also may contribute to tree mortality if HWA is already present. Elongate hemlock scale also is a vigorous competitor with other scale species (McClure 1980b), which may indicate how it interacts with HWA. At present, EHS abundance is greatest within a 300-km radius of New York City.

Unless effective natural enemies of these two exotic pest species can be found and successfully utilized and their dispersal impeded, significant reductions of eastern hemlock across a broad geographic area will continue (Orwig and Foster 1996). An important step towards achieving the goal of reducing eastern hemlock mortality is to understand how these two exotic insects impact hemlock stands. For pest management purposes, it also is important to understand which environmental factors determine the spread and establishment of harmful infestations, and to investigate the spatial distribution of infested trees.

To address these ends, we had four research goals in this study. First, we estimated levels of infestation of *A. tsugae* and *F. externa* in an eastern hemlock stand in the Black Rock Forest, Orange County, New York. We then estimated the relative abundance of each of these insects and the levels of needle loss and new growth on these hemlock trees. Third, we tested whether position of trees relative to a stream affected insect infestation or impact levels. Last, we attempted to determine whether HWA and EHS abundance was significantly correlated with advanced stages of hemlock health decline.

We assumed that tree health declines in a regular and orderly manner with increasing levels of infestation by EHS and HWA. After the initial outbreak of these pest insects on a tree, the tree will begin losing photosynthate, which will intensify with increasing pest population size. At this point, the tree will halt new growth and enter a period of stasis, whereby no new growth occurs and the tree is able to maintain already existing foliage. If phloem feeding rates further intensify, the tree will begin losing energy. Needle loss will then follow, which will then lead to further tree decline and death if needle loss occurs for a long enough time. Under this model, suppression of new growth will occur before needle loss as pest infestation increases and the tree declines in health.

## Methods

The Black Rock Forest (BRF)is located in the Hudson Highlands of Orange County, New York, approximately 2 km west of the Hudson River and 80 km north of Manhattan. The forest covers more than 1,600 ha. Elevation reaches peaks of 425 m above sea level and the area receives approximately 125 cm of precipitation per year. The tree species composition of the site is typical of the hickory-oak (*Carya-Quercus*) forest that extends from Massachusetts to Ohio. The underlying geology of the area is uniformly Precambrian gneiss (Berkey and Rice 1921), and the soils of the Black Rock Forest are all Hollis-Rock outcrop soils (Wright and Olsson 1972).

As is typically found throughout the range of the tree in this area of the Northeast, hemlock forms monospecific stands in the few steep ravines with good drainage that are present in the BRF (Maenza-Gmelch 1997; D'Arrigo et al. 2002). There are three streams that have dense stands of hemlock within the BRF, which cover an approximate total of 66 ha (Friday and Brady 1985). The hemlocks in these stands extend along the length of each stream and from 30 to 280 m uphill from the streamsides.

For this study, a 2,300 m transect was selected that followed both branches of the entirety of the Black Rock Brook (BRB), a contiguous 38 ha stand. The two branches of the BRB start below two separate reservoirs and merge approximately 1,200 m south from the transect's northern limit

(Figure 1). The brook ends when it crosses under a road and exits the Black Rock Forest. The BRB runs from south to north in the northeastern corner of BRF. The hemlock stand traces the entirety of the BRB, but terminates in the north when the stream leaves the BRF and the terrain flattens.

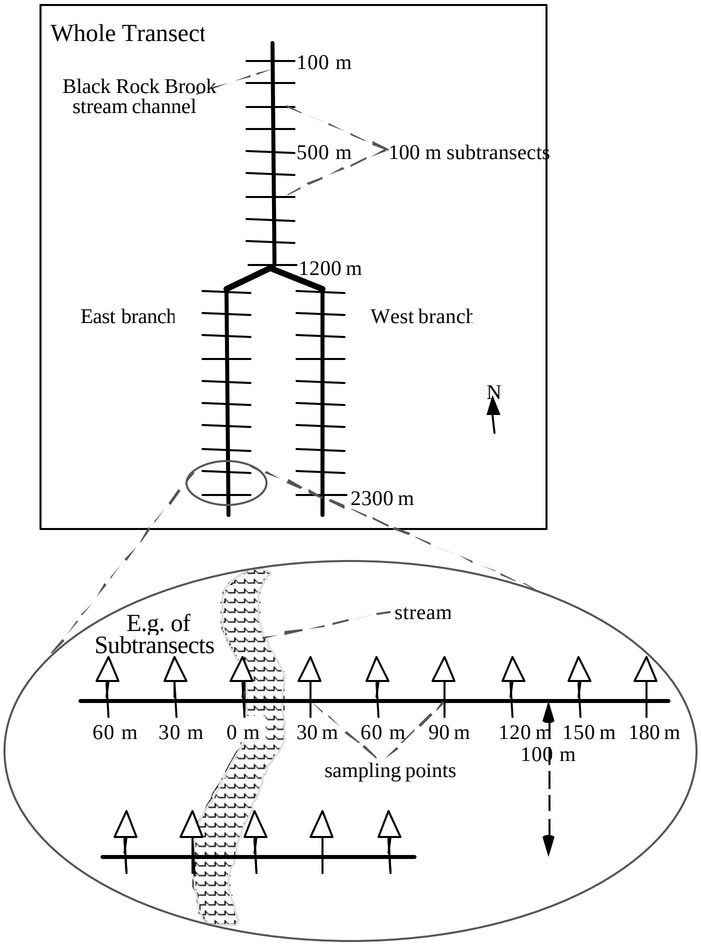

**Figure 1.** Study site transect layout.

A subtransect was placed every 100 m along the 2,300 m transect of the entire stream, including both upper stream branches from 1,200 m to 2,300 m and then for the remaining 1,200 m of the main stream branch (Figure 1). Subtransects ran east to west from the brook. A single eastern hemlock tree was selected for sampling every 30 m along the subtransects for the duration of the hemlock stand (Figure 1). Hence, some subtransects were longer and had more sampling points than others due to the variation in width of the hemlock stand around the stream. We selected the closest living subemergent tree to the 30 m markers along each subtransect for sampling. Trees were between 50 and 100 years of age and approximately 15 to 20 m tall. A total of 153 trees were sampled.

One branch sample was collected from each sampled tree. The terminal 40 cm was removed from the branch closest to being 3 m from the ground on the upslope side of the tree. All sampled branches were placed in labeled, sealable plastic bags and then transported to the lab for subsequent analysis.

Qualitative estimations of four index values were made in the laboratory for each branch sample: HWA infestation level, EHS infestation level, amount of needle loss, and amount of light green new growth. Each index had an integer value between 1 and 10. For insect infestation indices, branch samples were assigned a value of 1 if no insects were present on the entire sample and a value of 10 if all of the appropriate plant matter (branchlets for HWA and needles for EHS) was covered in insects. For the needle loss index, branch samples were assigned a value of 1 if all needles were present, and a value of 10 if all needles were missing. For the new growth index, samples were assigned a value of 1 if all branchlets had new growth, and a value of 10 if no branchlets had new growth.

Each index therefore varied from 1 to 10, which represented “good” to “poor” in terms of tree health. Higher values therefore corresponded to lower tree health. Three separate sets of index estimations were made by three different workers to control for experimenter bias. Mean index values were generated for each sample from these three estimations. These mean values were used for all subsequent analyses.

Statistical analyses were performed using Statview® computer software (Abacus Concepts 1996). Correlation analyses were performed between HWA and scale infestation levels, needle loss, and new growth. Pearson correlation coefficients were calculated in each case to generate a correlation matrix. For each pairwise comparison, Fisher’s r to z transformation was used to test the null hypothesis that the correlation was equal to zero. Mean index values were calculated for data split by distance from stream and by direction from stream, and Mann-Whitney and Kruskal-Wallis non-parametric means tests were performed to detect for significant relationships. Tree count data was generated by grouping all samples into three classes of tree condition based on mean index values: for each of the four indices, a sample was classed as “good” for values < 3.3; as “medium” if between 3.3 and 6.6; and “poor” if > 6.6. Chi-square tests were performed on the resulting tree count data to test for relationships between the four indices and alternatively distance from stream or direction from stream.

## Results

HWA and scales were each present on every tree sampled. The majority of eastern hemlock trees sampled (66%) had a medium level of HWA infestation, with only 14% of trees being classed as severely infested (Table 1). A greater proportion of trees (42%) were classed as being highly infested with the elongate hemlock scale (Table 1). Most trees (70%) had a medium level of needle loss and the majority (88%) lacked new growth (Table 1).

Mean values for all four indices did not significantly differ with distance from the stream, as indicated by nonsignificant Kruskal-Wallis tests (Table 2). Likewise, Mann-Whitney tests indicated that the mean values of all four indices did not significantly differ between the eastern and western slopes along the subtransects (Table 2).

**Table 1. Summary of Tree Condition Data.**

| Tree Condition[a] | HWA Presence | Scale Presence | Leaf Loss | New Growth |
|---|---|---|---|---|
| Good[b] | 38 (24.8)[c] | 20 (13.1) | 39 (25.5) | 5 (3.3) |
| Medium | 101 (66.0) | 69 (45.1) | 106 (69.3) | 14 (9.2) |
| Poor | 14 (9.2) | 64 (41.8) | 8 (5.2) | 134 (87.6) |

[a] Mean index values were grouped into classes as follows: < 0.3 (Good), 3.3 to6.5 (Medium), and > 6.6 (Poor).

[b] "Good" refers to low insect infestation levels, low leaf loss, and high new growth.

[c] Values are total number of trees in each index class with percentages (n = 153) in parentheses.

**Table 2. Mean HWA, Scale Presence, Leaf Loss, and New Growth by Distance From Stream and Tree Position.**

| Distance From Stream (m) | Number of Trees | Mean HWA Presence | Mean Scale Presence | Leaf Loss | New Growth |
|---|---|---|---|---|---|
| 0[a] | 32 | 4.37 (1.5)[b] | 6.13 (2.5) | 4.02 (1.5) | 8.99 (1.8) |
| 30 | 52 | 4.45 (1.6) | 5.67 (2.0) | 4.05 (1.3) | 9.08 (1.8) |
| 60 | 29 | 3.86 (1.6) | 5.24 (2.0) | 3.97 (1.4) | 8.60 (2.3) |
| 90 | 14 | 4.91 (1.3) | 6.26 (1.8) | 3.99 (1.3) | 9.43 (1.4) |
| 120 | 11 | 5.04 (1.6) | 6.24 (2.5) | 3.99 (1.3) | 8.76 (2.2) |
| 150 | 6 | 4.61 (1.67) | 6.61 (1.1) | 4.56 (1.0) | 9.89 (0.3) |
| 180 | 4 | 4.25 (0.3) | 5.33 (1.6) | 4.50 (1.5) | 9.92 (0.2) |
| 210 | 4 | 2.58 (1.0) | 4.58 (2.1) | 3.17 (0.7) | 7.83 (3.7) |
| 240 | 1 | 2.67 (-) | 6.33 (-) | 3.33 (-) | 9.67 (-) |
| Tree Position Relative to Stream | | | | | |
| East | 51 | 4.22 (1.5) | 5.89 (2.0) | 4.06 (1.2) | 9.10 (1.6) |
| West | 102 | 4.41 (1.6) | 5.73 (2.2) | 4.00 (1.4) | 8.95 (2.1) |

[a] Only the western portion of subtransects included trees at distance 0 m since each subtransect ran east and west from the same point at the stream.

[b] Values are means calculated from averaged index values from the three estimates taken; values in parentheses are standard deviations. Mann-Whitney and Kruskall-Wallis non-parametric tests indicated no significant differences between means for distance from stream or tree position.

Chi-square tests on tree count data confirmed these results, in that distance and direction from stream did not have a significant effect on any of the four indices (Tables 3 and 4).

**Table 3. Number of Trees in Tree Condition Classes Split by Distance From Stream.**

| | Distance from Stream (m) | | | |
|---|---|---|---|---|
| | 0-30 | 60-120 | >120 | |
| I. HWA Infestation | | | | |
| Good[a] | 17 | 15 | 6 | Chi-square = 3.62 |
| Medium | 60 | 33 | 8 | Chi-square *P* = 0.46 |
| Poor | 7 | 6 | 1 | Cramer's V = 0.11 |
| II. Scale Infestation | | | | |
| Good | 10 | 8 | 2 | Chi-square = 0.28 |
| Medium | 38 | 24 | 7 | Chi-square *P* = 0.99 |
| Poor | 36 | 22 | 6 | Cramer's V = 0.03 |
| III. Leaf Loss | | | | |
| Good | 21 | 15 | 3 | Chi-square[b] = 1.38 |
| Medium | 57 | 37 | 12 | Chi-square *P* = 0.50 |
| Poor | 6 | 2 | 0 | Cramer's V = 0.10 |
| IV. New Growth | | | | |
| Good | 3 | 1 | 0 | Chi-square[b] = 1.56 |
| Medium | 6 | 8 | 0 | Chi-square *P* = 0.50 |
| Poor | 76 | 45 | 14 | Cramer's V = 0.10 |

[a] "Good" refers to low insect infestation levels, low leaf loss, and high new growth.

[b] The 60 to120 m and > 120 m categories were combined into one class for the Chi-square test for Leaf Loss and New Growth.

Pairwise correlations suggested that HWA infestation level was positively correlated with a decreased new growth, but was not significantly correlated with needle loss (Table 5; Figure 2). Scale infestation was positively correlated with both needle loss and decreased new growth (Table 5; Figure 2).

HWA and scale infestation were positively correlated with each other (Table 5; Figure 3). Pearson values suggest that the strongest relationships were the correlation between HWA infestation level and lack of new growth, and the correlation between HWA infestation level and scale infestation level. The estimations of the four indices by the three different workers produced some variation in correlation analysis results, although the estimates by workers one and two showed similar trends (Table 5).

**Table 4. Number of Trees in Tree Condition Classes Split by Direction From Stream.**

| | Tree Position | Relative to Stream | | |
|---|---|---|---|---|
| | East[a] | West[a] | | |
| I. HWA Infestation | | | | |
| Good[b] | 14 | 24 | Chi-square = | 0.37 |
| Medium | 32 | 69 | Chi-square *P* = | 0.83 |
| Poor | 5 | 9 | Cramer's V= | 0.05 |
| II. Scale Infestation | | | | |
| Good | 4 | 16 | Chi-square = | 1.68 |
| Medium | 23 | 46 | Chi-square *P* = | 0.43 |
| Poor | 24 | 40 | Cramer's V= | 0.11 |
| III. Leaf Loss | | | | |
| Good | 13 | 26 | Chi-square = | 1.68 |
| Medium | 37 | 69 | Chi-square *P* = | 0.43 |
| Poor | 1 | 7 | Cramer's V= | 0.11 |
| IV. New Growth | | | | |
| Good | 1 | 4 | Chi-square = | 0.44 |
| Medium | 5 | 9 | Chi-square *P* = | 0.80 |
| Poor | 45 | 89 | Cramer's V= | 0.05 |

[a] East and west refer to the position of trees relative to stream.

[b] "Good" refers to low insect infestation levels, low leaf loss, and high new growth.

**Table 5. Correlation Matrix for Index Values of HWA Presence, Scale Presence, Leaf Loss, and New Growth.**

| | HWA Presence | Scale Presence | Leaf Loss | New Growth |
|---|---|---|---|---|
| I. Estimate 1[a] | | | | |
| HWA Presence | X | 0.31*[b] | 0.14 | 0.30* |
| Scale Presence | 0.31* | X | 0.38* | 0.28* |
| Leaf Loss | 0.14 | 0.38* | X | 0.33* |
| New Growth | 0.30* | 0.28* | 0.33* | X |
| II. Estimate 2[a] | | | | |
| HWA Presence | X | 0.59* | 0.25* | 0.37* |
| Scale Presence | 0.59* | X | 0.35* | 0.35* |
| Leaf Loss | 0.25* | 0.35* | X | 0.40* |
| New Growth | 0.37* | 0.35* | 0.40* | X |
| III. Estimate 3[a] | | | | |
| HWA Presence | X | 0.16 | -0.09 | 0.37* |
| Scale Presence | 0.16 | X | 0.15 | 0.27* |
| Leaf Loss | -0.09 | 0.27* | X | 0.20† |
| New Growth | 0.37* | 0.27* | 0.20† | X |
| IV. Mean Index Values[c] | | | | |
| HWA Presence | X | 0.40* | 0.08 | 0.42* |
| Scale Presence | 0.40* | X | 0.32* | 0.33* |
| Leaf Loss | 0.08 | 0.32* | X | 0.36* |
| New Growth | 0.42* | 0.33* | 0.36* | X |

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[a] These three categories represent separate and independent estimations of index values by different workers.

[b] All values are the Pearson correlation coefficient (varies -1 to 0 to 1), $n = 153$.

[c] Values are means of means of index values calculated from the three estimations above.

* Indicates a correlation coefficient significantly different from 0 at the $p < 0.01$ level following a Fisher's r to z transformation and significance test.

† Indicates a correlation coefficient significantly different from 0 at the $p < 0.05$ level.

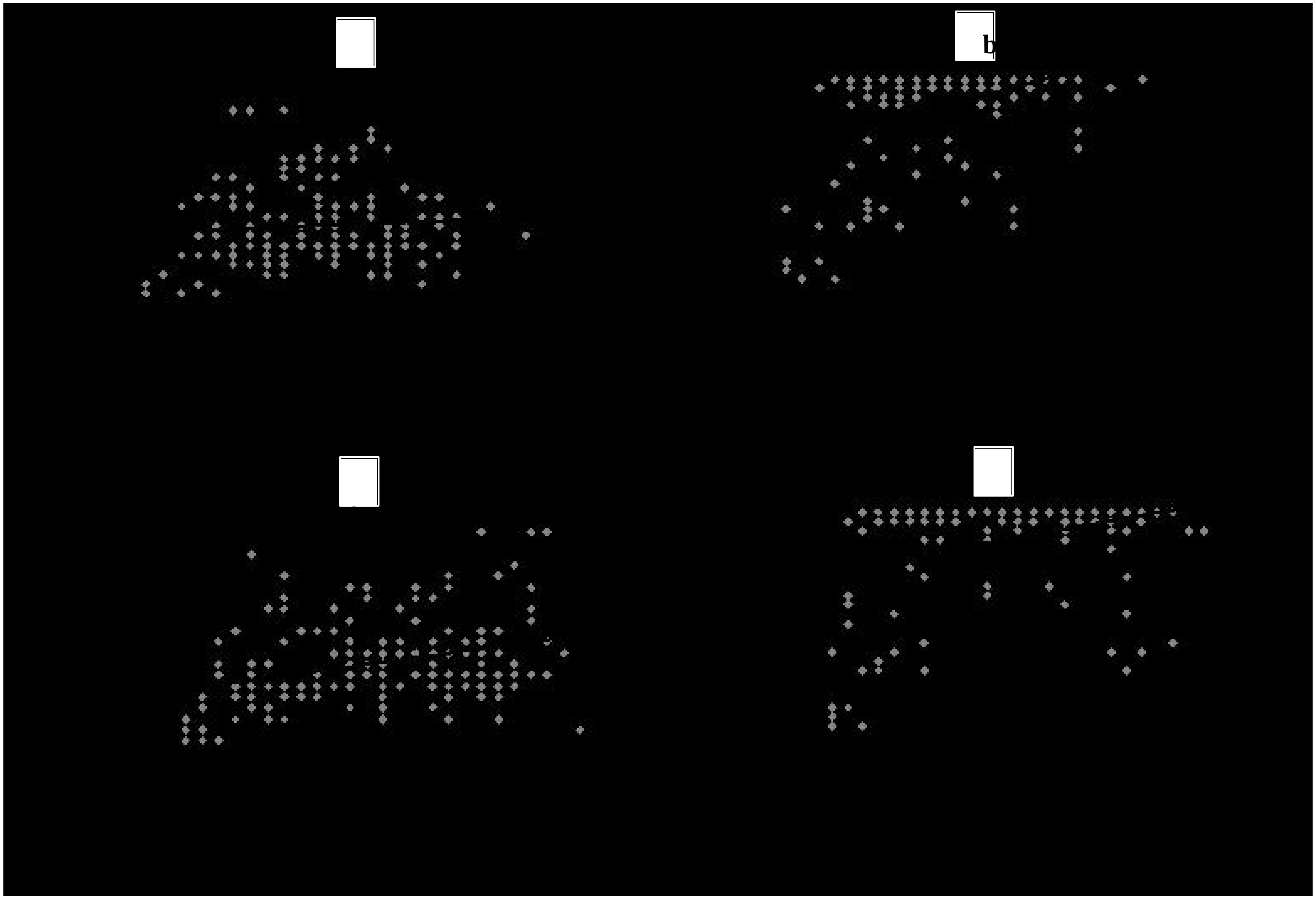

**Figure 2.** Bivariate scatter plots of a. hemlock woolly adelgid (HWA) infestation versus needle loss; b. HWA versus new growth; c. elongate hemlock scale (EHS) versus new growth; and d. EHS versus new growth.

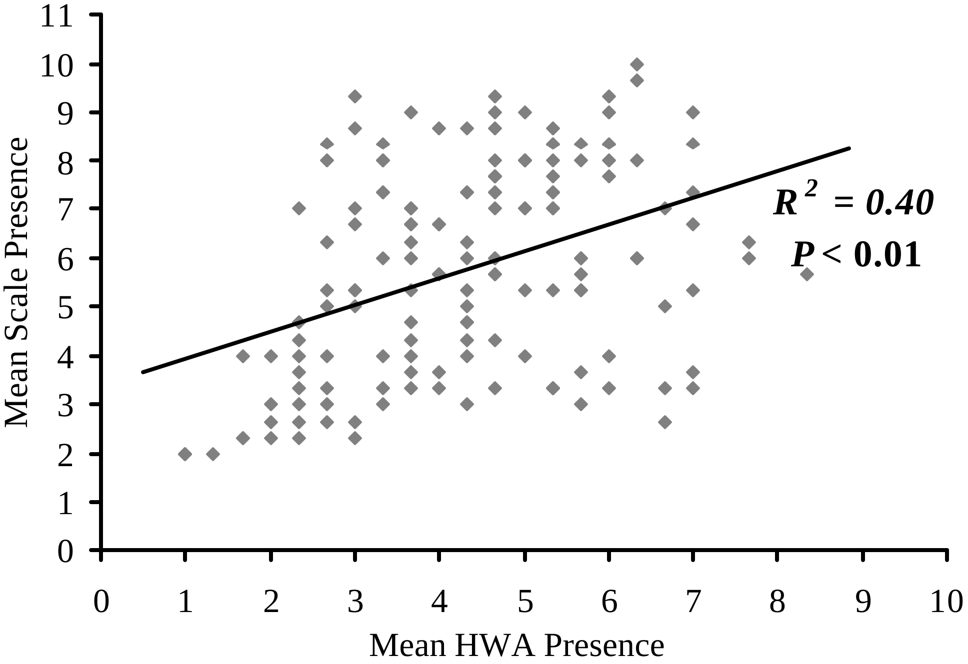

**Figure 3.** Bivariate scatter plot of hemlock woolly adelgid infestation level versus elongate scale infestation level.

## Discussion

The overall condition of the eastern hemlock stand studied here had an intermediate infestation level for both HWA and EHS with respect to our estimation levels ranging between one and ten. At present there is unfortunately no further infestation data for other areas of BRF or Orange County, New York for comparison with our dataset. In order to determine how widely applicable our results are, a broad effort to measure the infestations of both species and their ecological impacts is needed. What our data do indicate is that both pest species are very much present in this forest and have the potential to spread and cause further damage to hemlock trees in this geographic area. These data also indicate that EHS, rather than HWA, may be the chief cause of hemlock tree decline in this forest, contrary to the accepted assumption among foresters in this area (D'Arrigo et al. 2002).

Significant needle loss and tree mortality caused only by HWA infestation has been reported in many other studies (e.g., Orwig and Foster 1996, 1998; McClure 1996). This observation may point towards significant environmental differences between the BRF site and other geographic locations. Environmental conditions have been cited as important determinants of HWA infestation and impact (Young et al. 1999), including distance and direction from streams. However, these two factors appear to have no relationship with the indices of infestation levels for HWA and EHS, needle loss, and new growth in this study. HWA has been suggested to vary widely across forest landscapes and microenvironments (Orwig and Foster 1996) and our relatively fine-scale data supported this point. The fact that HWA and EHS infestation levels did not correlate with either distance or direction from stream clearly indicates that other environmental factors are controlling the pattern of insect infestation in this hemlock stand. Investigating potential environmental determinants, such as the soil's physical and chemical properties, amount and distribution of soil organic matter, drainage patterns, and microclimatic conditions should help explain which factors are more influential on HWA and EHS infestation.

Correlation analysis suggested that HWA is not causing significant needle loss in these hemlock trees in the Black Rock Forest. HWA-infestation level was significantly correlated with reduced new growth (Figure 2), indicating that its feeding does have an impact on hemlocks in the BRF. However, because only EHS infestation was significantly correlated with both needle loss and reduced new growth, it seems that its role in tree mortality may be at least as important as HWA. As tree health declines due to increasing infestation of phloem-feeding pests, suppression of new growth should occur prior to leaf loss. As such, the two species may in tandem lead to the death of the hemlocks in the Black Rock Forest.

Feeding by HWA may first weaken trees, as evidenced by the low levels of new growth in highly HWA-infested trees. The weakening may be due to the energetic loss to phytophagy, which may in turn allow EHS to become established and explode in population size. The addition of EHS then causes the majority of needle loss and the potential tree mortality associated with defoliation. HWA has been shown to affect nutrient dynamics in hemlock stands (Jenkins et al. 1999) and this could feasibly reduce tree vigor sufficiently to allow scale insects to invade.

Elongate hemlock scale has been shown to be an effective competitor with other scales (McClure 1980b), and may be a better competitor than HWA as well. The BRF also is almost at the northern limit of the range of HWA in New York State, whereas EHS is most abundant in an area centered in New York City with an approximate radius of 300 km, including parts of Connecticut, New York, Pennsylvania, and New Jersey. Insects at the fringes of their geographic distribution often are environmentally stressed and therefore less effective competitors than when they are in the geographic center of their distribution (Huston 1994). Perhaps EHS is less impacted by the microclimatic conditions occurring in the BRF than is HWA and is thus the better competitor of the two pests. Elongate hemlock scale may thereby exclude HWA when their population sizes become large enough and then continue to feed until the tree dies. Hence, it may be EHS and not HWA that is the primary mortality agent for hemlocks in the Black Rock Forest.

If these interactions between HWA and the scale are indeed occurring, forest managers may have to rethink their strategy for reducing HWA infestations and associated hemlock mortality, at least in areas where both species are attacking the same trees. Targeting HWA alone with beneficial insect predators (McClure 1995; Cheah and McClure 2000) or chemical controls (Gouger 1971; McClure 1987), may not be enough to reduce hemlock mortality if EHS is a significant contributor. A better understanding of the interactions, ecology, and seasonal population cycles of both insects, plus the nature of their interaction, is required to evaluate how to cope with these twin-species infestations. These interpretations are likely of greatest relevance to locations where EHS is most abundant and HWA is most cold stressed.

An understanding of which biotic and environmental factors are important in determining stand risk will obviously be of great benefit to forest managers. Our study indicates that controlling EHS may be of at least equal importance to controlling HWA to preserve the eastern hemlock. Further investigation of these relationships should aid efforts to help arrest the widespread tree mortality these insects cause, mortality that is threatening the unique eastern hemlock ecosystem in the northeastern United States.

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