Hemlock Health and Hemlock Woolly Adelgid Management in the Urban Forest

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Abstract

A comprehensive management program for urban hemlock, *Tsuga canadensis* (Carriere) under pressure of *Tsugae adelges* (Annand) is presented. Hemlock management includes assessment of hemlock condition noting HWA infestation and its impact to tree health, soil and tissue analyses, therapeutic intervention(s), and application of soil amendments to manage environmental stresses. The key to optimizing hemlock vitality is a proactive plant health program including early therapeutic intervention. In this study, hemlocks were assessed using several plant health parameters including on-site assessment of tree condition (size, percent infestation). Soil and tissue samples were taken for independent and in-house laboratory diagnostics. In-house diagnostics included measurement of change in shoot extension, estimate of percent chlorosis and needle shed, Munsell Color assessment, and needle dry weight. Therapeutic treatments for HWA suppression were applied using the Arborjet microinjection device.

Keywords:

HWA, Hemlock Health Index, soil and foliar analyses, organic amendments, Arborjet microinjection.

Introduction

Hemlock woolly adelgid (HWA), an introduced piercing-sucking insect that threatens forest and landscape hemlock species (*Tsuga canadensis, T. caroliniana*), affects hemlocks by extracting carbohydrates from the xylem ray parenchyma cells. The tree's vitality depends upon these carbohydrates, as this captured energy is crucial for growth, maintenance, reproduction, defense, and storage (Shigo 1991). McClure et al. (1996) have reported that dieback in hemlock may occur in two years, affecting the lower canopy first, and moving upward, even with HWA infestation distributed throughout the canopy. McClure (1991) has reported that as few as 4 adelgids/20 mm^2 of branch seriously affect growth in forest stands. Decreased carbohydrates make the host less suitable to HWA, resulting in reduced hemlock vitality—suggesting the need for a diagnostic and treatment. Hemlock will respond to HWA infestation by measurable and observable changes, e.g., reduction of shoot growth (stunting), chlorosis (yellowing), and shedding (needle loss). Quantifying this response may enable arborists to make proper management decisions in the urban landscape affected by HWA. The Hemlock Health Index (HHI) described in this paper may be a useful quantifying tool.

For managing HWA infestations, three options for therapeutic approaches are available. These include foliar sprays, soil injection, and microinjection. A biannual application of horticultural oil is the standard treatment for HWA, but this depends upon thorough foliar coverage as a contact insecticide and is subject to aerial drift. Soil injection eliminates the problem of drift inherent in foliar applications, but leaching in the soil profile is of concern in sensitive sites. Microinjection is the most environmentally sensitive approach to pesticide application, but wounding and the possibility of subsequent girdling are of concern to the arborist. Arborjet microinjection was designed to address the concerns of environmental sensitivity and wounding in trees. It eliminates the need to drill into trees, relying on the insertion of a 2-mm wide needle into the xylem to deliver product. The Arborjet system was selected for use in therapeutic treatments in this study.

Whereas foliar health supports photosynthetic processes, another major component of hemlock health is soil. Ideal soil conditions for hemlock growth are moist, well drained, rich in humus, and acidic to neutral pH (Ohio State). Maximizing plant vitality does not necessarily mean maximizing growth, but optimizing photosynthetic processes. Factors that stress urban hemlocks can include deicing salts, protracted dry or wet soils, and insect or mite infestations. Addition of organic soil amendments buffers against stress, supports mycorrhizal associates, and reduces leaching of essential mineral cations. The additions of compost derived from diverse woody plant sources and supplemental mineral applications will improve soil structure, support microbiology (Ingham 1991), and provide the elements essential to hemlock health. Foliar analyses combined with soil quality assessment are the basis of managing hemlock health.

The Hemlock Health Index. The Hemlock Health Index (HHI) (Doccola, submitted) is a simple and efficient diagnostic tool designed to help the arborist or forest manager quantify change in hemlock health, measure the effects of adelgid pressure, and make informed management decisions. The Index is based on the average last three-year twig growth in cm x 100. An estimate of percent chlorosis and needle drop observed in the three-year twig examined is subtracted from the mean twig extension calculated. The HHI was developed based on the observation that HWA infestation reduces stem elongation (causes stunting), and, depending on the severity or protracted nature of infestation, results in no growth, chlorosis, and needle loss. Samples showing these extreme changes in plant vitality are assigned a rating category such as a “low” or “very low” index. Such ratings are associated with a range of numeric values, summarized in Table 1 (see also Doccola, submitted). By dividing these numeric index values by 100, one can quickly calculate a rough estimate of three-year twig extension. For example, trees rated “low-moderate” (i.e., HHI falls between 348 and 542) have 3.5 to 5.4 cm of growth (mean twig extension) over the last three years. The same relationship may be found using dry needle-weight (in grams), as a direct relationship exists between dry needle weight and shoot extension. Also, it follows that with decreased shoot extension (with increasing HWA pressure), lower dry needle-weights are observed.

Table 1. Hemlock Health Index.

Health Description:	V Low	Low	Low-Mod	Moderate	Mod-High	High
HHI Value:	0-179	180-347	348-542	543-717	718-917	918+

In assessing hemlock health, especially when dealing with HWA infestations, the HHI generates a precise, descriptive health rating for the arborist to record. For example, a "low-moderate" HHI rating may be synonymous with "tree stressed by adelgid infestation." The term "stress" is given a numerical value that denotes degree of tree health suppression. "Very low" HHI is associated with no current year growth, needle loss, and dieback, conditions that may be described as "strained." "Moderate" to "high" HHIs denote healthy trees, that is, values above 500 are normative for hemlock. Suppressing infestation to maintain tree health at 500 or greater is desirable. "Moderate" or better HHI is maintained when HWA management is proactive, that is, therapeutic treatments are within the first year or two. (A word of caution: Using shoot extension as a basis for measuring health does not mean *more* growth equals health. Rather, it is a measure of how far from the norm twigs are by degree. In other words, it does not imply growth-boosting programs such as nitrogen-based fertilization for hemlock management.)

The Hemlock Health Index is a procedure that takes the approach that efficacy of HWA management be based upon tree health rather than assessment of insect mortality. Assessing mortality is an important, but time-consuming tool. For arborists who wish to gauge their HWA suppression efforts, we offer the HHI as a simple and efficient alternative. Further, HHI may be used to graphically illustrate the profile of hemlocks being managed by a survey of twig samples, upon which management decisions may be based.

Methods

Tree Microinjection. Hemlocks in this study were microinjected in the spring of 2001 (between May 17 and June 28) for HWA suppression. Trees were treated using 10% formulation of 1-[(6-chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinime (imidacloprid) by trunk injection into the active sapwood. Dosage was based on dbh (diameter breast height, or 54 in. [135 cm] from soil level, using a Lufkin 20 ft. diameter tape) and extent of infestation. Mean dosage applied per caliper inch at dbh = 1.4 ml, with a range of 1 to 2 ml/caliper inch. Heavily infested trees received the higher rate of 2 ml/ caliper inch, whereas lightly infested trees received the lower dosage of 1 ml/caliper inch. Mean dbh of microinjected hemlocks was 16.4 in. (41 cm), and ranged from 6.2 in. (15.5 cm) to 32.9 in. (82.3 cm). Mean height for the sample was 58.9 ft. (17.7 m), with a range of 30 ft. (9 m) to 100 ft. (30 m.). All the microinjected trees were established urban forest trees. On-site observations created the following tree profile: 36.3% of the trees appeared to be non-infested by HWA (healthy), 44.5% showed stunted growth (stressed), and 19.3% were heavily infested or showed dieback (strained).

Collecting Samples From Hemlock. Twig samples were harvested in the fall of 2001 (between November 6 and December 18) from 24 hemlocks in Winchester, Massachusetts, that were injected in spring for HWA suppression. Eight samples measuring 18 to 24 in. (45 to 60 cm) long

were cut, bagged, labeled, refrigerated (at ca. 45°F), and evaluated within seven days. Samples were taken using a No. 180 ARS Long Reach Pruner capable of 10 feet extension, effectively reaching to 16 feet into the canopy. Typically, half the samples were taken from the lower to mid-canopy and half from the mid- to upper canopy. For the plant tissue analyses of the non-injected hemlock population, 192 hemlock twig samples were collected January 2 to 9, 2002, from properties on which soil analyses were conducted in 2001.

Evaluating Efficacy. Microinjection treatment efficacy was evaluated on the basis of insect mortality. HWA mortality was based on a percentage of dead insects (adults and nymphs) as determined by microscopic inspection of 125 18-in. (45 cm) samples infested with HWA. Insects were regarded as dead if they appeared desiccated, hard, discolored (darkened), and/or were not responsive to stimuli (appendage, stylet, probe). Percent mortality is the number of dead adelgid divided by total observed. HWA density is the number of adelgid observed per linear centimeter of twig sample.

Evaluating Hemlock Health. Three parameters were used on all twig samples in evaluating hemlock health, including Hemlock Health Index, Munsell color values, and dry needle weight (in grams).

The HHI utilizes three parameters to establish an index: the presence of HWA infestation; qualitative assessments of percent needle chlorosis and loss; and quantitative measurement of 3-year twig shoot extension (elongation). By combining these three parameters, the Hemlock Health Index is developed using the formula:

100 – (% chlorosis + % needle shed) x 3-year mean shoot extension .

For this study, 164 samples were examined using HHI analysis.

The Munsell Color Chart for Plant Tissues (Munsell Color, GretagMacbeth LLC) was used to assess hemlock 3-year growth, as abnormal needle color may indicate a deficiency or physiological problem.

Dry weight was measured using a custom-built laboratory dehydrator (at 130˚F) into which samples were placed and dried to 12% humidity (~ 48 hrs). A total of 181 samples were processed (89 for microinjection study, 92 for plant tissue study).

Soil and Plant Tissue Analyses. Soil samples obtained from 24 properties in the towns of Winchester and Dover, Massachusetts, were taken by tube probe to a depth of 6 in. (15 cm) on a grid for a representative property sample. The samples were then sent for analysis to an independent laboratory (CLC Labs, 325 Venture Drive, Westerville, Ohio 43081) for the following: soil pH; cation exchange capacity (CEC); organic matter (OM3); macroelements (expressed as available mineral in ppm), including phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg); and microelements (in ppm), including iron (Fe), manganese (Mn), zinc (Zn), and copper (Cu). Of the sites in this subpopulation, 37.5% of the hemlocks sampled were treated with organic granular and liquid soil amendments in year 2000, and 58% were treated with organic granular and liquid soil amendments in year 2001.

Twig samples from each of the 24 sites were prepared for foliar analysis, separating current year growth from 1- and 2-year growth. Current-year twigs and 1- to 2-year-old twigs from each site were analyzed by ICP Spectrometry of dry-ash sample in 10% HCl at the University of Massachusetts Soil and Plant Tissue Analysis Laboratory in Amherst, Massachusetts. Hemlock tissue P, K, Ca, Mg, Fe, Mn, Zn, and Cu were compared to values reported in the soil analyses. Mean dbh for this (non-injected) subpopulation of trees was 16 in. (40 cm) with a range of 2 to 22.5 in. (5 to 56.3 cm). Mean height was 18.2 ft. (5.4 m) with a range of 6 to 40 ft. (1.8 to 12 m). Growth was moderate to vigorous for this subpopulation, but 12.5% were newly planted, non-established trees, showing signs of physiological stress due to limited root mass or improper (deep) planting.

Results

Percent of Samples Infested Versus Noninfested. Upon careful inspection (in laboratory) of the 164 samples analyzed for microinjection efficacy, 83.5% were found to be infested, while 16.5% were noninfested. Of the 24 sample sites analyzed for soil and tissue mineral content (non-injected population), 83.3% were from noninfested hemlock, while 16.7% were infested with HWA.

Percent HWA Mortality and Viable HWA Density. Based on 125 infested samples, mortality ranged from 2.4% to 100%. We observed mortality values above 80% in approximately half of the samples (52.8% or 66 samples). The mean mortality observed was 73.4%, with 57.6% of the samples above the mean and 42.4% below. Viable HWA density values ranged from 0 per cm to 5.5 per cm. The observed mean was 0.6 HWA/cm, with 29.6% (37 samples) above the mean and 70.4% (88 samples) below. Seventy-six percent of the samples were found to have low density, that is, less than one viable HWA/cm (95 samples). Viable HWA density and percent HWA mortality, as one would expect, are inversely related, as shown in Figure 1. That is, as mortality increases, viable density decreases.

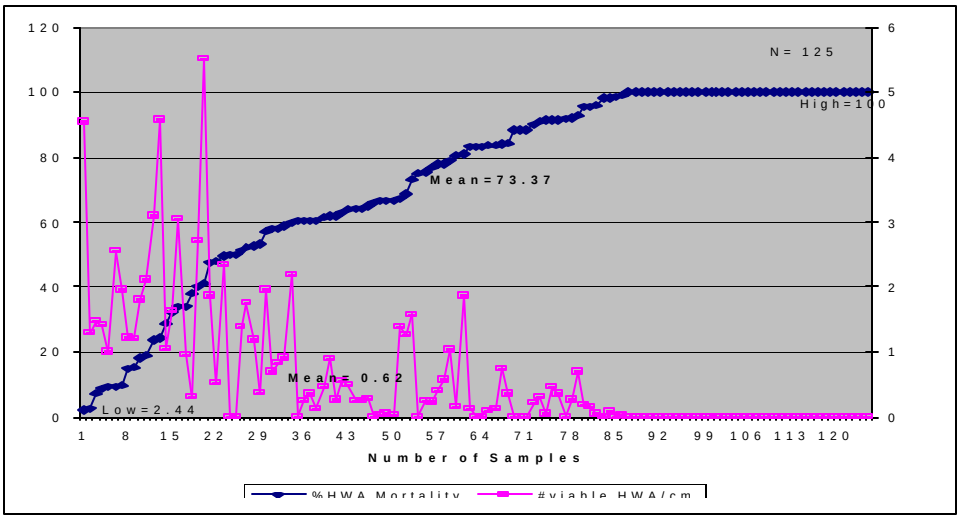

Figure 1. Percent mortality versus viable HWA density.

Hemlock Health Index. In more than 164 (all microinjected) samples, HHI values ranged from 10.5 to 1,950 with an observed mean of 437.1. In the microinjection study, the HWA-infested trees (83.5% of samples) had a mean HHI of 400.9 and a range of 10.5 to 1,950, with 65.6% of the data below the mean. Based on HHI rating, 73.2% are between "very low" and "low-moderate" index, 26.8% are between "moderate" and "high." These percentages approximate on-site observations, in which 63.8% are affected by HWA and 36.2% are healthy—reflective of the sampling technique (see Methods). Therefore, "very low" HHI (or 15.2%) is associated with infestation, no growth, and dieback ("strained"); "low" to "low-moderate" HHI (or 57.9%) are associated with infestation and stunting ("stressed"); and "moderate" to "high" HHI (or 26.8%) are associated with normative growth ("healthy").

Of the non-injected population (plant tissue analysis), 90.2% of the non-infested samples rated "moderate" to "high" in the HHI analysis. Of non-infested trees in the non-injected population, 90.2% rated "moderate" to "high" in the HHI analysis; 9.8% rated "low" to "low-moderate."

Comparison of 3-year Mean Shoot Extension, HHI, and Dry Needle Weight. Three-year mean shoot extension, HHI, and dry weight are directly related. In 125 samples analyzed (infested, microinjected trees), where mean HHI was 400.9 ("low-moderate"), the mean for twig extension was 5.2 cm, with 67.2% below the average. Three-year mean shoot extension (in cm) is directly related to needle mass (in g), and may be described as dry needle weight in grams per centimeter twig extension (see Figure 2). The mean for dry weight was 1.4 g, with 80.8% of values below the mean. As shown in Figure 2, higher dry weight corresponds to an increase in HHI. The values that depart from the dry weight curve correspond to samples that had vigorous growth, reflected in a high dry weight, yet a low HHI. These outlying values were a result of the samples' high percentage of chlorosis, effectively lowering the HHI.

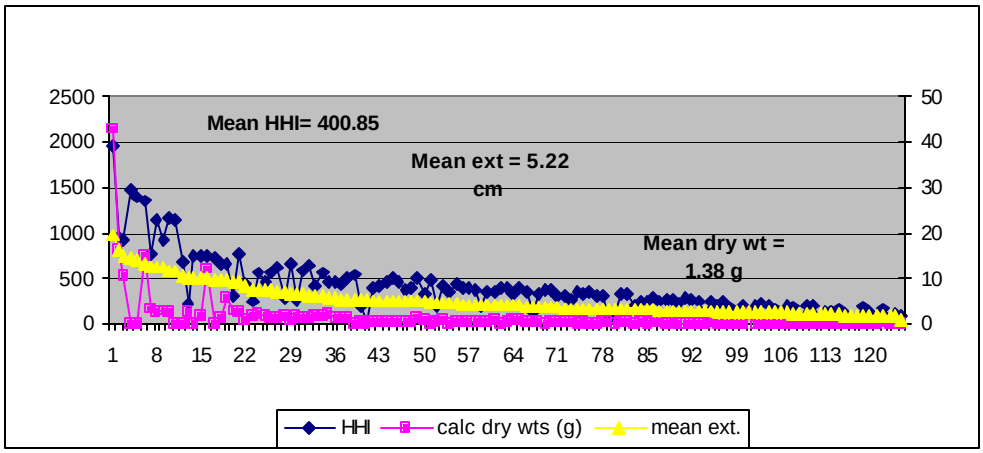

Figure 2. Three-year mean twig extension, HHI, and dry weight infested sample.

Noninfested samples bear the same relationship among mean twig extension, dry weight, and HHI. In non-injected, noninfested trees (80 samples), mean dry weight was 7.4g. Lower values of dry weight were observed in infested samples, with a mean of 1.4g. The difference between the means

is 5.3 x—a significant difference in needle density. One can extrapolate a concomitant decrease in photosynthetic capacity. Infested samples show less growth and less development than noninfested. The dry-weight curve of most of the infested samples (79.2%) is comparable to the very low and low-moderate categories in the HHI classification (see Figure 3).

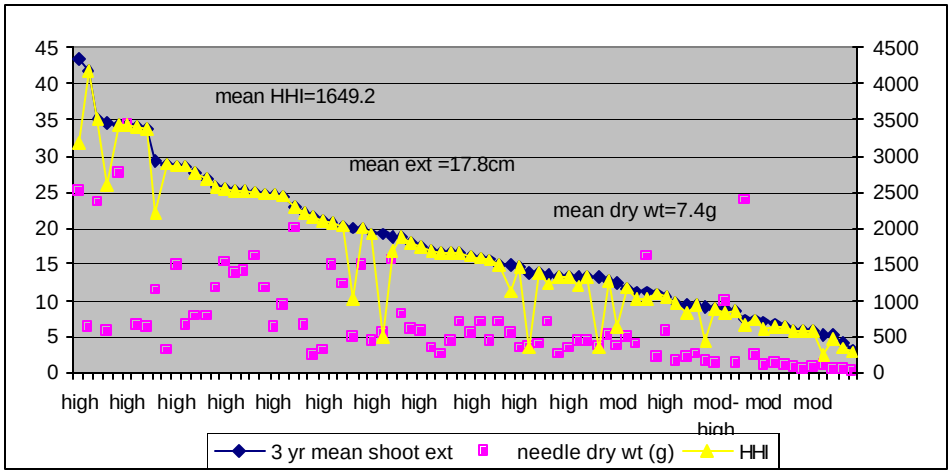

Figure 3. Three-year mean twig extension, HHI, and dry weight for non-infested sample.

Comparison of HHI vs. HWA Density of Infested Samples Sorted by 3-year Mean Shoot Extension. While dry weight, shoot extension, and HHI relate directly, all are inversely related to HWA infestation severity. As shown in Figure 4, plant health decreases as insect population increases. Across 125 samples, we observe an inverse relationship between HHI and HWA density (#HWA/cm). The data were sorted by 3-year mean shoot extension, then assigned Hemlock Health Index ratings. Mean HWA density was calculated for each of these subcategories, and plotted. High indices are associated with low mean HWA densities (mean = 0.64 HWA/cm), very low indices are associated with high mean HWA densities (mean = 3.48 HWA/cm), and intermediate mean density values correspond with moderate-high to moderate, low-moderate and low, with 0.89, 2.32, and 2.39 HWA/cm, respectively. When HWA density is greater than 1 (HWA/cm > 1), HHI shifts below 500 (from moderate to low-moderate). This is a critical point for intervention, as below an HHI of 500, twig vigor (or photosynthetic productivity) begins to spiral downward.

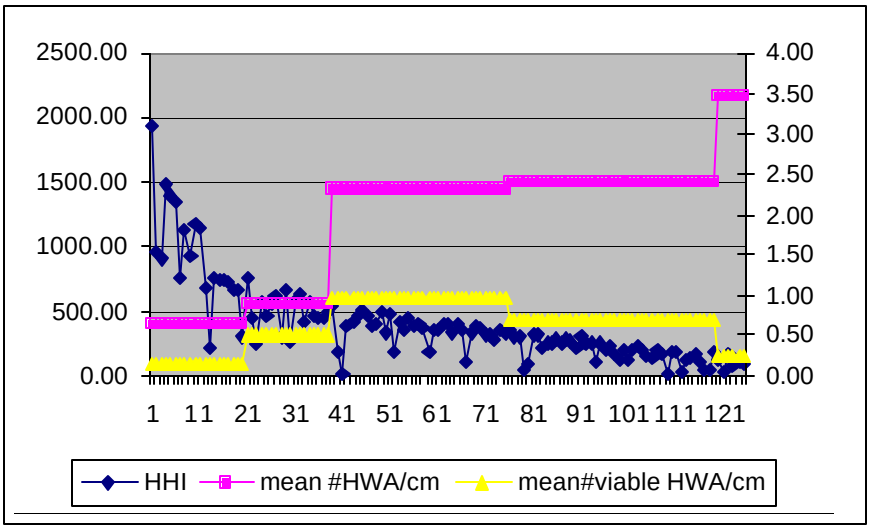

Figure 4. HHI and HWA density.

Similarly, viable HWA

density and HHI bear an inverse relationship. High indices correspond to low viable HWA densities (mean = 0.15 HWA/cm), as do very low indices (mean HWA/cm = 0.26 HWA/cm). Intermediate mean viable density values correspond to HHI ratings of moderate-high to moderate, low-moderate and low, with 0.51, 0.96, and 0.70 viable HWA/cm, respectively. The distribution of viable HWA density data in Figure 4 resembles a normal distribution (bell curve), which indicates an initial lag, exponential growth, and then gradual decline. New and old infestations both have lower densities of viable HWA, with new infestations having high HHI ratings, and old (more protracted) infestations rating low (infestation pressure peaks then declines, apparently as a result of competition and decreased food resources). The amplitude may have been moderated as a result of therapeutic treatment. One hundred twenty-five samples were used for this analysis.

Munsell Analysis of Noninfested Tsuga canadensis. Analysis of 80 non-infested (healthy) samples using the Munsell Color Chart for Plant Tissues identified 62.5% between 7.5GY 4/5 to 3/2 and 7.5GY 3/4 to 3/2. This range represents typical and normative coloration of hemlock needles. Thirty percent of the samples had values between 5GY 5/6 and 5GY3/4, associated with slight to moderate chlorosis. This range of color of plant tissues reflects either mineral deficiencies of the soil or physiological stress due to exposure (e.g., wind). Values of 2.5GY5/4 to 5GY5/6, representing moderate to severe chlorosis, occur in 5% of the sample. Interestingly, needle shed of 2-year-old, noninfested twigs is found to occur in 17.5% of the samples—hemlock may retain needles up to 5 years old (observation). This needle shed (in rapidly growing, moderate-high index trees) may indicate the need to reallocate mineral resources (from source to sink). Need for supplementation is suggested by this analysis in 31.7 to 37.5% of samples; 42.8% of chlorotic values (slight to moderate) were observed in current year growth—indicating limited non-mobile mineral (micro) elements (ISA).

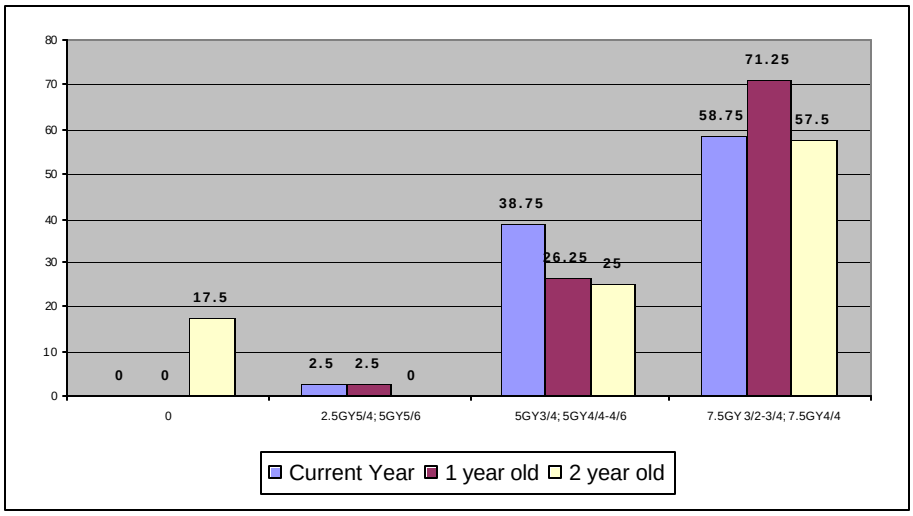

Figure 5a. Munsell analysis for noninfested samples.

Munsell Analysis in Tsuga Canadensis for Infested Samples. Analysis of 123 samples using the Munsell Color Chart for Plant Tissues identified 75% of values between 7.5GY 3/2 to 3/4 and 7.5GY 4/2 to 4/6, again, a typical and normative coloration of hemlocks needles. There was no current year growth on 34.1% of the samples, which was associated with HWA infestation.

Twenty-two and nine-tenths percent of the samples showed (slight to moderate chlorotic) values of 5GY3/4 to 5GY 4/4-4/6, while 6.6% of samples had (moderate to severe chlorotic) values of 2.5Y 6/6, 5GY 5/4-5/6, and 5GY4/8. This range of chlorosis reflected either mineral deficiencies of the soil or high infestation pressure, which induced physiological stress. This analysis indicates the need for therapeutic treatment to manage HWA infestation and supplementation to manage physiological stress in 29.4% of hemlock. Seventy-one and four-tenths percent of (slight to moderate) chlorotic values were observed in current year growth—suggesting limited non-mobile mineral (micro) elements.

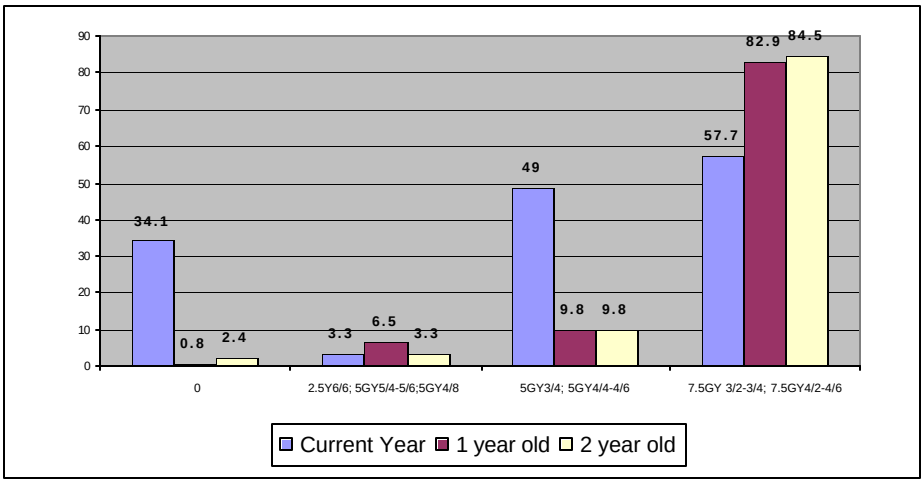

Chart 5b. Munsell analysis for infested samples.

Soil Analyses. Results of the soil tests for the 24 sample sites indicate a pH range of 4.7 to 6.7 with a mean of 6.0—adequate for hemlock health. Cationic exchange capacity (CEC) ranges from 4.8 to 16.2, with a mean of 10-meq/100 g soil. For silt loam soils, such as in the samples analyzed, CEC typically ranges from 8 to 25 meq per 100 g. Half of the samples turned out to be below 9.3 meq per 100 g. Mean values in ppm for macroelements are P = 94, K = 74, Ca = 870, and Mg = 142. Indicated as limiting in 50% of soils analyzed is potassium (K < 75ppm). Of the microelements, manganese (Mn < 5ppm) is limiting in 90.9% of soils analyzed, ranging from 1 to 5, with a mean of 2.3 ppm. Organic matter (OM) ranges from 2.8 to 9.6% with a mean of 7.2%. Although the study trees are competing with turf grasses where leaves are removed annually and not left to accumulate, mean OM in the study sample is higher than mean values reported by the USDA Forest Service. Forest hemlock, found on acidic, moist soils, ranges in OM from 1.2 to 28.3% with a mean 5.5% (USDA FS). With borderline CEC values, OM reported may be higher than actual. The error may have occurred in our sampling method. The silt loam soils in this study are prone to drought and mineral leaching—attributes that favors physiologically-induced stress in hemlock. Other exposures include deicing salts or chemical applications that may depress microbial associates. The addition of organic matter will help to buffer droughty soils (by increasing the available water-holding capacity), increase the CEC (and mineral-holding capacity), and support beneficial associates. It also is an alternative to nitrogen supplementation that may favor HWA infestation. It is our recommendation to increase OM in soil to 10% by weight for hemlock health. This area is of particular interest and the subject of continued study.

Plant Tissue Analyses. Based on samples from the 24 sites, comparison could be made of foliar and soil content of macroelements P, K, Ca, Mg, and microelements, Fe, Mn, Zn, and Cu (see Figures 6 and 7). As 90.2% of hemlock samples in the plant tissue analysis had moderate to high health indices, it was expected that the tissue analyses would reflect normative mineral levels. However, as noted in the Munsell analyses, 31.7% of non-infested hemlock show slight to severe chlorosis. Forty-two and eight-tenths percent of slight to moderate chlorosis observed occurred in current year growth—suggesting limited non-mobile microelements. Presented in Figure 8 are the ratios of mineral content in hemlock tissue to available minerals in soil. The greater the difference (or the higher the ratio), the more difficult for the plant to accumulate the mineral. The tissue/soil ratios suggest high K, P, and Mn requirements and relatively low availability. The macroelements K and P translocate within the plant sap (i.e., phloem mobile), therefore deficiencies tend to appear in mature needles first. This may account for early (2-year) needle loss in the moderate to high index trees. Manganese on the other hand does not translocate as readily, and will show deficiencies in new growth first, accounting for chlorotic values noted in current year needles. Recommendations for supplementation in hemlock are based upon observable foliar deficiencies (chlorosis) and soil and plant tissue analyses that identify specific deficiencies. Tissue analyses for microinjected trees were not part of this study.

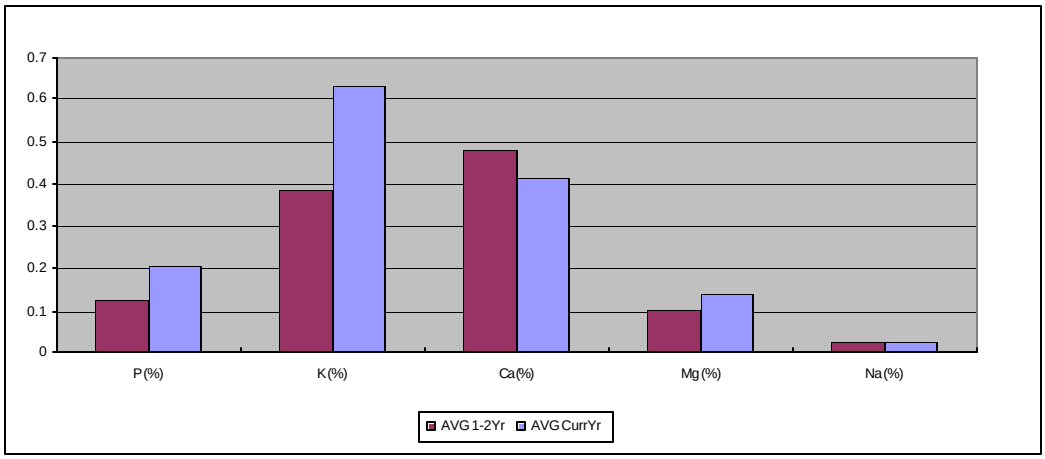

Figure 6. Plant tissue analysis macroelements.

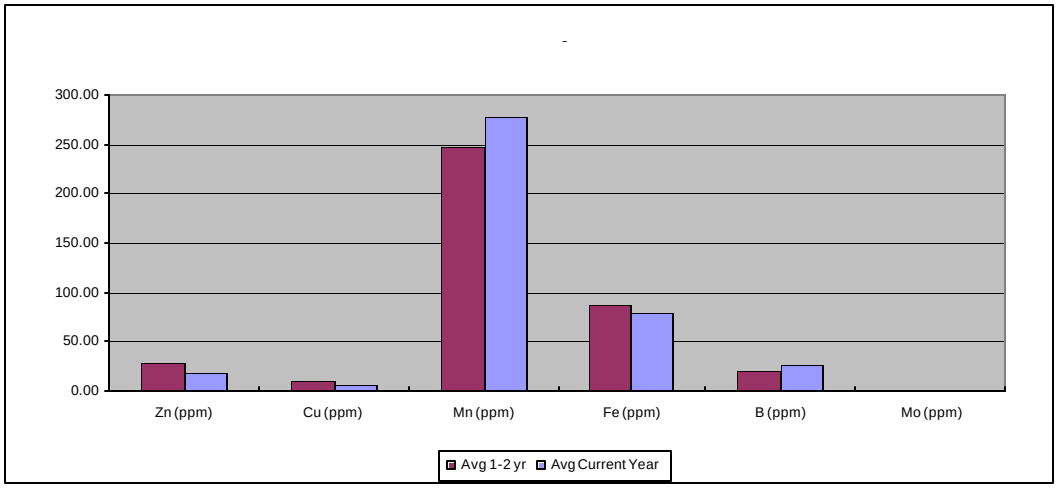

Figure 7. Plant tissue analysis microelements.

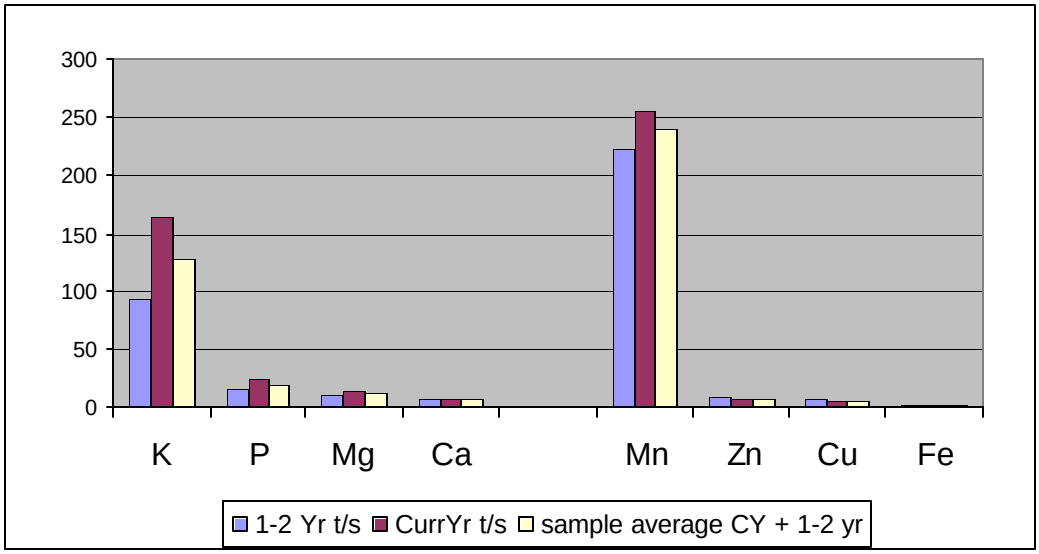

Figure 8. Mean plant minerals/mean soil minerals.

Discussion

The hemlocks of the microinjected population are under high HWA pressure and show signs of dieback and stunted growth, indicating the need for therapeutic and plant health interventions. The majority of trees treated had protracted infestations (high HWA pressure) and significantly compromised health indices. As the mean percent HWA mortality of spring-injected hemlocks is 73.4%, limited efficacy may be the result of less than optimal dosage delivery into the active sapwood. Dosage delivery may have been inconsistent and (in some instances) ineffectual, due to occasional injector needle clogging in the prototype device, and may have resulted in dosages significantly less than the calculated mean of 1.4ml/caliper in. Follow-up application is being pursued.

The data indicate that newly infested trees (low HWA pressure < 1 HWA/cm) have moderate to high health indices, that is, there is little impact on hemlock health. Keeping insect population pressure low minimizes impact on tree health, indicating the necessity for early, proactive therapeutic intervention. A higher HWA density leads to a lower health index. When HWA pressure exceeds 1 HWA/cm, the index drops to low-moderate to very low. Lower indices are generally associated with protracted infestations, and low dry needle weight. Very low to low indices are associated with no growth, chlorosis, needle shed, and dieback. Delay of therapeutic intervention results in protracted infestations (high insect pressure) and consequent degrading in tree health, making recovery efforts difficult.

Hemlock Health Index has a direct relationship with both mean 3-year twig extension and dry needle weight. HHI is based on shoot extension (cm), needle loss, and chlorosis, whereas dry weights are a measure of needle mass (g) present. As infestation pressure increases, both HHI and dry weight decrease. Hemlock Health Index will give the arborist a quick assessment (15-minute diagnostic) of tree condition, and may be determined with the use of a hand (10x) lens. Dry weights

require more time (48 hour drying cycle) and are very objective and accurate measurements, but require specific laboratory equipment not necessarily available to the arborist.

A combined use of foliar indications (Munsell analyses) tissue and soil analyses, aid in diagnosing deficiency symptoms. Munsell analyses indicate deficiencies in 29.4 to 37.5% of the hemlock examined, suggesting supplementation. In infested hemlock, total chlorosis observed occurs about as often as in noninfested trees (22.7% and 31.5%, respectively). Chlorotic symptoms are consistently higher in current season growth (infested and non-infested), suggesting deficiency of immobile mineral elements. Soil analyses suggest amendment with organic matter to increase the cationic exchange capacity (CEC), and the available water-holding capacity (AWHC) to reduce physiological stress in hemlock. Plant tissue analyses of high index trees indicate normal minerals (percent, ppm) present in hemlock. A simple comparison of mineral content in hemlock tissue and soil available minerals may be used to help guide fertilization practices. Indicative in this analysis is the need for Mn, K, and P supplementation—fertilization practices do not necessarily need to rely on nitrogen applications. Phosphorus and Mn are critical to photosynthesis (ISA), and P is essential to energy utilization (ADP, ATP). Maximizing photosynthetic capacity also maximizes production of allelopathic extractives of which carbohydrates are prerequisite (ISA) without necessarily favoring lush growth. This may be accomplished through organic sources, including composts, sea kelp, and chelated microelements that are soil amendments (i.e., are humus forming), and supplementary minerals without high nitrogen applications. Applications of amendments are indicated when these are determined to be limiting by soil and foliar analyses.

Conclusions

Hemlock health assessment involves determining the condition of the tree and its response to environmental stress, including insect pressure. HWA infestations are strongly associated with shoot stunting—the basis of the health assessment described in this paper. When compared to noninfested samples, shoot extension may be reduced by as much as 75%. In-house analysis includes a health assessment that includes presence and degree of HWA infestation, the average last 3-year twig growth, and an estimate of percent of needle loss and chlorosis. Use of the Munsell Color Chart for Plant Tissues helps to characterize the extent and location of chlorotic response. A comparison of current season needles with 1- and 2-year needles helps to broadly identify (macro- vs. microelements) the reallocation of mobile minerals within the plant. Immobile mineral deficiencies will appear at the twig tips, whereas mobile mineral deficiencies first appear in older needles. These analyses are designed as tools for informed decisionmaking in hemlock health and HWA management. Unlike gypsy moth, hemlock is not immediately defoliated, so the cues to the property owner will likely be missed. The arborist may use a simple diagnostic (HHI) to inform clients of infestation severity, its consequence, and as a basis for a program of hemlock health and HWA management. Proactive, early intervention practices for hemlock health care are strongly recommended.

Plant health care practices that focus on mitigating physiological stresses, such as drought and mineral deficiencies, will help keep photosynthesis and production of protective plant chemicals high. A plant health care system requires three things: a visual signal of a deficiency (e.g., chlorosis); determination

of the deficiency–that is, which particular mineral? (plant tissue analysis); and determination of availability of minerals in deficit (soil analysis). The additions of composted organic matter with a high fungal component (Ingham 1991) will serve to buffer soils against drought by increasing the available water-holding capacity, reducing mineral leaching by increasing the cationic exchange capacity, and providing substrate for microbial activities, including supporting mycorrhizal associates. The addition of mineral supplements, such as soluble kelp and chelated microelements, to minimize physiological deficiencies is likewise indicated. This recommendation avoids high nitrogen supplementation that may favor HWA, yet serves to enhance plant health. Plant health and growth are not necessarily the same. Amendments and microelement supplements have a place in hemlock health care.

Spring microinjections with the Arborjet injector device resulted in HWA mortality sufficient to maintain health in trees with recent infestations. In trees with lower observed mortality, follow-up therapeutic application and supplemental PHC is being pursued. Microinjection system design changes, include self-cleaning injection needle design, and indication of full dose delivery, will be reflected in future studies.

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