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Prioritizing eastern hemlock (*Tsuga canadensis*) for secondary imidacloprid treatment against the invasive hemlock woolly adelgid (*Adelges tsugae*) in Shenandoah National Park

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ABSTRACT

Shenandoah National Park (SNP) contains over 20,000 eastern hemlocks (*Tsuga canadensis*); a foundation species in the southern Appalachian Mountains. Hemlock is shade-tolerant and retains a dense needle canopy year-round, creating a unique microclimate providing habitat for many species. The decline in eastern hemlock from hemlock woolly adelgid (*Adelges tsugae;* HWA) infestation has negative implications for the overall function of forest ecosystems. The effect of slope aspect and time since imidacloprid insecticide treatment on crown health change and diameter growth of eastern hemlock in SNP was quantified. Data was compared from hemlock trees located on southeastern (SE) and northwestern (NW) aspects at sites that were either treated two, five or eight years ago. Trees at control sites received no treatment. Change in crown health was significantly affected by aspect and time since treatment ($p<0.001$) but change in diameter growth rate was not affected by either variable. Crown health decreased in trees treated eight years ago on both aspects and remained the same as initial treatment health in trees treated five years ago. The SE aspect trees treated two years ago showed a decline in crown health while the NW aspect trees experienced a significant increase in crown health. Increased precipitation on the SE aspect may be causing the insecticide to break down faster resulting in insufficient absorption of treatment. This hypothesis is supported by significantly lower imidacloprid residue detected in branch samples from SE aspect trees ($p=0.04$) and could explain the continued decline of SE aspect hemlock crown health after treatment. Aspect may have a role in treatment effectiveness initially, but within five years, hemlock trees will exhibit similar health decline. A concerning observational finding was the lack of cones on either aspect, despite evidence of

treatment effectiveness. Treatment may result in short-term hemlock recovery and survival, but not reduce HWA stress long enough to allow for reproduction. It is recommended that SNP management select a subset of the eastern hemlock population for future imidacloprid treatment due to the costs of time, money and ecological degradation. Based on this research, the selected trees should be adult hemlocks located in hemlock dominated stands on higher elevations of NW aspects.

INTRODUCTION

Eighty-five national parks, including Shenandoah National Park (SNP) in the southern Appalachian Mountains, contain eastern hemlock (*Tsuga canadensis*) stands (Abella 2014). Eastern hemlock is severely threatened by an invasive insect, the hemlock woolly adelgid (HWA; *Adelges tsugae*). A native to Japan, HWA was first discovered near Richmond, Virginia in the 1950s (Souto et al. 1996). Since then, it has infested Eastern Hemlock (*Tsuga canadensis*) trees throughout nineteen states, as far north as Maine and south to parts of Georgia (USFS 2012). In Japan, HWA has several natural predators and is not considered a pest. The U.S. lacks native predators capable of keeping HWA densities low enough to prevent hemlock decline, allowing HWA to become a significant problem (Havill et al. 2012).

From 1990 to 2000, eastern hemlock trees within SNP experienced an 80% reduction in the number of trees with excellent crown health and a 49% increase in mortality rate (Willeford Bair 2002). A Forest Vegetation Simulator predicted that in 20 years, less than 2% of hemlocks will remain in hemlock stands as a result of HWA infestation (Spaulding and Rieske, 2010). Shenandoah National Park is likely to experience changes resembling those observed in the Delaware Water Gap National Recreational Area (Eschtruth et al. 2006). Within 9 years of hemlock decline, understory light levels doubled, vascular plant cover experienced a fourfold increase and there was a drastic increase in colonization of invasive plant species in this recreational area (Eschtruth et al. 2006). The risk to eastern hemlock is so great that the International Union for Conservation of Nature added eastern hemlock to the red list of threatened species (Farjon 2013).

The loss of eastern hemlock may have devastating ecological consequences such as a loss in biodiversity, which threatens ecosystem stability. Eastern hemlock is a foundation species, meaning that it is large in number but also has a very large impact on the ecosystem. It performs ecological functions unlike other tree species in eastern North American forests due to its ability to retain a dense canopy of needles year-round creating a distinctive microclimate (Ellison et al. 2005; Vose et al. 2013). Ingwell et al. (2012) reports over 600 species of arthropods are found in hemlock stands, of which, 250 are exclusive to hemlock. Furthermore, there are at least 96 bird and 47 mammal species directly associated with eastern hemlock forests (Yamasaki et al. 2000). Hemlocks are also common in riparian areas where they influence stream conditions, impacting the flora and fauna of the stream ecosystems as well. (Siderhurst et al. 2010).

Hemlocks can be found in pure stands or mixed stands with deciduous species such as *Betula* spp., *Fagus grandifolia*, *Liriodendron tulipifera*, *Acer rubum* and *Balesia carolina* (Kincaid 2007). However, these deciduous, canopy species cannot provide the same function as eastern hemlock (Evans et al. 2011). A study conducted by Vose et al. (2013) suggested that the eastern white pine may be the closest functional replacement for hemlocks in the Appalachians. Unlike hemlock, white pine is less tolerant of shade and does not maintain a dense lower canopy. In the event of eastern hemlock decline, deciduous species are predicted to fill the forest gaps (Evans et al. 1996).

While there have been several attempts at introducing predator beetles to feed upon HWA, currently, the most effective management practice for HWA suppression is the application of the insecticide, imidacloprid. Over the last seven years, one park ranger in SNP has used low-dose, soil-injection imidacloprid treatments on over 20,000 hemlock trees. Recent research suggests that these treatments may only last four to six years (Doccola et al. 2012). Physiography may have an effect on treatment longevity. Studying HWA infestation and imidacloprid treatment efficiency on hemlock trees growing on the opposing mountain aspects may help park management prioritize future treatment and retreatment sites within the park.

The Blue Ridge Mountains of SNP in Southern Appalachia, are dominated by two slope aspects, the northwest (NW) and southeast (SE). It is predicted that these aspects have different environmental conditions that will affect soil-injected imidacloprid treatment longevity and efficiency on eastern hemlock trees infected by the HWA (**Figure 1**). NW aspects of this region are predicted to have less soil moisture due to a rain shadow effect. Most storms on the east coast arise from the Atlantic Ocean. The SNP mountain peaks inhibit storm cloud movement, trapping precipitation on the SE aspect. Since eastern hemlock is not a drought tolerant species, it is predicted that hemlocks on NW slopes will be stressed from less soil moisture (Bonneau et al. 1999). Forest environments with less soil moisture are also less productive, meaning there is a lower turnover of vegetation resulting in less organic matter in the soils. Imidacloprid is also known to readily bind to organic matter (Knoepp et al. 2012), increasing the longevity of the insecticide in soils with high organic matter. This increases the time the insecticide is available for the hemlocks to uptake. Since the SE aspects have more moisture, it is predicted that there will be more organic matter as well, resulting in healthier hemlock trees from the extended availability of insecticide. Furthermore, it is predicted that lower concentrations of imidacloprid residue will be found in the branches of hemlocks on the NW slopes. Trees with less residue will likely harbor a larger HWA population, adding to the tree stress. Finally, it is predicted that hemlocks under stress may have an increased cone density. Several northern hemisphere trees, such as pine species, have been found to invest resources on reproduction rather than growth when stressed (Koenig and Knops 1999).

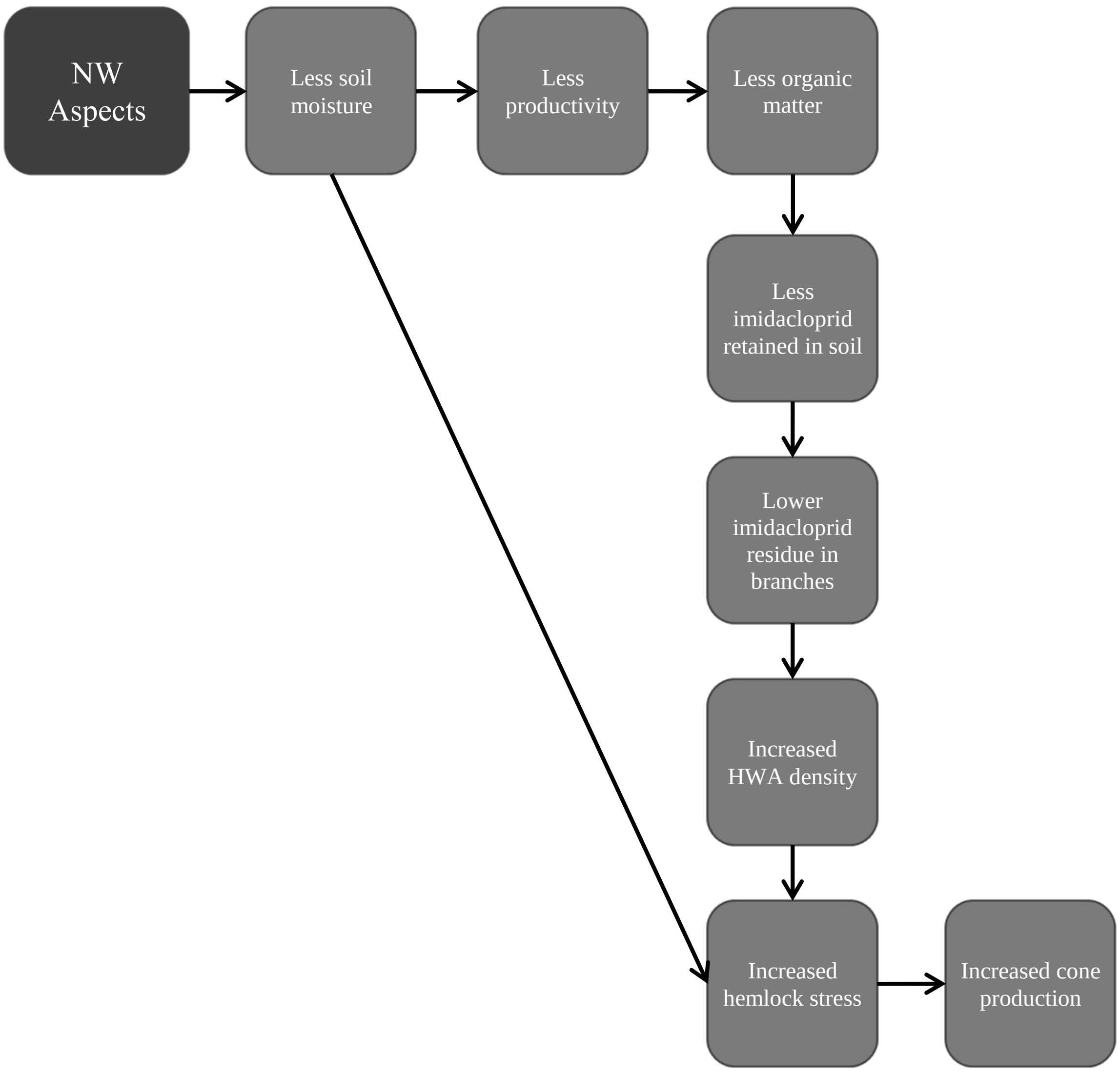

Figure 1: Flow chart detailing the predictions that the NW aspect will require more treatments due to less efficient use of imidacloprid.

METHODS

Study Area

The research was conducted in Shenandoah National Park, a part of the Appalachian mountain range, located in the western portion of Virginia. Eight locations within the park were sampled based on information provided by a park ranger including a list of all eastern hemlock sites, the year and amount of imidacloprid treatment each site received, the diameter at breast height (DBH) and initial crown health of individual trees and a GIS (Geographic Information Systems) shapefile containing the coordinates for approximately half of the treated trees. Sites were paired so that one site represented the SE side of the mountain range and the other represented the NW side, with both sites receiving low dose, soil-injected treatment in the same year. Using ESRI GIS ArcMap 10.1, paired sites were shown to have similar geographic features such as stream proximity, elevation, solar radiation, slope and soil type. The sites were narrowed down to the following; for treatment year 2007 (8 years ago), Jeremy's Run (NW) and Thornton Run (SE), for treatment year 2010 (5 years ago), the Skyline Drive site was divided into SE slope and NW slope trees, and for treatment year 2013 (2 years ago), Jollet (NW) and Piney Branch (SE) were used. The three untreated control sites chosen were Ivy Creek (SE), Madison Run (NW) and Meadow Run (NW) (**Figure 2**).

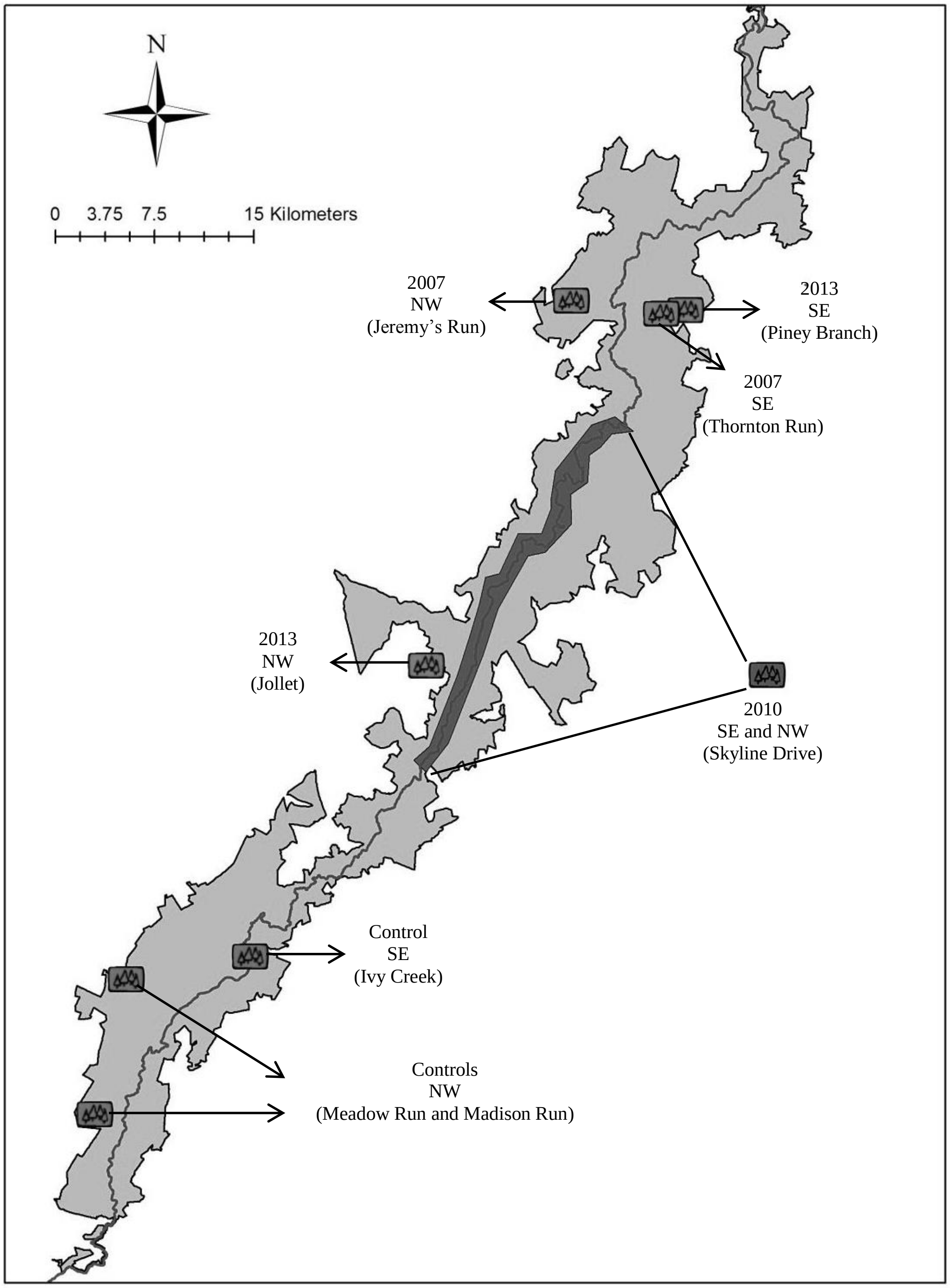

Figure 2: Map of Shenandoah National Park with Skyline Drive shown to indicate the approximate top of the mountain. Hemlock sites utilized are emphasized, with dominant slope aspect and treatment year given.

Data Collection

Using GIS, hemlocks with GPS coordinates were selected based on size for each site (with the exception of the controls). Only canopy, adult trees with a DBH greater than or equal to 18 cm were used. As many trees as possible were then located in the field between July and October 2015. Chemical treatment was confirmed by locating a small spray paint marking at the base of the trunk and individual trees were identified by comparing current and initial DBH. The current DBH was then recorded and a crown health estimate was collected. Crown health estimates were obtained utilizing similar methodology that was used by SNP staff. Two to four field assistants would approximate what the tree would look like with a full canopy and then assign a percentage to that approximation based on the foliage actually present (**Figure 3)**. The crown health estimates of each field assistant were then averaged for the final estimate. Additional notes were made about each tree including the presence/absence of HWA and cones, multiple trunks, close proximity to other trees and barren spots in the crown. The same data were collected at the control sites but there were not pre-existing GPS coordinates to relocate trees.

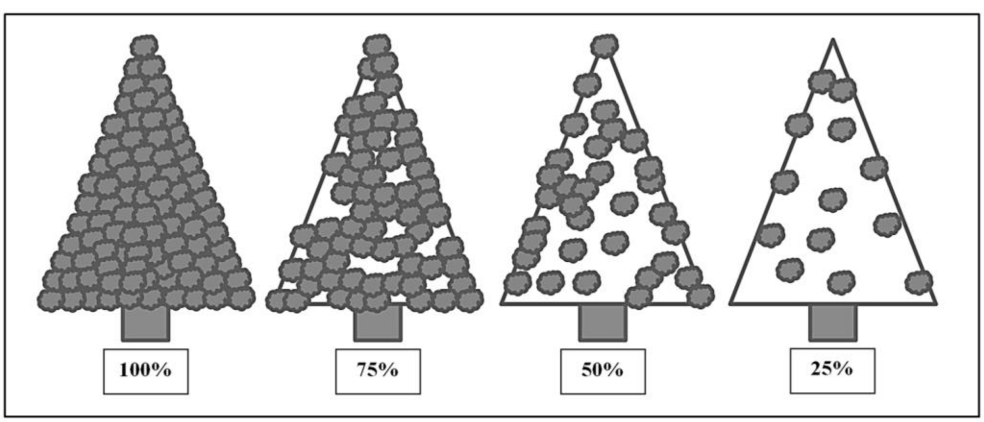

Figure 3: Visual diagram illustrating how crown health estimations were made in the field.

Soil and Branch Sample Collections from 2010 Skyline Drive Site

The soil and branch sampling was performed on September 19, 2015. A total of 20 hemlocks, found during initial data collection of the Skyline Drive site, were randomly selected for further testing. Ten of these trees were from the SE aspect while the other ten were from the NW aspect. Using an 18-foot, arborist pole pruner, a 50 cm branch sample was clipped from the mid-canopy of each cardinal direction, for a total of four branches, from each tree. The samples were observed for HWA and cones and then they were sealed in individual Ziplock bags. Two, 10 cm soil samples were collected from the canopy edge of each tree using a standard forestry soil probe. Notes were taken regarding soil conditions and the samples were stored in individual Ziplock bags. The pruner and soil probe were sterilized using Lysol between each sample.

Soil Analysis

Upon returning to the lab, the initial 'wet' weight of the soil samples was recorded. The samples were then transferred into individual paper bags and dried in an oven at 80 degrees C.. After one week, the 'dry' weight of the samples was recorded. The percentage of soil moisture in the samples was then calculated using:

$$\%\, moisture = \frac{(final\ weight - intial\ weight)}{intial\ weight} x100$$

The soil samples were then used for organic matter analysis via the weight loss on ignition method. After heating 5 g of each soil sample in a Fisher Scientific Isotemp Muffle Furnace for 2 hours at 105^{o} C, the initial mass of samples was obtained. The samples were then super-heated in the muffle furnace at 360^{o} C for 2 more hours. After the samples had cooled, the final masses were obtained and the percent loss on ignition was calculated using the same formula as the soil moisture analysis. Percent organic matter can be inferred from percent loss on ignition.

Imidacloprid Residue Analysis

The branch samples were stored in a household 20° C freezer until analysis. The method used to prepare the samples for imidacloprid residue analysis was extracted from Cowles *et al.* (2006). Using a coffee grinder, needle and stem parts of individual samples were ground to a fine powder. A one-gram sample of the powder was added to a 15 mL test tube with 10 mL of histological grade acetone. The test tubes were then sealed and placed on a horizontal shaker and shaken overnight. Twenty-four hours later, the contents of the tubes were allowed to settle and then a 1 mL aliquot was pipetted into a fresh 15 mL test tube. The new tubes were placed in a fume hood for approximately 2 hours to allow the acetone to evaporate. Once the acetone had completely evaporated, 1 mL of water was vortexed with the remaining residue. Samples were then frozen until the enzyme-linked immunosorbent assay (ELISA) could be performed.

Imidacloprid concentrations were measured using an Envirologix ELISA Kit for Imidacloprid. The range of detection for the assay is 0.2 to 6 ppb. Initially, an undiluted 100 µL aliquot was used to test all samples. The samples that were above the test range were retested using a 1:2 dilution. Only 3 strips were run at once due to time constraints when loading the wells and the lack of an available multi-channel pipette. A 100 µL aliquot of each imidacloprid standard (0, 0.2, 1, 5ppb) was loaded into the first 4 wells of the first 2 strips to run as duplicates (**Figure 4**). The remaining wells contained unknown samples which were also run in duplicate. The protocol provided with the kit was then used to properly utilize reagents. The absorbance of the plate was read on a Thermo

Scientific Multiskan GO spectrophotometer at 450 nm and 630 nm (for reference). Using SkanIt RE for Multiskan GO 3.2, the computer produced optical density (OD) readings for each well.

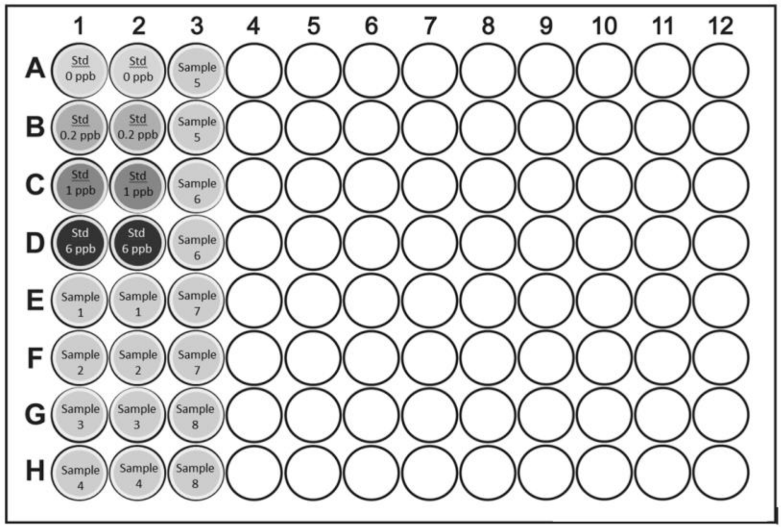

Figure 4: Visual diagram of ELISA plate set-up

To determine the results, a $\%B_0$ had to be calculated for each calibrator and sample using the following equation:

$$\%B_0 = \frac{average\ OD\ of\ calibrator\ or\ sample}{average\ OD\ of\ negative\ control} x100$$

The validity of the calibrators was determined by the $\%B_0$ values. If each calibrator $\%B_0$ value fell within the accepted range, then the $\%B_0$ value was graphed against the calibrator's imidacloprid concentration on a semi-log scale (**Figure 5**). Using interpolation, the imidacloprid concentrations of the unknown samples were calculated from the equation of the best fit line between the calibrator points.

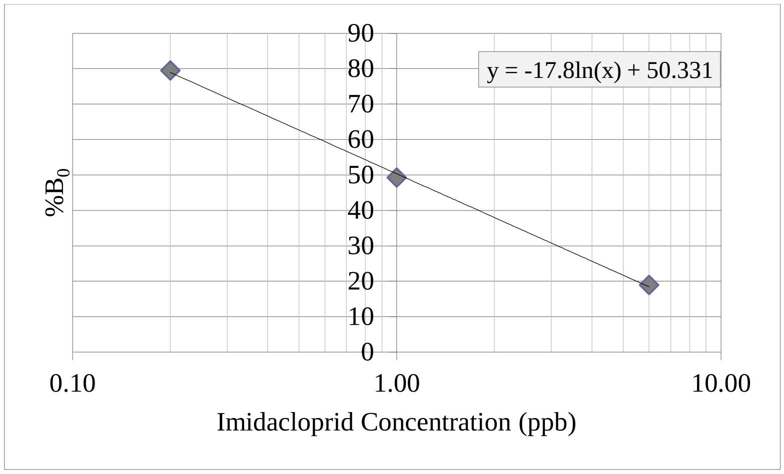

Figure 5: Example plot of $\%B_0$ values for each calibrator. The equation from the line was used to interpolate imidacloprid concentrations in unknown samples.

Statistical Analysis

IBM SPSS Statistics 22 was used for all statistical analysis, graphing and normality testing.

For treated site data, a multivariate analysis of variance (MANOVA) was performed on DBH growth rate and crown health change data based on treatment year (3 levels) and aspect (2 levels). This model was invalidated based on an interaction between the two independent variables. Therefore, the dependent variables were separated into two-way analysis of variance (ANOVA) tests using both independent variables. Regression analysis was used to determine if a relationship existed between the DBH growth rate and crown health change of the treated sites.

Since there was no pre-treatment data at the control sites, the present DBH and crown health measurements were compared to assess hemlock differences based on aspect without any treatment. Due to skewed distribution, Kruskal Wallis analysis was used. Mann-Whitney U was used for post-hoc analysis of the Kruskal Wallis.

Regression analysis was used to determine relationships between crown health and DBH for control sites.

Chi-square analysis was used to compare adult hemlock abundance on SE and NW aspects using all available hemlock GIS data points provided by SNP.

For the 2010 soil and residue sample data, Mann-Whitney U tests were performed on the soil moisture, organic matter and imidacloprid residue data between the two aspects. Regression analysis was also performed to determine relationships between variables.

RESULTS

Untreated Control Sites

No HWA or cones were observed at any of the three untreated, control sites. The majority of the hemlocks were small and likely too young to produce cones. The two NW control sites contained significantly larger hemlocks in terms of DBH (X^2=40.48, p<0.001) and had significantly lower crown health (X^2=28.75, p<0.001) then the SE site (**Figure 6**). Evidence of the relationship between crown health and DBH was supported by regression analysis (r^2=0.220, p<0.001) (**Figure 7)**.

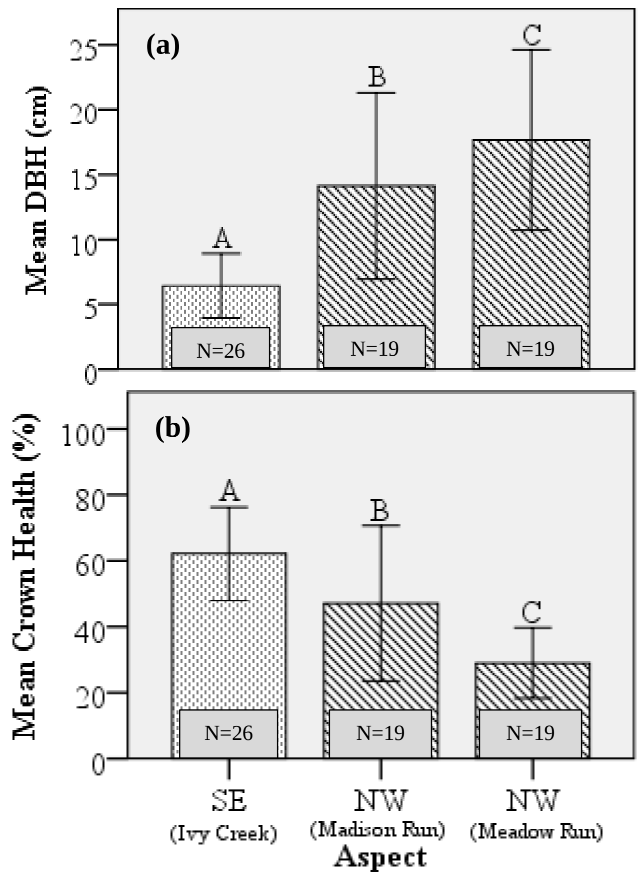

Figure 6: (a) average DBH (X^2=40.48, p<0.001) and **(b)** average crown health (X^2=28.75, p<0.001) of eastern hemlock at the three untreated, control sites within Shenandoah National Park. A total of 64 trees were sampled. Significant differences from Kruskal-Wallis with Mann Whitney U post-hoc analysis, at alpha level 0.05, designated by letters. Error bars show (+/-) one standard deviation.

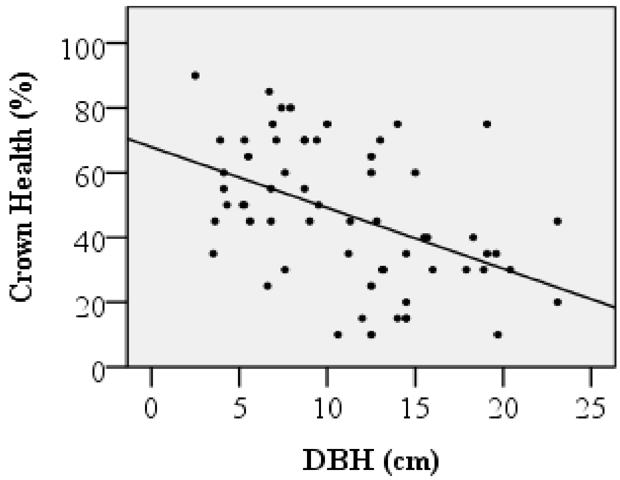

Figure 7: Regression analysis showing a weak, negative correlation between DBH and crown health (r^2=0.220, p<0.001). A total of 64 trees were sampled from control sites.

Treated Sites

HWA and cones were not observed at any of the six treated sites on either aspect. Neither aspect nor time since imidacloprid treatment affected average rate of DBH increase (F=0.772, p=0.573) (**Figure 8**). However, it is interesting to note the trend showing trees treated earlier appear to have a slowing growth rate. Also, at all treatment time points, the growth rate is slightly higher on NW aspects. Average change in crown health was significantly affected by aspect and time since treatment (F=9.22, p<0.001) (**Figure 9**). In addition, the interaction between the two independent factors was significant (F=7.23, p=0.001). The model reveals that hemlocks treated eight years ago (2007) significantly decreased in crown health compared to more recently treated hemlocks (2010, 2013) on both aspects. The hemlocks treated five years ago (2010) were at approximately the same crown health on both aspects as they were at the time of treatment and were significantly less healthy than trees treated two years ago (2013). Aspect only had a significant effect in the two-year post-treatment sites (2013), where the

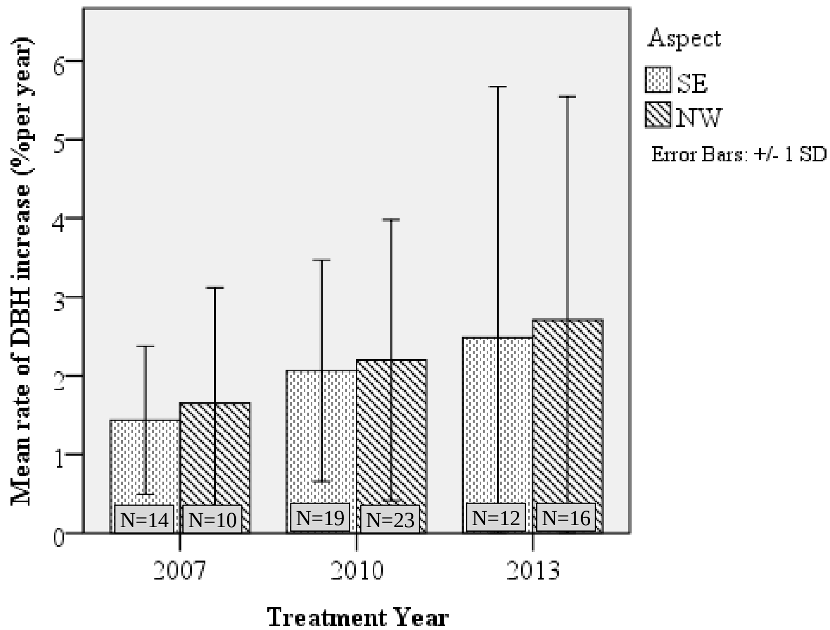

Figure 8: Eastern hemlock average rate of DBH increase per year at the treated sites in Shenandoah National Park. A total of 94 trees were sampled. No significant differences observed at alpha level 0.05. Error bars show (+/-) one standard deviation.

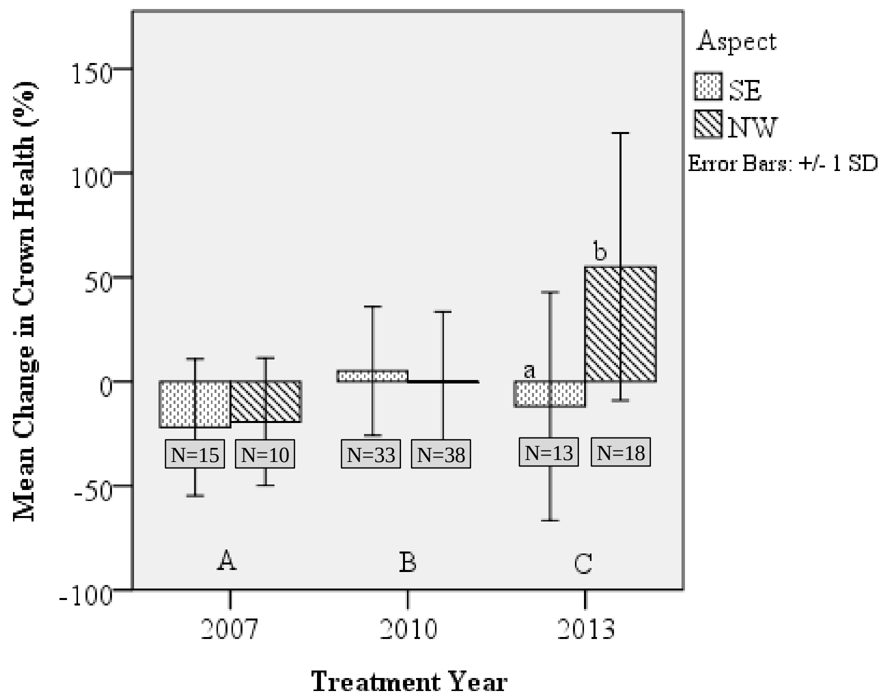

Figure 9: Eastern hemlock average change in percent crown health for treated sites within Shenandoah National Park. A total of 127 trees were surveyed. Significant differences, at alpha level 0.05, based on treatment year ($F=11.43$, $p<0.001$) indicated by letters. Significant differences, at alpha level 0.05, based on aspect ($F=5.64$, $p=0.019$) indicated numerically. Error bars show (+/-) one standard deviation.

NW site had a significantly greater increase in crown health than the SE site, which showed a decline in crown health.

During data collections of the treated sites, it was observed that the NW sites appeared to have more hemlock trees than the SE sites. This observation was later supported by GIS analysis of all treated eastern hemlock in SNP. The NW side of the mountain contained significantly more hemlock (>18cm DBH) than the SE side (X^2=636.96, p<0.001) (**Figure 10**).

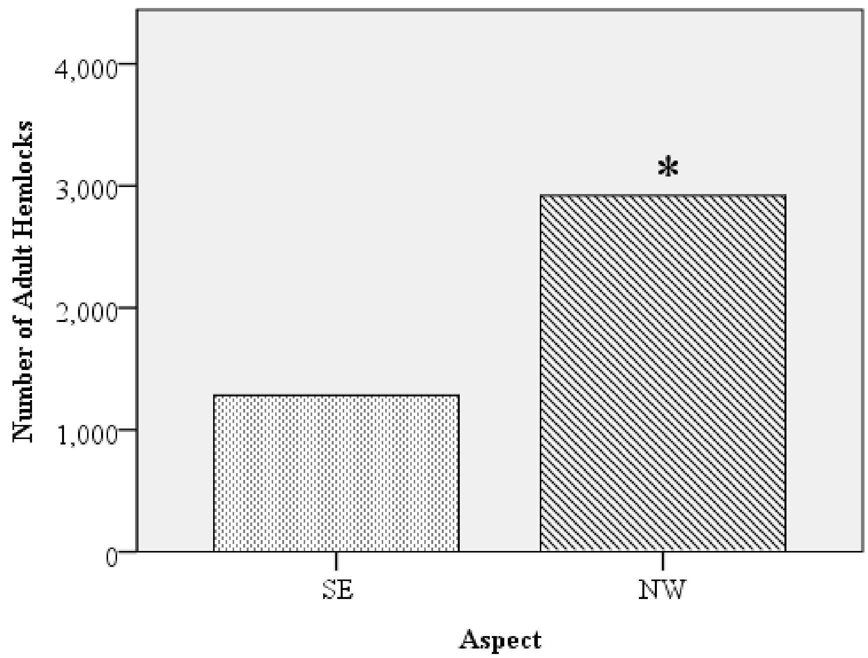

Figure 10: Number of known, greater than18cm DBH, adult, eastern hemlock in Shenandoah National Park. Dominant mountain aspect determined by GIS analysis of GPS located trees. Significant difference, at alpha level 0.05, indicated by asterisk (X^2=636.96, p<0.001).

Soil and Imidacloprid Residue Sampling

Aspect had no effect on soil moisture (U=35, p=0.26) or soil organic matter (U=41, p=0.50) in samples taken from the understory of hemlocks at the 2010 site (**Figure 11**). However, aspect had a significant effect on imidacloprid residue (U=23, p=0.04). More residue was detected in the branches of the hemlocks from the NW aspect (**Figure 12**).

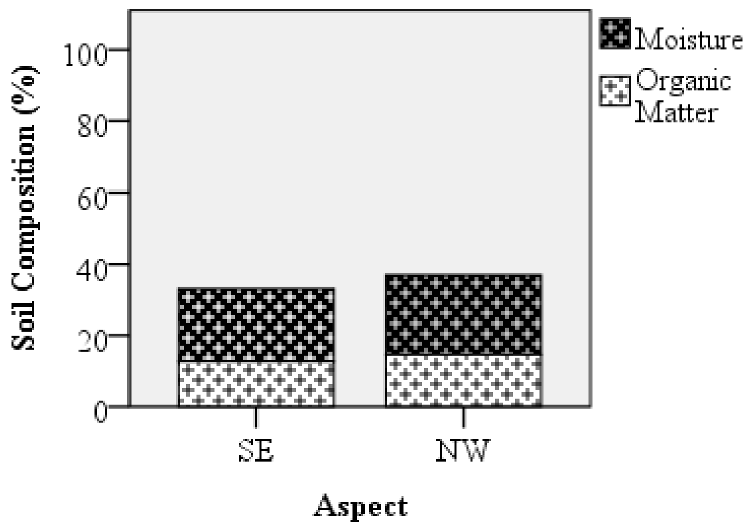

Figure 11: Percentage of soil moisture and organic matter in soil samples from the understory of 20 eastern hemlocks treated five years ago (2010 site) in Shenandoah National Park. Two 10 centimeter samples were collected from the canopy edge of each tree. No significant differences detected at alpha level 0.05.

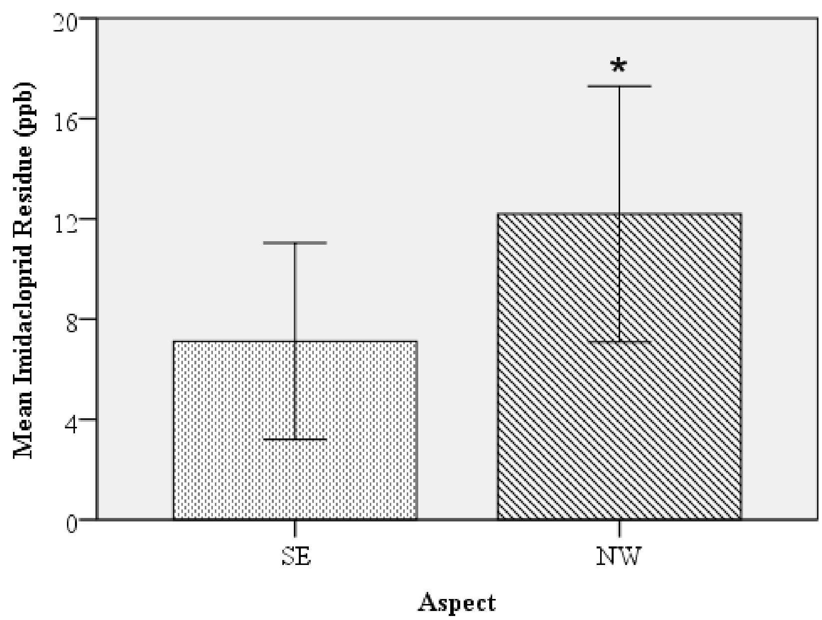

Figure 12: Average imidacloprid residue from four branch samples of 20 eastern hemlocks treated 5 years ago (2010 site) in Shenandoah National Park. Significant difference, at alpha level 0.05, indicated by asterisk (U=23, p=0.04). Error bars show (+/-) one standard deviation.

DISCUSSION

In 2015, no living HWA were found on any hemlocks in SNP, even at untreated control sites. Average annual temperatures during the winter months may explain this current and most likely temporary, decline in infestation. Previous studies attributed cold winters to reductions in HWA (Paradis et al. 2008). HWA has demonstrated a lack of cold-tolerance which has limited their spread north and into higher elevations (Willeford-Bair 2002). Historical temperature data was obtained from U.S. Climate Data for locations near SNP and showed the winters of 2013 and 2014 were colder than average **(Figure 13)**. The very cold days likely caused high mortality of over-wintering HWA, resulting in drastically reduced 2015 spring and summer HWA generations.

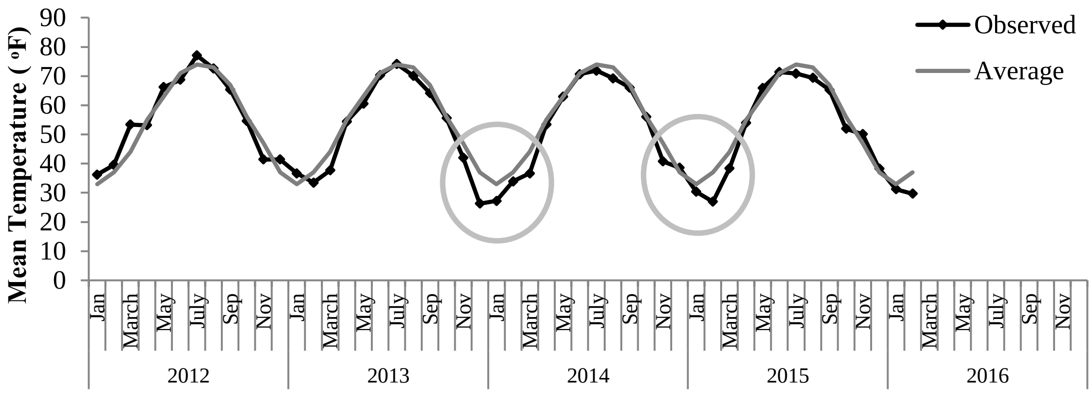

Figure 13: Mean temperatures in Shenandoah National Park from January 2012 to January 2016. The gray line shows average temperature cycles while the black line with points shows actual observed average temperatures. The winters of 2013-2014 and 2014-2015 are circled to show colder than average temperatures that were likely detrimental to HWA populations.

Despite reprieve from HWA infestation at the time of data collection for this project, evidence of HWA damage was present in SNP. Many groves of large hemlock trees were found to be dying or already dead. Evidence from control sites suggest smaller hemlocks have improved crown health compared to larger trees. This could be the result of the passive dispersal of HWA via wind. In forest systems, wind has greater strength in the canopy layer. This would result in increased dispersal of HWA among the large, canopy hemlock trees.

HWA damage was also evident by the lack of cones observed. Alarmingly, very few hemlock trees were reproducing in the park. Eastern hemlock produce cones when they reach 15 years of age (Godman and Lancaster 1990). In the southern Appalachians, a 23cm DBH hemlock is approximately 40 years of age (Tubbs 1977). From this, it can be inferred that the hemlocks surveyed with greater than 18cm DBH are of appropriate age for reproduction. Hemlocks are one of the most prolific cone producers compared to similar tree species, with consistent high yields of cones in successive years (Wang 1974). It is unclear what is inhibiting hemlock reproduction. It was predicted that hemlock would produce more cones in response to stress; however, it appears hemlock is not allocating resources to reproduction. It may be that even with HWA suppression, the hemlocks do not recover enough to produce cones.

Growth rate of eastern hemlock in terms of DBH was not affected by slope aspect (SE or NW) or time since imidacloprid treatment (2, 5, or 8 years). However, change in crown health was affected by both variables. Hemlock location on NW or SE slope aspect initially plays a role in the effectiveness of imidacloprid. Hemlocks treated two years ago on the NW aspect significantly increased in crown health while hemlocks on the SE aspect declined in crown health.

The initial difference in crown health change may be due to increased precipitation on the SE aspect (**Figure 14**). Increased precipitation may increase primary productivity and consequently organic matter, which readily binds imidacloprid. However, imidacloprid also degrades in the presence of water and sunlight. Graebing and Chib (2004) found that the half-life of imidacloprid in moist soils was 1.8 times shorter than in air-dry soils due to the active movement of imidacloprid dissolved in water through the photolytic layer of soil during evaporation and condensation cycles.

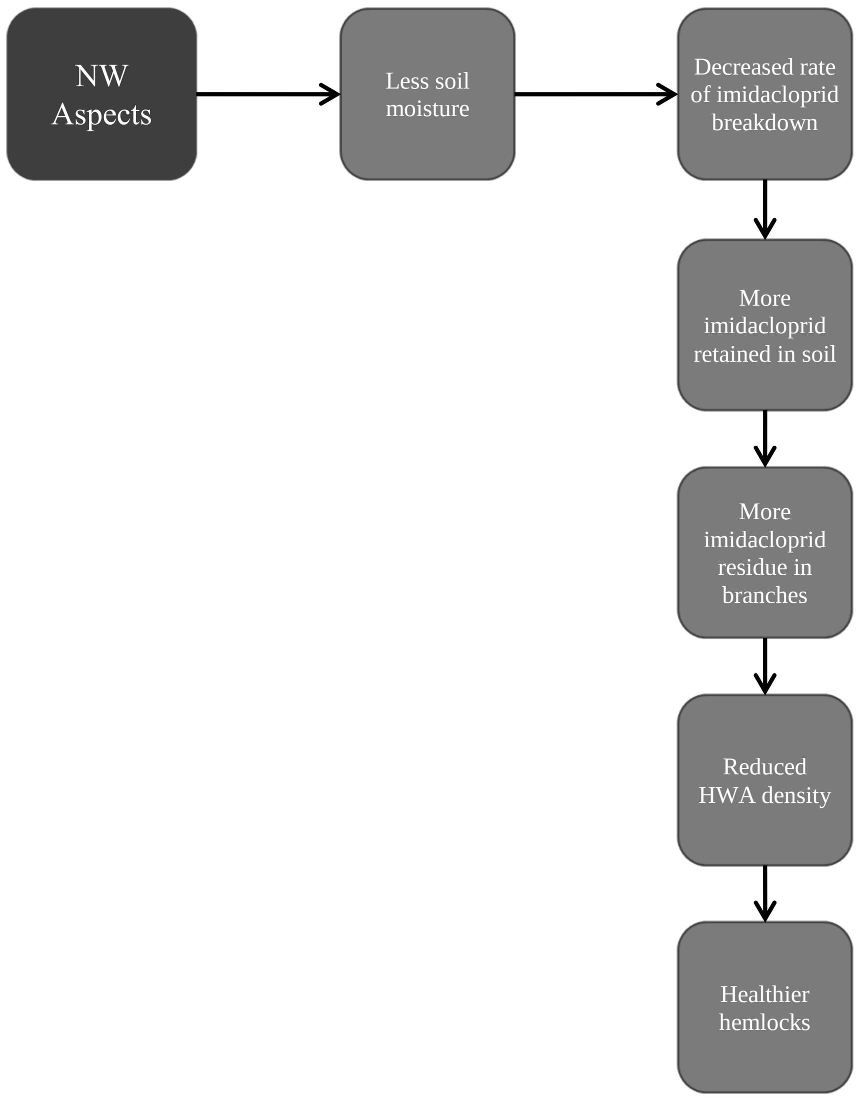

Figure 14: Redesigned flow chart detailing the new hypotheses and predictions based on the results showing NW hemlocks have an initial increase in crown health post-imidacloprid treatment.

SE hemlock trees may not have sufficient time to absorb enough insecticide to adequately reduce HWA populations before imidacloprid breaks down. Low-dose imidacloprid treatments are currently utilized, but the SE trees may require a higher dose to see the same recovery as NW hemlocks. This hypothesis is supported by the branch sampling data that showed significantly lower levels of imidacloprid in SE hemlocks. The soil samples did not show increased moisture levels on SE aspects, but this was likely due to abnormally moist September when the samples were taken (U.S. Climate Data). However, precipitation data shows the SE side of the mountain receives 12cm of additional precipitation than the NW aspect in consecutive years (**Figure 15**).

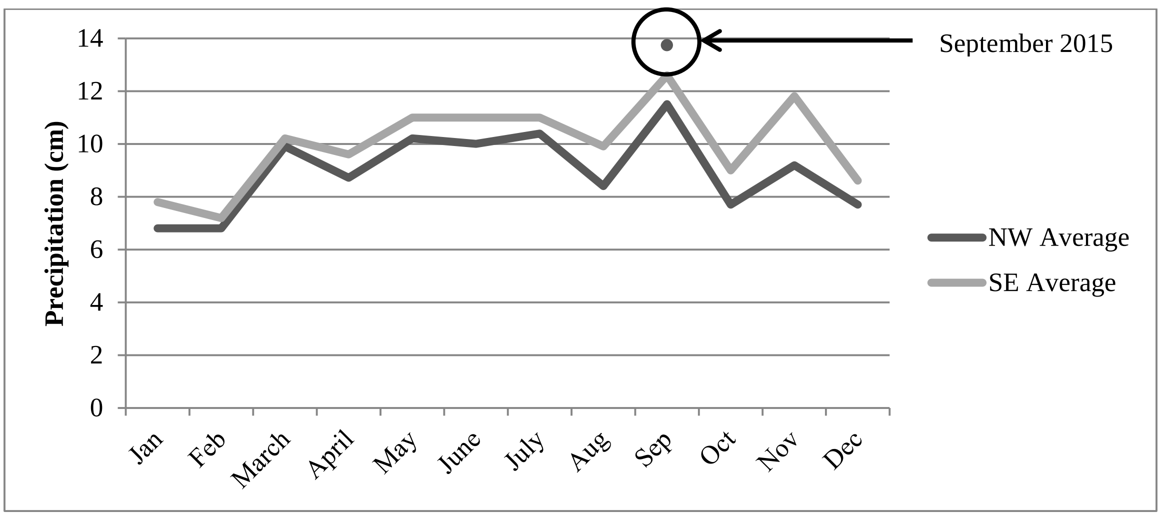

Figure 15: Average precipitation on both sides of the Blue Ridge Mountains. The SE aspect consistently receives more precipitation throughout the year, accumulating approximately 12cm more moisture than the NW aspect. In September 2015, the NW aspect experienced abnormally high rainfall amounts likely accounting for the lack of differences in soil moisture seen in the soil samples collected.

Aspect did not have an effect on imidacloprid treatments beyond the two years post-treatment sites. While NW aspect hemlocks treated two years ago increased in health, both NW and SE hemlocks treated five years ago returned to the initial, declining crown health state recorded prior to treatment. NW and SE hemlocks treated eight years ago had even poorer crown health than when they were initially treated. This decline, despite lack of present infestation, can be attributed to the decrease in imidacloprid effectiveness after 4 to 6 years. The present research suggests the longevity of imidacloprid treatments in SNP is likely closer to 4 years before the HWA are able to re-infest.

Interestingly, in addition to initial health improvements of NW hemlocks, the present data and historical forest composition data prior to HWA infestation in SNP, suggests eastern hemlock is naturally more abundant on the NW aspect (Lipford 1984; Harrison et al. 1989). Lower numbers of eastern hemlock on SE aspects may be the result of natural disturbance patterns; such as wind throw or ice damage from large coastal storms on the SE side of the mountain (Landfire). Eastern hemlock is a slow-growing species and does not stump sprout which further limits hemlock recovery after damage.

CONCLUSIONS AND RECOMMENDATIONS

Despite the short-term recovery of hemlocks on NW aspects, after five years, all hemlocks regardless of aspect are likely to be in a state of declining crown health again. Continuing imidacloprid treatments on over 20,000 hemlocks in SNP may not be the best management practice. Both monetary and ecological costs as well as the extended amount of time it has taken a single park personal to apply treatments must be considered.

Each packet of Prokoz Zenith 75 WSP imidacloprid costs $6.28. Using low-dose guidelines, each packet treats approximately twelve, 10-centimeter diameter at breast height (DBH), hemlock trees at a cost rate of 5 cents per centimeter DBH. For all 20,000 trees the total cost exceeds $10K. In addition, SE hemlocks appear to not receive enough imidacloprid from the low-dose treatments. Utilizing a high-dose treatment for the SE trees would be even more costly.

Since imidacloprid in a non-specific pesticide, there has been widespread concern about the impacts of imidacloprid on non-target organisms. One study found that imidacloprid is harmful to insect guilds associated with hemlocks, especially other species that feed directly upon treated hemlocks (Dilling et al. 2009). Another study linked imidacloprid to increased earthworm mortality (Kreutzweiser et al. 2008). Treatment of hemlocks along streams may result in contamination that would be detrimental to several aquatic species (Cowles 2009). Continued usage of imidacloprid may slow hemlock decline, but it may also have many negative consequences for the biodiversity and ecosystems of the park.

Finally, the time required for repeated imidacloprid treatments to stall hemlock decline cannot feasibly be met by one person. Based on the present research, imidacloprid treatments should be repeated every five years. However, the first round of treatments required seven to eight years to complete.

It is recommended that the park select a subset of the hemlocks to continue treating with imidacloprid. This would give more attention to preserving select members of the species, with routine treatments and monitoring until a more effective HWA control measure is developed. The trees that should be selected for continued treatments should be located on NW aspects due to their successful natural abundance and their effective use of low-dose imidacloprid treatments. Furthermore, the trees selected should be at elevations exceeding 700 meters based on evidence of increased hemlock health at higher elevation and limitation of HWA by their lack of cold-tolerance (Willeford-Bair 2002). The most benefit would come from preserving trees in forest stands where hemlock is dominant, since these stands would experience more drastic change from the loss of hemlock. Even though the results from the control sites depict smaller hemlocks are in greater health, it is recommended that the trees selected be large, adult hemlocks that are capable of reproduction when sufficient recovery is achieved. Finally, it would be beneficial to the park to protect the hemlocks that are in the public view both for aesthetic and educational purposes.

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