IMPACTS OF THE HEMLOCK WOOLLY ADELGID (ADELGES TSUGAE) ON HEADWATER STREAM WOOD LOADS IN THE SOUTHERN APPALACHIAN MOUNTAINS

A Thesis
by
BURKE ALEXANDER MCDADE

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Abstract

IMPACTS OF THE HEMLOCK WOOLLY ADELGID (ADELGES TSUGAE) ON HEADWATER STREAM WOOD LOADS IN THE SOUTHERN APPALACHIAN MOUNTAINS

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The hemlock woolly adelgid (*Adelges tsugae*) is responsible for wide-spread mortality of eastern hemlock (*Tsuga canadensis*), a foundation species of southern Appalachian forest ecosystems. Given the hemlock's high tolerance for shade and adaptation to moist and well drained soils, this species of tree preferentially grows in riparian zones. Conceptual models suggest that hemlock mortality could serve as a forest disturbance event that will increase the large wood (LW) load found within headwater streams. Further, it is well known that elevated LW loads induce geomorphic change and consequently impact ecological functions of aquatic systems. The objectives of this research are to (1) Characterize the health and abundance of hemlock trees in riparian forests of select Southern Appalachian watersheds, (2) Quantify in-channel LW loads in the same watersheds, and (3) Investigate the relationship of forest and geomorphic characteristics to wood load variables in the streams. Analysis of 26 stream sites located in headwater streams of the Blue Ridge Mountains with varying degrees of hemlock decline and composition revealed that streams draining watersheds with elevated levels of hemlock decline have greater quantities of in-channel LW. Correlations suggest that streams experiencing moderate to severe hemlock decline have resulting elevated wood loads ($r = 0.79$, $p < 0.001$). Findings from this research could result in beneficial contributions to the management of the hemlock woolly adelgid as well as headwater mountain streams of the region.

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I would like to thank all of the faculty and staff of the department of Geography and Planning for making me feel welcome and guiding me through my education in graduate school. I offer my gratitude to Appalachian State University and their Office of Student Research for providing me with funding that made it possible to present the findings of my research at the 2018 American Association of Geographers annual meeting.

Thanks must also be given to all of the other graduate students in the department, whom I can now confidently call friends. Finally, I would like to thank my parents and my girlfriend for their support, as this journey would not have been possible without their constant encouragement.

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Foreword

The main body of this thesis will be submitted to *The Southeastern Geographer*, a peer-reviewed journal distributed by the University of North Carolina Press; it has been formatted according to the style guide for that journal.

Introduction

Eastern hemlock (*Tsuga canadensis*) is experiencing decline and mortality throughout much of its range due to the hemlock woolly adelgid (*Adelges tsugae*). The hemlock woolly adelgid (HWA) is an invasive insect species native to Asia that resembles an aphid and was imported to an ornamental tree nursery in the United States in 1954. The original site of infestation was in close proximity to Richmond, Virginia. Currently, the HWA is found in 18 states and well over half of the native range of the Eastern Hemlock (Royle & Lathrop 2002). The exotic pest feeds off the nutrient-rich ray parenchyma cells of the hemlocks. This process results in the gradual defoliation of the trees and eventual mortality (Young et al. 2002). Upon infestation, complete tree mortality is estimated to occur in the range of 4-15 years (McClure 1990).

Unlike Western Hemlock (Tsuga heterophylla) and other Asian Hemlock species, Eastern Hemlock shows no natural defense or genetic resistance to the HWA (McClure 1990). Biocontrol agents such as insecticidal sprays, injections, and predatory beetles have shown some success at preventing invasion and mortality of hemlocks, but these methods prove to be exhaustive in terms of financial resources and time taken for application. These biocontrol methods may be useful at smaller spatial scales, but not applicable at the landscape level (Dukes et al. 2009). Considering this information, severe decline and even extirpation will likely be prevalent throughout the native range.

The Eastern Hemlock inhabits a diverse landscape in terms of latitude and elevation. Its range extends from southern Quebec and Ontario, west to Minnesota, and south to Alabama. The most continuous part of its range lies within the Appalachian Mountains from Maine to Georgia (Kessell 1979). The tree is a late-successional coniferous species that can live over 800 years, grow over 40 meters tall, and have a trunk diameter of 2 meters (Godman and Lancaster 1990). Hemlocks are also among the most shade tolerant trees in the United States (Jenkins et al. 1999). In the northern half of the Eastern Hemlock's range (Pennsylvania and north), the trees are found in a wide variety of habitats and elevations ranging from coastal forests to mountain ridges. Stands here can be comprised almost completely of hemlocks in the overstory (Dukes et al. 2009; Orwig et al. 2012).

In the southern Appalachian Mountains, the Eastern Hemlock represents a relatively small area of the landscape because the tree is confined to riparian and cove forests. Hemlocks can be the dominant tree species within these specific areas of the landscape. Recent research has documented the rapid spread of the HWA southward. Mortality of 11% for overstory hemlocks and 34% for understory hemlocks was recorded in the Great Smoky Mountains National Park only 5-6 years after invasion (Krapfl et al. 2011). A study at Coweeta Hydrologic Laboratory in the mountains of North Carolina documented 50% hemlock mortality in six years within a watershed (Ford et al. 2012). The Adelgid's rapid expansion south can likely be explained by a combination of a warmer winter climate and host availability (Evans et al. 2012).

Stream banks serve as moist, well shaded environments for hemlock thrive conditions in the southern Appalachian Mountains. As Hemlocks are found in large numbers in these suitable habitats any disturbance event that impacts hemlock populations will ultimately impact streams as well. Conceptual models suggest that mortality of hemlocks attributed to the HWA could serve as a forest disturbance event that will increase the large wood (LW) load found within headwater streams (Costigan et al. 2015).

Large wood is defined as a piece of wood within the bank full channel measuring at least 1 m in length and 0.1 m in diameter (Fetherston et al. 1995). Increasing wood loads due to hemlock mortality will likely have physical, biological, and ecological ramifications. Specific effects could include reduced carbon, sediment, and nutrient yields downstream (Costigan et al. 2015). Large accumulations of wood could also create temporary novel habitats for in-stream aquatic species. A proposed conceptual model suggests LW jams are likely to become more frequent and larger in volume as time after hemlock mortality ensues (Costigan et al. 2015). These jams will trap additional wood, sediment, and nutrients that would generally be transported downstream in the drainage. Large wood jams will also likely alter the existing channel unit sequences, creating additional step and pool stream sequences. Modified sediment, carbon, and nutrient fluxes, in addition to geomorphic change will have impacts on aquatic life in these systems (Costigan et al. 2015, Evans et al. 2012).

Considering the limited amount of literature relating to LW in the southern Appalachian Mountains, this research explored relationships between wood load and hemlock mortality while also considering other geomorphic variables known to impact wood in streams. We proceeded with these objectives by first quantifying wood loads at 26 stream sites with varying quantities of hemlocks and varying levels of hemlock decline. Succeeding stream sampling, transects were established in the riparian forest of each site and health and abundance of hemlock trees was quantified. The percentage of hemlocks in the forests and a decline scale for each hemlock ranging from 1-5 (1:>75% of foliage remains, 2: 51-75%, 3: 26-50%, 4:1-25%, 5: dead) was used to create a variable called the hemlock decline index (HDI). This variable ranging from 1-5, and considering hemlock presence and status, was used as the primary explanatory variable for wood load characteristics.

In total, 26% of the trees surveyed were hemlock and 71% of those were dead, of the remaining live hemlocks, 70% were exhibiting some amount of stress related to the adelgid presence. Additionally, correlations between the percentage of rhododendron in understory plots and the HDI yielded a significant positive correlation indicating the possibility of heightened rhododendron growth and coverage due to hemlock die off. Statistical comparisons were made between the level of hemlock decline (HDI) and LW characteristics (length of large wood, diameter of large wood, and large wood load). Boxplots revealed positive trends between increasing levels of hemlock decline and LW variables. This was statistically verified using non-parametric Kruskal-Wallis tests and Mann-Whitney U test Results indicated significantly different medians for both length of LW and LW load. Positive trends found were analyzed further using Spearman rank correlation and the resulting significance supported an association between LW load and hemlock decline metrics.

Elevated wood loads will induce habitat change and altered nutrient, sediment, and carbon fluxes for streams surrounded by stands of dead hemlocks. Subsequently, these changes could also drastically effect ecosystems downstream through reduced sediment and nutrient connectivity due to entrapment by LW upstream. The results of this study provide further understanding of this complex spatiotemporal forest disturbance event that will likely impact both terrestrial and aquatic environments for years to come. What follows is the manuscript for this research that will be submitted to the Southeastern Geographer for peer review.

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ABSTRACT

The hemlock woolly adelgid (*Adelges tsugae*) is responsible for wide-spread mortality of eastern hemlock (*Tsuga canadensis*), a foundation species of southern Appalachian forest ecosystems. Given the hemlock's high tolerance for shade and adaptation to moist and well drained soils, this species of tree preferentially grows in riparian zones. Conceptual models suggest that Hemlock mortality could serve as a forest disturbance event that will increase the large wood (LW) load found within headwater streams. Further, it is well known that elevated LW loads induce geomorphic change and consequently impact ecological functions of aquatic systems. The objectives of this research were to (1) Characterize the health and abundance of hemlock trees in riparian forests of select Southern Appalachian watersheds, (2) Quantify in-channel LW loads in the same watersheds, and (3) Investigate the relationship of forest and geomorphic characteristics to wood load variables in the streams. Analysis of 26 stream sites located in headwater streams of the Blue Ridge Mountains with varying degrees of hemlock decline and composition revealed that streams draining watersheds with elevated levels of hemlock decline have greater quantities of in-channel LW. Correlations suggest that streams experiencing moderate to severe hemlock decline had elevated wood loads ($r = 0.79$, $p < 0.001$). Findings from this research could result in beneficial contributions to the management of the hemlock woolly adelgid as well as headwater mountain streams of the region.

Key Words: Large Wood, Hemlock Wooly Adelgid, Headwater Streams

INTRODUCTION

Eastern Hemlock (Tsuga canadensis) is experiencing decline and mortality throughout much of its range due to the Hemlock Woolly Adelgid (Adelges tsugae). The Hemlock Woolly Adelgid (HWA) is an invasive insect species native to Asia that resembles an aphid and was imported to an ornamental tree nursery in the United States in 1954. The original site of infestation was near Richmond, Virginia. Since introduction, the HWA has spread to 18 states and over half of the native range of the Eastern Hemlock (Royle and Lathrop 2002). The exotic pest feeds off the nutrient-rich ray parenchyma cells of the hemlocks. This process results in gradual defoliation of the trees and eventual mortality (Young et al. 2002). Following infestation, complete tree mortality is estimated to occur in the range of 4-20 years (McClure 1990). However, the time interval for mortality is highly dependent on climatic and environmental conditions. Unlike Western Hemlock (*Tsuga heterophylla*) and other Asian Hemlock species, Eastern Hemlock shows no natural defense or genetic resistance to the HWA (McClure 1990). Biocontrol agents such as insecticidal sprays, injections, and predatory beetles have shown some success at preventing mortality of hemlocks, but these methods are only effective locally and not at landscape scale levels. Severe decline and even extirpation will likely be prevalent throughout portions of the native range.

The Eastern Hemlock inhabits a diversity of latitudes and elevations. Its range extends from southern Quebec and Ontario, west to Minnesota, and south to Alabama. The most continuous part of its range lies within the Appalachian Mountains from Maine to Georgia (Kessell et al. 1979). The Eastern Hemlock is a late-successional coniferous species that can live up to 800 years old, grow over 40 meters tall, and extend 2 meters in diameter (Godman and Lancaster 1990). Hemlocks are also among the most shade tolerant trees in the United States (Jenkins et al. 1999). In the northern half of the Eastern Hemlock's range (Pennsylvania and north), the trees are found in a wide variety of habitats and elevations ranging from coastal forests to mountain ridges. In this portion of the range forest stands can be comprised almost completely of hemlocks in the overstory (Dukes et al. 2009; Orwig et al. 2012). In the south, hemlocks are confined to the foothills and mountains of Appalachian riparian and cove forests.

Hemlocks as a Foundation Species

Despite eastern hemlock only representing a relatively small area of the landscape in the southern Appalachians, they are regarded as a foundation species in the unique ecosystems they inhabit (Ellison et al. 2005). The term foundation species is used to describe a species that has a strong role in structuring the local community (Day and Monk 1974). Hemlocks possess a variety of attributes that qualify them as a foundation species. Among the traits that qualify eastern hemlock as a foundation species are the ability to create a separate type of microclimate than the surrounding forest at different times of the year. In the summer, the high leaf area index of hemlocks provides shade for the underlying forest floor and streams, often keeping areas dominated by hemlocks cooler than the surrounding forest. In the winter, when broadleaf species of trees lose their foliage, hemlocks retain theirs' and can insulate the understory from cold temperatures and harsh winds (Young et al. 2002). Year-round transpiration of hemlocks can also moderate soil moisture levels, stabilize stream base-flows and decrease diurnal variation in stream temperatures. Hemlock stands also offer habitat for a unique variety of fish, salamanders, and freshwater invertebrates that can be intolerable to seasonal desiccation. Snyder et al. (2005) found that hemlocks support significantly more taxa of invertebrates than hardwood stands. Hemlock stands also provide refuge for terrestrial animals such as small and large mammals and birds (Webster et al. 2012).

Recent research has documented the rapid spread of the HWA southward. Mortality of 11% for overstory hemlocks and 34% for understory hemlocks was recorded in the Great Smoky Mountains National Park only 5-6 years after invasion (Krapfl et al. 2011). A study at Coweeta Hydrologic Laboratory in the mountains of North Carolina documented 50% hemlock mortality in six years within a watershed (Ford et al. 2012). The swift spread of the HWA has also been recorded at the county-level by the U.S Forest Service. The Adelgid's rapid expansion south can likely be explained by a combination of a warmer winter climate and host availability.

As hemlocks are restricted primarily to riparian zones adjacent to headwater streams in the southern Appalachian Mountains, any disturbance that affects hemlocks will ultimately impact streams as well. Adelgid-induced hemlock mortality will create excessive amounts of falling leaf litter, falling branches, and eventually whole trees. A large quantity of this wood could be recruited into the headwater streams of the region (Ellison et al. 2005). Fluvial wood or large wood (LW) is known to influence various processes both geomorphic and ecological. This potential increase in the volume of LW would alter stream processes and dynamics.

Large Wood and River Systems

Extensive research has resulted in the understanding and importance of fluvial wood in geomorphic, hydrologic, and ecological functioning of aquatic systems. The geomorphic influence of LW is a function of arrangement and quantity of wood in the channel, which is defined as the wood load. Fluvial wood can alter stream geomorphology through creating waterfalls, forming pools, and changing channel direction (Keller and Swanson 1979). This process results in increased structural complexity of streams such as more frequent, or altered longitudinal patterns of, step-pool or riffle-pool sequences. Lower stream velocities attributed to wood obstacles allow sediment deposition and accumulation behind LW pieces or LW jams. The residence time of these sediment sinks vary considerably across temporal scales because of wood size, channel characteristics, and hydrologic regime. Montgomery and Piégay (2003) found that sediment yield in some mountainous streams is 10 times less than sediment storage associated with LW. In addition to sediment storage, LW in the channel also often results in the storage of nutrients such as carbon and nitrogen. Accessible supplies of these nutrients are primarily contained in coarse particulate organic matter which serves as the exclusive diet of numerous invertebrates in aquatic systems. Previous research has found that the removal of LW results in a significant increase of particulate organic matter downstream (Bisson et al. 1987). Large wood is one of the most used methods of river restoration because of its role in providing habitat for fish and other aquatic biota, and in bank stabilization (Alexander and Allen 2006).

Large Wood recruitment can be defined as the processes that moves wood from the riparian area to the channel. Recruitment is usually a function of two different mechanisms; riparian forest stand and valley characteristics (Bragg 2000; Gregory et al., 2003). Riparian forest stand characteristics that are important for wood recruitment include forest seral stage and natural and anthropogenic disturbance regimes. Specific variables related to these characteristics that could result in wood recruitment include riparian tree mortality, tree blowdown from storms, and forest disturbance events, among many others (Wohl and Jaeger 2009). Valley characteristics that influence wood load include channel slope, valley side slope, drainage area, and confinement (Hassan et al. 2005).

Once LW is in the channel, retention characteristics determine the duration of immobility of the wood. Variables that impact retention or transport of the wood can be classified into two categories: 1) characteristics of the wood itself, and 2) characteristics of the channel. Characteristics of the wood that might impact retention are piece size, branching complexity, and orientation (Gurnell et al. 2002). Channel characteristics include stream velocity, roughness, width and depth (Nakamura and Swanson 1993; Wohl and Cadol 2011).

The HWA is inducing a disturbance event in the riparian forest that could influence the amount of LW recruited into streams. Few studies have examined the relationship between hemlock mortality and LW in streams. Webster et al. (2012) found that the hemlock component of LW in eight streams ranged from absent to 56%. Another study investigated the role of adelgid-induced Hemlock mortality on LW in 47 riparian stands in 15 different states (Evans et al. 2012). This research found that Eastern Hemlock LW volume in streams adjacent to stands with HWA present was almost three times greater than those streams where the HWA was absent (Evans et al. 2012). The same study also found that there was a significant positive relationship between hemlock decline and Eastern Hemlock LW. A more recent study conducted on 24 headwater streams in the central Appalachians also investigated Hemlock decline characteristics and in-stream wood (Costigan et al. 2015). This paper used a principal component analysis for both recruitment and retention parameters of LW before using multiple linear regression. The researchers ultimately found that differences in LW characteristics and decline classes were not statistically significant. One principal component made up of hemlock basal area and elevation explained 15% of large wood variance. They did state that generally, streams experiencing high riparian mortality had elevated wood loads, especially for smaller diameter pieces of LW.

Two studies have proposed conceptual models for this forest disturbance and how it will impact stream morphology. Webster et al. (2012) presented the first model and it states that large wood in streams will increase beyond normal conditions due to the death of hemlocks. This pulse of recruited wood may increase channel complexity initially. However, it will take some time for other tree species to replace Hemlocks and begin contributing to the wood load in streams once again. After an increase in wood loads following hemlock decline, there will be a time lag before other mature trees can be recruited into the channel. Also, the LW equilibrium could potentially be permanently altered depending on if the succession of hemlocks is by rhododendron or broadleaf tree species. Rhododendron thickets have been found to inhibit the germination of tree species below (Beckage et al. 2000; Beier et al., 2005). If rhododendron succeeds hemlock in these riparian areas, less LW will be available for recruitment into the stream channel (Webster et al. 2012). If species of broadleaf trees dominantly replace Hemlock, a pre-disturbance wood load equilibrium may be achieved.

The second model, proposed by Costigan et al. (2015), was largely consistent with the first model but elaborated on more specific details of the timing and sizes of wood recruited and the repercussions this might have. Their model is a statement that debris jam frequency and volume will increase as time after tree mortality occurs due to consecutively large pieces of the tree entering the stream before eventually the whole tree itself. They also suggested that elevated wood loads will be a function of time of decline, mortality, breakage, toppling, and recruitment. These elevated wood loads may occur anywhere from 12 to more than 30 years following initial infestation (Costigan et al. 2015). Once mortality occurs, tree fall predictions for hemlocks range from 8-20 years, but is highly dependent on climatic and other variables (Costigan et al. 2015).

When dynamics of streams and riparian forests are altered, changes can be observed beyond the reach scale, further downstream (Fetherston et al. 1995). Increasing wood loads due to hemlock mortality will likely have physical, biological, and ecological consequences for watersheds draining hemlock. However, the timing of these changes and the intensity of those changes is not currently known. By testing the models conceived by other researchers, our goal was to provide some understanding of this complex disturbance event in the southern Appalachian Mountains.

OBJECTIVES

The objectives of this research are to: (1) Characterize the health and abundance of Hemlock trees in riparian forests of select Southern Appalachian watersheds, (2) Quantify in-channel LW loads within the same watersheds, and (3) Investigate the relationship of forest and geomorphic characteristics to wood load variables in the streams. The project objectives will test the two conceptual models mentioned earlier. This research will also contribute to the limited amount of literature related to responses of woods loads influenced by forest disturbance events in the Southern Appalachians.

STUDY AREA

The study area for this research is in the Appalachian Mountains of northwest North Carolina. Of specific interest are three headwater watersheds located within Watauga, Avery, and Caldwell counties (Figure 1). The USFS reports that these counties were invaded by the HWA in 2001 and 2002. This timing suggests that many locations have been exposed to the Adelgid for 15 or more years. Watersheds have been defined by the USGS as 12-digit hydrologic unit codes and consist of the headwaters of the South Fork of the New River (050500010201), the headwaters to the Watauga River (060101030301), and Upper Wilson Creek (030501010502). Their respective drainage areas are 90.7 km2, 67.98 km2, and 104.31 km2. These areas were selected for study because of the high elevations (>1000 m) from which the streams originate, the large amount of forest coverage, the ample amount of Hemlock habitat, and the accessible public lands within the watersheds (Figure 1).

METHODS

Site Selection

Constraints on site selection included the presence of a perennial stream, relatively undisturbed riparian forest, and the location on public lands. Sites were selected to attempt to capture the gradient of hemlock abundance and hemlock decline within the riparian forests throughout the three watersheds. Stream study sites were identified using a combination of field observations and remotely sensed images. National Agriculture Inventory Program (NAIP) imagery from 2014 was used to visually identify dead hemlocks from the surrounding forest canopy (Figure 2). Additionally, false color composite images from 2016 were acquired from Planet Labs Inc. These 3 m resolution images also aided in distinguishing both dead and living hemlock stands (Figure 2). Areas of hemlock mortality were identified and shapefiles of them were created using ESRI's ArcMap 10.4.1 software. Many of these locations were field verified to check that the dead trees were largely Hemlocks and not other tree species. Both ArcMap 10.4 and ENVI software programs were used for digital image processing.

In total, 26 sites at streams with surrounding riparian forests were identified using the methods mentioned above. A relatively even number of sites were selected for each basin with 11 residing in the headwaters of the South Fork of the New River drainage, eight in the headwaters of the Watauga drainage, and seven in the Upper Wilson Creek drainage.

Stream Characteristics

Geomorphic characteristics for each site were recorded in the field using appropriate instruments or using a Geographic Information System (ESRI, ArcMap 10.4). Bank full width was recorded in the field and defined by changes in vegetation, scour marks, or changes in slope. Stream slope was also measured in the field using a hand level, stadia rod, and tape measure. Watershed slope, side valley slope, and drainage area were obtained using a digital elevation model (DEM) with a resolution of 10 m using ArcMap for processing. Watershed slope was calculated by first creating a raster file of the contributing drainage area to each site. The slope for this entire drainage was then averaged to obtain watershed slope. Valley confinement ratio for each site was calculated by estimating the width of the active floodplain (if present) at each stream site using ArcMap and dividing this number by the bank full channel.

Forest Transects

A random point based on the field observations and remotely sensed images was chosen for where forest transects should begin. Parallel to the stream, forest transects were established at 10, 20, and 30 m distances from the stream. Beyond 30 m wood is much less likely to be recruited into the channel, especially in the case of mountain headwater streams. The bank that transects were established on was determined by accessibility and the lowest relative amount of human disturbance. Transect length was dependent on continuous valley conditions and encompassed at least three hydrologic unit sequences so that heterogeneity in channel form and riparian forests was captured (Curran and Wohl 2003). Similar methods have been used in studies that quantify characteristics of riparian hemlock forests (Costigan et al. 2015; Eschtruth et al. 2006; Martin and Goebel 2012).

Along each 25 m segment of transect, a random number generator was used to select a number ranging from 0-25, representing each meter along that segment. At each of these random points along transects a point-centered-quarter (PCQ) plotless method of measuring forest composition was established (Bonham et al., 2013). Random points were separated by at least 10 m to minimize overlapping PCQs. Plotless techniques of vegetation measurement are often used because of their efficiency and ability to save time by not measuring each tree in a forest plot (Bonham et al. 2013). This method involves creating four quadrants extending from the point. These quadrants will be based on cardinal directions and can be assigned labels of North East, South East, South West, and North West. The closest tree to each center point in each quadrant was then located and distance from the center point recorded. All tree stems measuring >12.5 cm for diameter at breast height (DBH) were included. The DBH for each of these trees (four per point) was recorded and classified either as broadleaf, hemlock, or other evergreen species. Subsequently, each tree was assigned a crown class based on the amount and direction of intercepted light consisting of dominant, co-dominant, intermediate, or overtopped (Oliver and Larson, 1996). All hemlocks counted were graded for health based on the estimated amount of foliage remaining. The scale ranged from 1-5 where 1:>75% of foliage remains, 2: 51-75%, 3: 26-50%, 4:1-25%, 5: dead (Orwig and Foster, 1998). In addition, fixed 0.01 ha (r = 5.66m) radius circular plots were established at each PCQ point center. The percentage cover in each understory plot of Rhododendron (*Rhododendron maximum*) was also estimated to the nearest 10%. An illustration of a sample survey is provided in Figure 3.

Due to a varying number of hemlocks and degree of decline at field sites, we created a variable called the hemlock decline index (HDI), which could be assigned to each site. The value of the HDI is calculated by multiplying the average hemlock decline number for a site (1-5) by the fractional percentage of hemlocks in the riparian forest. This resulted in a scale that ranges from 0-5 (Figure 4). An HDI of 0 thus represents a riparian forest that contains no hemlocks and an HDI of 5 represents a riparian forest that is entirely hemlock and all dead. Hemlock decline index values for data collected at sites for this study ranged from 0 to 3. The creation of the HDI combined two important metrics regarding the infestation of the HWA. This index served as an important explanatory variable when considering associations between hemlock decline and wood loads.

Large Wood Sampling

Surveys of LW within the channel at field sites were the same length as the parallel forest transects and follow the methods described by Wohl et al. (2010). A piece of large wood is >1 m in length and 0.1 m in diameter and must be present in at least part of or suspended above the bank full channel. Three or more pieces of large wood in contact with each other are considered a jam. Length and diameter of each piece of LW was recorded along with the type, location with respect to the channel, and any notable geomorphic effects. The volume of jams was calculated by taking the approximate dimensions of length, width, and height of debris comprising the jam.

Data Analysis

Once all field data was collected and variables summarized, we began to explore trends between hemlock decline and LW characteristics. The HDI variable was broken up into three groups (<1, 1-2, and >2) roughly following an equal interval classification for this data. These HDI classes were then compared to LW length, LW diameter, and total wood load for each site in a series of boxplots. Statistical validation of any observed visual trends was accomplished by running a Kruskal-Wallis nonparametric test to identify differences in the medians of HDI classes ($p<0.05$). If results were significant, a Mann-Whitney U test was used to reveal which groups were statistically different compared to each other. Spearman's rank correlation was used to identify any relationships between hemlock decline variables (HDI and % hemlocks) and LW characteristics (length, diameter, wood load, and jam frequency) and test for significance at $\alpha=0.05$. This correlation was also used together with the same LW characteristics and geomorphic variables such as watershed slope, valley side slope, and confinement ratio. Lastly, a power function was fitted to the relationship between HDI and wood load.

RESULTS AND DISCUSSION

Riparian Forest Characteristics

Forest transects indicated the composition of the riparian forest overstory was a mixture of hardwoods and hemlocks. Approximately 620 trees were surveyed and the DBH averaged 36.3 cm. At least one hemlock was surveyed in the riparian forest at 22 of the sites and the HWA was found to be present at all of these sites. Hemlocks comprised 26% of trees surveyed. However, hemlock composition in the riparian forest varied greatly among sites ranging from 0-67%. Figure 5 shows the gradient of both number of hemlocks and hemlock decline captured at each site. Over 71% of the hemlocks were classified as dead and of the remaining live hemlocks 70% were experiencing HWA stress. The average percentage of hemlock in the riparian forest sites was 25.8% ranging from 0 - 66.7%. The average HDI value was 1.1 with values ranging from 0 – 3.0 (Table 1). The histogram in Figure 6 shows that many of the largest diameter trees were hemlock. Therefore, the largest trees in the riparian forest may eventually be recruited in streams.

Rhododendron cover dominated the shrub layer ranging from 22% coverage to 86% coverage of understory plots. Data from the riparian forest understory plots show a significant positive correlation between HDI and % rhododendron cover ($r = 0.63$, $p < 0.001$) (Figure 7). One competing hypothesis is that rhododendron will become increasingly prevalent in the riparian forest as hemlocks continue to die (Evans et al. 2012). Rhododendron has been documented to prevent the germination of tree species below by using defensive chemistry (Beckage et al. 2000; Beier et al. 2005). The defensive chemistry would create a lag period before a tree species is able to establish itself where hemlocks once occurred in the riparian forest. For a period of time following recruitment of hemlock LW, not as much LW will be available for recruitment into streams due to smaller diameter stems of rhododendron and a lack of riparian trees (Webster et al. 2012).

Large Wood and Geomorphic Characteristics

Stream surveys for LW yielded a total of 356 pieces with a frequency of 19.6 pieces per 100 m. Average diameter of all LW was 22 cm and the average length was 4.8 m. LW volume per 100 m ranged from 0.55 m^3 to 68.9 m^3 with an average of 22.6 m^3. There were a total of 33 jams found at all the sites and the jam volume averaged 4.7 m^3 (Table 2)

Most stream sites were characterized as steep and confined headwater streams that were all greater than 85% forested. The channels consisted mostly of bedrock, boulders, cobble, and sand with a small fine sediment component. A combination of coarse substrate and channel slope resulted in most of the streams sampled being dominated by step-pool morphology. Channel slope ranged from 1% to 14% with an average of 6%. Bank full width ranged from 1.6 m to 11.1 m and an average of 6 m. Mean drainage area size of the stream sites was 2.9 km^2 and ranged from approximately 0.5 km^2 at site N-9 to 9.7 km^2 for site N-7 (Table 1).

Further, average watershed slope and stream valley side slope for all sites averaged 32.4% and 30.3%. Most streams were highly confined with an average confinement ratio of 2.2 for all channels. 14 streams were found to be fully confined (completely colluvial, with no floodplain development). Thus, riparian forest condition likely dominates LW recruitment to the channel in these systems.

Hemlock Decline and LW Associations

The boxplots of HDI and LW variables revealed a successively increasing trend in wood dimensions as HDI increased (Figure 8). The Kruskal-Wallis test indicated that both length and wood load had at least one statistically significant pair of groups in the test. Significance for HDI and wood length was $p = 0.03$ and for HDI and wood load the significance was $p < 0.001$. For wood length, the Mann-Whitney U test indicated that HDI classes of <1 and 1-2 were significant ($p=0.02$), but none of the other groups were significantly different from each other. This test also showed that wood load and HDI groups of <1 and 1-2, in addition to groups <1 and >2 were significant ($p<0.001$ for both). The test did not yield any significant results when LW diameter and HDI groups were compared.

Evidence of the Kruskal-Wallis and Mann-Whitney U tests suggested that there is a possible trend between sites experiencing substantial hemlock mortality and increasing LW characteristics in streams. To further investigate potential relationships, Spearman rank correlation was analyzed for different hemlock decline variables, geomorphic variables, and LW variables (Table 3).

Surprisingly, none of the geomorphic variables used in the matrix had significant correlations with wood load characteristics. Lack of significance could be attributed to the relatively small number of sites used in this study ($n=26$), as many of the geomorphic variables show moderate relationships with some wood variables. For example, wood load and side valley slope had a correlation values of $r=0.28$, but were not statistically significant. Confinement ratio and wood load also had a moderate positive correlation ($r = 0.24$). The low and nonsignificant correlations could also mean that the geomorphic characteristics in the case of these streams don't influence wood recruitment as much as riparian forest variables do. It is also interesting that channel slope and wood load had a negative relationship of r = -0.31. This relationship could possibly be explained by outliers. The sites with the highest two wood loads had average channel slopes of only 1%.

Average riparian forest DBH showed significant ($p<0.01$) positive relationships with LW load, LW diameter, LW frequency, and jam frequency. This likely demonstrates that tree size in the riparian forest and consequently stand age, influence the amount of large wood found in the channel. The HDI exhibited statistically significant ($p<0.05$) correlation values with all LW variables in Table 3 (Length, Diameter, Wood Load, and Jam Frequency). Particularly high correlations were observed for wood load and jam frequency (r = 0.79 and 0.62). This analysis reinforces trends found previously using the Kruskal-Wallis and Mann-Whitney U tests. From these three tests and with supporting context of relationships of HDI to other geomorphic variables, it seems likely that the deterioration of hemlock trees is causing recruitment of LW into streams. We also fit a power function to HDI compared with wood loads (Figure 9). The fit of this power function hints that the association between wood load and hemlock degradation may not be linear and that a certain level of decline must occur, or a certain percentage of riparian trees must be hemlock before noticeable changes occur in wood loads.

Visual observations from the field also coincide with the results of the correlations. At several of the field sites experiencing moderate or high hemlock mortality, recently toppled or broken trees were observed and could be identified confidently as hemlocks due to branching structure and bark characteristics. In many cases the wood from these dead hemlocks was residing in the stream channel. Often large dead hemlocks would serve as a key member upon which other pieces of LW would accumulate to form jams (Figure 10).

Comparison of Results with other Studies

Few papers have explored wood loads of headwater streams in the central and southern Appalachian Mountains. However, we felt it was pertinent to make comparisons between results found in this project and those established in related studies. Large wood volume per stream area allows for a comparison to the results of a study by Webster et al. (2012). Large wood data collected from eight streams in the southern Appalachian Mountains for this study yielded a volume per area of 0.016m3/m2. An additional study investigating impacts of the HWA on wood loads at sites ranging from Maine to Alabama recorded a volume per area value of 0.004 (Evans et al. 2012). However, it is important to note that different recruitment processes for LW due to the larger geographic area and varying physiographic characteristics make this study not as comparable as others.

The average wood load of 22.62 m^3/100 m found in our study was substantially higher than that found in other studies. In similar studies covering the same region, wood loads ranged from 3.88-14.85 m^3/100 (Hedman et al. 1996; Warren and Kraft, 2008; Warren et al., 2009; Costigan et al. 2015). The HWA was only present in the riparian forest in one study that used the wood load variable (Costigan et al. 2015). Wood load for our study drops to 7.35m^3/100 m when only including sites with a HDI value of less than 1 (n = 13). Wood load values for regional studies are far closer to this number. The removal of the sites with moderate or severe hemlock decline reinforces our finding that streams draining areas with the HWA present are experiencing elevated wood loads.

Future implications on Wood Loads

Evidence from this study suggests that the HWA-induced forest disturbance event is already having an impact on streams approximately 15 years after invasion. Wood loads at stream sites with the five highest HDI values had a wood load four times higher than the rest of the sites. Field data from the forest transects also suggests that there are still a substantial amount of dead or declining hemlocks still standing in the riparian forests of these streams. Based off visual observations in the field, it does not seem that the three watersheds used in this study have reached the time of peak wood recruitment in the model put forth by Evans et al. (2012). The peak of wood recruitment, linked to this forest disturbance event could occur in the next 1-5 years, but is highly dependent on environmental conditions such as temperature, precipitation events, wind storms, and ice storms.

We agree with the model proposed by Costigan et al. (2015), that both jam frequency and jam volume in streams will increase as more wood from dead hemlocks is recruited to the stream. This study showed that streams with high HDI values (>2) have over twice the number of jams compared to streams with little to moderate HDI values (0-1.9). Many of the hemlocks already recruited into the channel and standing hemlocks are very large (>50 cm DBH), and were likely not cut when much of the other forest in the Appalachian Mountains was clear cut in the late 19th and early 20th centuries

Watersheds in this study will likely endure a variety of ecological changes as a function of increased wood input. Greater complexity of habitat will be produced as LW acts as a barrier and creates changes in water velocity and direction resulting in pool and waterfall formation (Keller and Swanson 1979). This new habitat complexity could be beneficial to populations of benthic invertebrates and fish by providing refuge. Increased densities of invertebrates will provide more prey for higher trophic levels and could be beneficial to aquatic communities as a whole (Angermeier and Karr 1984).

Rapid accumulation of LW in aquatic systems will also interrupt natural sediment transportation processes downstream. Sediment that would have normally been flushed downstream periodically is prone to accumulate behind fluvial wood due to lower stream velocities (Dumke et al. 2010). Increased sediment storage in headwater streams may alter the life cycles and reproduction of organisms. Brook trout (*Salvelinus fontanalis*), the only salmonoid native to the southern Appalachian Mountains, rely on silt free-substrate when making redds (nests for eggs) to reproduce. Increased sedimentation could result in suffocation of brook trout eggs (Angermeier and Karr 1984). Negative impacts might also impact aquatic organisms downstream that receive less sediment as result of the HWA. The disrupted longitudinal connectivity of sediment sources and sinks will likely alter these stream's natural sediment regimes. However, in many streams, sediments are considered the primary pollutant and decreased sedimentation could potentially be beneficial to aquatic organisms. Increased wood loads may also result in localized nutrient storage which will alter carbon cycling in the watersheds. Increased benthic invertebrate production may result from more stored carbon in headwater streams of the watershed. This altered equilibrium of biogeochemical processes could be detrimental to organisms downstream that rely on specific nutrients for survival. Even though hemlocks do not dominate the entire riparian forest of watersheds in this research, their mortality will have repercussions further downstream in watersheds.

CONCLUSION

Research from this study adds to a body of literature that is investigating the impacts of the HWA not just on terrestrial ecosystems, but aquatic ones as well. On average, riparian forests in our study have a hemlock decline classification of 3.1, indicating hemlock stands are in a state of moderate to severe decline throughout the study area. Our study has shown that as hemlock decline continues to progress, wood loads in associated streams will increase. While correlation does not imply causation, our results are partially validated because of significant high correlations of HDI with LW diameter, LW length, wood load, and jam frequency. Positive associations between LW length and diameter show that as time after hemlock death advances, progressively larger pieces of trees will end up in streams until the entire trunks are recruited via tree fall. Interestingly, correlations revealed that rhododendron coverage in the understory is increasing with hemlock decline. Based on a combination of these characteristics we estimate that hemlock forests are approaching peak mortality due to the HWA but have not yet reached the peak of large wood recruitment in the model proposed by Evans et al. (2012). Our results also follow the narrative that Costigan et al. (2015) proposed in their model that jam volume and frequency will rise as time after hemlock death continues. Considering this, a summarization can be made that wood loads in headwater streams throughout the southern Appalachians will continue to grow over the next several years and persist from decades to a century. Continued monitoring of this forest disturbance event is necessary if we intend to manage these forest and stream resources for conservation of the landscape and biota. Future research should focus on the nutrient, sediment, and geomorphic effects of the HWA on aquatic ecosystems.

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Table 1 - The site designates which watershed the stream was in and what number within that watershed. A_d is the total drainage area from the site upstream. S is the percentage slope of the channel while W_{bf} is the bankfull width of the channel. HDI represents each site's value for the hemlock decline index. Confinement is the ratio of valley width to bankfull width. Reach length is reported in meters and defines the length of large wood surveys and forest transects.

Site #	A_d	S	W_{bf}	HDI	Confinement	Valley Side Slope (%)
C-3	4.04	7	9.1	0	1.0	29
C-4	3.38	8	7	0	1.0	24
N-9	0.05	5	1.6	0	1.9	22
W-8	1.81	1	4.5	0	5.6	4
W-4	0.39	8	2.7	0.04	2.2	32
W-6	1.61	6	5.3	0.04	1.0	43
W-2	3.06	9	11.1	0.08	1.0	26
C-1	0.91	12	6.1	0.21	1.0	44
N-1	4.32	10	7.8	0.43	1.0	35
N-2	2.66	14	6.4	0.48	1.0	31
N-5	1.69	2	4.3	0.5	1.6	26
N-10	1.96	1	4.7	0.52	4.3	30
W-7	0.16	14	2.2	0.67	1.0	36
W-3	3.6	2	6	1.33	1.7	6
C-6	3.26	12	6.8	1.34	1.0	47
C-2	3.87	10	8.7	1.43	1.0	59
N-4	2.16	3	5.4	1.46	1.0	47
N-8	1.51	3	4	1.61	2.0	12
W-5	1.97	4	4.3	1.65	2.3	10
W-1	1.19	4	5.1	1.84	2.0	52
C-7	3.23	9	7.4	1.92	1.0	43
N-3	2.13	2	5.8	2.02	1.0	42
C-5	5.65	8	10	2.29	1.0	62
N-7	9.71	1	7.5	2.38	6.7	10
N-11	0.13	3	3.1	2.49	6.5	6
N-6	9.7	1	7.7	3	6.5	12
Average	**2.85**	**6**	**5.9**	**1.07**	**2.2**	**30**

Table 2 – Figure showing large wood characteristics for each stream site surveyed for this study.

Site #	LW Frequency	Jam Frequency	Diameter (m)	LW Length (m)	Wood Load (m^3/m)	LW volume per area (m^3/m^2)
C-3	8	0	0.2	4.7	7.5	0.0082
C-4	4	0	0.18	1.3	0.55	0.0008
N-9	12	0	0.14	4	4.9	0.0306
W-8	10	0	0.22	4.2	7	0.0156
W-4	10	0	0.21	4.5	8	0.0296
W-6	14	1	0.27	3.3	13.8	0.026
W-2	10	0	0.14	5.7	3.5	0.0032
C-1	20	1	0.23	3.7	11.2	0.0184
N-1	12	2	0.24	4.4	11.6	0.0149
N-2	6	0	0.16	7.8	4.8	0.0075
N-5	18	2	0.27	3.5	11.7	0.0272
N-10	10	2	0.23	4.6	8.1	0.0172
W-7	10	0	0.17	2.7	2.96	0.0135
W-3	16	2	0.16	7.3	7.98	0.0133
C-6	44	3	0.23	4.5	48	0.0706
C-2	10	0	0.22	9.2	23.6	0.0271
N-4	46	3	0.23	4.8	35.9	0.0665
N-8	5	0	0.22	5.2	13	0.0325
W-5	34	2	0.36	4.4	41.2	0.0958
W-1	14	0	0.25	4.6	45.7	0.0896
C-7	18	2	0.27	5	34.25	0.0463
N-3	28	2	0.24	5.5	31	0.0534
C-5	44	4	0.2	4.4	43.1	0.0431
N-7	48	2	0.27	4.5	84.3	0.1124
N-11	16	2	0.24	6.5	15.7	0.0506
N-6	42	3	0.26	5	68.9	0.0895

Table 3 – Spearman's correlations of large wood variables with hemlock decline index, drainage area (A_d), stream slope (S), confinement, and valley slope.

Variables	HDI	Spearman's Rank Correlation A_d	S	Confinement	ValleySlope
LW Frequency	0.62***	0.24	-0.27	0.12	0.14
Wood Load	0.79***	0.32	-0.31	0.24	0.28
Length	0.43*	0.26	-0.09	0.06	-0.04
Diameter	0.50**	0.06	-0.37	0.29	0.05
Jam Frequency	0.62***	0.4*	-0.32	0.07	0.14

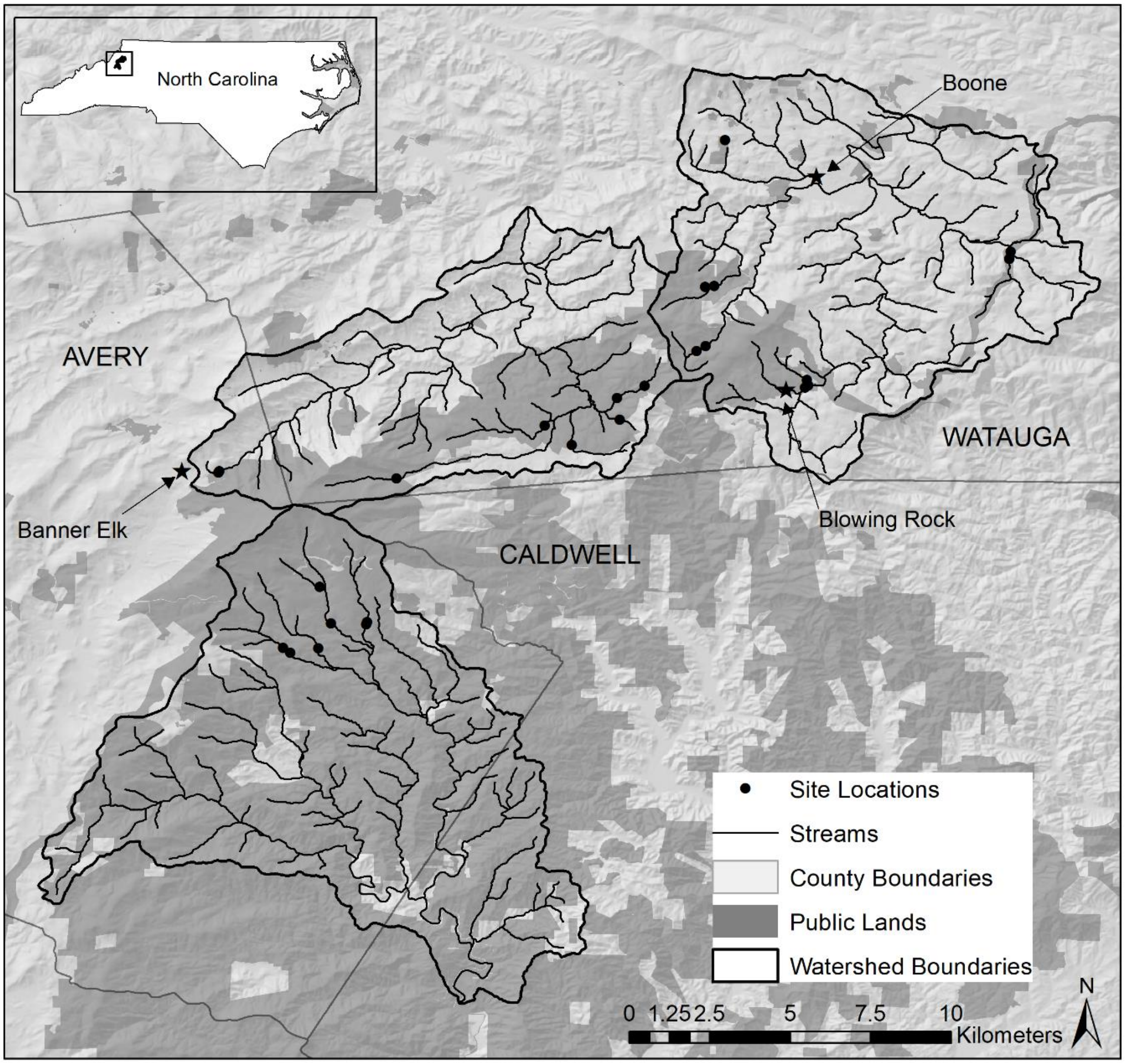


Figure 1 - Terrain, area cities, public land, hydrography, watershed boundaries, and specific field sites for the proposed research. The watershed that extends farthest left is Wilson Creek, the middle watershed is the headwater of the Watauga River, and the watershed on the right is the headwater to the South Fork of the New River.

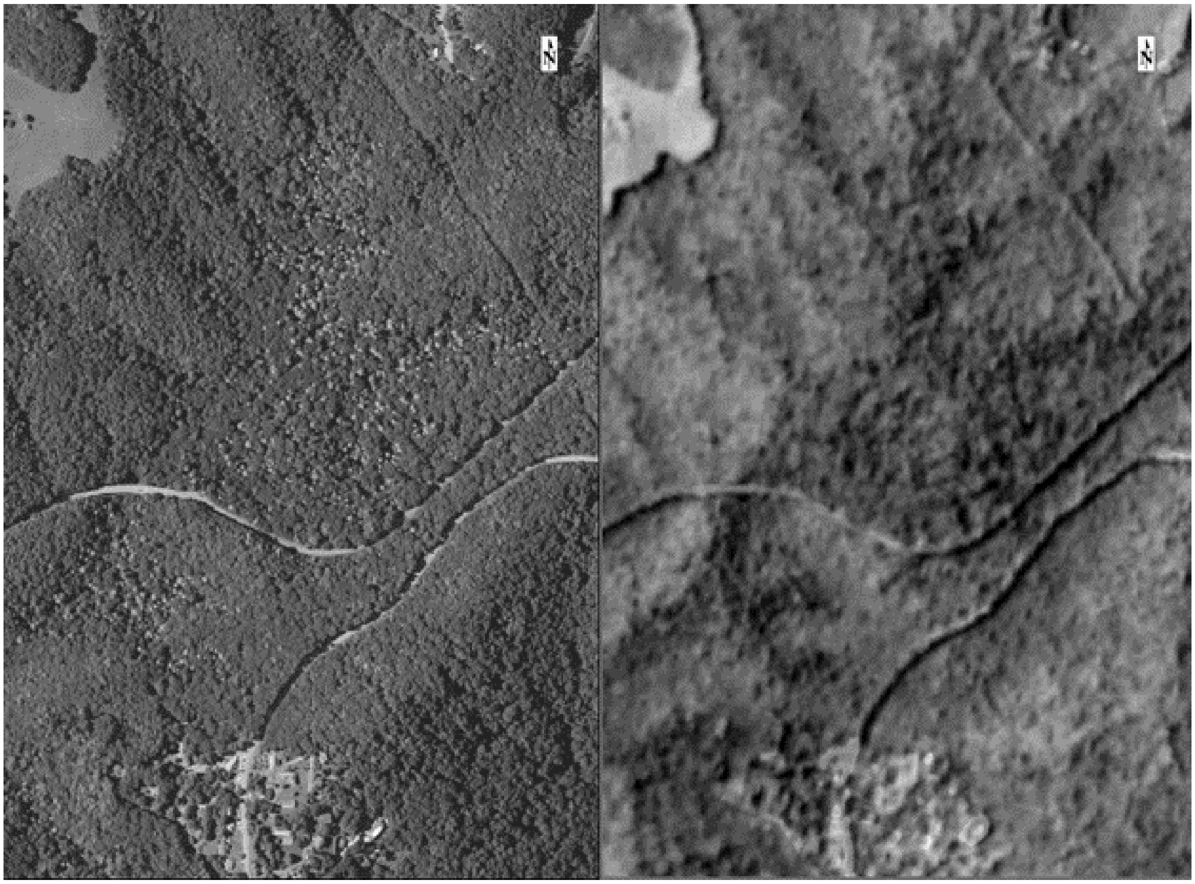


Figure 2 - One meter resolution NAIP image (left) showing Hemlock decline along the Blue Ridge Parkway. Dead hemlocks appear lighter than the surrounding summer foliage. Three meter false color image (right) showing the near-infrared band loaded as the red band. Darker areas on the map represent dead hemlock stands.

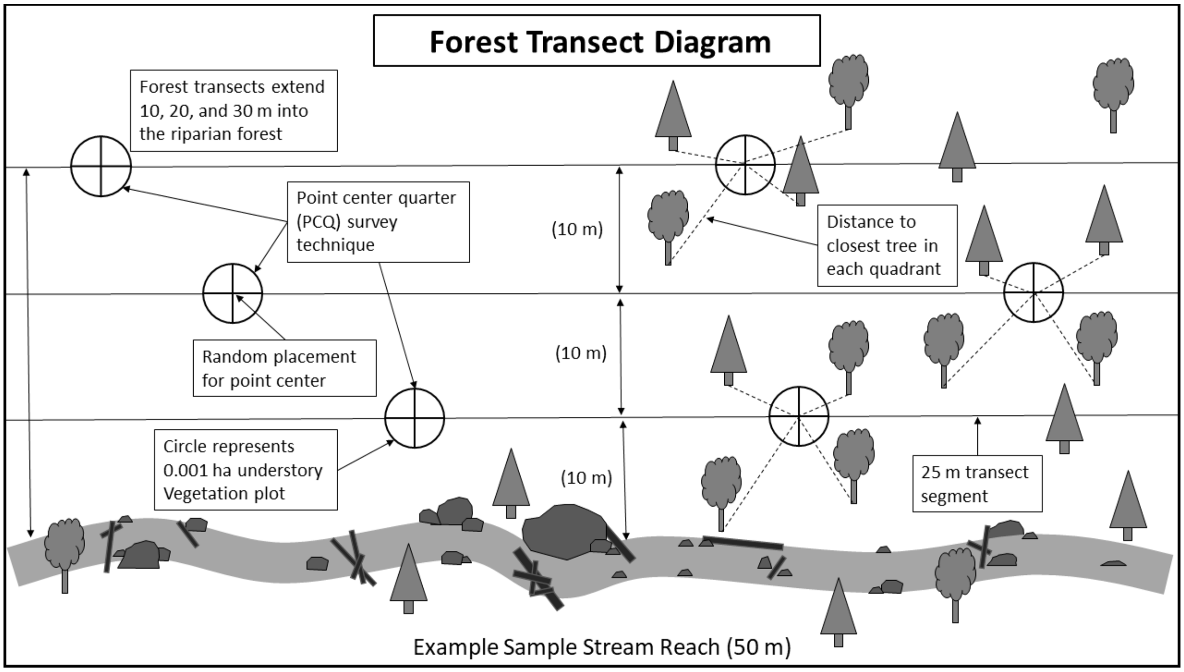


Figure 3 – Diagram of Point-Center-Quarter plotless survey technique, riparian forest transects and understory plots.

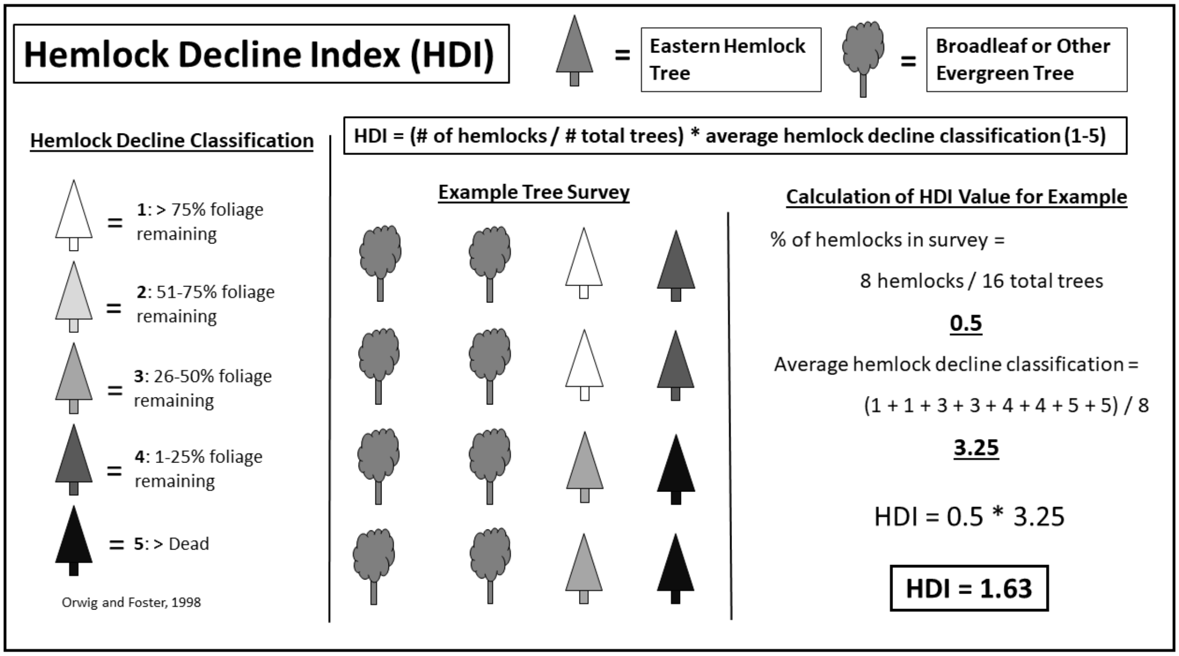


Figure 4 – Schematic demonstrating a calculation of the hemlock decline index (HDI) value used as a measure of riparian forest degradation in this study.

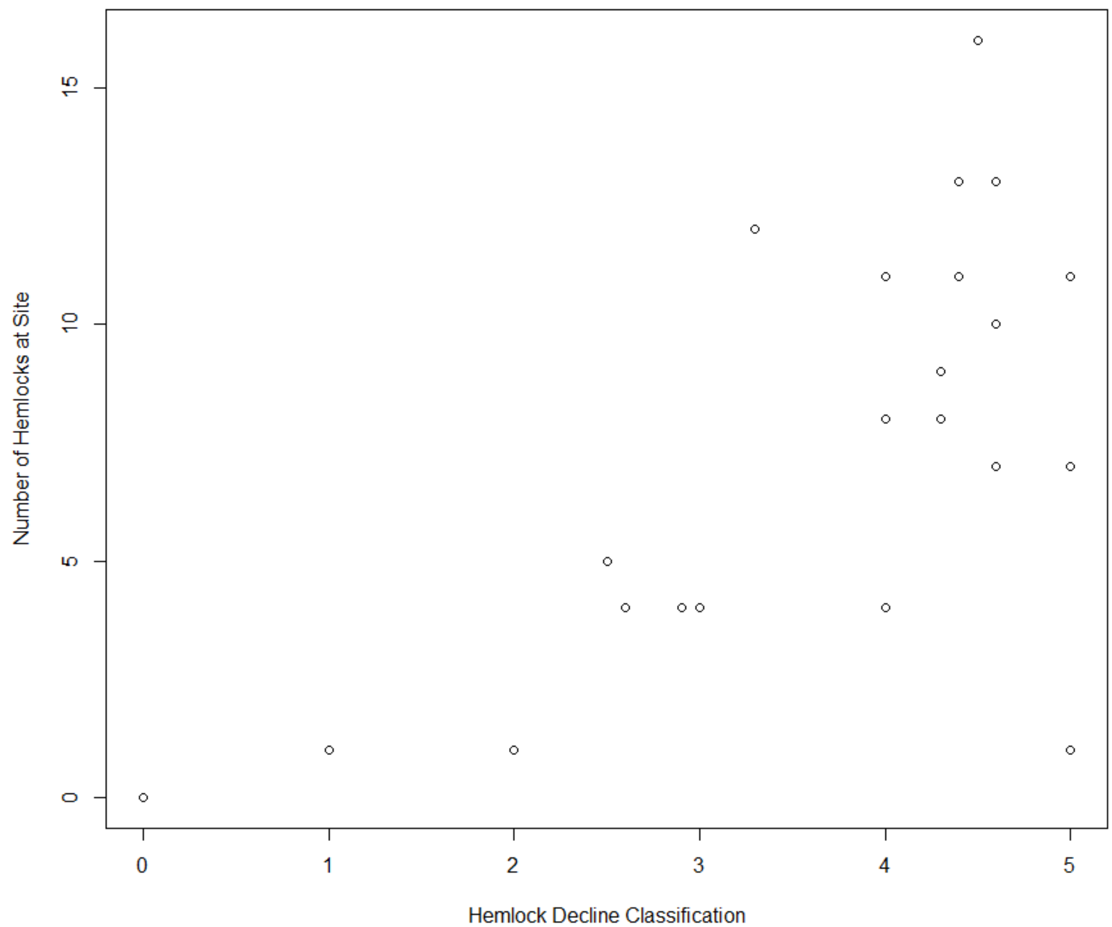


Figure 5 – Scatterplot depicts the number of hemlock plotted at each site with the hemlock decline classification (Orwig and Foster, 2002).

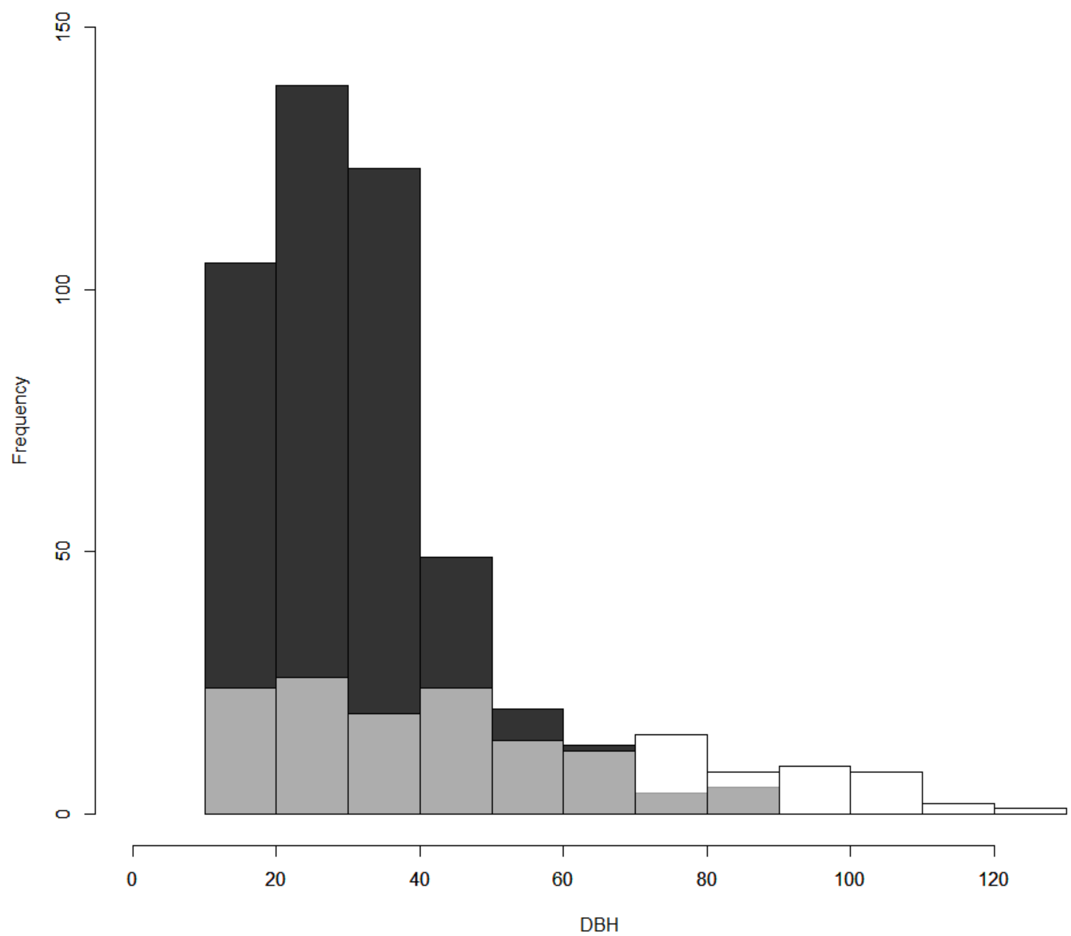


Figure 6 - Histogram of the diameter at breast height (DBH) for hemlocks (White) and all other trees (dark grey). Light grey color is where the distributions overlap.

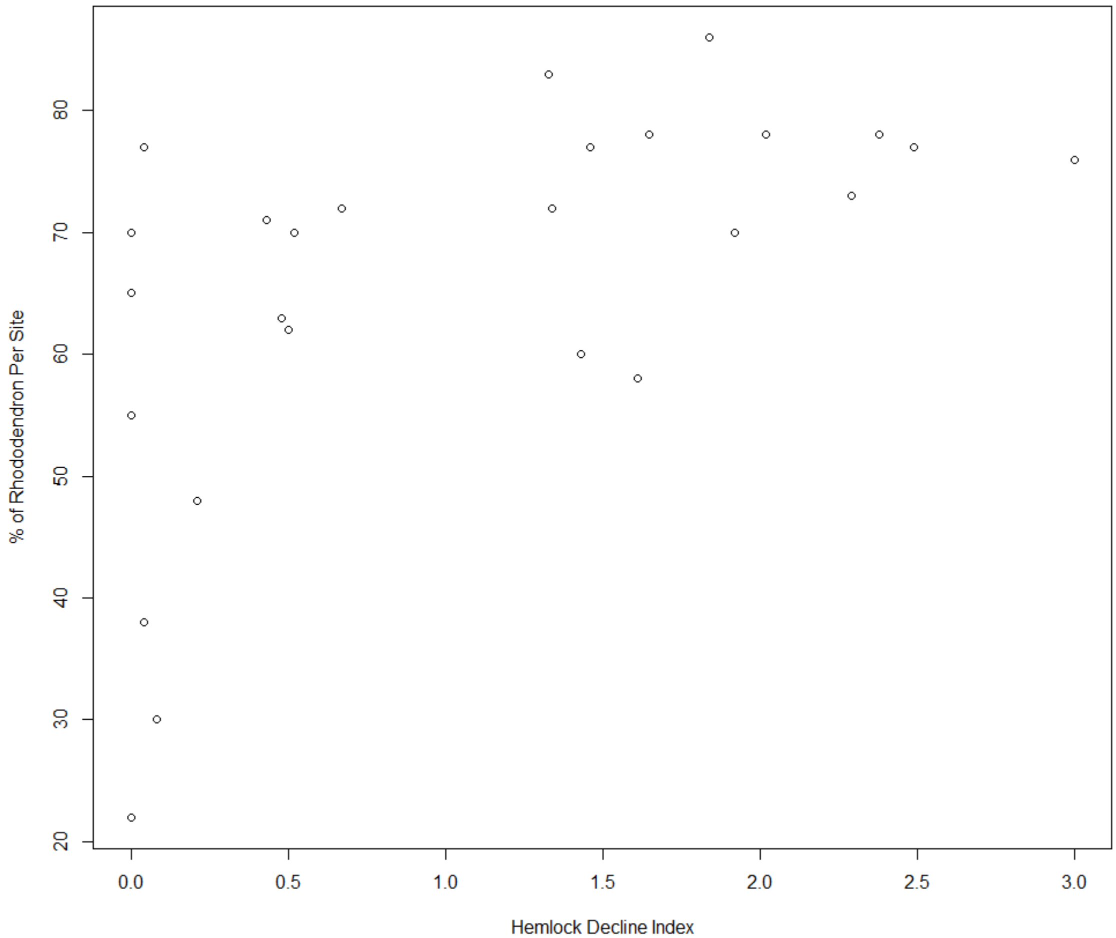


Figure 7 – Scatterplot of the hemlock decline index and % rhododendron in understory plots at each site.

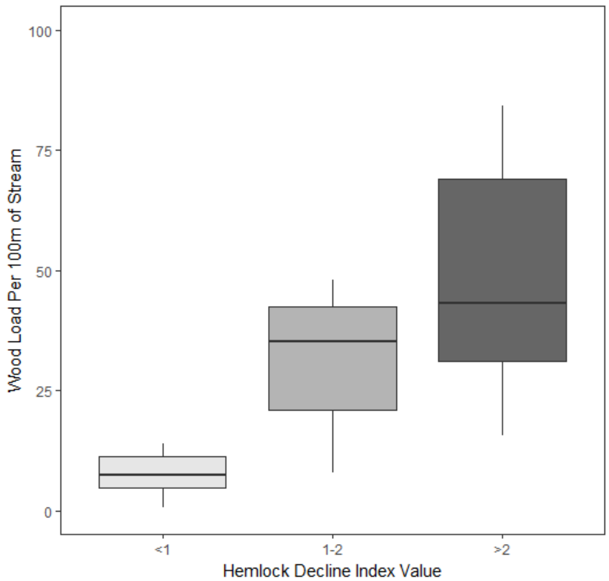
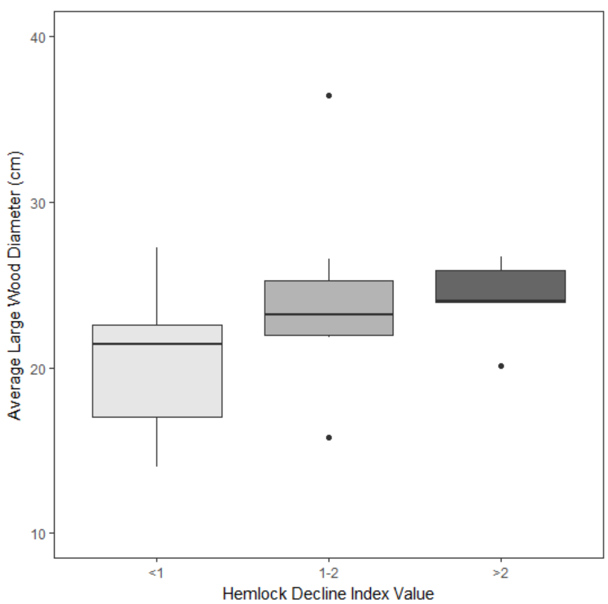
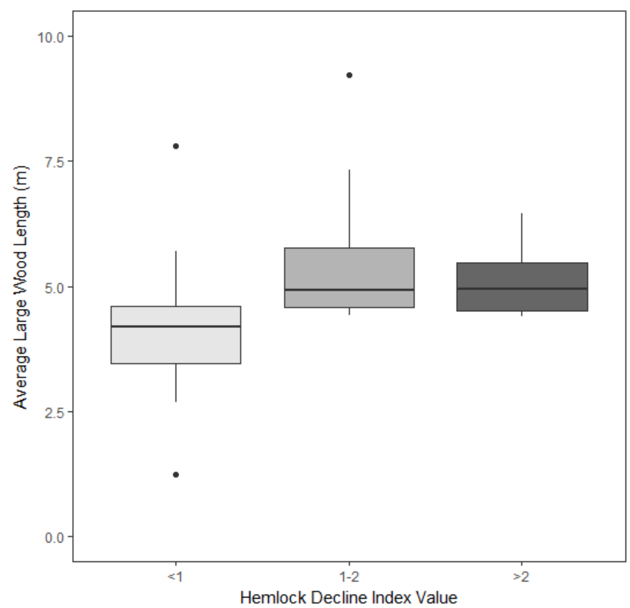


Figure 8 – Box plots showing hemlock decline index values broken into three classes plotted with wood load, LW length, and LW diameter.





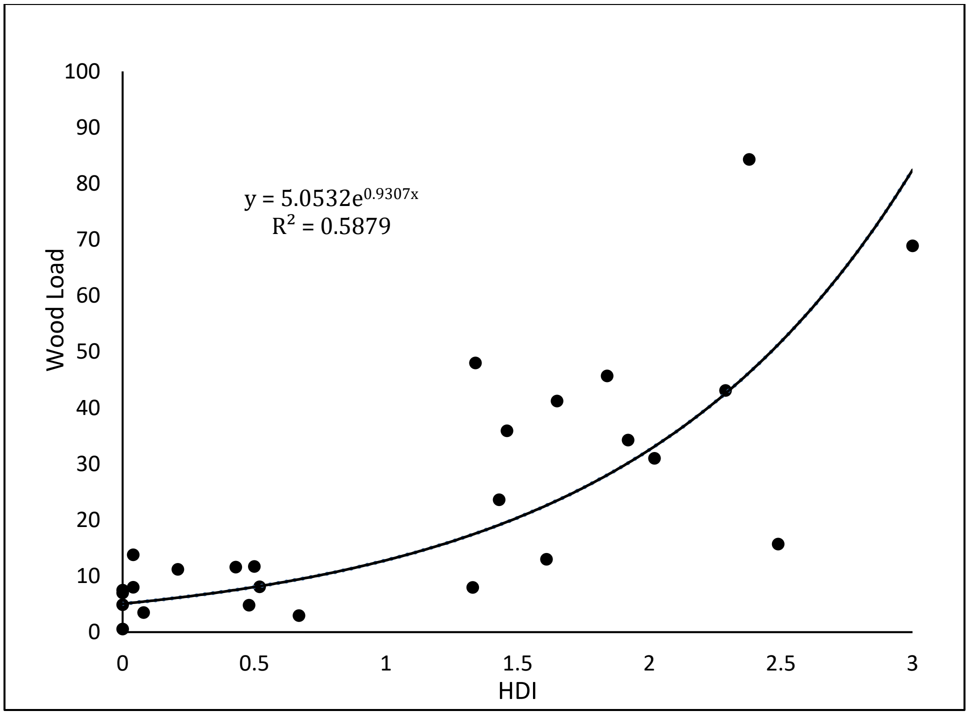


Figure 9 – Scatterplot of the hemlock decline index values and average wood load values for each site with a fitted power function.

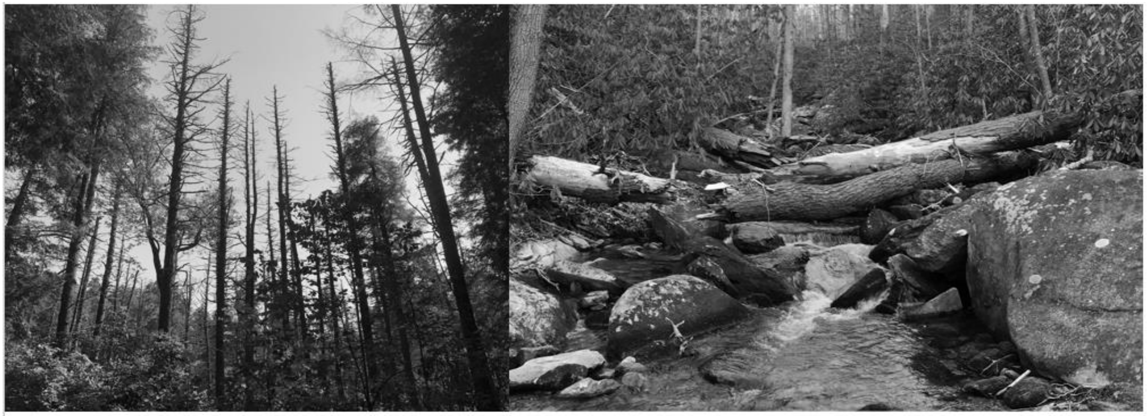


Figure 10 - Picture on the left shows dead hemlocks surrounding a stream. Picture on the right is large hemlock trunks that have recently fallen into the channel.

Appendix A – Raw Field Data

Site: W-1

Large Wood Data

Diameter (m)	Length (m)
0.55	7.9
0.2	2.3
0.23	5.9
0.22	2.64
0.2	1.7
0.45	3
0.7	7.5

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NW	H	2	103	10
NE	B	1	29.5	10
SW	H	5	66	10
SE	H	1	97	10
NE	H	5	24	20
NW	B	1	60	20
SW	H	5	101	20
SE	H	5	95	20
SE	H	5	101	30
SW	B	1	42	30
NW	H	5	84	30
NE	H	5	88	30
NW	B	1	31	10
SE	B	1	22	10
SW	B	1	81	10
NE	H	1	47	10
SE	H	5	128	20
NW	B	1	83	20
SW	B	1	31	20
NE	B	1	30.5	20
NE	B	1	30.5	30
NW	B	1	31	30
SE	B	1	16	30
SW	B	1	63	30

Site: N-1

Diameter (m)	Length (m)
0.11	1.3
0.135	3.5
0.125	3.5
0.11	1.5
0.7	2.5
0.23	9

Quadrant	Treetype	Decline Class	DBH	Transect
NW	B	5	20.5	10
NE	H	5	50.5	10
SE	B	1	21	10
SW	B	1	26	10
NW	H	1	16.5	20
SW	B	1	36	20
SE	B	1	29	20
NE	E	5	12.5	20
NE	H	1	13	30
NW	B	1	37	30
SW	B	1	27	30
SE	B	1	23	30
SE	B	1	35	10
NE	B	5	57	10
NW	B	1	21	10
SW	B	1	25	10
SW	B	1	17.5	20
NE	B	1	26	20
SE	B	1	27.5	20
NW	B	1	37	20
SW	B	1	21	30
SE	H	1	12	30
NE	B	1	37	30
NW	B	1	21.5	30

Site: N-2

Large Wood Data

Diamter (m)	Length (m)
0.2	15.1
0.15	2.3
0.14	6

Tree Transect Data

Quadrant	Tree type	Status	DBH	Transect
NW	b	1	17	10
NE	b	1	35	10
SW	b	1	27.5	10
SE	b	1	13	10
NW	b	1	51	20
NE	b	1	14	20
SW	b	1	27	20
SE	b	5	17	20
NW	b	1	20	30
NE	h	3	17	30
SW	h	2	24	30
SE	b	1	28	30
NW	b	1	31	10
NE	b	1	25	10
SW	b	1	23	10
SE	b	1	32	10
NW	b	1	42	20
NE	b	1	25	20
SW	b	1	19	20
SE	b	1	30	20
NW	b	1	66	30
NE	b	1	28	30
SW	h	5	17	30
SE	b	1	31	30

Site: W-3

Large Wood Data

Diameter (m)	Length (m)
0.15	3.2
0.25	1.5
0.15	6
0.14	5
0.17	4.5
0.13	4.5
0.2	1.2
0.1	7

Tree Transect Data

Quadrant	Tree type	Status	DBH	Transect
NW	H	5	35	10
SW	B	1	12	10
NE	B	1	19	10
SE	H	5	12	10
NW	B	1	13.5	20
SW	H	5	29.5	20
NE	B	1	33.5	20
SE	B	1	13.5	20
NW	H	5	30	30
SW	H	2	33	30
SE	H	2	40	30
NE	H	5	32	30
NE	B	1	24	10
SE	B	1	39	10
NW	B	1	32	10
SW	B	1	19	10
NE	B	1	22	20
NW	B	1	38	20
SE	B	1	25	20
SW	B	1	32	20
NE	B	1	30	30
SE	H	3	17	30
NW	B	1	60	30
SW	B	5	58	30

Site: W-2

Diameter (m)	Length (m)
0.13	8
0.115	7
0.11	1
0.13	9
0.215	3.5

Large Wood Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	50	10
SE	B	1	25	10
SW	B	1	17	10
NW	E	1	26	10
SW	B	1	50	20
NW	B	1	14	20
NE	B	1	30	20
SE	B	1	28	20
SW	B	1	40	30
NW	B	1	25	30
SE	B	1	65	30
NE	E	1	12.5	30
NW	B	1	38	10
SW	B	1	27	10
SE	B	1	31	10
NE	B	1	48	10
SW	B	1	28	20
NW	B	1	34	20
NE	B	1	44	20
SE	H	2	18	20
NW	B	1	36	30
NE	B	1	22	30
SW	B	1	17	30
SE	B	1	36	30

Site: N-4

Diameter (m)	Length (m)
0.29	4.2
0.15	6.1
0.1	5
0.12	3
0.5	1
0.21	14
0.15	10
0.12	2.5
0.11	3.5
0.12	1.5
0.4	2
0.12	1
0.2	13
0.17	4.1
0.35	8.4
0.16	8.5
0.45	2
0.4	1.5
0.25	6.3
0.1	5
0.39	1
0.29	3.5
0.2	3.1

Large Wood Data

Quadrant	Tree type	Status	DBH	Transect
SW	B	5	45	10
NW	B	1	36	10
NE	H	5	60	10
SE	H	5	70	10
NW	H	5	69	20
NE	B	5	42	20
SE	B	1	77	20
SW	H	5	63	20
NW	B	1	39	30
NE	B	1	19	30
SW	B	5	35	30
SE	B	1	40	30
NW	H	5	80	10
SW	H	5	35	10
SE	B	5	29	10
NE	B	5	45	10
NW	B	1	25	20
SW	B	1	21	20
NE	B	1	65	20
SE	B	5	40	20
SW	H	5	65	30

Quadrant	Tree type	Status	DBH	Transect
NW	B	1	26	30
NE	B	1	18	30

Site: N-3

Large Wood Data

Diameter (m)	Length (m)
0.4	7.5
0.23	2.5
0.15	4
0.33	6
0.21	4
0.32	6.2
0.22	15
0.2	5
0.14	7.5
0.12	5
0.17	1.5
0.33	3
0.18	7
0.35	2.5

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	35	10
NE	H	5	29	10
SW	H	4	45	10
SE	H	5	47	10
NE	H	5	53	20
SE	B	1	35	20
SW	H	5	75	20
NW	B	1	55	20
NE	H	2	53	30
SE	B	1	43	30
SW	B	1	24	30
NW	B	1	36	30
NE	B	1	30	10
SW	B	1	17	10
SE	H	5	72	10
SW	H	5	79	10
SE	B	5	41	20
NE	B	1	22	20
NW	B	1	33	20
SW	B	1	14	20
NE	H	2	80	30
NW	H	5	46	30
SE	B	1	40	30
SW	B	1	46	30

Site: N-5

Large Wood Data

Width (m)	Length (m)
0.1	8
0.3	1.8
0.19	6
0.35	1.5
0.4	1
0.15	3.1
0.2	4.4
0.33	2.1
0.43	3.2

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	17.5	10
NW	B	1	21	10
SW	B	1	14	10
NE	B	1	70	20
SE	B	1	28	20
SW	B	1	26	20
NW	B	1	34	20
NE	B	1	61	30
SE	B	1	27	30
NW	B	1	45	30
SW	B	1	59	30
NE	H	5	12	10
NW	B	1	36.5	10
SW	B	1	19	10
SE	H	1	13	10
NW	B	1	53	20
NE	B	1	18	20
SE	B	1	15	20
SW	H	1	19	20
NW	H	5	14	30
NE	B	1	29	30
SE	B	1	39	30
SW	B	1	37	30

Site: C-1

Large Wood Data

Diameter (m)	Length (m)
0.12	5
0.3	1
0.23	7
0.24	1.3
0.16	2
0.25	1.9
0.18	6
0.17	4
0.25	5.3
0.35	3

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
SW	B	1	66	10
SE	B	1	26	10
NW	B	1	18	10
NE	B	1	82	10
NW	B	1	33	20
NE	B	1	41	20
SE	B	1	48	20
SW	B	1	24	20
SE	B	1	58	30
NE	B	1	44	30
NW	B	1	13	30
SW	B	1	35	30
NW	B	1	14	10
NE	B	1	42	10
SE	B	1	23	10
SW	B	1	33	10
NE	B	1	51	20
NW	H	5	46	20
SE	B	1	28	20
SW	B	1	27	20
NE	B	1	18	30
NW	B	1	23	30
SE	B	1	38	30
SW	B	1	42	30

Site: W-4

Large Wood Data

Diameter (m)	Length (m)
0.1	3.2
0.14	4.1
0.25	3.3
0.27	7.3
0.31	4.4

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NW	B	1	54	10
NE	B	1	28	10
SE	B	5	33	10
SW	B	1	36	10
NW	B	1	63	20
SW	B	5	33	20
NE	B	1	47	20
SE	B	1	37	20
NW	B	1	47	30
SW	B	1	35	30
NE	B	1	84	30
SE	B	1	47	30
NE	B	1	29	10
NW	B	1	32	10
SW	H	1	19	10
SE	B	1	31	10
NW	B	1	34	20
NE	B	1	28	20
SW	B	1	41	20
SE	B	1	35	20
NW	B	1	24	30
SW	B	5	29	30
NE	B	1	28	30
SE	B	1	63	30

Site: W-5

Large Wood Data

Diameter (m)	Length (m)
0.11	4.5
0.12	2
0.12	3
0.55	6
0.15	3
0.24	8
0.18	7
0.12	1.5
0.1	4
0.3	2
0.1	2.5
0.19	10
0.13	3
0.2	3
0.1	2.3
0.4	16
1.1	0.4

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	35	10
SW	B	1	27	10
SE	H	3	30	10
NW	B	1	28	10
NE	H	3	32	20
NW	B	1	33	20
SE	H	2	24	20
SW	H	5	17	20
SE	B	1	36	30
NE	H	2	13	30
SW	B	1	40	30
NW	B	1	22	30
SE	H	2	38	10
sw	H	1	29	10
NE	B	1	14	10
NW	H	5	48	10
NE	H	5	25	20
NW	B	1	32	20
SW	B	1	22	20
SE	H	3	38	20
NW	H	4	56	30
NE	B	1	51	30
SE	B	1	17	30
SW	B	1	23	30

Site: W-6

Large Wood Data

Diameter (m)	Length (m)
0.14	1.8
0.34	4
0.1	3
0.3	3
0.4	2
0.2	3
0.4	6

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	42	10
NW	B	1	17	10
SW	B	1	18	10
SE	B	1	26	10
NW	B	1	60	20
NE	B	1	16	20
SW	B	1	31	20
SE	B	1	25	20
NW	B	1	32	30
SW	B	1	27	30
NE	B	1	36	30
SE	B	1	32	30
NE	B	1	12	10
SW	B	1	27	10
SE	B	1	34	10
NW	B	1	21	10
NE	B	1	33	20
NW	B	1	31	20
SE	H	1	14	20
SW	B	1	42	20
SE	B	1	37	30
NE	B	1	19	30
SW	B	1	36	30
NW	B	1	13	30

Site: W-7

Large Wood Data

Diameter (m)	Length (m)
0.12	2.1
0.26	3.5
0.14	1.2
0.17	4
0.16	2.6

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	36	10
NW	B	1	21	10
SW	B	1	14	10
SE	H	1	13	10
NW	B	1	58	20
NE	B	1	42	20
SW	B	1	26	20
SE	H	5	39	20
NW	B	1	44	30
SW	B	1	22	30
NE	B	1	29	30
SE	B	1	50	30
NE	H	5	24	10
SW	H	5	33	10
SE	B	1	12	10
NW	B	1	30	10
NE	B	1	23	20
NW	B	1	31	20
SE	B	1	40	20
SW	B	1	44	20
SE	B	1	21	30
NE	B	1	18	30
SW	B	1	27	30
NW	B	1	32	30

Site: C-2

Large Wood Data

Diameter (m)	Length (m)
0.5	12
0.11	10
0.15	15
0.2	6
0.13	3.1

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	23	10
NW	B	1	34	10
SW	H	5	45	10
SE	H	5	36	10
NW	H	5	75	20
NE	B	1	41	20
SW	B	1	29	20
SE	B	1	13	20
NW	H	3	59	30
SW	H	5	30	30
NE	B	1	36	30
SE	B	1	26	30
NE	H	2	30	10
SW	H	5	101	10
SE	B	1	34	10
NW	B	1	26	10
NE	H	5	45	20
NW	B	1	14	20
SE	B	1	39	20
SW	B	1	18	20
SE	B	1	24	30
NE	B	1	16	30
SW	B	1	32	30
NW	B	1	31	30

Site: C-3

Large Wood Data

Diameter (m)	Length (m)
0.3	10
0.12	2
0.23	4
0.13	2.8

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	23	10
NW	B	1	27	10
SW	B	1	15	10
SE	B	1	13	10
NW	B	1	30	20
NE	B	1	20	20
SW	B	5	46	20
SE	B	1	33	20
NW	B	1	19	30
SW	B	1	29	30
NE	B	1	40	30
SE	B	1	32	30
NE	B	1	31	10
SW	H	5	14	10
SE	B	1	12	10
NW	B	1	37	10
NE	B	1	19	20
NW	B	1	42	20
SE	B	1	35	20
SW	B	1	20	20
SE	B	1	33	30
NE	B	1	33	30
SW	B	1	17	30
NW	B	1	22	30

Site: C-4

Large Wood Data

Diameter (m)	Length (m)
0.25	1.2
0.1	1.3

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	21	10
NW	B	1	24	10
SW	H	2	18	10
SE	B	1	19	10
NW	B	1	35	20
NE	B	1	16	20
SW	B	1	28	20
SE	B	1	15	20
NW	B	1	27	30
SW	B	1	28	30
NE	B	1	44	30
SE	B	1	24	30
NE	B	1	15	10
SW	B	1	30	10
SE	B	1	41	10
NW	B	1	19	10
NE	B	1	28	20
NW	B	1	29	20
SE	B	1	31	20
SW	B	1	16	20
SE	B	1	26	30
NE	B	1	13	30
SW	B	1	22	30
NW	B	1	12	30

Site: C-5

Large Wood Data

Diameter (m)	Length (m)
0.2	5
0.15	4
0.15	2
0.16	3.5
0.16	3.5
0.25	2.6
0.22	1.5
0.1	3.4
0.1	2
0.17	8
0.19	4
0.1	7
0.12	1.5
0.22	5
0.45	15
0.25	6
0.4	5
0.35	7
0.1	4
0.18	3
0.18	2
0.22	1.8

Forest transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	53	10
NW	H	5	37	10
SW	H	5	88	10
SE	B	1	21	10
NW	B	1	31	20
NE	H	5	91	20
SW	H	5	80	20
SE	B	1	16	20
NW	B	1	20	30
SW	B	1	30	30
NE	H	5	44	30
SE	H	5	76	30
NE	H	5	93	10
SW	H	5	68	10
SE	B	1	17	10
NW	H	5	72	10
NE	H	5	48	20
NW	B	1	28	20

Quadrant	Tree type	Status	DBH	Transect
SW	B	1	24	20
SE	B	1	32	30
NE	B	1	16	30
SW	B	1	14	30
NW	B	1	46	30

Site: C-6

Large Wood Data

Diameter (m)	Length (m)
0.1	1.5
0.12	1
0.12	2.5
0.2	5
0.36	5
0.48	2.5
0.1	2
0.17	2
0.18	1.5
0.12	3
0.4	1.2
0.24	12
0.4	20
0.28	12
0.17	8
0.2	5
0.26	4
0.12	3
0.3	2
0.1	2
0.38	2.5
0.29	2

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	84	10
NW	B	1	28	10
SW	B	1	14	10
SE	H	5	30	10
NW	B	1	21	20
NE	H	5	76	20
SW	H	2	36	20
SE	B	1	37	20
NW	B	1	33	30
SW	B	1	16	30
NE	B	1	12	30
SE	B	1	34	30
NE	H	5	96	10
SW	B	1	28	10
SE	B	1	31	10
NW	B	1	77	10
NE	H	5	46	20
NW	H	5	56	20
SE	B	1	22	20

Quadrant	Tree type	Status	DBH	Transect
SE	P	1	57	30
NE	B	1	33	30
SW	B	1	27	30
NW	B	1	19	30

Site: C-7

Large Wood Data

Diameter (m)	Length (m)
0.36	7
0.3	3
0.44	9
0.11	6
0.48	9.1
0.1	3
0.16	3
0.14	3
0.3	2.2

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	103	10
NW	B	1	29.5	10
SW	H	5	43	10
SE	B	1	45	10
NW	H	5	24	20
NE	B	1	60	20
SW	H	5	101	20
SE	H	5	73	20
NW	H	5	82	30
SW	B	1	41	30
NE	H	5	82	30
SE	H	5	50.5	30
NE	B	1	31	10
SW	B	1	20	10
SE	B	1	81	10
NW	H	1	47	10
NE	H	5	94	20
NW	B	1	45	20
SE	B	1	33	20
SW	B	1	30.5	20
SE	B	1	30.5	30
NE	B	1	31	30
SW	B	1	17	30
NW	B	1	31	30

Site: N-6

Large Wood Data

Diameter (m)	Length (m)
0.3	3
0.5	10
0.24	2
0.2	9
0.28	6
0.23	9
0.57	8
0.32	5
0.34	11
0.12	2
0.26	1.5
0.32	5
0.35	3
0.1	2
0.13	3.5
0.1	2
0.14	3
0.16	2
0.25	4
0.22	6
0.3	7

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NW	B	1	48	10
SW	B	1	38	10
SE	H	5	48	10
NW	H	5	45	20
NE	H	5	39	20
SW	H	1	22	20
SE	B	1	26	20
NW	H	5	97	30
SW	H	5	42	30
NE	B	1	46	30
SE	B	1	50	30
NE	B	1	29	10
SW	H	3	44	10
SE	H	5	94	10
NW	H	5	79	10
NE	H	5	103	20
NW	H	5	60	20
SE	H	3	83	20
SW	H	5	47	20
SE	H	5	67	30

Quadrant	Tree type	Status	DBH	Transect
SW	B	1	66	30
NW	H	5	70	30

Site: N-7

Large Wood Data

Diameter (m)	Length (m)
0.33	6
0.21	5
0.28	4.5
0.12	5
0.16	3
0.14	2.5
0.1	1
0.28	3
0.12	4
0.1	3
0.16	2
0.12	3
0.24	10
0.34	8
0.6	8
0.42	4
0.6	5
0.22	4
0.1	5
0.45	2
0.11	5
0.1	4
0.36	5
0.74	6

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NW	B	1	74	10
SW	H	2	32	10
SE	B	1	16	10
NW	H	5	106	20
NE	B	1	46	20
SW	B	1	33	20
SE	B	1	62	20
NW	H	5	18	30
SW	H	2	26	30
NE	H	5	61	30
SE	H	5	112	30
NE	H	5	66	10
SW	H	5	41	10
SE	H	5	19	10
NW	B	1	53	10
NE	B	1	33	20
NW	B	1	15	20
SE	H	3	78	20

Quadrant	Tree type	Status	DBH	Transect
SE	B	1	36	30
NE	B	1	14	30
SW	H	5	86	30
NW	B	1	44	30

Site: N-8

Large Wood Data

Diameter (m)	Length (m)
0.3	5
0.34	12
0.22	2.7
0.1	3
0.14	3.5

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	32	10
NW	B	1	16	10
SW	H	5	23	10
SE	B	1	25	10
NW	B	1	19	20
NE	B	1	31	20
SW	B	1	24	20
SE	H	5	41	20
NW	H	5	26	30
SW	H	2	16	30
NE	B	1	15	30
SE	B	1	34	30
NE	B	1	24	10
SW	B	1	33	10
SE	H	2	21	10
NW	B	1	19	10
NE	H	5	45	20
NW	H	5	21	20
SE	H	5	17	20
SW	B	1	29	20
SE	B	1	30	30
NE	B	1	20	30
SW	B	1	18	30
NW	B	1	26	30

Site: N-9

Large Wood Data

Diameter (m)	Length (m)
0.1	3
0.11	1.2
0.24	6
0.2	8
0.1	2
0.11	4

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	33	10
NW	B	1	21	10
SW	B	1	15	10
SE	B	1	22	10
NW	B	1	43	20
NE	B	1	12	20
SW	B	1	28	20
SE	B	1	19	20
NW	B	1	26	30
SW	B	1	34	30
NE	B	1	39	30
SE	B	1	21	30
NE	B	1	23	10
SW	B	1	19	10
SE	B	1	21	10
NW	B	1	27	10
NE	B	1	14	20
NW	B	1	36	20
SE	B	1	12	20
SW	B	1	15	20
SE	B	1	32	30
NE	B	1	24	30
SW	B	1	21	30
NW	B	1	15	30

Site: W-8

Large Wood Data

Diameter (m)	Length (m)
0.38	4
0.16	6
0.23	2
0.21	5.2
0.12	3.8

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	32	10
NW	B	1	45	10
SW	B	1	21	10
SE	B	1	19	10
NW	B	1	32	20
NE	B	1	36	20
SW	B	1	28	20
SE	B	1	22	20
NW	B	1	40	30
SW	B	1	21	30
NE	B	1	16	30
SE	B	1	28	30
NE	B	1	42	10
SW	B	1	13	10
SE	B	1	19	10
NW	B	1	29	10
NE	B	1	21	20
NW	B	1	25	20
SE	B	1	18	20
SW	B	1	17	20
SE	B	1	32	30
NE	B	1	33	30
SW	B	1	27	30
NW	B	1	44	30

Site: N-10

Large Wood Data

Diameter (m)	Length (m)
0.32	4
0.16	7
0.27	5
0.1	3
0.28	4

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	B	1	54	10
NW	B	1	22	10
SW	H	2	17	10
SE	B	1	16	10
NW	B	1	68	20
NE	B	1	25	20
SW	H	1	29	20
SE	H	5	36	20
NW	B	1	52	30
SW	B	1	27	30
NE	B	1	47	30
SE	B	1	58	30
NE	H	1	26	10
SW	B	1	34	10
SE	B	1	19	10
NW	B	1	13	10
NE	B	1	56	20
NW	B	1	19	20
SE	B	1	17	20
SW	H	5	24	20
SE	B	1	14	30
NE	B	1	14	30
SW	B	1	44	30
NW	B	1	37	30

Site: N-11

Large Wood Data

Diameter (m)	Length (m)
0.32	12
0.36	7
0.12	3
0.17	6
0.4	14
0.17	3
0.25	4.6
0.13	2

Forest Transect Data

Quadrant	Tree type	Status	DBH	Transect
NE	H	5	63	10
NW	H	5	79	10
SW	B	1	31	10
SE	H	5	45	10
NW	H	5	56	20
NE	H	5	53	20
SW	B	1	47	20
SE	B	1	18	20
NW	H	5	94	30
SW	H	2	67	30
NE	B	1	22	30
SE	B	1	39	30
NE	B	1	32	10
SW	B	1	20	10
SE	H	5	60	10
NW	H	5	25	10
NE	H	5	49	20
NW	H	5	71	20
SE	B	1	14	20
SW	B	1	33	20
SE	H	5	53	30
NE	B	1	16	30
SW	H	3	29	30
NW	B	1	30	30

Vita

Burke Alexander McDade was born and raised in Lexington, North Carolina. His interest in the natural world and its workings began when he was young. In elementary school, he received the nickname “nature nut” by a teacher. This moniker seemed to prove itself true in the years that followed as he decided to attend Appalachian State University and pursue a degree in ecological, environmental, and evolutionary biology. Following graduation, he held an internship with the N.C. Wildlife Resources Commission and taught as a lateral entry science teacher at a middle school. In this year of teaching, Burke was accepted into the graduate program in the Department of Geography and Planning at Appalachian State University. After much pondering, he finally found a project that fit his many interests including water resources, invasive species, and the Appalachian Mountains. His future intentions are to pursue his passion in the sciences by holding a research or teaching position.