Impacts of the Hemlock Woolly Adelgid (Adelges tsugae) on Headwater Stream Large Woody Debris Loads in the Southern Appalachian Mountains

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HIGHLIGHTS

- A hemlock decline index (HDI) was developed to characterize hemlock mortality induced by the hemlock wooly-adelgid (HWA).
- HDI is significantly associated with in-channel large woody debris (LWD) loads in southern Appalachian streams
- Ecosystems have not yet reached peak mortality, therefore LWD loads are likely to continue to increase.
- The LWD response to HWA-induced forest disturbance follows previously theorized disturbance-recovery models.

ABSTRACT*: The hemlock woolly adelgid (HWA; Adelges tsugae) is responsible for widespread mortality of eastern hemlock (Tsuga canadensis) throughout its range. Models suggest that HWA-induced mortality could serve as a disturbance event that will increase large woody debris (LWD) loads in headwater streams. The objective of this research was to investigate the extent to which HWA infestation has impacted in-channel LWD loads in southern Appalachian headwater river systems. We surveyed 26 sites within the Blue Ridge Mountains with varying degrees of eastern hemlock composition, and HWA-induced decline. We combined these into a Hemlock Decline Index (HDI) that served as an explanatory variable for analyses. Results revealed that high HDI values were associated with higher LWD loads, higher frequency of LWD jams, and larger diameter LWD. These findings indicate that the HWA is significantly impacting LWD loads in streams, and subsequently impacting stream ecology. Additionally, the*

HDI developed here could be a useful tool for making regional comparisons of the impacts of the HWA on forest ecosystems.

KEYWORDS: Large woody debris, Hemlock wooly adelgid, Eastern hemlock, Headwater streams

INTRODUCTION

Across the globe, anthropogenic forest disturbance events are increasing in frequency and intensity (Dale et al. 2001, Turner 2010, Trumbore et al. 2015). As such, disturbance-recovery regimes of forest ecosystems are being altered, and subsequently altering those of coupled biogeomorphic systems as a whole (Phillips et al. 2015, Verstraeten et al. 2017, Viles 2019). The research presented here looks specifically at the relationship between such a coupled system whereby eastern hemlock mortality as a result of an invasive species may be responsible for enhancing large woody debris (LWD) loads in headwater river systems of the southern Appalachian Mountains. Understanding the coupled impacts associated with changing forest disturbance-recovery regimes will be critical to our ability to manage key ecosystem services and to plan for future climate resiliency (Johnstone et al. 2016, Seidl et al. 2016, Moreno-Mateos 2017). Here we focus on how HWA infestation in the southern Appalachians has changed LWD loads, which has subsequently affected stream geomorphology and aquatic communities.

Adelges tsugae and hemlock decline in the Appalachians

Eastern hemlock (*Tsuga canadensis*) is experiencing decline and mortality throughout much of its range due to the hemlock woolly adelgid (*Adelges tsugae*) (Ellison et al. 2018). The hemlock woolly adelgid (HWA) is an invasive aphid-like insect species native to Asia. The insect was imported to an ornamental tree nursery in Richmond, Virginia, in 1954. Since the introduction, the HWA has spread to 19 states and nearly two-thirds of the native range of the eastern hemlock (Figure 1) (Ellison et al. 2018). Infestation results in gradual defoliation of the trees and eventual mortality (Young et al. 2002). Complete tree mortality is estimated to occur within 4–20 years after infestation (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 1987). As a result, severe decline and even extirpation will likely occur throughout the native range (Ellison et al. 2018).

In the southern Appalachian Mountains, eastern hemlocks grow preferentially in riparian zones adjacent to headwater streams. Therefore, any disturbance that affects hemlocks theoretically can impact streams as well. Adelgid-induced hemlock mortality will likely create excessive amounts of falling leaf litter, falling branches, and eventually whole trees. A large quantity of this wood will be available for recruitment into the headwater streams of the region as large woody debris (LWD) (Ellison et al. 2005). The potential increase in the volume of LWD would undoubtedly alter stream processes and

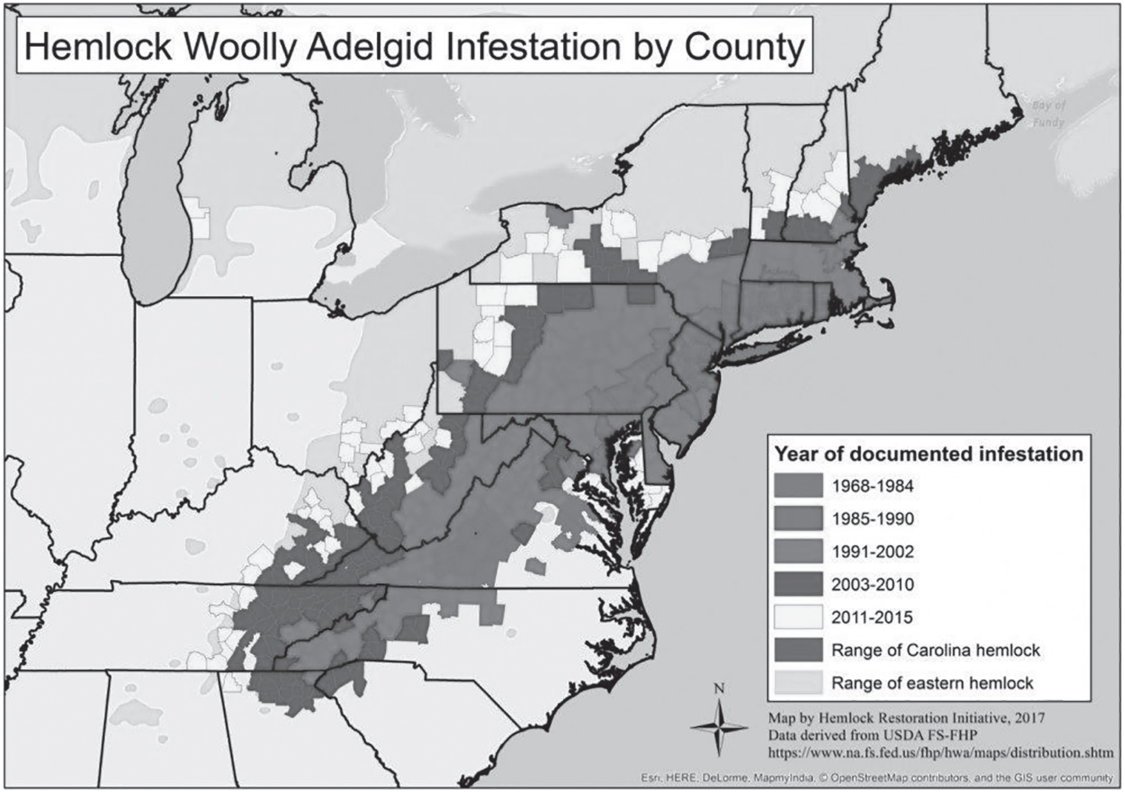

*Figure 1. Map showing the range of the eastern hemlock (*Tsuga canadensis*) throughout the United States and Canada and the spread of infestation by the hemlock woolly adelgid (*Adelges tsugae*) by county (Source: Hemlock Restoration Initiative).*

dynamics as LWD is known to be a strong influence on fluvial geomorphic and ecological processes (Gregory et al. 2003).

Large woody debris and river systems

Large woody debris (LWD) can alter stream geomorphology by creating waterfalls, forming pools, and altering flow 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, and lowers stream velocities, inducing sediment deposition and accumulation behind LWD pieces or LWD jams (Potts and Anderson 1990, Diehl 1997, Wallerstein et al. 1997, Downs and Seimon 2001, Montgomery et al. 2003). The residence time of these sediment sinks varies considerably across temporal scales because of wood type and the resultant decay resistance (Dolloff, C.A., 1996, Hyatt and Naiman 2001), wood size, channel characteristics, and hydrologic regime. Sediment yield in some mountain streams is ten times less than sediment storage associated with LWD (Montgomery et al. 2003). LWD in the channel can also result in the storage of nutrients such as carbon and nitrogen and significantly contribute to the regulation of biogeochemical cycles (Bilby and Likens 1980, Benke et al. 1985, Gurnell et al. 2002, Gurnell 2013). Particularly, LWD and LWD jams are responsible for storing large quantities of coarse particulate organic matter (CPOM), which serves as the exclusive diet of numerous invertebrates in aquatic systems. Studies have shown that the removal of LWD, as a management practice or as a result of extreme flood events, results in a significant increase in CPOM downstream (Jochner et al. 2015). Additionally, artificial placement of LWD has become a popular river restoration technique because of its role in providing habitat for fish and aquatic biota, as well as for bank stabilization (Alexander and Allen 2006).

Large woody debris enters the channel through a variety of mechanisms but is primarily controlled by valley and riparian forest stand characteristics (Bragg 2000, Gregory et al. 2003). Valley characteristics that have been shown to influence wood load include channel slope, valley side slope, drainage area, and confinement (Hassan et al. 2005). Riparian forest stand characteristics that can influence wood accumulation include the seral forest stage and natural and anthropogenic disturbance regimes. Specific variables related to these characteristics that result in wood recruitment include riparian tree mortality, tree blowdown from storms, and forest disturbance events (Wohl and Cadol 2011). Considering the HWA as a disturbance event, two similar conceptual disturbance/response models have been suggested (Webster et al. 2012, Costigan et al. 2015). Both models predict increasing LWD recruitment as a function of time since infestation, and estimate post-mortality tree fall to occur within 8–20 years. They estimate disturbance-induced wood loads to then peak anywhere from 12 to 30 years following the initial infestation.

Given our contemporary understanding of the important ecogeomorphic role that LWD serves in river systems, and the increasing frequency and intensity of forest disturbance events, there is a critical need to develop a better quantitative and theoretical understanding of how disturbance events, such as the infestation of the HWA,

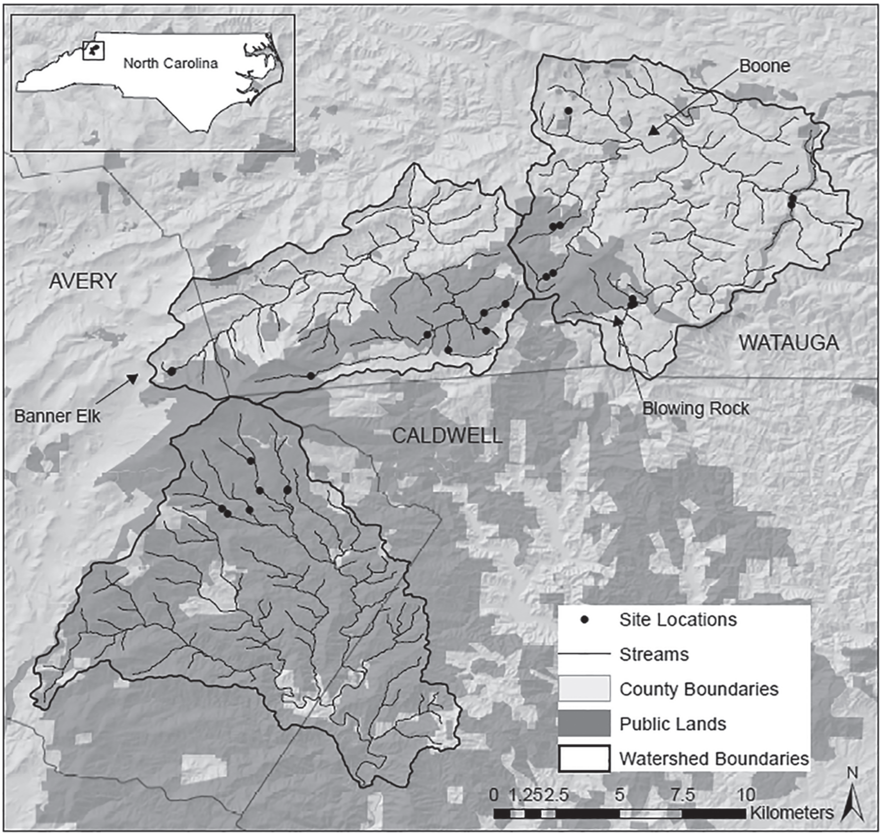

Figure 2. Map showing location of the study reaches where in-channel LWD and riparian forest characteristics were measured. The watershed that extends farthest left is Wilson Creek, the middle watershed is the upper Watauga River basin, and the watershed on the right is the upper South Fork of the New River.

impact in-channel LWD loads. The objective of this research was thus to investigate the extent to which HWA infestation has affected in-channel LWD loads in southern Appalachian headwater river systems. We accomplished this by investigating the relationships between the health and abundance of eastern hemlock trees, and in-channel LWD loads in three headwater sub-basins of the Blue Ridge Mountains of southern Appalachia.

STUDY AREA

We compared three headwater watersheds located within the Blue Ridge Mountains physiographic region of the Appalachian Mountains of North Carolina (Figure 2) within Watauga, Avery, and Caldwell Counties. The sites span numerous headwater streams within the South Fork of the New River (HUC 050500010201), the Watauga River (HUC 060101030301), and Wilson Creek (HUC 030501010502). Their respective drainage areas are 90.7 km^2, 67.98 km^2, and 104.31 km^2. All sites are within a Köppen Cfb climate region, which is characterized by moderate to high temperatures during the summer months and cool temperatures capable of producing frozen precipitation during the winter months, and annual precipitation totals generally ranging between 50 and 250 cm, with a high level of local orographic variability. And although formal historical land-use/forest stand information is not available for this specific location, it is likely that the region followed similar 19^{th} to 20^{th} century deforestation patterns to the rest of the southern Appalachian region. The USFS reports that the HWA invaded these counties in 2001 and 2002 (Havill et al. 2014). Hemlock woolly adelgid has been present at our locations for 15 or more years.

METHODS

Site selection

This study was conducted at 26 sites within headwater sub-basins of the Blue Ridge Mountains (Figure 2). Site selection requirements were: 1) a tree overstory, 2) the presence of eastern hemlock, and 3) public land access within the watershed. The three 12-digit HUC watersheds within which our sites were located capture the gradient of eastern hemlock abundance and eastern hemlock decline within the region. Individual stream study sites were identified using a combination of field investigations/observations and remotely sensed imagery.

National Agriculture Inventory Program (NAIP) imagery from 2014 was used to visually identify dead hemlocks from the surrounding forest canopy (Figure 3). We used 3-m resolution false-color composite images from 2016, acquired from Planet Labs, Inc., as an aid in distinguishing both dead and living hemlock stands. We identified areas of hemlock mortality and created shapefiles of them using ESRI's ArcMap 10.4.1 software. Many of these locations were field verified to be sure that the dead trees were mostly eastern hemlock (Figure 4). We used ArcMap 10.4.1 and ENVI software programs for digital image processing. In total, we identified 26 sites at streams with surrounding riparian forests containing a wide range of hemlock occurrence and mortality. We had 11 sites in the headwaters of the South Fork of the New River Basin, 8 in the headwaters of the Watauga Basin, and 7 in the Upper Wilson Creek Basin.

Stream characteristics

Geomorphic characteristics for each site were recorded in the field using standard field instruments or using a Geographic Information System (ESRI, ArcMap 10.4). Bankfull width was recorded in the field and defined by changes in vegetation, stain lines on rocks, or changes in slope or bank material (Harrelson et al. 1994). We measured stream

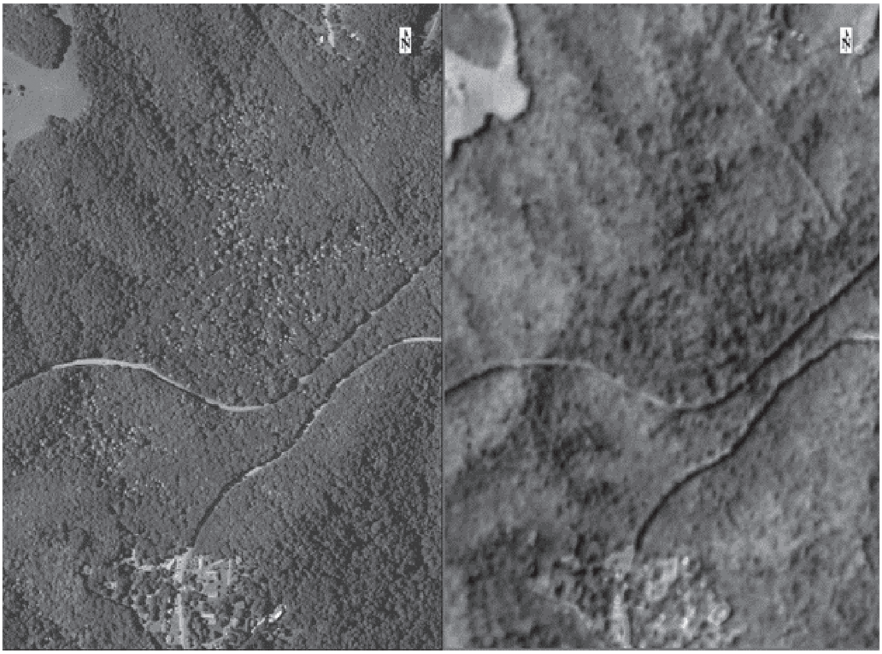

Figure 3. One-m resolution NAIP image (left) showing Hemlock decline along the Blue Ridge Parkway. Dead hemlocks appear lighter than the surrounding summer foliage. 3-m false-color image (right) with near-infrared band, which appears darker in the grayscale image above, representing dead hemlock stands.

Figure 4. Dead hemlocks surrounding a stream (left) and a large hemlock trunk that has recently fallen into the channel (right).

slope 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 the entire drainage was then averaged to obtain a watershed slope. We calculated a valley confinement ratio for each site by estimating the width of the active floodplain (if present) at each stream site using ArcMap and dividing this number by the field-derived bankfull channel width.

Forest transects

Forest transects were established parallel to the stream at 10, 20, and 30 m from the stream bank. It has been established that beyond 30 m, wood is much less likely to be recruited into the channel, especially in the case of mountain headwater streams (Curran and Wohl 2003, Eschtruth et al. 2006, Martin & Goebel 2012, Costigan et al. 2015). Transect length was dependent on continuous valley conditions and encompassed at least three hydrologic unit sequences in the adjacent channel so that heterogeneity in channel form and riparian forests was captured.

Along each 25 m segment of the transects, 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 applied (Bonham et al. 2013). The closest tree to each center point in each quadrant was then located and distance from the center point recorded. All tree stems measuring >12.5cm for diameter at breast height (DBH) were included. The DBH for each of these trees was recorded, and the tree was classified either as a broadleaf, eastern hemlock, or other evergreen species. Subsequently, each tree was assigned a crown class based on the amount and direction of the 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 0–5 where 0: no evidence of infestation, 1: >75% of foliage remains, 2: 51–75%, 3: 26–50%, 4:1–25%, 5: dead (Orwig and Foster 1998). Fixed radius 0.01 ha circular plots (radius = 5.66 m) were established at each PCQ center to quantify understory shrub and tree species composition. The percentage cover in each understory plot of Rhododendron (*Rhododendron maximum*) was also estimated to the nearest 10% (Figure 5).

Hemlock decline index

Due to the wide variability of stand compositions and statuses of decline among the sample sites, we developed a new metric, which we termed the hemlock decline index (HDI). The HDI allows for more generalized comparisons between watersheds by not only taking into account the level of decline, but also the percent composition of eastern hemlock at the site. We calculated the value of the HDI by multiplying the average eastern hemlock decline number for a site (0–5) by the fractional percentage

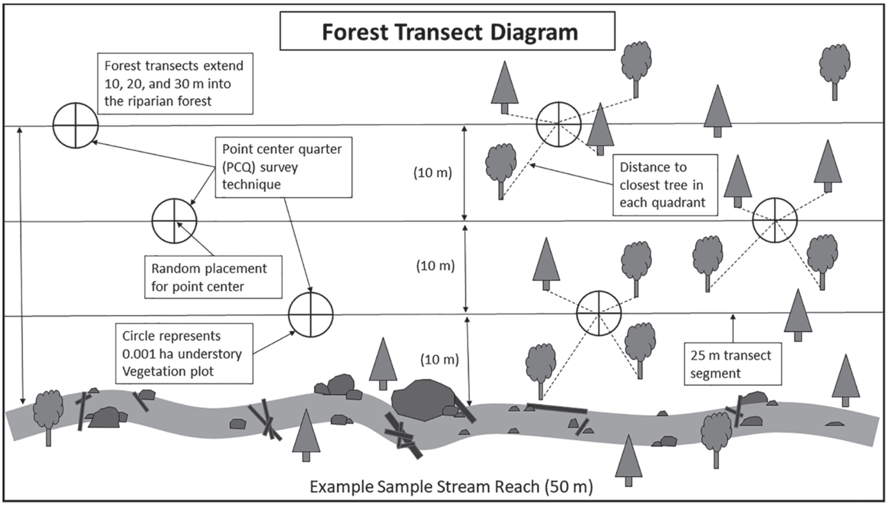

Figure 5. Diagram of Point-Center-Quarter plotless survey technique, riparian forest transects, and understory plots.

of hemlocks in the riparian forest at the site. This resulted in a scale that ranges from 0–5 (Figure 6). An HDI of 0 thus represents a riparian forest that contains either no hemlocks and/or no infestation, and an HDI of 5 represents a riparian forest where the trees are exclusively eastern hemlock, and all trees are dead (peak mortality). Hemlock decline index values for data collected at sites for this study ranged from 0 to 3. The HDI served as our explanatory variable when considering associations between hemlock decline and LWD.

Large woody debris sampling

The stream reaches within which LWD was measured were the same length as the parallel forest transects and followed the methods described by Wohl et al. (2010). To be considered LWD, the wood had to be >1 m in length and 0.1 m in diameter and had to be present in at least part of or suspended above the bankfull channel. Three or more pieces of large wood in contact with each other were classified as a jam. The length and diameter of each piece of LWD were recorded along with the type, location with respect to the channel, and any notable geomorphic effects. We calculated the volume of jams by taking the approximate overall dimensions of length, width, and height of debris comprising the jam.

Data analysis

The HDI was divided into three groups (<1, 1–2, and >2), roughly following an equal interval classification for this data. We compared median LWD length, median LWD diameter, and total wood load for each site using a non-parametric

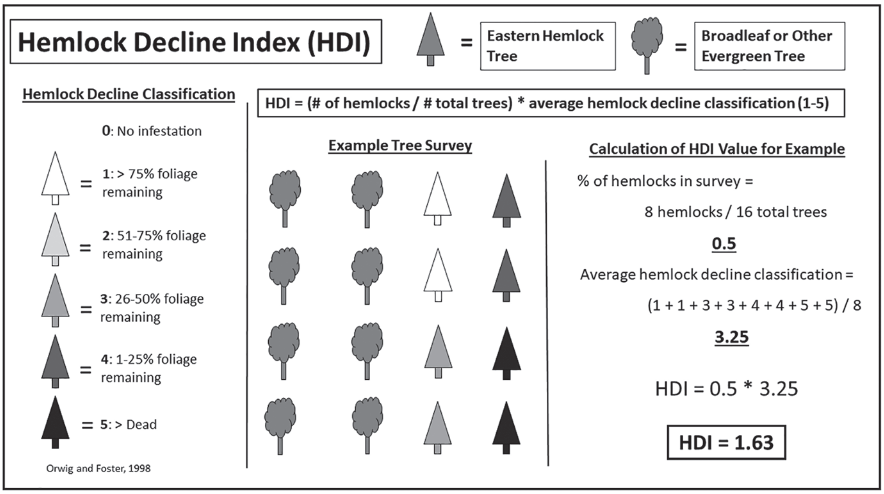

Figure 6. Schematic demonstrating a calculation of the hemlock decline index (HDI) value, a new metric developed for this study to represent the level of decline within a forest plot.

Kruskal-Wallis test. If results were significant, we used a Mann-Whitney *U*-test to reveal which groups were statistically different. Additionally, Spearman's rank correlation was used to identify associations between hemlock decline variables (HDI and % eastern hemlocks) and LWD characteristics (length, diameter, wood load, and jam frequency). We also applied the Spearman's rank correlation to investigate associations between LWD characteristics and the geomorphic variables of watershed slope, valley side slope, and confinement ratio. In all cases, we interpreted statistical significance as $p < 0.05$.

RESULTS

Riparian forest characteristics

Forest transects indicated that the composition of the riparian forest overstory was a mixture of hardwoods and hemlocks. We surveyed approximately 620 trees, and the DBH averaged 36.3 cm. At least one eastern hemlock was surveyed in the riparian forest at 22 of the 26 sites, and the HWA was found to be present at 100% of the eastern hemlock-dominated sites. Eastern hemlocks comprised 26% of trees surveyed. However, eastern hemlock composition in the riparian forest varied greatly among sites ranging from 0–67%. In total, over 71% of the hemlocks were classified as dead, and of the remaining live hemlocks, 70% were experiencing stress from the HWA. The average HDI value was 1.1, with values ranging from 0–3.0 (Table 1). Many of the largest trees in terms of DBH were hemlock (Figure 7). Therefore, future decline will eventually result in recruitment of the largest trees in the riparian forest.

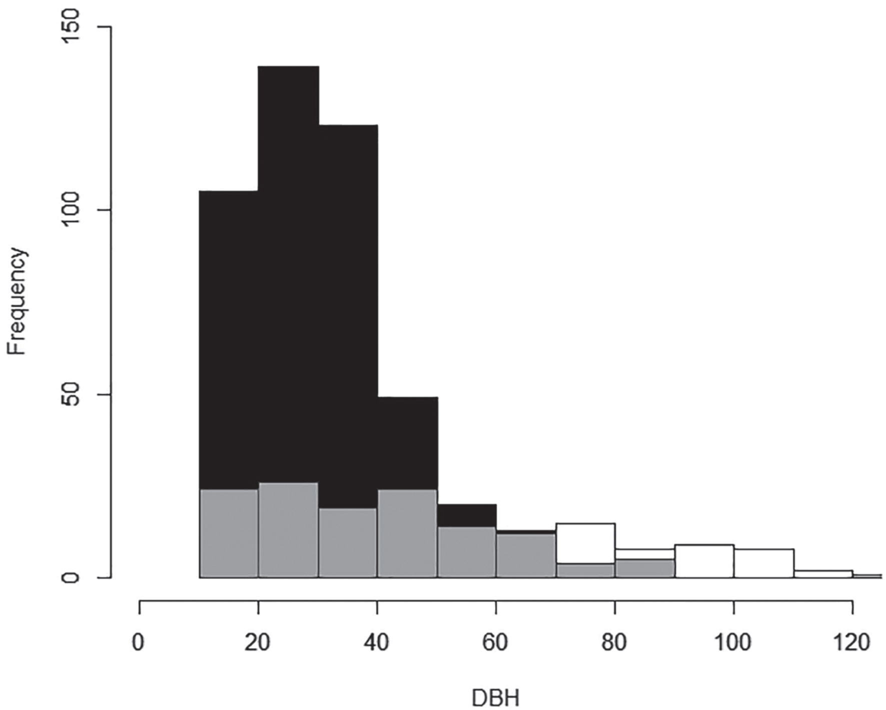

Figure 7. The diameter at breast height (DBH) for both hemlocks (white) and all other trees (black). Gray bars indicate overlapping distributions.

Rhododendron cover dominated the understory layer ranging from 22% coverage to 86% coverage of understory fixed-radius plots. Data from the riparian forest understory plots show a significant positive correlation between HDI and % rhododendron cover ($r = 0.63$, $p < 0.001$), supporting a hypothesis proposed by Evans et al. (2012) suggesting that rhododendron will become increasingly prevalent in the riparian forest as hemlocks continue to die. When regressed on HDI, % rhododendron can be modeled with a simple power function that suggests possible rhododendron establishment even at relatively early stages of HWA induced decline (Figure 8). Rhododendron has been documented to prevent the germination of tree species below by using defensive chemistry (Beckage 2000, Beier et al. 2005, Lei et al. 2006). If this scenario persists, there may be a substantial lag period before a tree species is able to establish itself where hemlocks once occurred in the riparian forest. Therefore, following recruitment of hemlock LWD from the HWA infestation, there will likely be a lag in LWD recruitment as rhododendron slows the establishment of new riparian trees (Webster et al. 2012).

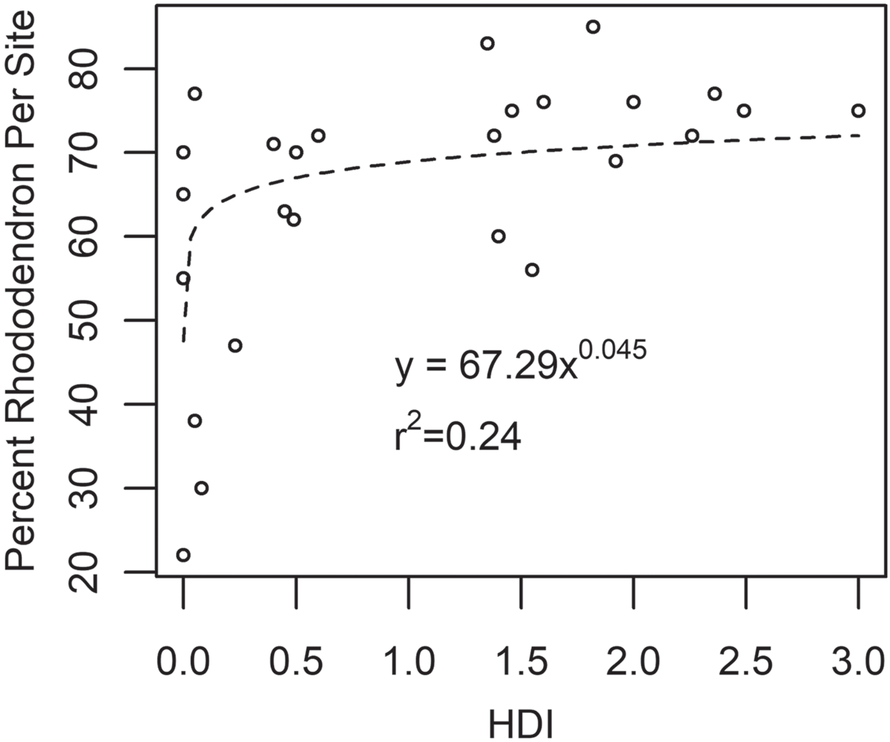

Figure 8. The nonlinear relationship between HDI and percent rhododendron.

Large woody debris and geomorphic characteristics

We found 356 pieces of LWD with a frequency of 19.6 pieces per 100 m. The average diameter of all LWD was 22 cm, and the average length was 4.8 m. LWD volume ranged from 0.55 m^3/100 m to 84.3 m^3/100 m, with an average of 22.6 m^3/100 m (Table 1). There were a total of 33 jams found at all the sites, and the jam volume averaged 4.7 m^3.

Most sites were steep and confined headwater streams that consisted mostly of bedrock, boulders, cobble, and sand with minimal amounts of fine sediment. A combination of coarse substrate and steep slope resulted in most of the streams sampled being dominated by step-pool morphology. Channel slopes ranged from 1% to 14%, with an average of 6%. Bankfull width ranged from 1.6 m to 11.1 m and an average of 6 m. The mean drainage area for all study sites was 2.9 km^2 and ranged from approximately 0.5 km^2 to 9.7 km^2 (Table 1).

The average watershed slope and valley side slope for all sites was 32.4% and 30.3%, respectively. Most streams were highly confined, with an average confinement ratio of 2.2 for all channels. Fourteen streams were found to be fully confined (completely colluvial, with no floodplain development). Thus, LWD recruitment mechanisms at the study

Table 1. Summary of the defining watershed, LWD, and riparian forest characteristics of each site. Sites are listed in order of increasing HDI values.

Site #	A_d (km^2)	W_{bf} (m)	LWD Load (m^3/m)	Hemlock %	HDI
C-3	4.04	9.1	7.5	4.2	0
C-4	3.38	7	0.55	4.2	0
N-9	0.05	1.6	4.9	0.0	0
W-8	1.81	4.5	7	0.0	0
W-4	0.39	2.7	8	4.2	0.04
W-6	1.61	5.3	13.8	4.2	0.04
W-2	3.06	11.1	3.5	4.2	0.08
C-1	0.91	6.1	11.2	4.2	0.21
N-1	4.32	7.8	11.6	16.7	0.43
N-2	2.66	6.4	4.8	12.5	0.48
N-5	1.69	4.3	11.7	16.7	0.5
N-10	1.96	4.7	8.1	20.8	0.52
W-7	0.16	2.2	2.96	16.7	0.67
W-3	3.6	6	7.98	33.3	1.33
C-6	3.26	6.8	48	29.2	1.34
C-2	3.87	8.7	23.6	33.3	1.43
N-4	2.16	5.4	35.9	29.2	1.46
N-8	1.51	4	13	37.5	1.61
W-5	1.97	4.3	41.2	50.0	1.65
W-1	1.19	5.1	45.7	45.8	1.84
C-7	3.23	7.4	34.25	41.7	1.92
N-3	2.13	5.8	31	45.8	2.02
C-5	5.65	10	43.1	45.8	2.29
N-7	9.71	7.5	84.3	54.2	2.38
N-11	0.13	3.1	15.7	54.2	2.49
N-6	9.7	7.7	68.9	66.7	3

sites are dominated by riparian forest conditions (i.e., branches and trees tumbling into the stream from windthrow and/or mortality) and channel/hillslope processes (i.e., landslides/mass wasting). Additionally, the steep slopes, boulder-cobble substrate, and relatively narrow bankfull widths suggest that LWD mobility is limited at these sites, and residence times are likely to be on the order of years to decades.

Hemlock decline and LWD associations

Our Kruskal-Wallis comparison of LWD characteristics between the three HDI classes indicated a statistically significant difference between HDI groups for both length ($p = 0.03$) and wood load ($p < 0.001$). The Mann-Whitney *U*-test indicated that LWD length at sites with an HDI of < 1 was significantly less than LWD length at sites with HDI values > 1 (Figure 9). This could be indicative of increases in the number of

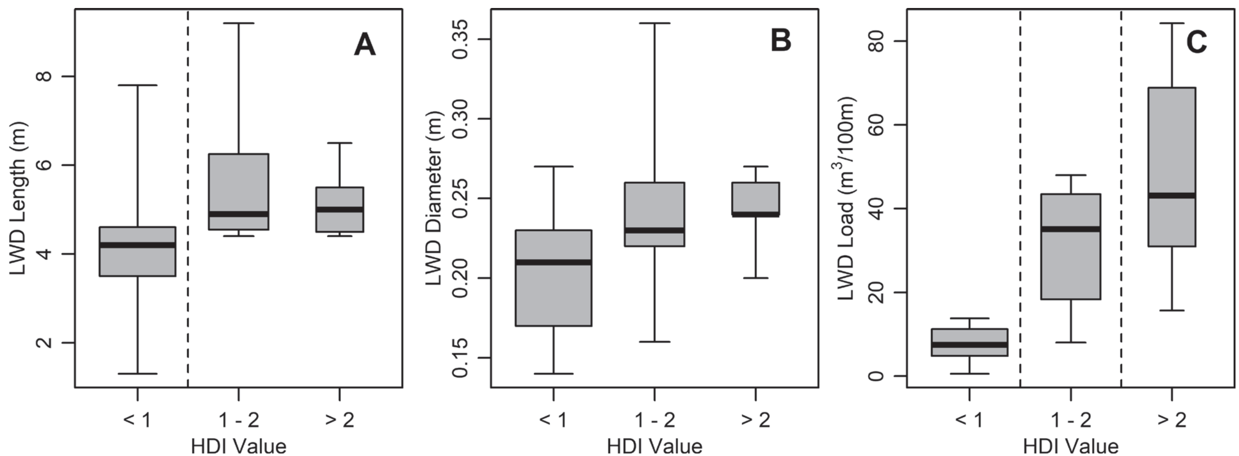

Figure 9. Box plots showing differences in LWD length (A), LWD diameter (B), and LWD load (C) between sites classified into one of three HDI classes. Dotted lines between classes indicate statistically significant (p < 0.05) differences.

Table 2. Spearman's correlations of LWD variables with hemlock decline index, drainage area (A_d), stream slope (S), confinement ratio, and valley slope.

Variables	HDI	A_d	S	Confinement	Valley Slope
LWD Frequency	0.62***	0.24	−0.27	0.12	0.14
LWD Load	0.79***	0.32	−0.31	0.24	0.28
LWD Length	0.43*	0.26	−0.09	0.06	−0.04
LWD Diameter	0.50**	0.06	−0.37	0.29	0.05
Jam Frequency	0.62***	0.4*	−0.32	0.07	0.14

large branches and/or entire trees being recruited to the channel as decline advances. Additionally, the Mann-Whitney *U*-test indicated that significant differences in wood load occurred between each of the three HDI groups ($p < 0.001$), with sites that have an HDI of > 2 having significantly higher loads than sites with an HDI of 1–2, which had significantly higher loads than sites with an HDI of < 1. This indicates that wood loads are higher at sites with higher levels of hemlock decline. The test did not show any significant differences in LWD diameter between the sites. The significant differences identified between sites of varying HDI values suggest a probable association between sites experiencing substantial hemlock mortality and increasing LWD recruitment. To further investigate that association, and others, a Spearman rank correlation was applied for DBH, HDI, geomorphic variables, and LWD variables (Table 2).

First, Spearman rank correlation analyses identified significant associations between numerous riparian forest conditions and in-stream LWD variables. Average riparian forest DBH showed a significant ($p < 0.01$) positive relationships with LWD load, LWD diameter, LWD frequency, and jam frequency indicating that: 1) larger DBH trees, when recruited to the channel, are possibly contributing to the production of LWD jams, 2) the LWD in these channels is likely sourced from hemlocks, as they tended to have higher DBH's than most of the surrounding riparian trees in the study plots, 3) the in-stream wood load is reflective of the characteristics of the surrounding riparian forest, which is also an indication that 4) LWD mobility and transport is limited at these sites, i.e., when they fall into the channel, they remain in place for long periods of time.

Second, the HDI exhibited statistically significant ($p < 0.05$) associations with all LWD variables (length, diameter, wood load, and jam frequency), broadly indicating that the frequency, size, and total volume of LWD increases in association with higher levels of hemlock decline (Table 2). More specifically, given the variables that the HDI takes into account (% of hemlocks in the stand and level of decline), streams draining riparian forests with a high percentage of hemlock that are concurrently experiencing high levels of decline will experience higher wood loads than streams draining riparian forests with fewer hemlocks and/or lower levels of decline. To further investigate the association of HDI with LWD load, we performed a regression of LWD load on HDI, yielding a simple exponential function to represent the relationship (Figure 10). Although the relationship was not particularly strong ($r^2 = 0.59$), it suggests a potential

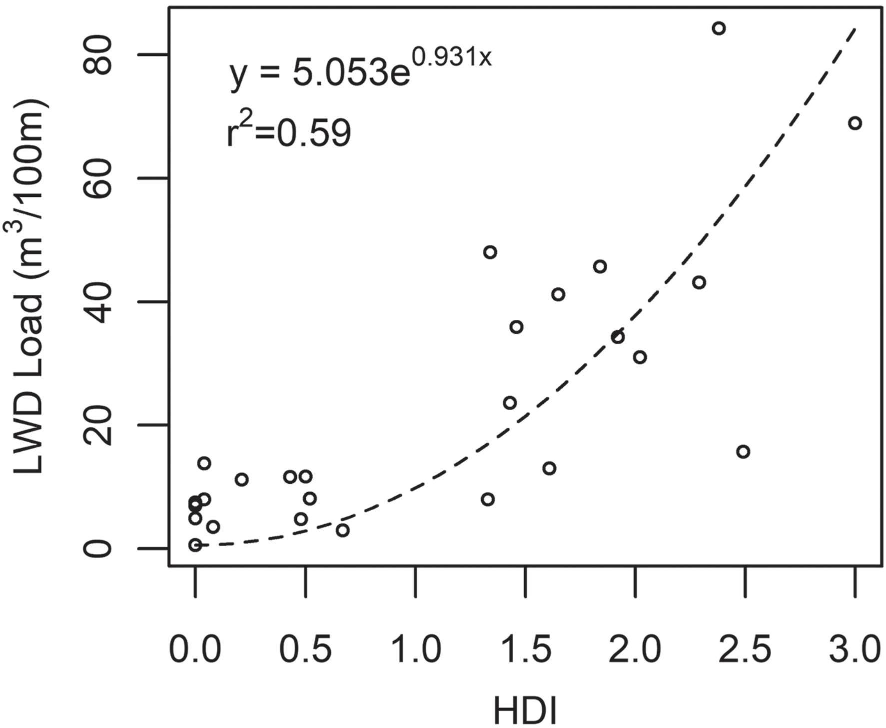

Figure 10. Scatterplot of the hemlock decline index values and average wood load values for each site with a fitted exponential function.

relationship whereby a particular combination of hemlock abundance and decline must occur (HDI > 1), before the stream experiences a significant increase in wood loads.

Finally, visual field observations help support our analyses. At several of the field sites experiencing moderate or high hemlock mortality, we observed recently toppled or broken trees in the stream channel that could be identified confidently as eastern hemlocks. Often large dead hemlocks would serve as a key member upon which other pieces of LWD would accumulate to form jams, which supports our finding of increased jam frequencies in association with HDI values.

DISCUSSION

The HWA-induced forest disturbance event is already having an impact on streams approximately 15 years after the infestation. Wood loads at stream sites with the five highest HDI values had a wood load four times higher than the rest of the sites. Also, the average wood load of 22.62 m^3/100 m found in our study is substantially higher than those found in a limited number of other Appalachian studies on hemlock-related wood loads (Hedman et al. 1996, Warren et al. 2009, Costigan et al. 2015). Wood load in our study drops to $7.35 m^3/100$ m in sites with less eastern hemlock present, including sites with an HDI value of less than 1 ($n = 13$). Regional comparisons such as these, however, should be approached cautiously given that riparian forest conditions differ substantially from region to region with respect to their species compositions and level of hemlock decline. For this reason, we believe the HDI developed for this study could be a useful tool for making comparisons across the eastern hemlock range.

The forest transect data also suggest that there are still a substantial amount of dead or declining hemlocks still standing in the riparian forests adjacent to these streams. The three watersheds used in this study have not yet reached peak wood recruitment. Peak recruitment linked to the HWA could occur in the near future but is highly dependent on environmental conditions such as drought, precipitation events, and wind storms. Given the results discussed here, our study helps support an existing conceptual model proposed by Costigan et al. (2015), which suggests that both jam frequency and jam volume in streams will increase as more wood from dead hemlocks is recruited to the stream. Streams with high HDI values (> 2) have over twice the number of jams compared to streams with low to moderate HDI values (0–2). Many of the dead eastern hemlocks already recruited into the channel and living standing eastern hemlocks are large (> 50 cm DBH). Large branches and trunks from these trees will be continually recruited into the channel during the next several years to decades, which will induce substantial changes to the aquatic ecosystem.

Watersheds in this study will likely endure a variety of ecological changes as a function of increased wood input. Complex habitats will be produced as LWD acts as a barrier and creates changes in water velocity and direction, resulting in pool and waterfall formations. This new substrate and heightened 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 LWD in aquatic systems will also interrupt the longitudinal connectivity of sediment and nutrients. Sediment that would normally flush downstream will be more prone to accumulate behind LWD due to altered stream velocities (Dumke et al. 2010), potentially impacting the life cycles and reproduction of organisms. For example, brook trout (*Salvelinus fontanalis*), the only salmonid native to the Southern Appalachian Mountains, rely on silt-free substrate when making beds to reproduce. Increased sedimentation could result in the suffocation of brook trout eggs (Angermeier and Karr 1984). Increased LWD loads may also result in localized nutrient storage, which will alter biogeochemical cycles in the watersheds by storing nutrients and reducing downstream nutrient flux. Additionally, increased benthic invertebrate production may result from more stored carbon in headwater streams of the watershed. This altered equilibrium of biogeochemical processes could impact downstream ecosystems that are currently equilibrated to pre-disturbance biogeochemical inputs and could be critical to our understanding of fluvial carbon flux as a whole. Even though eastern hemlocks do not dominate the entire riparian forest of watersheds in this research, their mortality will have repercussions much further downstream and for decades into the future.

CONCLUSION

Results of this study indicate that 1) eastern hemlock stands located in headwater sub-basins of the Blue Ridge Mountains are in a state of moderate to severe decline as a result of the HWA, 2) In-stream LWD loads (volume, piece length, piece diameter, jam frequency) are positively correlated with the hemlock decline index (HDI) that was developed for this study, and 3) the HDI may be a valuable index for making eastern hemlock range-wide comparisons of the impacts of the HWA on forest and riparian ecosystems.

Our data suggest that hemlock forests of the Blue Ridge Mountains are approaching peak mortality due to the HWA but have not yet reached peak recruitment to streams. LWD loads, including LWD jam volume and frequency, will likely continue to rise for at least the next decade as hemlock decline reaches peak mortality, and will persist in streams for the next several decades. Continued monitoring of this forest disturbance event is necessary if we intend to manage eastern hemlock forests and stream resources for riparian forest conservation initiatives. Future research should focus on the nutrient, sediment, and geomorphic effects of the HWA on fluvial systems.

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