Soil Erosion from Eastern Hemlock (*Tsuga canadensis*) Windthrow Mounds following Hemlock Wooly Adelgid (*Adelges tsugae*) Infestations in Riparian Areas of the Chattooga Wild and Scenic River and Tributaries

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Abstract

The Chattooga Wild and Scenic River, a scenic river corridor having important trout habitat, is a popular recreational site with thousands of annual visitor from around the world for fishing and other forms of outdoor recreation. In 1974, the Chattooga River was designated as a wild and scenic river under the Wild and Scenic Rivers Act of 1968 by the 93rd congress, the first river to be added since the passing of the Act. Recently recreationist and land managers have observed the severe decline of eastern hemlocks (*Tsuga canadensis*) in the riparian area due to hemlock woolly adelgid (*Adeles tsugae*) infestations that began over 10 years ago. Currently, eastern hemlock mortality is approximately 90% and dead hemlock are uprooting within the riparian. The uprooting of hemlock within the riparian zone has become a concern for managers with regard to potential sediment deposition in the Chattooga River and is the focus of this study. The objectives of this project were 1) to monitor the degree to which hemlock mortality was associated with windthrow mounds and 2) to estimate the erosion potential associated with such disturbances. Results indicate that the level of degradation of hemlock within the riparian area is extensive and poses an increased potential for windthrow; however, hemlock tip-ups do not appear to be a significant source of sediment.
Introduction

Chattooga Wild and Scenic River

The Chattooga Wild and Scenic River flows along the border of South Carolina and Georgia from North Carolina and is well known for its recreational values (e.g., fishing, white water sports). The river and its tributaries provide habitat for fish and wildlife including Rainbow Trout (*Oncorhynchus mykiss*), Brook Trout (*Salvelinus fontinalis*), and Brown Trout (*Salmo trutta*) (Addor and Smutko 2007). Anglers and adventurists, such as kayakers and canoers, are attracted to the Chattooga and its tributaries year round due to the experiences provided by its wilderness, scenery, wildlife, and water craft recreational options (Dye 1997). These factors allow the Chattooga to be a major tourism attraction for the east coast and led to the wild and scenic river designation.

In October 1973, a proposal was made to include the Chattooga River as a wild and scenic river under the Wild and Scenic Rivers Act of 1968. In May of 1974 the 93rd congress designated the Chattooga River as a wild and scenic river, the first river to be designated as such since the passing of the Wild and Scenic Rivers Act (Smith and Moore 2011). Since 1973 the 57 mile (92 km) protected segment (Wild and Scenic Rivers Amendments 1974) has provided wilderness and recreational opportunities to the local community as well as recreationists from around the country and world. With over 15,000 acres (6073 ha) of land encompassed along the 57 mile segment, recreational opportunities are abundant.

The USDA Forest Service (USFS) manages the Chattooga River for wilderness, wildlife, water and recreation within the Sumter National Forest. The USFS maintains service roads, recreational areas, monitors fish populations, manages vegetation and wildlife, conducts research, and performs tasks relating to the management and protection of the wild and scenic
river. Therefore, the USFS is interested in detecting and resolving potential issues that arise within the boundaries of the river within USFS jurisdiction. An ecosystem level disturbance was caused by the infestation of Hemlock Woolly Adelgid (*Adelges tsugae*) that was detected within the Chattooga River gorge in 2002 (Myers 2005). Since 2002, the Hemlock Wooly Adelgid has caused an extremely high mortality rate of Eastern Hemlock (*Tsuga canadensis*) along the Chattooga River and its tributaries, as high as 95% based on studies conducted to predict hemlock mortality in the central Appalachia (Spaulding and Rieske 2010). USFS personnel observed the high mortality rate of hemlock within the riparian zones and the observed windthrow mounds following tree mortality and speculated that such soil disturbances within the riparian buffer might lead to soil erosion and sedimentation of the stream. Thus, the USFS wished to monitor the degree of the potential problem in order to guide management responses. Thus, the objectives of this research were 1) to monitor the degree to which hemlock mortality was associated with windthrow mounds and 2) to estimate the erosion potential associated with such disturbances.

**Hemlock Woolly Adelgid**

Hemlock woolly adelgid (*Adelges tsugae*), a non-native invasive insect from Asia, was introduced into the United States in the 1950’s (Vose et al. 2013). This insect’s host includes the Eastern Hemlock which is highly vulnerable and susceptible to Wooly Adelgid infestation. Each year Hemlock Woolly Adelgid reproduces two generations on hemlock, sistens in the winter and progrediens in the spring (McClure 1989). The crawlers, or first instar nymphs, of each generation have sucking mouth parts that they insert into the base of the needle on the hemlock and extract nutrients from the xylem ray parenchma cells (Young et al. 1995), this process
ultimately results in defoliation and mortality in hemlock. Hemlock Wooly Adelgid is known to attack hemlock of any age and size (Orwig and Foster 1998) and the insects spread rapidly, causing high mortality rates in an entire forest setting, not just in individual trees or small areas. More rapid spread rates are observed in the south, at 15.6 km/yr., than in the north (Pennsylvania and north) at 8.13 km/yr. (Evans and Gregoire 2007), which can be contributed to the colder temperatures of the north (Evans and Gregoire 2007). However, Morin et al. (2009) found that greater spread rates in the south can also be attributed to increased density levels of hemlock. With an accelerated rate of spread and high mortality rates, Hemlock Wooly Adelgid has decimated stands of hemlock from New England to Alabama (Evans et al. 2011) and such mortality will undoubtedly affect the ecology and management of previously hemlock dominated forest ecosystems.

**Hemlock and Hemlock Mortality**

Eastern Hemlock (*Tsuga canadensis*) is a keystone tree species that has a range from as far north as Maine to as far south as Alabama and all along the Appalachian Mountains (Evans et al. 2011). It is a long lived (250 to 300 years) shade tolerant conifer species that is considered to be late successional and can be found in greatest abundance in cool mesic microclimates (Godman and Lancaster 1990). In the Southern Appalachians, Eastern hemlock is a co-occurring canopy species, often co-occurring with mixed hardwoods, usually found in riparian areas, but also exists in deep gorges and on steep slopes (Narayanaraj et al. 2010). Hemlock and hemlock forests provide extensive ecosystem benefits, thus warranting keystone species status. Eastern hemlock stands provide habitat for numerous wildlife species, including the Indiana Bat (*Myotis soldalis*) maternity roosting in eastern hemlock stands (Britzke 2003), and the dense canopy is an excellent source of shade for streams and waterways, thus protecting streams from thermal
pollution (McClure et al. 2001). Such cool streams are a critically important attribute for trout and overall stream health. Mortality of eastern hemlock and the subsequent replacement by mixed hardwoods, could drastically affect stream physical and chemical attributes (Snyder et al. 2005), modify nutrient fluxes from tree canopy to the litter and duff (Stadler et al. 2006), alter large woody debris in streams (Huddleston 2011; Evans et al. 2012), and affect the forest ecosystem processes.

Currently, Eastern hemlock mortality rates due to Hemlock Wooly Adelgid (HWA) are variable but in many cases extremely high, between 15% and 80% (Ford et al. 2012), and hemlock forests are declining especially in the Southern Appalachia (Ford et al. 2012). Some hemlocks can live greater than 10 years following an HWA infestation (Pontius et al. 2006), however, most do not. Additionally, the understory hemlock are suppressed, thus ensuring that adequate regeneration to replace dead overstory trees are lacking. Eschtruth et al. (2006) observed a higher rate of mortality in understory hemlock versus overstory hemlock due to the effects of suppression. This “bottom-up” elimination of hemlock greatly reduces hemlock recruitment in the overstory once the canopy opens (Krapfl et al. 2011); therefore, significant persistence of hemlock in future forests is uncertain. Ford et al. (2012) stated that hemlock are being replaced on the landscape with rhododendron (*Rhododendron ferrugineum*) and advanced regeneration of co-occurring hardwood species. Such species shifts will alter the forest ecosystem dynamic and have both immediate and long-term effects on trout stream habitat, terrestrial wildlife habitat, and other ecosystem functions. Hemlock mortality continues to progress due to the effects of HWA, and it appears that all hemlock stands are susceptible to HWA infestations (Faulkenberry et al. 2009). Evans et al. (2011) evaluated hemlock dominated
stands from the northern to southern range and concluded that these stands were likely to shift to hardwood dominated stands that were alter both terrestrial and aquatic ecosystems.

**Windthrow Causes, Site Factors, and Effects**

The high mortality rates of hemlock from HWA has created an abundance of dead standing hemlock. After death, the tree stem and root system decays and weakens over time. Although all trees are susceptible to wind damage, dead standing trees are particularly prone to wind damage such as stem breakage or tree uprooting (windthrow) (Galloway et al. 2009). In the southern Appalachian mixed hardwood forests wind damage is responsible for 11% of tree mortality (Clinton et al. 1993). However, winds are not the only contributing factor in windthrow. Additional factors that may acerbate windthrow are soil moisture levels, tree diameter at breast height (DBH), tree species, soil organic matter depth, effective rooting depth, tree height, tree density or basal area, and slope position of the tree (Delong et al. 2001, Steil et al. 2009). These site and tree factors act in concert with wind to determine the potential for windthrow.

Windthrow due to storms is the most widespread and immediate cause of damage to forests around the globe (Constantine et al. 2012). Forces of wind bursts in storms are major contributing factors to damage of forest trees and can cause of both uprooting and snapping off of trees. Uprooting of trees can expose both soils and bedrock (Constantine et al. 2012). Soil may be exposed when the tree falls and the leverage forces of the tree acting as a fulcrum levers the soil and roots out of the ground. Such soil exposures are known as root wads, soil tip up mounds, root mounds and such exposed mineral soils could theoretically lead to increase soil erosion and stream sedimentation if root mounds were in sufficient numbers and proximities to
streams. Eastern hemlocks tend to grow in cool mesic areas such as riparian forests directly next to a waterway. In addition to potential sediment increases, immediate ecological impacts from windthrow include formation of pit and mound topography, potential addition of large wood to stream channels, bank stability decreases as trees immediately adjacent to the stream are uprooted, and fine branch materials introduction into waterways (Lewis 1998, Bahuguna et al. 2010). Such effects may be considered negative or positive depending on the interest of concern. Large wood in the stream channel often improves aquatic habitat for many fish species (Evans et al. 2012), yet may impede recreational access. Pit and mound topography creates microhabitats for a variety of species including amphibians and exposes buried seed banks which ultimately can provide for re-establishing fauna on the site (Clinton and Baker 2000). However, the same windthrow could potentially lead to increased stream sedimentation and reduce aquatic habitat suitability.

**Soil Erosion and Sedimentation Causes and Potential Effects**

Accelerated or anthropogenic soil erosion and soil sedimentation are associated with anthropogenic activities including agricultural, silvicultural, urban, mining, and recreational activities (Yoho 1980, Pimental and Kounang 1998). However, soil erosion is also a natural process and even undisturbed forests have some level of erosion due to natural disturbances such as windthrow. Patric (1976) evaluated eastern forest land and concluded that typical natural erosion rates ranged between than 0.05 and 0.1 tons /acre/year (0.11 and 0.22 metric tons/hectare/year). Within the Chattooga Wild and Scenic River corridor potential soil erosion could be from natural disturbances such as windthrow in riparian zones, stream bank erosion during
flood events and/or erosion from anthropogenic disturbances such as recreational trails, access roads, and camp grounds.

Sediment is comprised of the three soil textural classes: sand (<2000 micro-meters, >63 micro-meters), silt (<63 micro-meters, >2 micro-meters), and clay (<2 micro-meters) (Te Slaa et al. 2013). Larger sand particles are more rapidly deposited from suspension in water while clay particles can remain suspended for many hours and are more readily transported to waterways. The degree to which surface runoff, erosion and subsequent sedimentation take place is a complex interaction of soil physical and chemical factors including texture, soil structure, roots reinforcement, surface cover, soil infiltration rates, soil moisture levels, and slopes. Eroded material can be deposited on land or it can reach waterbodies and become stream sediment. Sedimentation is the largest non-point source pollutant problem in the United States (Lenat et al. 1981). Sediment decreases the utility of water for human consumption and irrigation and degrades the aquatic habitat. Furthermore, sediment can carry attached pollutants such as nutrients, metals, and pesticides (Lenat et al. 1981). Sediment can increase turbidity, reduce light penetration into the water, and affect primary productivity which could impact the aquatic food chain (Wood and Armitage 1997). Fine sediment in the waterway can reduce fish populations by entering their gills and reducing their ability to absorb oxygen, as well as increased turbidity could potentially lead to fish population dispersing or migrating from the area (Duda 1985). Over an extended period of time sedimentation in waterways can have lasting if not permanent effects on the ecosystem and aquatic habitat (EPA 2000). Sedimentation is known to reduce available food which could potentially result in depressed growth rates of fish, reduced reproduction, and recruitment for future generation (Henley et al. 2000). Clearly, soil erosion and subsequent sedimentation can have numerous detrimental effects; thus, managers of
wild and scenic protected river such as the Chattooga River are attentive in identifying and managing significant sources of sediment.

**Sediment Trapping in the Riparian Area, and SMZ benefits**

In order to minimize stream sedimentation, erosion can be prevented or sediment can be trapped before it enters a waterway. Maintenance of soil cover is an important technique for prevention of soil erosion from natural forests. Riparian buffer strips between the potential erosion and the waterbody provide a common and effective mechanism for trapping erosion before it reaches the water’s edge. Anderson and Lockaby (2011) concluded that streamside management zones (SMZs), and managed riparian buffers (SMZs, riparian buffers) are a very effective and efficient best management practice for the protection of streams form sediment. With regard to hemlock windthrow and potential for subsequent-sediment from exposed root mounds within riparian zones, we considered the effectiveness of the existing riparian zone for trapping sediment. Numerous studies have found riparian buffers to be effectual for sediment filtering. Lakel et al. (2010) found that SMZs between 7.6m to 20.4m SMZs (7.6m, 15.2m, and 30.4m) were effective sediment filters. Lacey (2000) found that narrow undisturbed forest buffers trapped almost 100% of sediment entering from skid trail sources under all flow conditions experienced within the study. Ward and Jackson (2004) also found that SMZs worked well to filter and trap sediment from overland flow from harvested and site prepared areas. Riparian areas slow the flow of water which allows the sediment to be deposited within the riparian area rather than the waterway. Some SMZs are not 100% effective and SMZ failures have been reported when concentrated flows bypassed the riparian area or the riparian area was compromised by activities such as stream crossings (Lacey 2000, Ward and Jackson 2004, Lang
et al. 2015). However, riparian areas commonly provide effective protection for water quality by filtering sediment, up-taking and transforming nutrients, and provision of shade (Lee et al. 2003).

In addition to protecting water quality, riparian forests are beneficial to both aquatic and terrestrial wildlife. Riparian forests have been found to support in stream habitat and food chain by providing large and fine wood to the waterway (Dolloff and Webster 2000). Riparian forests have also been shown to possess many positive attributes for overall environmental quality including water quality, terrestrial habitat quality, and aquatic habitat quality (Aust and Blinn 2004). Riparian forests also serve the needs of recreationist and anglers, having an abundancy of positive effects for forest and habitat conservation. In a study conducted by Backlund et al. (2006), anglers were surveyed to rate the importance of 12 attributes while deciding upon a suitable substitute stream for the Chattooga river. The most important attribute found was water quality; which can be improved or maintained by a healthy riparian area. Increasingly, riparian forests have proven to be effective means to trap sediment as well as provide ecosystem services in many other ways; therefore, a healthy riparian area often equates to a healthy terrestrial and aquatic ecosystem. In this study we examined the riparian area as a means to ascertain the potential of sediment reaching the waterway from uprooted hemlocks, which are often found directly on or extremely close to the stream bank.

**Purpose and Objectives**

The overall goal of this project is to understand the potential for soil erosion and potential stream sedimentation from uprooted eastern hemlock. Specific objectives of this study were 1) to document the degree of hemlock decline and associated windthrow and 2) to ascertain whether soil erosion from eastern hemlock uprooting is a significant contributing problem to sediment in the Chattooga Wild and Scenic River. Primary tasks were to A) conduct an inventory hemlock in
the riparian forests, B) estimate erosion from the sampled uprooted hemlocks C) ascertain the potential for sedimentation to the waterway, D) locate the areas of highest concern for uprooting, and E) provide managers with insight to the extent and severity of the potential problem to allow informed management decisions concerning dead standing hemlock in the riparian area of the Chattooga River and its tributaries.

**Methods**

**Study site description**

The Chattooga River is 57 miles (91.7 kilometers) long flowing south from North Carolina into South Carolina and Georgia. The Chattooga River consists of a 15,432 acre (6248 ha) corridor within three national forests; the Natahala NF in North Carolina, the Chattahoochee NF in Georgia, and the Sumter NF in South Carolina (USDA Forest Service 2008). The selected tributaries and study area were determined by the United States Forest Service as being representative of the Eastern Hemlock riparian forests affected by Hemlock Wooly Adelgid that have potential for uprooting and contributing sediment to the Chattooga River. The study area for this project was five tributaries of the Chattooga River: 1) East Fork Chattooga River, 2) Fowler Creek, 3) Indian Camp Branch, 4) King Creek, and 5) Crane Creek. The combined length of the tributaries was 20.0 miles (32.25 kilometers) and the width inventoried on either side of the stream was 98.4 feet (30 meters), which provides a study area of 478 acres (193.5 hectares). Within this study area we inventoried eastern hemlock and estimated potential soil erosion along 7.8 miles (12.5 km) of stream and 185 acres (75 ha) of riparian forest.

**Office Methods**

ArcGIS was used to point delineate 1640 feet (500 m) reaches of the tributaries and those stream reaches were uploaded onto GPS units to be taken into the field. These stream reaches
were also delineated onto 1:24,000 scale USGS topographic maps for field use. Inventory equipment included GPS units, handheld electronic data collection devices with data collection sheets uploaded, spot units in case of distress, write in the rain note books for hand written data collection, 100ft cloth tape measures, USLE for forestland users guide manual (Dissmeyer and Foster 1984), USLE data collection sheets, waterproof backpacks, clinometer, and maps.

Field Methods

Field data were collected during summer 2016 by a six-person field team from the USDA Forest Service Center for Aquatic Technology Transfer (CATT). Personnel were cross trained for data collection and always worked in at least two person crews.

Hemlock inventory

The USGS website for gauge number 02176930 for the Chattooga River at Burrells Ford near Clayton Georgia was used to determine when water flow levels of the Chattooga River were conducive to stream wading and data collection. The Eastern hemlock inventory counted every eastern hemlock, dead or alive, within the riparian zone and was not separated into dead or alive categories as the majority of hemlock were dead or dying. All inventoried eastern hemlock were \( \geq 10 \) centimeters in diameter at breast height (visually estimated) and were within 30 meters of the stream (visually estimated) from both the right and left bank. Eastern hemlock were recorded as standing, snapped off and standing, or uprooted. Uprooted hemlocks were noted and were also marked with flagging tape so they could be revisited for soil erosion estimates. This process was conducted within each 1640 ft (500 m) tributary segment in the study area. Some waterway reaches that were originally selected for data collection were not traversable (due to waterfalls, overgrown conditions, other safety hazards) and were therefore rejected from the study. Twenty
five 1640 ft (500m) segments were inventoried providing a total 7.77 miles (12.5 kilometers) of stream reaches that were used in the inventory and soil data collection. These techniques were adopted following a similar protocol originally developed by Dolloff, Krause and Roghair (USDA FS report 2014).

**Soil erosion estimates**

Potential soil erosion rates were estimated for each uprooted hemlock by applying the Universal Soil Loss Equation (USLE) forestland soil erosion estimation method. All uprooted Eastern hemlocks within the riparian area (30 meters on both sides of the waterway) were sampled. At each uprooted hemlock we recorded data on rainfall and runoff, soil erosivity, slope percent, slope length, percent bare soil, width and length of the pit and mound. Uprooted hemlock pits and mounds were photographed with a photo reference (Figure 10) and geo-tagged using the GPS units. Additional notes described condition of uproot, condition of bank, or distance from water’s edge to further analyze the area of erosion. We also measured widths and lengths of each uproot pit and mound and converted those measures to estimates of area. Finally we used the potential erosion estimates of mass/area/time and area of root wad disturbances to estimate the potential erosion per year for the stream reaches. This process was applied to each hemlock uproot observed and measured in our study.

**Modeling Methods for the Universal Soil Loss Equation (USLE)**

The USLE is an empirical model that considers six major factors in order to predict potential soil erosion. Major factors include rainfall and runoff index (R), soil erodibility (K), slope percent and slope length (LS), and cover and support practices (CP). The CP factors contain an additional 5 sub-factors; bare soil and fine roots, canopy cover above bare soil, onsite depression storage, and high organic matter content (Dissmeyer and Foster 1980). At each
uprooted hemlock these factors were determined by applying the “Guide for Predicting Sheet and Rill Erosion on Forest Land” (Dissmeyer and Foster 1980) and using the values within the equation; \( A(\text{estimated soil erosion}) = RKSCP \). \( A \) is estimated in tons per acre per year and subsequently converted to appropriate units (lbs/acre/yr and kg/ha/yr).

**Analysis and Interpretations**

Data were entered into a Microsoft Excel Spreadsheet. Inventory data were used to generate the total inventory count of hemlock within the riparian buffer, as well as total counts for standing whole, snapped off, or uprooted categories. This was completed for each tributary sampled and for the entire data set. From these data the sampling percentages within tributaries were determined so that overall potential effects could be estimated. Potential soil erosion data were used to develop means, medians, high values, and low values for the estimated soil erosion at each hemlock uproot; this repeated for each tributary that was sampled and for the data set as a whole. The length of tributary sampled and the actual length of the tributary were used to extrapolate the potential soil erosion over the entire area of interest.

**Results**

**Inventory Results**

Water levels and flow rates were relatively low during the field data collection, thus sampling was facilitated by the opportunity to wade for a majority of the inventory. We sampled 7.77 mi (12.5 km) of five Chattooga River tributaries equating to 185.3 acres (75.0 ha) of inventoried area (Table 1 and Figure 5). The East Fork Chattooga River inventory consisted of fifteen 500m segments at 4.66 mi (7.5 kilometers) sampled (Table 1). The East Fork
Chattooga River Tributary comprised 69.6% of the total inventory (Table 2, Figure 2) and contained 2722 total hemlocks ≥ 10 cm within the designated riparian zone and 433 hemlocks were broken off while 42 had been uprooted (tip-ups) (Table 2). Indian Camp Branch consisted of 4 segments at 1.24 mi (2 kilometers) sampled (Table 1) and this tributary comprised 11.84% of the inventory (Table 2, Figure 2). Indian Branch had 463 hemlocks within the designated riparian zone, including 66 break offs and 8 tip-ups (Table 2). Crane Creek’s two segments provided 0.62 mi (1 kilometer) of inventory (Table 1), thus containing 9% of the inventory observations (Table 2, Figure 2). The 352 hemlocks along Crane Creek’s designated riparian zone included 37 break offs and 5 tip-ups (Table 2). The three segments along Fowler Creek at 0.93 mi (1.5 kilometers) sampled (Table 1), made up 5.14% of inventory observations (Table 2, Figure 2) and included 201 hemlocks within the designated riparian zone, including 41 break offs and 2 tip-ups (Table 2). Finally, the King Creek inventory contained only one 0.31 mi (0.5 kilometer) stream segment. King Creek comprised only 4.42% of inventory observations (Table 2, Figure 2) and the 173 hemlocks within King Creek’s riparian zone included to include 31 break offs and 1 tip-up (Table 2).

A total of 3911 eastern hemlocks were inventoried and consisted of 3245 standing whole hemlocks (82.97%), 608 break offs (15.55%), and 58 tip-ups (1.48%) (Table 2, Figure 1). The majority of our sampling (60%) occurred in the East Fork Chattooga River (Table 3, Figure 3), due to the size and access of the East Fork Chattooga River in comparison to the other tributaries sampled. The data from the other 4 tributaries are representative of the smaller sizes of these tributaries and the adverse access conditions. Certain segments were not sampled due to the inaccessibility and dangerous sampling conditions.
The quantity of potential soil erosion from hemlock uprooting that could potentially deliver sediment to the waterways was estimated by evaluating the average distance of each detected root mound from the stream channel, 27 observations of distance to the waterway were noted giving an average distance of 9.18 feet (2.8 meters) (Table 5). Based on previous research, riparian buffers of 25-50 feet (7.6m and 15.2 m) have been found effective for sediment prevention (Lakel et al. 2010). We used the tree locales, frequencies, and erosion estimates to predict sediment loading attributable to hemlock root mounds.

**Estimated Soil Erosion Results**

Potential soil erosion at each tip-up as estimated by the Universal Soil Loss Equation (USLE) was expressed as Lbs/ac/yr (Kg/ha/yr) or Lbs/ac (Kg/ha) due to the small area and quantities of erosion associated with each tip-up. The area and potential soil erosion at each tip-up were used to estimate potential soil erosion from the entire riparian sample area for each tributary and for the entire riparian area. Sample data were extrapolated to estimate the entire potential for each riparian area (sampled and non-sampled) and the entire Chattooga riparian area. Potential soil erosion was estimated from all tip-ups (with the exception of one older tip-up that was completely covered with litter). In the East Fork Chattooga River the 36 tip-ups observed comprised 63.16% of all pit and mounds observed from uprooted hemlock (Table 3) and the potential soil erosion from the East Fork Chattooga River averaged 22.1 lbs/ac/yr (24.81 kg/ha/yr) (Table 3). The extrapolated soil erosion estimate for hemlock tip-ups along the entire length of the East Fork Chattooga River equaled 35.4 lbs/ac/yr (39.69 kg/ha/yr) (Table 3). In Indian Camp Branch eight tip-ups comprised 14.04% of all pit and mounds from uprooted Eastern hemlock (Table 3). Potential soil erosion averaged from Indian Camp Branch equaled 21.1 lbs/ac/yr (23.65 kg/ha/yr) (Table 3) and extrapolated potential soil erosion estimates for the
entire length of Indian Camp Branch provided 36.9 lbs/ac/yr (41.38 kg/ha/yr) (Table 3). Along Crane Creek five tip-ups were detected (8.77% of all pit and mounds observed from uprooted hemlock) (Table 3), with an average potential soil erosion of 1.8 lbs/ac/yr (1.99 kg/ha/yr) (Table 3). Crane Creek had an extrapolated soil erosion for the entire tributary length 8.9 lbs/ac/yr (9.93 kg/ha/yr) (Table 3). The Fowler Creek tributary provided six tip-ups (10.53% of all pit and mounds observed from uprooted hemlock) (Table 3), with an estimated soil erosion in the Fowler Creek inventory of 22.3 lbs/ac/yr (24.98 kg/ha/yr) (Table 3) and an extrapolated potential soil erosion estimate for the entire length of Fowler Creek of 100.4 lbs/ac/yr (112.39 kg/ha/yr) (Table 3). King Creek contained the lowest number of tip-ups (2 tip-ups, 3.51% of all pit and mounds observed from uprooted hemlock) (Table 3). Potential soil erosion from inventoried area of King Creek was predicted to average 13.6 lbs/ac/yr (15.24 kg/ha/yr) (Table 3) and extrapolated soil erosion estimation for the entire length of King Creek of 136.2 lbs/ac/yr (152.41 kg/ha/yr) (Table 3).

Finally, data for all 57 tip-ups observed in the total inventory of all tributaries were used to provide an overall estimate of potential erosion for the entire sample area 7.77 mi (12.5 kilometers) (Table 1) at 185.3 acres (75 ha) (Table 1) and for the entire area of the five tributaries total distance of 32.25 kilometers (20.04 mi) (Table 1) at 478.1 acres (193.5 ha) (Table 1). Potential soil erosion for all 57 tip-ups observed over the 7.77 mi (12.5 kilometers) averaged 19.7 lbs/ac/yr (22.03 kg/ha/yr) (Table 3) with an average of 63.9 lbs/yr (28.98 kg/yr) per tip-up, median of 19.6 lbs/yr (8.89 kg/yr) per tip-up, maximum of 450.3 lbs/yr (204.24 kg/yr) per tip-up, and minimum of 0.2 lbs/yr (0.09 kg/yr) per tip-up (Table 3, Figure 4). Extrapolated over the entire 20 miles (32.25 kilometers) the estimated soil erosion is 9418.57 lbs/yr (4272.19 kg/yr).
Distances from tip-up to stream bank was not recorded for all 57 tip-ups observed, but was recorded for a sub-sample of 27. The average distance of hemlock tip-ups from the stream bank was 9.18 feet (2.8 m) (Table 5) with the minimum observed distance being 0 feet (directly in the stream), the maximum observed distance being 55 feet (16.8 m) (Table 5), and the median distance to the stream being 1 ft (0.3 m); same as the “on stream notation” (Table 5). While this is not all inclusive it provides an assessment of hemlock tip-up locations that is representative of the site based on field observations of all hemlock pit and mounds. All 57 tip-ups analyzed in this study were relatively close to the channel within the riparian area.

**Discussion**

During the inventory, visual observations indicated the mortality of eastern hemlock in this area to be greater than 90% and all were either dead, or in immediate danger of dying from heavy infestations of hemlock wooly adelgid. Due to the effects of HWA infestation, 15.55% of hemlocks observed were snapped off along the stem and 1.48% of all hemlocks observed were uprooted (Figure 1). Approximately 83% of all hemlocks observed in the study were still standing and whole, yet the number of snap offs and tip ups will continue to increase as the stems decompose and increase in fragility (Figure 1). Thus, dead hemlocks will continue to contribute both fine and coarse wood to the watersheds, but the shade and litter provided by the hemlocks will be declining. Other researchers have evaluated the effects of hemlock decline and speculated that the hemlocks will be replaced by rhododendron and riparian hardwoods depending on current stand conditions (Ellison et al. 2005, Ford et al. 2012, Spaulding and Rieske 2010). These trends are anticipated for the Chattooga tributaries.

The estimated erosion rate from hemlock uprooting in the sample area was determine to be 19.7 lbs/ac/yr (22.03 kg/ha/yr) (Table 3). This number is very low, almost nullified, when
compared to the normal sediment levels of undisturbed forestland (Table 4) which is approximately 100 to 200 pounds of soil per acre per year (Patric 1976, Stuart and Edwards 2006). Estimates of potential soil erosion rates indicate that potential sediment delivery to the Chattooga and its tributaries due to tip-up mounds are very low and the rates are below or near normal geologic erosion rates. Thus, increases in sediment due to the erosion associated with tip up mounds are not a significant management concern along the observed tributaries. Indeed, the estimates are actually assuming that all of the eroded material would reach the stream, yet since the tip up mounds are located within forested riparian buffers having good litter cover, these values are significantly inflated. Erosion from three forest harvesting sites in the Virginia mountains (Worrell et al. 2011) produced potential erosion rates from skid trails as high as 17.2 tons/ac/yr and erosion rates from spur roads were found to be as high as 25.1 tons/acre/year. These rates are over 1000x greater than the contributions associated with tip up from Hemlock wooly adelgid mortality in the Chattooga tributaries. In agricultural practices 1 millimeter of soil can erode from one rain event and go unnoticed, but over one hectare equals to 6.07 tons/acre/year erosion (15 tons/hectare/year) (Pimentel 2006). Furthermore, the worse-case scenario for potential soil sedimentation in the Chattooga from the uprooting of hemlock would still be minuscule if all the standing whole hemlocks uprooted at the same time, 3245 hemlocks in total as indicated above. In this case the amount of erosion is estimated to be 343.24 pounds of soil per acre per year (Table 4), just 143.24 pounds greater than what is expected from normal sediment rates in an undisturbed forest. These figures show how low the estimated erosion amount is compared to other erosion amounts seen in forested settings, and how low the potential is for sediment impact on the Chattooga River and its tributaries from uprooted hemlocks.
Further analysis was done to ascertain the volume of soil that was being displaced by each pit and mound created by these tip-ups. Doing this analysis did reveal that the initial spike of erosion and possible sediment in the waterway could be somewhat large compared to the USLE estimate. Based on the volume equation for an ellipsoid divided by two because the pit is only half an ellipsoid, then divided by two once again to account for root mass and estimating pit depth based on the width measurements and photos taken, we estimated that the soil displaced in our sample area due to tip-ups was 7.31 tons/acre (Table 4). This estimate is an overestimate but does indicate that when the tree uproots it’s potential to introduce a spike of initial erosion and sedimentation is great; however, it would only be a spike of erosion due to landscape changes over time. To discover this estimate we used the above mentioned equation and 76 pounds per cubic foot for soil weight ([http://www.engineeringtoolbox.com/dirt-mud-densities-d_1727.html](http://www.engineeringtoolbox.com/dirt-mud-densities-d_1727.html)) determining the tons of soil displaced by each tip-up and across an entire stand. This done for the purpose of understanding the full potential of erosion and sedimentation from tips-ups along the Chattooga River and its tributaries.

**Future Research Needs**

These findings indicate that hemlock tip-up mounds are not a significant source of sediment to the Chattooga tributaries. Thus, there is a need for continued and further research in the future to better understand the potential sources of sediment to the Chattooga River. Additional avenues of investigation in order to understand the current sediment levels might include stream bank erosion, authorized and unauthorized recreation trails in the area alongside the Chattooga River and its tributaries, and access roads and stream crossings within the
watershed. These sources of sediment have proven to be significant in other studies and such investigation could help managers understand and mitigate current sources of sediment.

**Conclusions**

This study was conducted to understand the potential for sedimentation in the Chattooga River and its tributaries from Hemlock Wooly Adelgid that might be accredited to Eastern hemlock uprooting inside the riparian area. Estimates of erosion from hemlock pits and mounds were low and were within normal erosion rates for undisturbed forestland. Even using the scenario of 100% hemlock death and tip-up within a short time frame, the levels of erosion are relatively minor when compared to other potential sediment sources. In conclusion, sedimentation from hemlock tip-ups is not an issue of concern, but rather within the expectation for normal sedimentation expected in an undisturbed forest setting.

The inventory of hemlocks in the riparian area of the streams studied revealed that the mortality rate of hemlocks in the area of the Chattooga River and its tributaries is extremely high, greater than 90% by observation. The density of hemlocks in this area is high, as 3911 hemlock were observed in the 12.5 kilometer stretch we studied. The percentage of hemlocks snapped off along the stem of the tree was over 15%, indicating the level of degradation that the dead and dying hemlocks are in is extensive. The implication of this, as stated above, is of less concern for uprooting but more so for snapping off along the stem creating a safety hazard for recreational users and forest managers. The greater potential concern for HWA affected hemlock along the Chattooga River and its tributaries would be safety rather than sedimentation. A possible mitigation of this potential issue is to fell the trees of greatest concern near high visitation areas. Felling could also mitigate uprooting of hemlock in the riparian which still has safety implications even though the sediment concern has been shown to be rather minor.
A potential way to manage dead stand hemlock to mitigate concern over safety implications, whether by trees snapping off along the stem or uprooting entirely, would be to utilize a GIS map highlighting areas that are of greatest concern for snapping off or uprooting. By overlaying layers in GIS that have all the factors that contribute to uprooting and snapping off managers could pinpoint the areas that are currently most likely to experience these types of disturbances and use that to focus management efforts (Figures 6 through 9). This would reduce the cost of management as well as increase efficiency of management while mitigating the concerns related to hemlock mortality along the Chattooga Wild and Scenic River.

Based on previous research findings that a 7.6 meter (25 feet) SMZ is appropriate to trap most erosion that would make it to a waterway and become sediment (Lakel et al. 2010), and the findings of this study that the average distance an uprooted hemlock from the stream was 9.18 feet (2.8 meters) (Table 5), we can assume that most erosion from these tip-ups is making it to the stream. The distance to the stream is likely inadequate to filter much of the erosion prior to reaching the waterway; however, the amount of soil erosion delivered from these uprooted hemlock is insignificant and not a lasting delivery of sediment as it will naturally decrease over time given vegetative growth and cover of the exposed bare soil.
Acknowledgements

We would like to thank the USDA Forest Service CATT (Center for Aquatic Technology Transfer) team that participated in the set up and data collection of this study to include Craig Roghair, USFS, Colin Krause, USFS, Lilly O'Dea, Allison Bryan, Cantley Krafft, Kallie Thornhill, and Laura Guthrie for their support in collecting the data and their unquestionable professionalism throughout the process. We would like to thank Richard McBride for his assistance in the initial reconnaissance of the study area and for his assistance with the GIS map that was created, his effort and enthusiasm was greatly appreciated. We would also like to recognize Tyler Hemby for his assistance with the GIS map creation, without the help and assistance of all mentioned this project would not have happened the way that it did, their work in this was invaluable.
References Cited


### Tables and Figures

Table 1. Distance and area for each tributary sampled and actual; percentage of actual length sampled.

<table>
<thead>
<tr>
<th>Tributary</th>
<th>Tributary Distance Sampled (km)</th>
<th>Tributary Area Sampled (ha)</th>
<th>Tributary Area Sampled (ac)</th>
<th>Tributary Total Distance (km)</th>
<th>Tributary Total Area (ha)</th>
<th>Tributary Total Area (ac)</th>
<th>Tributary Sample (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Fork Chattooga</td>
<td>7.5</td>
<td>45</td>
<td>111.2</td>
<td>12</td>
<td>72</td>
<td>177.9</td>
<td>62.5</td>
</tr>
<tr>
<td>Indian Camp</td>
<td>2</td>
<td>12</td>
<td>29.7</td>
<td>3.5</td>
<td>21</td>
<td>51.9</td>
<td>57.1</td>
</tr>
<tr>
<td>Crane Creek</td>
<td>1</td>
<td>6</td>
<td>14.8</td>
<td>5</td>
<td>30</td>
<td>74.1</td>
<td>20</td>
</tr>
<tr>
<td>Fowler Creek</td>
<td>1.5</td>
<td>9</td>
<td>22.2</td>
<td>6.75</td>
<td>40.5</td>
<td>100.1</td>
<td>22.2</td>
</tr>
<tr>
<td>King Creek</td>
<td>0.5</td>
<td>3</td>
<td>7.4</td>
<td>5</td>
<td>30</td>
<td>74.1</td>
<td>10</td>
</tr>
<tr>
<td>All five Tributaries</td>
<td>12.5</td>
<td>75</td>
<td>185.3</td>
<td>32.25</td>
<td>193.5</td>
<td>478.1</td>
<td>38.8</td>
</tr>
</tbody>
</table>

Table 2. Hemlock inventory and percentages of whole inventory for each tributary. Note, 58 tip-ups are tallied in this table, 57 were used in the erosion estimation, this is because all tip-ups were inventoried but not all were eroding soil based on the age of the tip-up and the lack of bare mineral soil.

<table>
<thead>
<tr>
<th>Stream Name</th>
<th>Standing</th>
<th>Break offs</th>
<th>Tip-ups</th>
<th>Total</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Fork Chattooga</td>
<td>2247</td>
<td>433</td>
<td>42</td>
<td>2722</td>
<td>69.6</td>
</tr>
<tr>
<td>Indian Camp</td>
<td>389</td>
<td>66</td>
<td>8</td>
<td>463</td>
<td>11.84</td>
</tr>
<tr>
<td>Crane Creek</td>
<td>310</td>
<td>37</td>
<td>5</td>
<td>352</td>
<td>9</td>
</tr>
<tr>
<td>Fowler Creek</td>
<td>158</td>
<td>41</td>
<td>2</td>
<td>201</td>
<td>5.14</td>
</tr>
<tr>
<td>King Creek</td>
<td>141</td>
<td>31</td>
<td>1</td>
<td>173</td>
<td>4.42</td>
</tr>
<tr>
<td>All Five Tributaries</td>
<td>3245</td>
<td>608</td>
<td>58</td>
<td>3911</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 3. Estimated soil erosion based on the Universal Soil Loss Equation for tip-ups on each tributary sampled and total sample with given mean, median, high and low observed at each tributary and total sample and the estimated soil eroded extrapolated to the entire distance of each tributary and total sample.

<table>
<thead>
<tr>
<th>Tributary</th>
<th>Stream Distance Sampled (mi) (kg)</th>
<th>Stream Distance Sampled (ac) (ha)</th>
<th>Percent Of Total Study Area (%)</th>
<th>Total Count of Tip-ups Per Tributary</th>
<th>Tip-ups Per Tributary (%)</th>
<th>Average Erosion Per Tip-up (lbs/yr) (kg/yr)</th>
<th>Median Erosion Per Tip-up (lbs/yr) (kg/yr)</th>
<th>Maximum Erosion Per Tip-up (lbs/yr) (kg/yr)</th>
<th>Minimum Erosion Per Tip-up (lbs/yr) (kg/yr)</th>
<th>Potential Erosion For Sample Area (lbs/ac/yr) (kg/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Fork Chattooga</td>
<td>4.66 7.5</td>
<td>111.2 45</td>
<td>60</td>
<td>36</td>
<td>63.16</td>
<td>68.4 31.01</td>
<td>23.3 10.58</td>
<td>450.3 204.24</td>
<td>1.5 0.69</td>
<td>22.1 24.81</td>
</tr>
<tr>
<td>Indian Camp</td>
<td>1.24 29.7</td>
<td>16</td>
<td>8</td>
<td>14.04</td>
<td></td>
<td>78.2 35.47</td>
<td>15.7 7.11</td>
<td>443.4 201.12</td>
<td>0.5 0.24</td>
<td>21.1 23.65</td>
</tr>
<tr>
<td>Crane Creek</td>
<td>0.62 14.8</td>
<td>8</td>
<td>5</td>
<td>8.77</td>
<td></td>
<td>5.3 2.38</td>
<td>4.3 1.93</td>
<td>10.3 4.66</td>
<td>0.2 0.09</td>
<td>1.8 1.99</td>
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<tr>
<td>Fowler Creek</td>
<td>0.93 22.2</td>
<td>12</td>
<td>6</td>
<td>10.53</td>
<td></td>
<td>82.6 37.46</td>
<td>45.9 20.84</td>
<td>219.2 99.41</td>
<td>6.5 2.95</td>
<td>22.3 24.98</td>
</tr>
<tr>
<td>King Creek</td>
<td>0.31 7.4</td>
<td>4</td>
<td>2</td>
<td>3.51</td>
<td></td>
<td>50.4 22.86</td>
<td>50.4 22.86</td>
<td>96.5 43.79</td>
<td>4.3 1.93</td>
<td>13.6 15.24</td>
</tr>
<tr>
<td>All five Tributaries</td>
<td>7.77 185.3</td>
<td>100</td>
<td>57</td>
<td>100</td>
<td></td>
<td>63.9 28.98</td>
<td>19.6 8.89</td>
<td>450.3 204.24</td>
<td>0.2 0.09</td>
<td>19.7 22.03</td>
</tr>
</tbody>
</table>
Table 4. Comparison of erosion rates and amounts between a known harvest site, normal undisturbed forest and this site. Both sample site erosion and normal erosion are based on an area of 185.3 acres. Data for harvest site is from Worrell et al. 2011, data for normal erosion rates for undisturbed forest is from Patric 1976 and Stuart and Edwards 2006.

<table>
<thead>
<tr>
<th>Harvest Site Erosion Rates</th>
<th>Erosion Rates from this Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skid trail (lbs/ac/yr)</td>
<td>Normal erosion (lbs/ac/yr)</td>
</tr>
<tr>
<td>34,400</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>19.7</td>
</tr>
<tr>
<td>343.24</td>
<td></td>
</tr>
<tr>
<td>Harvest site Erosion (lbs/yr) Worrell et al.</td>
<td>Sample site Erosion (lbs/yr) from this study</td>
</tr>
<tr>
<td>47,200</td>
<td>3,650.40</td>
</tr>
</tbody>
</table>

Data for harvest site is from Worrell et al. 2011, data for normal erosion rates for undisturbed forest is from Patric 1976 and Stuart and Edwards 2006.
Table 5. Observed distance to stream from uprooted hemlock pits and mounds.

<table>
<thead>
<tr>
<th>Noted Observation</th>
<th>Distance (ft)</th>
<th>Distance (m)</th>
<th>number of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Distance</td>
<td>20</td>
<td>6.1</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>25</td>
<td>7.6</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>20</td>
<td>6.1</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>20</td>
<td>6.1</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>30</td>
<td>9.1</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>10</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>50</td>
<td>15.2</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>55</td>
<td>16.8</td>
<td>1</td>
</tr>
<tr>
<td>Actual Distance</td>
<td>5</td>
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<td>1</td>
</tr>
<tr>
<td>&quot;In Stream&quot; Notation</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>&quot;On Stream&quot; Notation</td>
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<td>0.3</td>
<td>13</td>
</tr>
<tr>
<td>Total/Average</td>
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<td>2.8</td>
<td>27</td>
</tr>
<tr>
<td>Median</td>
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<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>55</td>
<td>16.8</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Percent of total inventory in standing whole, break offs, and tip-ups.

Figure 2. Percent of total inventory contributed from each tributary sampled.
Figure 3. Percent contribution to whole sample from each tributary.
Figure 4. Range of soil erosion from all tip-ups sampled in study
*Note: EF = East Fork, IC/IU = Indian Camp, CC = Crane Creek, FC = Fowler Creek, KC = King Creek
Figure 5. Map of study area with tributaries sampled segmented into 500 meter stretches.
*Note: Bad Creek is labeled on this map but was not part of our study due to access issues.

Figure 6. Picture of the identify tool in the GIS ArcMap model, used to identify features on the landscape that help determine windthrow potential.
Figure 7. Picture of Oconee County, South Carolina in GIS ArcMap model
Figure 8. Picture of Chattooga River with elevation and topography from GIS ArcMap model.
Figure 9. Picture of Fowler Creek close up with elevation and topography from GIS ArcMap model.
Figure 10. Photo of uproot on stream bank with myself as a size reference (6 feet).